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CARLOS FEDERICO HOJVAT
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A METHOD FOR DETERMINING TOTAL PROTON REACTION CROSS SECTIONS

ABSTRACT

Measurements of total proton reaction cross sections by the beam-attenuation method involve determinations of the number of protons removed from the incident beam by an absorber compared to those transmitted. This work presents an adaptation of the associated particle technique to enable total reaction cross section measurements for the 15.8 MeV protons from the $^3\text{He}(d,p)^4\text{He}$ reaction. A thick heavy ice target is bombarded with 600-kev $^3\text{He}$ particles. The $^4\text{He}$ particles are detected in a silicon surface-barrier detector, and the protons, after traversing the absorber, in a CsI scintillation counter. Both the spatial collimation and the time of arrival of the proton are defined by the detection of the associated $^4\text{He}$ particle. Thus, removal of a proton from the proton "beam" is identified by an anticoincidence between the $^4\text{He}$ and proton counters, whereas proton transmission is identified by a coincidence. The limitations and applications of the technique are presented, as well as a discussion of the critical portions of the experimental design.
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We accept this thesis as conforming to the
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A mis padres.

To Sally.
Measurements of total proton reaction cross sections by the beam-attenuation method involve determinations of the number of protons removed from the incident beam by an absorber compared to those transmitted. This work presents an adaptation of the associated particle technique to enable total reaction cross section measurements for the 15.8 MeV protons from the $^3\text{He}(d,p)^4\text{He}$ reaction. A thick heavy ice target is bombarded with 600-keV $^3\text{He}$ particles. The $^4\text{He}$ particles are detected in a silicon surface-barrier detector, and the protons, after traversing the absorber, in a CsI scintillation counter. Both the spatial collimation and the time of arrival of the proton are defined by the detection of the associated $^4\text{He}$ particle. Thus, removal of a proton from the proton "beam" is identified by an anticoincidence between the $^4\text{He}$ and proton counters, whereas proton transmission is identified by a coincidence. The limitations and applications of the technique are presented, as well as a discussion of the critical portions of the experimental design.
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INTRODUCTION

From the phenomenological point of view, the most successful method of describing the average interaction between a nucleus and an incoming particle has, without doubt, been the optical model description.

In this description the properties for the potential describing the interaction are assumed on physical basis and expressed in terms of a number of parameters. By solving the wave equation with this potential a certain number of observables are calculated and compared to experimental results. The parameters are then adjusted in order to obtain a good description of the experimental data. Values obtained for these parameters are not necessarily unique, since their ambiguity depends on the amount and accuracy of the experimental data with which the comparison is made.

In Chapter 1, a simple description of the origin of the Optical Model, the parameterization of its complex potential, the method of calculation and the importance of experimental results in determining the uniqueness of the parameters is presented. Of special interest for our work is the restriction in the parameters that arises from including in the experimental data values for total reaction cross sections for protons measured with errors of the order of 3%. In addition, measurements of the differences between total reaction cross sections for neighbouring nuclei, will provide valuable information on the interactions of the incoming particle with a few nucleons.

Chapter 2 is a review of the different methods emp-
loyed in proton total reaction cross section measurements. Proton reaction cross sections at energies of the order of the Coulomb barrier energies (approximately 10 Mev in medium weight nuclei) are expected to be particularly dependent on the characteristics of the nuclear potential. Accurate measurements at these energies are made difficult by the limit imposed on the sample thickness by the energy loss by the proton beam in it. This results in attenuations to be measured of the order of a few parts in $10^{-4}$.

The description of a new method to measure total proton reaction cross sections, based on the "associated particle technique", is the aim of this thesis. The method is introduced in Chapter 2 Section 4.6.3 as a modification to the coincidence method there described.

A detailed discussion of the design of the experiment is presented in Chapter 3 together with a description of the "associated particle technique" in general. Special attention was placed on analysing the possible sources of background.

As a result of the design considerations, the experimental set up was constructed in order to investigate the usefulness of the method. The set up is described in detail in Chapter 4.

The performance of the system is presented in Chapter 5 together with results for readily available targets of natural copper, iron and gold. These measurements obtained with errors in the order of $14\%$ are in good agreement with values measured by other authors in the same energy range. Possible methods of
improving the technique in order to decrease these errors are presented in Section 5 of Chapter 5.

In Section 4.3 of Chapter 5 the method of performing accurate measurements of differences between total proton reaction cross sections, with our technique, is presented.

The references cited in Chapter 2 are not intended as a complete review of the different methods or their origin, but merely to provide examples complementing the exposition of the subject.

NOTE: Effort has been made throughout the thesis to be consistent with the nomenclature, symbols and units according to the "INTERNATIONAL UNION OF PURE AND APPLIED PHYSICS" published in NUCLEAR PHYSICS 81(1966)677.
1. **THEORY**

1. **General introduction.**

The aim of this Chapter is to briefly introduce the nuclear "Optical Model". Emphasis will be put on the influence of the experimental data in determining the phenomenological parameters of the model, the ambiguities in these parameters, and the importance of the total reaction cross section measurements.

There are available a large number of good review articles and books dedicated to the theoretical aspects and the fitting of experimental data by means of the "Optical Model". See for example (Fe 54), (Br 58), (Bu 60), (Fr 62), (Ho 63), (Ho 64).

2. **Early models.**

The description of a simple event such as the elastic scattering of a nucleon by a nucleus, becomes extremely difficult if detailed account is to be taken of the interactions of the projectile, with each one of the nucleons in the target nucleus. The use of a simplified description is necessary, and normally involves approximation of the many-body interactions in terms of a single particle potential, which represents the average effect of the many target nucleons on the incoming particle.

For incident neutrons, the average potential is an attractive one of nuclear dimensions. For incident charged particles, the net potential is considered as the sum of such a nuclear potential and the Coulomb potential of a finite nuclear charge distribution.

The first attempt in this direction involved the use
of a particularly simple approximation for the nuclear potential, viz., a square well. For this case, a straightforward solution of the Schrödinger equation was possible without the necessity of lengthy numerical integrations. This simple model was used by Bethe in 1935 (Be 35) and even though it yielded some results in agreement with experiments, it failed to account for a number of particularly obvious experimental effects. The extremely large values of the scattering cross sections obtained at widely spaced resonances (approx. 10 MeV spacing, 1 MeV width) were in disagreement with the experimentally observed sharp resonances separated by a few electron volts characterizing neutron scattering.

As an alternative approach to the single particle description mentioned above, Bohr proposed in 1936 (Bo 36) the immediate formation of a many-body state after the incident particle impinges on the target nucleus. This is justified on the basis that many-particle states are necessary in order to explain the closely spaced resonances.

The incoming particle and the nucleons in the target nucleus will all interact strongly with each other, or in other words, the incoming particle will be absorbed by the target nucleus to form a new one: the "Compound Nucleus". Due to this sharing, by the nucleons in the compound system, of the energy brought in by the incoming particle, a much larger number of quantum states are available for excitation. This approach accounted for the low energy neutron resonances that the single particle model failed to account for.

However, subsequent studies of total neutron cross
sections as a function of energy using poor energy resolution gave results similar to those obtained in the single particle model (Fo 50, Ba 52). In addition, compound nuclei were found to decay emitting particles with energies larger than expected on the basis of complete sharing of the incident energy by all nucleons (Gu 54). This indicated that immediate formation of a compound nucleus did not necessarily take place when the incoming particle reached the nuclear surface. After all, the success of the "Shell Model", that had been developed in the interim, demonstrated that nucleons could exist within the nucleus in states of definite angular momentum and definite orbits, without sharing their energy with other nucleons within the nucleus.

3. The optical model.

See (Be 40, Fe 54)

As described previously, neither the single particle model nor the strong interaction one, could provide a complete description of the experimental data. Both seemed to explain qualitatively different aspects of the data. The single particle model explains satisfactorily the average trends for large variations of incoming energy, whereas compound nucleus formation is necessary to explain the fine structure present for small energy variations.

A potential well model could satisfactorily account for the large energy interval effects if proper account is taken of the probability of forming a compound nucleus. In other words, the potential well should accommodate absorption of a certain
fraction of the incoming wave. The way this absorption is introduced into the single particle model, is by allowing the potential well to be complex.

A complex potential gives rise to a complex wave number for the incoming particle inside the nuclear region. Thus the incoming wave is attenuated in propagating within the complex potential. This attenuation, or absorption, is directly related to the introduction of the imaginary term in the nuclear potential.

When the experimental results exhibit a many-particle structure, i.e. sharp separated resonances, the model can not be expected to account for its structure. On the other hand, if the results are "averaged" over a large number of resonances, the model will explain the gross behaviour.

The complex well is referred to as the "The Optical Model potential" due to the analogy with the propagation of light in a semitransparent medium.

An important consideration for the success of the model is to determine the actual shape to be taken into account for the potential. For a spherically symmetrical nucleus, only dependence of the potential on the nuclear radius is to be expected. The simplest potential well will then be a square well. As in any wave phenomena, a sharp edge potential, as the one defining a square well, will produce a large reflection of the incoming wave. In the optical model description, this reflection is just too large to accommodate enough absorption.

If a smoothly varying potential, at the nuclear boundary, is considered, the particle can penetrate into the absorption
part of the potential without being reflected beforehand. Certainly a smooth variation of the potential is physically more reasonable than a sharp boundary. Even when assuming a nucleus with a well defined geometrical boundary, the nuclear interaction will be expected to reach beyond it for a distance determined by the range of nuclear forces. In addition, the actual physical radius of the target nucleus will not be well defined due to oscillations of the constituent nucleons.

From the Optical Model point of view, compound nucleus formation occurs via the absorption arising from the imaginary part of the potential. We must mention here the case of "Compound Elastic Scattering", discussed in detail in Section 2.1 of Chapter 2. This is the decay of the compound nucleus into the same particle and energy that gave rise to it. Such processes can complicate the experimental identification of simple potential scattering as compared to compound nucleus formation.

We must emphasise here the phenomenological nature of the model. The general form of the potential is chosen using some theoretical guidance, but the numerical values are then varied to obtain a "good fit" to the experimental data.

Unfortunately, the vast amount of fitting of experimental data which has been accomplished to date has failed to define a unique shape for the components of the complex potential, (providing a smooth boundary is used). The shape of the imaginary part is particularly ill-defined by the experimental data. This is perhaps expected from simple considerations, the different types of mechanisms involved in the process of absorption can vary
in importance from the nuclear centre to the nuclear surface. As extreme cases we have the possibility of volume absorption, where the imaginary part of the potential extends across the nuclear interior uniformly, following the shape of the real potential; and alternatively, surface absorption, where the imaginary potential is assumed to be localized on the nuclear surface. An increase of absorption in the region of the nuclear surface, with respect to the nuclear interior, is suggested by the possibility of absorption of the incoming wave by excitation of some of the target nucleons into neighbouring quantum states.

These states will be available in the surface region, whereas in the nuclear interior the Pauli principle will forbid transitions into them. The relative values of the Coulomb barriers and the incident energy, for the case of charged particles, will also determine how much of the nuclear interior is exposed to the incoming wave.

4. The terms of the potential.

In this section we will describe the different terms generally used for the optical model potential and their parameterization.

The potential can be written as the sum of:

\[ U(r) = V(r) + i W(r) + V_{SO}(r) + V_C \]

where \( V(r) \) is the real term, \( W(r) \) is the imaginary term, \( V_{SO}(r) \) the spin-orbit term and \( V_C \) is the Coulomb potential for incident charged particles.
4.1. The real term.

The real term can be written as:

\[ V(r) = V \cdot f(r) \]

where \( f(r) \) defines the radial dependence of the term.

The radial form commonly used is the so called "Saxon-Woods" potential or:

\[ f(r) = \left\{ \frac{1 + \exp[(r-R)/\alpha]}{1} \right\} \]  \hspace{1cm} (1.1)

where

\[ R = R_0 \cdot \frac{A}{3} \quad \text{nuclear radius} \]
\[ \alpha = \text{Surface diffuseness} \]  \hspace{1cm} (1.2)
\[ A = \text{Atomic weight} \]

The two parameters governing the radial shape are \( R_0 \) and \( \alpha \); \( R_0 \) determines directly the nuclear radius by the relation (1.2), and due to the assumptions of the model, is expected to be constant for all nuclear species except the light nuclei where a constant density of nuclear matter in the core is not a good assumption.

The constant \( \alpha \) determines how diffuse the nuclear radius is. The interval, centered about the average nuclear radius, where the function \( f(r) \) falls from .9 to .1 of the value at \( r = 0 \) is given by:

\[ D = 4 \alpha \ln 3 = 4.40 \alpha \]  \hspace{1cm} (1.3)

The variations of these two parameters with energy is not so simple to predict. One would not expect the target nucleus to change with the incident particle energy, but the parameters describe the average potential and not the actual nucleus itself. With increasing energy the result can for example become more insensitive to the details of the nuclear
surface and the effective interaction could appear to be restricted to shorter radii. We will see that the existence of ambiguities between the effects of different parameters makes it difficult to obtain phenomenological evidence for such changes.

The third parameter associated with the real part of the potential is the amplitude or strength $V$ whose variation between different nuclear species is not expected to be strong. The model considers each nucleus as an amount of uniform nuclear matter with a size determined by its radius (or mass number). This is justified qualitatively by fitting elastic scattering data for different nuclei at the same energy. On the other hand, the model turns out to be sensitive to the incident energy and the potentials must be changed to obtain even qualitative agreement. This can be interpreted in terms of both the incident particle and the potential being extended in space and at least the real interaction is non-local in character. The formulation of the problem is relatively easy in terms of a local potential. By fitting data for different nuclei at different energies the dependence of the real part of the local potential can be expressed as (Pe 63):

$$V = 53.3 - 0.55 E + 0.4 Z A^{-1/3} + 27 (N-Z) A^{-1}$$

and generally referred to as the "Perey potential" (obtained from proton elastic scattering data in the range of 9 to 12 MeV and for nuclei from Fe to Au. The third term arises from the energy dependence of the real potential in the presence of a Coulomb field (La 57). The fourth term, depending on the nucleon symmetry number, $(N-Z) A^{-1}$, characterizing the target nucleus is expected theoretically on the basis of isospin dependence of nuclear
interaction (La 62). For a recent review concerning these two last terms see (Ho 67).

4.2. The imaginary term.

The imaginary term can be written as:

\[ W(r) = W \cdot g(r) \]

If the radial shape is assumed to be the same as the real term the only parameter specifically associated with it is the strength \( W \). Extra parameters are introduced when a shape different than that of the real term is considered.

In the case of surface absorption usually a Gaussian shape is used. This is described by:

\[ g(r) = \exp \left[ -\frac{(r-R)^2}{b^2} \right] \]

The nuclear radius \( R \) can be taken as equal to that defined for the real term and one more parameter eliminated. The parameter 'b', somewhat analogous to diffusness, defines the "surface thickness" for absorption.

Much effort has been expended in the past in trying to determine the nature of the absorptive imaginary potential, in particular, whether it is primarily a surface or volume term. If a constant volume absorption with surface peaking is used, then at least another parameter must be introduced. See for example (Lu 63).

Another frequent way of introducing a surface plus volume absorption involves a decomposition of the imaginary term of the potential into two terms:

\[ W(r) = W_v f(r) + 4 a_1 W_s \frac{d \left[ f(r) \right]}{dr} \]  

(1.6)
each term with its own strength. The volume part is normally
assigned the same radial dependence as the real part and the
surface contribution the derivative of the volume. The $4a_1$
factor is introduced to make the peak value of the radial
distribution equal to unity. As before another parameter, $W_s$, is introduced.

4.3. The spin-orbit term.

Polarization of the incoming particles occurs when they are elastically scattered by nuclei (Ox 53, Wi 64). As had been proposed by Fermi (Fe 54a) this effect can be taken into account in the optical model by including a "Spin-Orbit" term in the potential. Thus, an extra term will be introduced, of the form:

$$V_{SO}(r) = - C'(\mathbf{l} \cdot \mathbf{\sigma})$$
(1.7)

where $C'$ determines the strength of the interaction, $\mathbf{\sigma}$ is the spin of the incident particle, and $\mathbf{l}$ its angular momentum. This also accounts for the asymmetrical distribution of polarized particles experimentally observed (Fe 55). The shape of the Spin-Orbit potential has been calculated in detail from nucleon-nucleon interaction and is found to be of the form:

$$V_{SO}(r) = - C (\mathbf{l} \cdot \mathbf{\sigma}) \left( \frac{d \varphi}{dr} \right) / r$$
(1.8)

where $\varphi$ is the nuclear density, assumed to be only a function of the nuclear radius. This term has the same form as the Thomas term for the Atomic Spin-Orbit interaction (Fe 55a, Br 57). From this follows the form commonly used for the Spin-Orbit potential,

$$V_{SO}(r) = - V_{SO} (\mathbf{l} \cdot \mathbf{\sigma}) \left( \frac{b}{r} \right) \frac{df(r)}{dr}$$
(1.9)

where $f(r)$ is the radial form of the real potential, and $b$ is a constant equal to $10^{-26}$ cm$^2$ introduced to keep $h(r)$ dimensionless.
and to normalize $r$ to fermis ($10^{-13}$ cm). The negative sign is introduced so that $h(r)$ is always positive. Some authors take the constant $b$ to be similar in form to the one appearing in the Thomas term in atomic physics involving, in this case, the mass of the pion or the proton. This lack of standardization in the definitions must be taken into account when comparing different calculations.

The only parameter to be determined experimentally is the strength $V_{so}$, in energy units.

Polarization measurements are valuable mainly because it arises from the interference between different partial waves. It is reasonable to expect that it depends to a greater extent on the partial wave scattering amplitudes than the elastic differential scattering cross section, and is more sensitive to the nuclear surface structure.

Similar interactions involving target spins are in general neglected. These forces will be expected to affect the polarization results. Experimentally, nuclei with totally different spins are found to yield almost identical polarization results. [See for example: Co($I = 7/2$) and Ni ($I = 0$) in the work of Rosen et al (Ro 65)]. This justifies the lack of consideration of target spins.

An imaginary spin-orbit term $W_{so}$ had been proposed but there is no strong experimental evidence requiring it and so it is generally not considered.

5. The optical model calculations.

In this section we will briefly describe the calculation of observable from an assumed potential. For a detailed
description of the calculations the reader should refer, for example, to the article by Buck et al (Bu 60) or the book by Hodgson (Ho 63).

From the description of the different terms of the potential well of the previous section, the interaction potential can be written as:

\[ U(r) = V \cdot f(r) + iW \cdot g(r) + V_{SO} \cdot h(r) + V_C \ (I.10) \]

where \( r \) is the relative coordinate between the target nucleus center and the incoming particle. With this potential, the radial part of the wave equation can be written down for each partial wave considered. Due to the complex nature of the potential used, the solution of the wave equation will also have real and imaginary components.

The solutions to the wave equation are obtained by dividing the radius \( r \) into two regions, one within the potential well and extending to a radius \( r_M \), where the nuclear potential can be neglected; the other one from \( r_M \) to infinity, a region where the equation can be solved analytically. The solution for the region within the nuclear potential may be obtained by performing a step by step numerical integration. The solution for the region outside the potential, i.e. the asymptotic form of the radial wave function, is analytically known (Sc 55).

All the effects of the interaction are contained in the complex partial wave scattering amplitudes \( S_1 \).

The matching of the logarithmic derivatives of the interior and asymptotic solutions at the radius \( r_M \) provides a continuous wave function over the boundary region. This matching
condition permits the determination of $S_1$. The scattering amplitude $f(\theta)$ is then found using the relation \[(\text{for } V_c=0)\] \[f(\theta) = \frac{1}{2ik} \sum_{\ell=0}^{\infty} (2\ell+1) (\ell\ell-1) P_{\ell}^{(\ell)}(\cos \theta) \tag{1.11}\]

The differential cross section for elastic scattering $\sigma^e(\theta)$, the total elastic scattering cross section $\sigma^e_T$, the absorption cross section $\sigma^a$, and the total cross section $\sigma^T = \sigma^e_T + \sigma^a$ are given by:

\[
\begin{align*}
\sigma^e(\theta) & = |f(\theta)|^2 \\
\sigma^e_T & = \frac{n}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1) |1 - S_\ell|^2 \\
\sigma^a & = \frac{n}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1) (1 - |S_\ell|^2) \\
\sigma^T & = \frac{n}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1) (1 - \text{Re } S_\ell)
\end{align*}
\tag{1.12}\]

Two equations that will be mentioned during chapter 2 are deduced from the set (1.12) and (1.11) One is the Wick's limit:

\[
\sigma^e(0^\circ) \geq \left( \frac{k \sigma^T}{4\pi} \right)^2 \tag{1.13}\]

and the other the optical theorem:

\[
k \sigma^T = 4\pi \text{ Im } f(0^\circ) \tag{1.14}\]

6. **The fitting of experimental data.**

The problem of determining a potential $U(r)$ from experimental data is the inverse one to the calculations described in the previous section. Extensive work went into solving the mathematical problem associated with it, with the result that, in
the general case, a unique determination of \( U(r) \) can not be obtained \( (\text{Ba 49}) \). When the potential \( U(r) \) has some special properties, only then, is this possible. A review of these results can be obtained in T.WU and T.OHMURA "Quantum theory of scattering" (1962) Section G.2. Here we shall just mention the results for a short range attractive potential, i.e. of the type of the nuclear potential. In this case the exact and complete energy spectrum of phase shifts for a given angular momentum are to be known. If this angular momentum is not one corresponding to a discrete eigenvalue, for the potential, the determination of \( U(r) \) is unique. If for the angular momentum value chosen exists 'm' discrete eigenvalues of the energy, then the determination of \( U(r) \) will give rise to an m-fold potential. Each potential of this set will be consistent with the phase shifts and energy eigenvalues.

Therefore, the large amount of accurate experimental data necessary, which for most cases is extremely difficult to obtain, makes this procedure of determining the potential \( U(r) \) impracticable at present.

The technique used to obtain an approximation of the potential involves assuming a form for it containing empirical parameters which are assumed to change slowly, in a uniform fashion from one nucleus to another. With this potential the set of observables is calculated as described in the previous section. The potential parameters are then varied so that a good fit to the experimental data is obtained.

We have used the word "good fit" and not "optimum fit" to the experimental data deliberately. The parameters are
chosen to correspond as much as possible to realistic physical quantities (such as nuclear radius, edge diffuseness, etc.).

The model does not take into account the structural details of each nucleus and so small divergencies from its results are to be expected. From the physical point of view the potential parameters that enable a reasonable fit to a large amount of data are more valuable than those selected to fit special cases well. If the variations of the parameters are done by "hand" a control of the correlations can be done. In the case of automatic fitting by computer, restrictions in the multiparameter space are introduced so that the fitting is made "good" and not optimized.

The comparison between theory and experimental data is normally done using the $\chi^2$ test. The quantity $\chi^2$ is defined as:

$$ \chi^2 = \sum_i \left( \frac{\sigma^i_{\text{exp}} - \sigma^i_{\text{theo}}}{\Delta \sigma^i_{\text{exp}}} \right)^2 \quad (1.15) $$

where $\sigma^i_{\text{exp}}$ corresponds to the experimental values; and $\sigma^i_{\text{theo}}$ to the theoretical values obtained as described in the previous section. For a derivation of this formula see (Ho 63, page 62).

The "optimum fit" can then be defined as the set of parameters that minimizes $\chi^2$.

When experimental values for different types of data are fitted (as elastic differential cross sections, polarizations as function of angle, absorption cross section, etc.) the sum over 'i' in equation (1.15) is understood to include all of them.
7. The importance of experimental uncertainties.

See (1) (Di 66a); (2) (Ho 64); (3) (Me 64)

When a set of experimental data is used to determine the parameters of a potential of given form, the results are not normally unique. How well the parameters can be defined is clearly a function of the quality of the experimental data. Quality is understood to refer to completeness as well as accuracy. Other ambiguities inherent in the model, are those like the \( V/R^2 = \) constant. This ambiguity is plausible theoretically, since two potentials with different values of \( V \) and \( R \), the values being selected only to maintain the requirement of \( VR^2 \) mentioned, give rise to the same number of waves within the nucleus (No 59). This ambiguity is also reported to disappear with improved experimental data (Ho 63, p. 69).

In reference (1) a detailed study of the influence of the different experimental uncertainties in elastic scattering data is presented. It is found that parameter sensitivity to change in experimental data is inversely proportional to the amount of definition of the diffraction pattern in the elastic scattering cross section as a function of angle.

Reference (2) is a general review of the success of the optical model calculations. The model is able to account for all neutron scattering data and reaction cross sections from the resonance region to around 25 MeV. Substantial difficulties are expected to appear if the errors of the experimental cross sections were decreased to about 3% and if measurements could be extended over the whole angular range. The potentials obtained from fitting the differential cross sections give, in general,
a good fit to the total reaction cross sections (to about 4\%) regardless of the detailed shape assumed for the imaginary part.

In reference (3) the influence that more accurate measurements of total proton reaction cross sections could have, in some cases, for reducing the ambiguities for optical model parameters is clearly pointed out by Melkanoff et al.

In Chapter 2 the experimental difficulties involved in obtaining accurate measurements of total reaction cross sections for protons are described. Only during the last few years methods capable of yielding measurements with errors in the 5\% order, for reasonable measuring times, have been published.

Accurate absolute measurements of these total reaction cross sections plus the increasing data available on polarization, see for example (Ro 65), will make complete sets of data for the same nucleus and at the same energy available for large numbers of nuclear species. This completeness in the experimental data will define more accurately the phenomenological parameters describing the potentials.

The experiment described in the present thesis, is a new technique developed to enable the measurements of values for total reaction cross sections for protons, with errors of a few per cent for running time of a few hours.

8. **Computer calculations.**

A complete, detailed discussion of the computational methods currently used for Optical model calculations is presented in "Nuclear optical model calculations" by Melkanoff,

In this section we will mention the programs available at the University of British Columbia.

Most of the calculations connected with the present Thesis were performed with a version of the SCAT-4 program [Melkanoff et al. "A fortran program for elastic scattering analysis with the optical model" University of California Press (1961)]. The program calculates in the center of mass system the differential elastic scattering cross section $\sigma_e(\Theta)$, the polarization $P(\Theta)$, and the total reaction cross section $\sigma_R$. Incoming particles of spin 0 or $\frac{1}{2}$ and spinless targets are considered. The program compares the calculations with experimental data by calculating the value for $X^2$ but does not contain automatic subroutine for varying the parameters to minimize the $X^2$ value. Modifications in the Input - Output statements were introduced to make it more versatile, and simple programs for integration of angular distributions and plotting of output data were added.

Later on, the program ABACUS-2 [E.H. AVERBACH BROOKHAVEN NAT.LAB. BNL6562 (1962)] became available. It is more versatile than SCAT-4 in the sense that it can automatically search for a minimum on the $X^2$ in a 5-parameter space.
2. TOTAL REACTION CROSS SECTION MEASUREMENTS.

1. General introduction.

The importance of the total reaction cross sections in determining the optical model parameters was discussed in the previous chapter. In the present chapter it is intended to review the different techniques used in measuring them, and to introduce the method developed in this laboratory.

First we will discuss the different decay mechanisms of the compound nucleus classified according to the final products, as they are important in the evaluation of the experimental data. Secondly we will describe the different experimental techniques used to obtain the total reaction cross sections.

2. The reaction channels.

The compound nucleus, formed when an incoming particle is absorbed by a target nucleus, will eventually decay to one of a number of possible final states of the reaction. The process that gave rise to the compound nucleus is referred to as the "INPUT CHANNEL".

The final states are referred to as the "OUTPUT CHANNELS" of the reaction. The number of such channels possible and their relative occurrence will depend on the particulars of the reaction involved.

"Partial reaction cross sections" are defined for each of the possible output channels, while the "total reaction cross section" is the sum of all the partial ones. As we will see later on, this adding of partial cross sections is one of the methods used to evaluate the total one.

Gross fluctuations in the partial reaction cross sections
can be expected both as a function of energy for a particular target, and for different nuclear species for fixed bombarding energy. The total reaction cross section, on the other hand, is expected, on the basis of the optical model of nuclear reactions, to be a smoothly varying function of those parameters. Partial cross sections will depend on the particulars of the output channels, such as presence of resonances, neutron thresholds, Q values and so on. The total cross section, however, is only related to the probability of forming a compound nucleus.

The classification of the different channels is indicated in Fig. 2.1. In the following discussion the output channels are divided into: re-emission into the input channel, inelastic scattering, emission of charged particles and neutron emitting channels.

2.1. The compound elastic channel.

Compound elastic events arise from compound nuclei that decay through the input channel, i.e. emission of the same particle
and energy as the incident one.

This process is, at first sight, similar to that of elastic scattering, except that it invokes the intermediate formation of a compound nucleus.

The two processes, elastic scattering and compound-elastic scattering, are experimentally indistinguishable, at present, for most experimental situations. (Ei 60). Recently indirect techniques such as that of "fluctuation analysis" (Er 65), have yielded a determination of the compound elastic for a special case. The technique however, requires spin 0 target nuclei and a very complete angular distribution data.

As seen in the previous chapter using the optical model one is able to calculate the absorption of the incoming wave, representing the removal of particles from the input channel, without detailed consideration of the decay of the system so formed. Since compound-elastic scattering cannot be resolved from that of direct elastic scattering, this contribution must be estimated in order to compare experimental non-elastic cross sections with theoretical values of the total reaction cross sections.

In the high energy region, or when the continuum of the compound system excited states is reached, the competition between the many open channels for decay makes the probability of re-emission into the entrance channel negligible. For low energies, where level density is lower, fewer open channels are possible for decay so that the re-emission probability may no longer be small. When neutron emission is a competitive channel, re-emission of charged particles is generally further inhibited by Coulomb barrier considerations.
One way of resolving compound-elastic from direct elastic scattering that may eventually be possible would involve recognizing the different timing characteristics. A time dependent treatment (Fr 62), shows that re-emission should take place later than the direct elastic scattering, even when experimentally they are not distinguishable by the present timing techniques. (Elastic scattering: $10^{-23}$ seconds, compound-elastic: $10^{-15}$ seconds).

In addition, calculations of compound-elastic cross sections seems to be possible for some simple cases using statistical theory for zero spin target and no possible elastic channels (Ca 60). For a small number of inelastic channels Hauser-Fesbach type calculations could be employed (Ha 52).

2.2 The inelastic scattering channel.

These are compound nuclei that decay by emission of the same incident particle but of different energy, leaving the target nuclei in an excited state. When the energy difference between these and the elastic scattered particles is greater than the resolution of the proton energy detection system, these channels can be experimentally resolved.

According to whether the energy spread of the incident beam is much less than the energy separation between the excited states or not, the energy distribution of the inelastic scattered particles will have definite peaking (corresponding to each possible inelastic channel), or will be a continuum. For the same target and increasing incident energy, first we will find separated inelastic peaks located at an energy equal to the incident energy minus the excitation energies of the respective inelastic channels, or low energy region; then more and more inelastic channels will
become energetically possible and the spectrum will become a continuum, or high energy region.

The inelastic scattering around 15 Mev has been the subject of extensive experimental work on a wide variety of targets (Co 59, Be 61).

For some target nuclei, especially deformed types as in the rare earth region, rotational and collective states can be excited and "inelastic like" scattering produced. The case is now the opposite to the "compound-elastic" situation. Here we have an elastic process, not involving absorption of the incoming wave, appearing as a compound nucleus decay. This contribution can be taken into account by energetically recognizing the levels involved or simply by selecting target nuclei where these effects are negligible.

2.3. The charged particles channels.

These are compound nuclei decaying via open channels involving the emission of a charged particle, other than the incident one.

Charged particles are easily detectable with 100% efficiency. Furthermore simple dE/dX counter techniques allow their identification.

2.4. The neutron channel.

These are compound nuclei that will decay with the emission of a neutron. Only the case of incident charged particles will be considered, since for incident neutrons this will be included in the types of scattering already discussed in sections 2.2 and 2.1.
Threshold measurements for neutron production are available for more than 40 reactions including, protons, deuterons, He$^3$ and alpha as incident particles (Ma 63 p. 1865).

As mentioned before, above the neutron threshold the compound nuclei are generally expected to decay mainly through this channel as the Coulomb barrier inhibits the probability of emitting a charged particle.

The behaviour of the partial cross section near threshold can be approximately described for light and medium nuclei, as proportional to $\Delta E^{3/2}$ (Ma 63 p. 1811), where $\Delta E$ is the energy above the threshold. (When mainly s-wave emission is important). This description is not correct when the threshold energy is close to a resonance of the compound nucleus, but illustrates the fast rise of the partial cross section for neutron production above the threshold energy. When higher angular momentum components are involved, then the dependence on $\Delta E$ is even stronger and neutron emission rapidly becomes the major contribution to the absorption cross section for increasing incident energy.

Accurate measurements of partial cross sections for neutron production had been hindered by difficulties involved in determining absolute efficiencies for neutron detection.

3. The indirect method.

The sum of the partial cross sections for all the open channels is a measure of the absorption of the incoming beam, the formation of compound nuclei or the total reaction cross section.

Obtaining the value of $\Sigma_R$ by adding up the partial reaction cross sections for all the possible open channels is
referred to as the "Indirect method".

From the experimental point of view absolute cross section data is necessary for all the relevant open channels. This summation is only practical for bombarding energies sufficiently low so that only a few decay channels are energetically possible.

The limit of accuracy is set by the difficulties in determining absolute neutron formation cross sections above the respective neutron threshold.

When fission becomes an important contribution, typically 80% to 90% of the total absorption, the method can be applied again (Fu 59).

For applications of the "Indirect method" see (Sl 59, Me 60).

4. The direct methods.

Direct methods are those aimed at measuring total reaction cross sections without detailed consideration of the reaction products. This is equivalent to measuring the attenuation of an incoming beam in going through the target under study.

As a whole these methods involve the comparison of a particle flux with and without the target. They therefore have the advantage that only a single measurement is involved rather than the measurement of a number of partial cross sections.

For reasons of convenience in introducing our method we will further classify the Direct methods according to the technique involved, not necessarily in chronological order.
4.1. The beam attenuation method.

If one can rely on the incident beam intensity being constant over some time 't', a direct comparison of fluxes can be made by alternately putting the target in and out of the beam for periods of time much shorter than 't'. The beam constancy can be checked by monitoring some secondary effect such as elastic scattering from the target or some other characteristic of the particle source dependent on beam intensity.

This method is especially attractive for neutron beam attenuation determinations since the relative nature of the measurement means that detailed knowledge of the absolute counter efficiency is not required.

The expected intensity change for an incident beam of intensity $I$, for a target of thickness $dx$ and $N$ nuclei $\text{cm}^{-3}$, due to a process with a cross section $\sigma$ is:

$$\frac{dI}{dx} = -I N \sigma dx$$

(2.1)

The relative change or beam attenuation $\delta$ is then,

$$\delta = \frac{dI}{I} = N \sigma dx$$

(2.2)

For a sample of thickness $L$ centimeters, we can integrate (2.2) and obtain:

$$\delta = \ln I_0 - \ln I = N \int_0^L \sigma dx$$

(2.3)

For charged particles, the mean energy of the incident beam in the target will be less than the incident energy because of the energy lost in ionization and inelastic collisions with the target atoms. In general $\sigma$ will be a function of energy. If the target is thin enough so that $\sigma$ can be considered constant (a
reasonable approximation for measurements of neutron attenuations):

\[ \delta = \ln \left( \frac{I_o}{I} \right) = N \sigma L \tag{2.4} \]

The "transmission" of the sample is defined as,

\[ T = \frac{I}{I_o} = \exp (-N \sigma L) = \exp (- \delta) \tag{2.5} \]

By measuring the transmission as a function of the target thickness, by the method described above, the exponential law can be checked. (for 95 Mev neutrons, Ju 50).

Expanding the exponential in (2.5),

\[ T = 1 - \delta + \frac{\delta^2}{2} - \ldots \tag{2.6} \]

and for \( \delta << 1 \)

\[ T = 1 - \delta \tag{2.7} \]

Thus,

\[ \delta = \frac{I_o - I}{I_o} \tag{2.8} \]

By measuring the fluxes with and without target the transmission \( T \) can be measured; while for targets with transmissions close to unity, \( \delta \) can be determined directly by using (2.8).

The value of the cross section \( \sigma \) involved will be given by either:

\[ \sigma = (N L)^{-1} \delta \tag{2.9} \]

or

\[ \sigma = (N L)^{-1} \ln (L T^{-1}) \tag{2.9a} \]

When the assumption of the cross section being constant is not valid, then the \( \sigma \) of equations (2.9) and (2.9a) should be
replaced by the mean value
\[ \overline{\sigma} = L^{-1} \int_0^L \sigma(\chi) \, d\chi \]  \hfill (2.10)
where
\[ \sigma(\chi) = \sigma(E - \varepsilon \, d\chi) \]  \hfill (2.11)
and \( \varepsilon \) is the sample stopping power.

When crystalline structure is present in the sample equations (2.9) and (2.9a) which are based on the assumption that the target is isotropic in nature, should be used with care. The effect of crystalline structure is described in section 4.1.3. of Chapter 3.

4.1.1. Statistical considerations.

If the "target in" and "target out" measurements are performed for the same time \( 't' \), then
\[ \frac{I}{I_0} = \frac{M}{M_0} \]  \hfill (2.12)
where \( M \) represents the total number of counts detected.

The contribution of statistical fluctuations in \( M \) and \( M_0 \) to the error associated with a determination of \( \sigma \) are readily determined.

The assumption of equal times for "target in" and "target out" measurements involved in (2.12) is used for convenience in the following discussion. If a fixed time is available for the measurement, the error in the cross section can be reduced by using unequal time intervals for "target in" and "target out" measurements.

By differentiating (2.9) and (2.9a) we find for the relative error,
\[ \eta = \frac{\Delta \sigma}{\sigma} = \frac{\Delta \varepsilon}{\varepsilon} = \frac{\Delta T}{T \ln T} \]  \hfill (2.13)
and from 2.5,

\[ \Delta S = T^{-1} \Delta T \] (2.14)

From the definition of \( T \) (2.5), using 2.12 and the standard deviations for the Poisson distributions of \( M \) and \( M_o \), we get for the variance of \( T \),

\[ (\Delta T)^2 = T M_o^{-1} (1 + T) \]

where the cross or quadratic terms are put equal to zero. From here we obtain the relative statistical error on the transmission as,

\[ \Delta T = (1 + T)^{1/2} \left( M_o T \right)^{-1/2} \] (2.15)

And from (2.13) for the relative errors on the cross section we get,

\[ \eta = \left( 1 + T \right)^{1/2} \left( M_o T \right)^{-1/2} \left( \eta T \right)^{-1} \]

Equations (2.16) permit calculation of the statistical accuracy limit for a sample of transmission \( T \), or attenuation, when the total number of counts without target is \( M_o \).

Figures 2.2 and 2.3 are a plot of \( (M_o)^{1/2} \eta \) as a function of the transmission \( T \) and the attenuation \( \xi \) as described by (2.16).

It is clear that the lower the transmission, or the higher the attenuation, of the sample the better the accuracy on the measurement for the same number of incident particles. This, in turn means better accuracy in the same beam time.

The limit to how thick a target can be is set by the secondary effects so introduced. In the case of charged particles, due to their high specific energy loss, corrections due to the
Figure 2.2: Relative error as a function of the sample transmission.
Figure 2.3: Relative error as a function of the sample attenuation.
averaging indicated in (2.7) are important unless the energy loss in the target is very small compared with the incident energy, or thin targets. Thicker targets, on the other hand, can be used if the trend of the cross section with energy is well known.

For example, for a 1 Mev thick copper target with 16 Mev protons, the expected attenuation of the incident beam will be only a few parts in $10^{-4}$. For a $\xi$ value of $1 \times 10^{-4}$ and a desired statistical accuracy of $\gamma = 5 \times 10^{-2}$, then from Fig. 2.2 we find,

$$\gamma \cdot M_0^{1/2} = 1.4 \times 10^4$$

or at least $M \simeq M_0 = 8 \times 10^{10}$ protons should be analysed.

Such large proton counts lead to severe experimental difficulties. For proton count-rates of even $10^5$ s$^{-1}$, at least 25 hours would be required for a single measurement.

For incident neutrons additional complications such as "multiple scattering" place a practical upper limit to target thickness, much before energy loss considerations are important (Ma 63 p. 992).

We will consider now, in more detail, the case for incident charged particles involving $\xi < 1$ ($T \simeq 1$). From (2.8) and (2.12), we get:

$$\xi = (M_0 - M) M^{-1}$$

(2.17)

We can envisage two types of experiments. As described before, we can measure directly $M$ and $M_0$, this we refer to as the "ATTENUATION BASIC METHOD".

On the other hand if the aim of the experiment is to measure directly the difference:

$$M_C = M_0 - M$$

(2.18)
such an experiment will be referred to as the "COINCIDENCE ATTENUATION METHOD". This technique will be discussed in detail in Section 4.6. At this time we want only to compare both methods from the statistical point of view.

For the basic method with $T=1$ we get from (2.16):

$$\eta = 2^{1/2} \sigma (S M_0)^{-1/2}$$  \hspace{1cm} (2.19)

For the coincidence method, we can rewrite (2.17) as:

$$S = M_c M_o^{-1}$$  \hspace{1cm} (2.20)

The statistical error on $S$ will be determined mainly by the distribution on $M_c$, by differentiating (2.20)

$$\frac{dS}{S} = \frac{dM_c}{M_c} - \frac{dM_o}{M_o}$$  \hspace{1cm} (2.21)

The value for the variance is then, assuming that the cross terms average out:

$$\left(\frac{\Delta S}{S}\right)^2 = \left(\frac{\Delta M_c}{M_c}\right)^2 + \left(\frac{\Delta M_o}{M_o}\right)^2$$

and for Poisson statistics:

$$\left(\frac{\Delta S}{S}\right)^2 = (1 + S) \sigma (S M_o)^{-1}$$

The relative error, given by the ratio of the attenuation standard deviation and the attenuation itself, is:

$$\eta_c = (1 + S)^{1/2} (S M_o)^{-1/2}$$

And for the case of $S \ll 1$ we can write:

$$\eta_c = (S M_o)^{-1/2}$$  \hspace{1cm} (2.22)

The ratio of the relative errors for the two methods is then given by:

$$\frac{\eta_c}{\eta_B} = S^{1/2} 2^{-1/2}$$  \hspace{1cm} (2.23)

where we assume the same number of incident counts in both type of
measurements.

The coincidence method thus offers at least an order of magnitude better accuracy than the basic method for the copper example mentioned earlier, for the same number of incident counts.

4.1.2. Geometry considerations.

In all previous discussions it was assumed that:

a) for target out measurements: all detected particles belong to the incident beam.

b) for target in measurements: all incident particles suffering nuclear interaction were not detected.

Figure 2.4 shows a schematic of a typical attenuation experiment.

A possible background flux of particles, not originating in the incident beam and not depending on whether the target is in or out, will be designated by $I_B$. During the time of measuring
M and \( M_0 \), \( I_B \) will give rise to a number of counts \( M_B \). The real values for \( M \) and \( M_0 \) will then be:

\[
M_0' = M_0' - M_B \quad ; \quad M = M' - M_B \quad ; \quad T' = M' / M_0
\]

where the primes indicate the measured values.

We can assume that \( M_B \) will be proportional to the detected number of particles without target, if both fluxes arose originally from the same source. Thus,

\[
M_B = \beta M_0'
\]

Then the target transmission will be given by:

\[
T = (M' - \beta M_0') (M_0' - \beta M_0')^{-1} = (T' - \beta (1 - \beta)^{-1}
\]

Here we are considering only those events \( M_B \) that are not distinguishable, at the detector, from those forming part of \( M \) and \( M_0 \).

Similar events produced by scattering of incident particles into the final detector by the target assembly could be present and will in general be dependent on the target position.

\( \beta \) can be measured by stopping the direct flux. The second type can be minimized by suitable mechanical design.

These considerations are important for neutron experiments due to the room-scattered background. In the case of incident charged particles, in general, \( \beta \) can easily be made negligible by proper geometrical design.

Let us consider the case of the experimental arrangement illustrated in Figure 2.4. Besides the direct absorption events leading to measurements of the reaction cross section, a number of secondary processes may occur. These processes can have sufficient
magnitude to require estimation in order to correct the measured attenuation.

If the attenuation of the beam is due to a combination of processes occurring in the target each one with a cross section $\sigma_i$, then from (2.1) the change in beam intensity is given by:

$$dI = \Sigma_i dI_i = \Sigma_i IN \sigma_i dx \quad (2.27)$$

and for the relative change:

$$d\delta = \Sigma_i N \sigma_i dx \quad (2.28)$$

Assuming that the target is thin enough for each $\sigma_i$ to be considered constant:

$$\delta = N L \Sigma_i \sigma_i \quad (2.29)$$

We can then define an attenuation $\delta_i$ related to each process $\sigma_i$ as:

$$\delta_i = N L \sigma_i \; ; \; \delta = \Sigma_i \delta_i \quad (2.30)$$

in terms of transmission this means:

$$T = \exp(-\delta) = \exp(-\Sigma_i \delta_i) \quad (2.31)$$

and defining for each process a transmission $T_i$:

$$T_i = \exp(-\delta_i) \; ; \; T = \prod T_i \quad (2.32)$$

Then the cross section calculated from the measurement of $\delta$ or $T$ will be given by:

$$\sigma = \Sigma_i \sigma_i \quad (2.33)$$

Referring back to Figure 2.4 we can, then, decompose the total measured cross section into several terms:

$$\sigma = \sigma_R + \int_{\alpha}^{\beta} \sigma (\theta) d\theta - \int_{\alpha}^{\beta} \sigma (\theta) d\theta - \sigma_M \sigma (\alpha) \quad (2.34)$$
where $\alpha$ is the half angle subtended by the detector.

The first term is the true total reaction cross section; the second term takes care of the attenuation contributed by elastic scattering of incident particles outside of the final detector acceptance angle; the third term takes care of the particles which suffered some nuclear interaction (e.g. compound-elastic scattering) but which are still detected as transmitted ones.

The fourth term takes care of multiple interactions. This will include corrections to the elastic scattering term due to multiple scattering into the detector and to the third term due to multiple scattering outside the detector. If one assumes that all products of the reaction can be distinguished at the detector, then this term will be only related to the elastic scattering. It is referred to, then, as the "in-scattering" correction term.

4.1.3. Total reaction cross section measurements.

From (2.34),

$$\sigma_R = \sigma - \int_0^{\pi} \sigma_E(\theta) d\theta + \int_0^{\alpha} \sigma_{CN}(\theta) d\theta + \sigma_{MS}(\alpha)$$

The "multiple scattering" term accounts for particles that after being elastically scattered outside the detector angle, as considered by the second term, are rescattered into it by a second or more scattering.

In order to obtain the order of magnitude of the multiple scattering term we can estimate the correction arising from double scattering. We will assume that to get "in-scattering" of a particle first scattered into an angle $\theta$ (greater than $\alpha$), a second scattering into $\theta$ is necessary. We can then write for
the double scattering contribution:

\[ \sigma^2 = NL \Omega_D \int_{\alpha}^{\pi} [\sigma_E(\Theta)]^2 d\Theta \]  
(2.37)

or:

\[ \sigma^2 \leq NL \Omega_D [\sigma_E(\alpha)]^2 2\pi (1 + \cos \alpha) \]  
(2.38)

where \( \Omega_D \) is the solid angle subtended by the detector.

The first order of scattering, \( \sigma^1 \), is the second term of (2.36) and can be written as:

\[ \sigma^1 \leq \sigma_E(\alpha) 2\pi (1 + \cos \alpha) \]  
(2.39)

Then:

\[ \sigma^2 / \sigma^1 \leq NL \Omega_D \sigma_E(\alpha) \]  
(2.40)

An order of magnitude for \( \sigma^2 \) is then given by the product of the attenuation due to single scattering into \( \alpha \) by the solid angle subtended by the detector. Typical values for the ratio (2.38) are in the \( 10^{-4} \) order for common experimental conditions. Since similar ratios are expected between each order of scattering and the next, the contributions to the multiple scattering term will decrease rapidly with increasing order. It is clear then that the multiple scattering correction term can be neglected for total reaction cross section measurements.

As is clear from (2.36) the accuracy in the determination of \( \sigma_R \) will be a function of the choice of the angle \( \alpha \). This will determine the relative importance of the elastic correction and the \( \sigma_{CN} \) terms compared to the experimental value of \( \sigma \). The accuracy of the experimental angular distribution data will determine, then, the error introduced in \( \sigma_R \) by these correction terms.
4.2. Basic attenuation method as applied to total reaction cross section measurements for protons.

An example of the basic attenuation method is the measurement of total reaction cross section for 9 MeV protons on copper by GREENLESS and JARVIS (Gr 61).

The beam intensity is assumed to be constant over short time intervals and the target is cyclically interposed in the beam with a frequency of twice a second. The transmitted beam intensity is thus measured with and without target. The use of a beam monitor makes the beam constancy not so critical.

The result quoted is $930 \pm 70$ mb. The experimental raw value of $1530 \pm 70$ mb is corrected by a number of terms adding up to $3405 \pm 76$ mb.

4.3. The charge method.

See (Be 65)

This method is appropriate only for incident charged particles. The schematic of the experiment is shown in Figure 2.5.

In this method, the attenuation of the beam is found by comparing the total charge transported by the beam to that transferred to the target system due to the absorption of charged particles by reactions in it. If an incident beam current of $1 \times 10^{-6}$ A is being used for example, then an attenuation of a few parts in $10^{-4}$ will mean a current transferred to the target of the order of $10^{-10}$ A, a value readily measured using an electrometer. Typically, running times of less than five minutes are quoted as adequate for such attenuation measurement. Basically if 'q' is the charge deposited on the target, and 'Q' the total
charge conveyed by the beam, then the uncorrected attenuation is given by:

$$\delta' = q Q^{-1}$$  \hspace{1cm} (2.41)

The expression (2.41) assumes the presence of negligible background, i.e. $q = 0$ for target-out measurements. Due to the scattering of the incident beam from the collimating slit edges, ionization of the residual gas by the incident beam and emission of secondary electrons from the target assembly, this assumption is not valid.

![Schematic of charge method experiment](image)

Figure 2.5: Schematic of charge method experiment

The attenuation for target-out, $\delta_{OUT}$, has to be considered. Then the real target attenuation is given by:

$$\delta' = \delta_{IN} - \delta_{OUT}$$  \hspace{1cm} (2.42)
The corrections involved for the target-in measurements are:

a) secondary electrons emitted from the target foils;

b) part of the transmitted beam suffers elastic scattering into the target assembly, contributing to the transferred charge;

c) decay channels involving charged particles that escape the target assembly via the entry and exit ports.

Correction c) can be particularly serious if the decay products are multiple charged, e.g. \((p, \alpha)\) reactions.

If the secondary electrons are stopped from leaving the target, e.g. by using a magnet, then the reaction cross section can be written as:

\[
\sigma_R = \frac{S^1}{NL} - \sigma_E + \int_{\text{ENTRY}} \sigma_{p,q}^{(0)} d\Omega + \int_{\text{EXIT}} \sigma_{p,q}^{(0)} d\Omega (2.43)
\]

where the terms are the same as those referred to in section 4.1.3. The \(\sigma_{p,q}\) terms are larger than those in experiments using counters due to the lack of energy discrimination on the beam transmitted to the Faraday cup, but the main correction is represented by the elastic scattering term, \(\sigma_E\), which can contribute up to 70% of the measured transferred charge. Although quoted errors are of the order of 5%, the method is very sensitive to experimental errors in the angular distributions for elastic scattering and for charged particle yield.

4.4. The optical theorem.

See (Ho 65, Ho 65a)

The interference between Coulomb and nuclear scattering at forward angles permits the measurement of magnitude and phase
of the nuclear scattering amplitude. If it is known, by applying the optical theorem:

\[ \sigma_T = 4\pi k^{-1} \text{Im} f(0^\circ) \quad (2.44) \]

where \( f(0^\circ) \) is the forward scattering amplitude, the total reaction cross section can be determined.

We will briefly describe the theory behind the method. The elastic scattering amplitude for an incident charged particle can be written as two separate terms:

\[ f(\theta) = f_{\text{Coulomb}}(\theta) + f_{\text{Residual}}(\theta) \quad (2.45) \]

The origin of the two terms is self explanatory. Now we apply the optical theorem, even when the total reaction cross section is infinite due to the Coulomb scattering:

\[ \sigma_T^{\text{Residual}} = (\sigma_T - \sigma_T^{\text{Coulomb}}) = 4\pi k^{-1} \text{Im} f_{\text{Residual}}(0^\circ) \]

Then, is obtained for the total reaction cross section the expression:

\[ \sigma_R = 4\pi k^{-1} \text{Im} f_{\text{Residual}}(0^\circ) - \sigma_E^{\text{Residual}} \quad (2.46) \]

where:

\[ \sigma_E^{\text{Residual}} = \int \{ \sigma_E(\theta) - \sigma_E^{\text{Coulomb}}(\theta) \} \, d\Omega \]

For very small angles \( f_{\text{Residual}}(\theta) \) can be taken as a constant equal to \( f_{\text{Residual}}(0^\circ) \), meanwhile \( f_{\text{Coulomb}}(\theta) \) is rapidly varying, in a well known form. Measurements of the elastic scattering at two small angles can then be used to determine \( f_{\text{Residual}}(0^\circ) \).

This method has recently been applied to 17.5 MeV protons on Al and Cu, by measuring \( \sigma_E(\theta) \) from 4° to 15° to 1% accuracy. The forward scattering amplitude was determined to 10%
accuracy (Po 67). The authors do not quote the reaction cross sections results, but they are "in agreement with the attenuation method". The uncertainty in these results is expected to be of the same order as the one in the determination of the forward residual scattering amplitude.

4.5. The range method.
See (Bu 59)

This method allows measurements of the reaction cross sections of elements constituting particle detectors, by detailed analysis of the shape of the pulse height spectrum of the particles stopped in the detector.

If the number of incident particles into the detector is known and compared with those detected in the full energy peak, an attenuation can be observed. It will arise from non-elastic collisions and reactions taking place in the detector.

An increase in the incident energy will have the same effect as adding a target made of the detector material, as thick as the increase in range. The attenuation will then increase. The energy dependence of this attenuation, in the detector, can be used as a measurement of the reaction cross section for the detector material.

The method depends on the analysis of the low energy region of the energy spectrum. Here, the contribution will originate from those particles that lost energy due to a nuclear interaction or where completely removed (via neutron emission) from the beam, after leaving only a fraction of their energy in the detector.
The difficulties arising from the assignment of pulses to the tail of the full energy peak may contribute with errors comparable to or higher than, statistical uncertainties. The method does not seem to be sensitive enough to measure small attenuations, corresponding to variations in the incident energy of the order of $10\%$. The results will then be an average of the total reaction cross section over a wide energy range. As an example, quoting from the work by E. Burge (Bu 59), the results for total proton reaction cross sections in Carbon are given as: $376 \pm 40$ mb at $25 \pm 15$ Mev and $355 \pm 50$ mb at $54 \pm 14$ Mev. This is not, by any means, the lower limit of the method, but results for an energy average comparable to that of the attenuation methods seem difficult to obtain.

4.6. **The coincidence method.**

The transmission, or attenuation measurements for charged particles described in section 4.1 involved the measurement of small difference between two large numbers. This problem is worse at low energies where targets with transmissions close to unity must be used to keep the relative energy loss in the target, at a reasonable magnitude. As a result, the number of events that have to be analysed is extremely large, as therefore is the beam time involved (See Section 4.1.1.) Basic attenuation methods can be modified so that each individual proton is analysed. By this is meant that signals indicating both the incidence of a particle in the target, and the emergence of the particle from the target are obtained. If now coincidence measurements between these signals are made, the fate of each proton, whether absorbed or transmitted, can be determined.
In the following sections a classification of coincidence methods is made according to the method of determining when a proton is incident. Coincidences and anticoincidences between different signals will be indicated with the following notation:

A coincidence between signals A, B and C as \(\ldots\ldots\) \(ABC\)

The same \(ABC\) in anticoincidence with signal D as \(ABC\overline{D}\)

The notation \(M(ABC\overline{D})\) is used to indicate a certain number of events of the kind indicated between brackets.

4.6.1. The basic coincidence method.

See (Ca 54)

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A series of thin transmission detectors on the incident beam path define when a proton is incident on the target. For example, in the schematics illustrated in Figure 2.6, two thin detectors, A and B, are located on the beam path to the target C.
The transmitted particles are detected in the full energy detector D. Signals from detectors A and B triggered in coincidence define the incidence of a proton. Transmitted particles will give rise to ABD events. Absorbed particles will give rise to ABD events. The uncorrected attenuation is then given by:

\[ \delta = \frac{M(ABD)}{M(ABD)} \]

where the two kind of events are recorded in the same given time.

A necessary correction is introduced by the fact that, even with no target in the beam, a significant number of ABD are detected, mainly due to non-elastic events in counter D. Let us call \( \delta_{\text{IN}} \) and \( \delta_{\text{OUT}} \) the attenuations for target-in and target-out respectively. The target attenuation is then given by:

\[ \delta_{\text{T}} = \delta_{\text{IN}} - \delta_{\text{OUT}} \]  \( (2.47) \)

A number of corrections must still be applied to this value. Those arising from geometrical considerations were described in section 4.1.2. Special consideration must be made for the fact that the energy of the protons, incident on the full energy detector, changes between the target-in and the target-out measurements due to the energy loss in the target.

The method as described is useful at energies high enough, such that the strong forward scattering makes the dispersion of the beam by the thin detectors negligible and thus reduces the geometrical contribution to the ABD events constituting \( \delta_{\text{OUT}} \).

For lower incident energies the collimation of the incident beam is lost due to Coulomb scattering in the dE/dx detectors. More complex telescopic arrangements have had to be used to define the incident beam of particles (W1 62). Figure
2.7 is the schematics for such a telescopic arrangement of detectors.

![Diagram of Low Energy Basic Coincidence method](image)

Figure 2.7: Schematic diagram of the Low Energy Basic Coincidence method

Coincidences and anticoincidences again define transmitted or absorbed particles. Thus:

- Transmitted: \( A \bar{B} C \bar{D} E \)
- Absorbed: \( A \bar{B} C \bar{D} E \)

Since the running time required for this type of measurement is limited by the "instantaneous" count-rates permitted in the first detectors of the telescope, namely A and B, it is clear that DC accelerators present significant advantages over pulsed machines.

We can then classify this type of measurement into two categories, according to the energy of the incident particle. The low energy one, where the target-out attenuation is determined by the scattering and reactions on the defining counters, plus the
full energy detector. The high energy one, when the target-out attenuation is determined largely by the non-elastic collision in the full energy counter.

In the low energy type of measurement the anticoincidence detector can fail to trigger, due to non-elastic collisions in it, and particles being considered as incident on the target, when they had actually been removed from the beam. The fraction of beam incident on the anticoincidence anular detector is determined by the scattering suffered on the previous dE/dx detector, which is large in this energy range.

The work for 134 Mev protons by Cassels and Lawson (Ca 54) reports errors on the reaction cross sections of the order of 10% with target-out corrections of the order of 30% the target-in values.

The work for 10 Mev protons by Wilkins and Igo (Wi 62) reports reaction cross sections with uncertainties between 2% and 10%. The target-out attenuations are reported in a ratio of 4/5 of the target-in values. A more recent work at a proton energy of 14.5 Mev (Di 66) uses a modified telescopic arrangement of detectors, and a combination of plastic scintillator and a lithium drifted detector instead of a single full energy counter. The total reaction cross sections are reported with errors of the order of 2%. The ratio of target-out to target-in attenuations is reduced to 1/2.2 from the value in the previous work.

4.6.2. The recoil method.

See (Bu 61) (Ar 64)

In this method the incident beam is actually the secondary beam produced by a primary scattering process. Since
the direction and kinetic energy of the recoil particles produced in the primary scattering are kinematically related to the particles of the incident beam, the presence of an incident particle can be determined by detecting the recoil particle at an appropriate angle and with appropriate energy. Then attenuations can be measured using the coincidence technique. The system has the advantage of not requiring the transversing of material objects by the incident beam before it reaches the target material.

The method can in principle be applied for any energy of incident beams with only geometrical changes necessary. To the author's knowledge this method had not been used for practical measurements until the present.

4.6.3. The associated particle method

This method is discussed in detail in the next chapter. It should be mentioned here as an alternative to the recoil method. Instead of producing a secondary beam by elastic scattering, a nuclear reaction is chosen that gives rise to two charged particles. Detection of one of the particles thus define by kinematical relations the direction and energy of the associated one. The latter then constitutes the incident beam in which a target followed by the full energy detector may be inserted. Again coincidence measurements permit attenuation determinations to be obtained.
3. EXPERIMENTAL DESIGN.

1. General introduction.

In the previous chapter difficulties associated with determining the incidence of a charged particle entering an attenuation apparatus has been pointed out. This is an important consideration for low incident energies, where the coincidence technique involves the use of complex telescopic arrangements of detectors.

The associated particle technique provides a new method for determining the arrival of an incident particle.

In this chapter we will briefly discuss the associated particle technique and its limitations.

Finally the reaction used in the present project will be discussed together with the design of the experiment. "Kinematical collimation" of the associated beam will be discussed in connection with thick targets in producing the associated beam.

2. The associated particle technique.

2.1. Production of associated beams.

As is implied by the technique's name, also referred to as the "Associated particle gating technique", it is the definition of the characteristics of a particle by the properties of a different one, associated with the first by a well defined kinematical relationship.

In a nuclear reaction with two particles as the final state, the principles of conservation of energy and momentum permits the correlation of the two products in an unambiguous way. This means that if one of the products is detected at some
angle with respect to the direction of the incoming primary beam the energy and angle of emission of the associated product are defined by the parameters of the reaction. The parameters are the masses of the initial and final products of the reaction and the Q-value associated with them.

Kinematical relationships can then be written down for a particular reaction, correlating the angles and energies of the outgoing particles using, for example, the incident energy in the input channel as a parameter. This will be illustrated in detail for the reaction $^3\text{He}(d,p)^4\text{He}$ used in the present experiment.

Furthermore, detection of one of the products not only defines the spacial aspects of the associated one but also useful temporal information. It provides, for example, a means of knowing when it was produced or is expected to arrive.

In what follows we will refer to the actual accelerator beam, defining the input channel, as the "primary beam"; to the defining beam of particles as the "secondary beam"; to the beam used for the attenuation measurements as the "associated beam"; and the reaction involved as the "source reaction".

The "associated particle technique" has been applied extensively to neutron work as a source of monoenergetic and well collimated neutron beams. It is also used as a convenient way of defining time zero in "Time-of-flight" techniques for measuring neutron energies.

2.2. Limitations of the technique.

The associated particle technique suffers, in general, from two disadvantages. The energy can not be varied as readily
as for the case of an accelerator beam, since here must be taken into account the kinematics of the reaction involved. In addition, the beam flux available is much less than obtainable in an accelerator by the limit set by the maximum acceptable counting rate on the secondary beam detector.

If the reaction used is endoenergetic, then above the reaction threshold the energy of the reaction products will be strongly dependent on the primary beam energy. On the other hand, if the reaction used is exoenergetic, then for primary energies much below the Q-value the energy of the reaction products will be mainly defined by the Q-value itself. When the primary energy becomes of the order of the Q-value, or higher, the dependence of the energies of the products on the incident energy returns. In fact this last consideration limits the range of energies available in the secondary and associated beams to energies below the Q-value. It provides thereby a means of obtaining high energy particles with relative low energy accelerators. The case is illustrated by the $^3$H(d,n)$^3$He ($Q=17.6$ Mev) and the $^3$He(d,p)$^4$He ($Q=18.352$ Mev) reaction, where with energies in the primary beam below 1 Mev, neutrons or protons above 10 Mev can be obtained.

The flux available in the associated beam will depend on the cross section for the source reaction to take place. In general, this is not limited by the fluxes available in the primary beam from a particle accelerator as much as it is from the problem involved in the design of source targets capable of withstanding the necessary beam currents without introducing unwanted scattering material in the secondary and associated
beam paths.

Choice of the source reaction depends also on the presence of competing reactions which may arise from the same target or contaminations on it. Ideally one should be able to either neglect their contribution if suitably minor, or experimentally resolve their effect.

2.3. Production of associated beams of charged particles.

For neutral beams it is difficult to obtain variable energy, good collimation or energy selection due to their lack of electric charge. The advantages of producing them by an associated particle technique are clear.

In the case of charged particles the situation is totally different. Particle accelerators can provide high fluxes of monoenergetic and well collimated charged particles of variable energy. It is clear that the production of an associated beam only involves the choice of an appropriate source reaction, giving rise to two charged products. The availability of accelerator beams makes it not surprising, then, that the production of associated beams of charged particles has not been pursued up to the present.

Some proton and deuteron producing reactions have been used as a source of polarized beams (Br 63), but without using the secondary particles to define the wanted beam.

Interest in associated charged particle beams will be more limited than in the neutron case. Application of the technique to the measurements of total reaction cross sections for protons is the object of the present work.
2.4. Requirements for an attenuation experiment.

The particular "associated particle technique" used for the measurement of total reaction cross sections for protons is a modification of the "Coincidence technique" described in the previous chapter.

![Diagram of an "Associated particle" attenuation experiment](image)

Figure 3.1 is a schematic diagram of such an experiment. The primary beam, originating from a particle accelerator, produces reactions in the source target that give rise to the secondary and associated beams. The angular correlation between the two final products can be kinematically calculated. By gating the detector D2, at angle $\psi$, with the output of the detector of the secondary beam, selected in angle ($\xi$) and energy at D1, an associated beam is selected out of the total flux of particles incident on D2. Neglecting both scattering effects in the source
target and losses in the detectors, to each particle of the secondary beam detected at D1 the corresponding associated particle will be detected on D2. The final target, whose attenuation is to be measured, is placed just before the detector D2. A fraction $\delta$ of the total number of particles in the associated beam will be removed from it when passing through the final target. Anticoincidence as well as coincidence measurements are obtained between detected events in D1 and D2. Let the numbers of such events recorded during an appropriate time interval be $M(D1 \overline{D2})$ and $M(D1 D2)$, respectively.

For the case when $\delta \ll 1$ the number of anticoincidences will be much smaller than the number of coincidences, or:

$$M(D1 \overline{D2}) \ll M(D1 D2)$$

so the total number of particles in the associated beam is

$$M(D1 D2) + M(D1 \overline{D2}) = M(D1 D2)$$

Using equations (2.8) and (2.12) we obtain:

$$\delta = \frac{M(D1 \overline{D2})}{M(D1 D2)} \quad (3.1)$$

Thus, the detection of a secondary particle D1 is used to replace the detector telescope employed in the coincidence technique in order to indicate the incidence of a particle into the final target.

As discussed in the previous chapter, some anticoincidence events will be present even when the final target is removed. In order for the attenuation of the final target to be measured with precision, this anticoincidence background should be reduced to the minimum possible and its origin and energy...
dependence well understood.

Choice of the source reaction was determined by the following considerations:

a) the proton total reaction cross sections should be measurable to an accuracy of a few percent in a reasonable beam time.

b) Energies of less than 1.5 Mev are readily obtained from the University of British Columbia Van de Graaff generator with currents of the order of microamperes at these energies.

c) Secondary particles must be charged particles (detection efficiency 100%) and easily distinguishable from the scattered incident beam.

d) Competing reactions in the source target must not give rise to particles at energies such that they can not be experimentally resolved from the secondary beam.

e) The dispersion of the associated beam, and its angular divergency should be kept at a minimum.

Points c) and d) were important in determining the attenuation background. Consideration of point e) is required when performing target corrections and for determining the size of the final target.

3. The $^3\text{He}(d,p)^4\text{He}$ reaction.

The particulars of this reaction fulfilled the requirements specified in section 2.4.

The reaction cross section has a pronounced resonance at 430 kev incident deuteron energy in the laboratory system, of
450 kev width (Bo 57). For incident \(^3\)He the resonance is observed at 640 kev laboratory energy with a width of 670 kev; the energy dependence of the cross section is shown in (Ku 52). The peak value is given as \((695 \pm 14) \text{ mb}\).

The high Q-value of 18.352 Mev permits the production of protons with energies between 12 and 18 Mev for incident \(^3\)He energies near that corresponding to the maximum in the cross section. This energy range is useful for optical model investigations for the following reasons. It is just above the Coulomb barrier for all the possible targets; contributions from compound elastic scattering can be expected to be small due to the number of competing channels; comparison with optical model calculations can be made easily due to the density of levels and the number of partial waves that must be considered is still relatively small.

The secondary beam is composed of \(^4\)He with energies in the 1 to 7 Mev range. They can be easily detected using solid state detectors with F.W.H.M. resolutions of less than 50 Kev. They can be easily distinguished experimentally from the incident scattered beam.

The presence of polarization in the proton beam is not relevant for the total reaction cross section measurements. If present, it will give rise to some left-to-right asymmetry in the differential elastic cross sections. The available experimental data (La 66), indicates that less than 5% polarization is to be expected at the energies involved in the present experiment.

The competing reactions are (La 66):

1) \(^3\)He(d, \(\gamma\))^\(5\)Li : Q-value = 16.388 Mev

\[
E_\gamma = 16.6 \text{ Mev}
\]
\[ \sigma = 50 \pm 10 \text{ } \mu\text{barns at } E_d = 450 \text{ kev} \]

Not only is the cross section very small compared with the \((d,p)\) channel but the \(^{7}\text{Li}\) recoil energy is too low to be detected. In addition, the detectors are not very sensitive to gamma radiation.

2) \(^{3}\text{He}(d,n)^{4}\text{Li} : \]
\[ \sigma = 3 \text{ to } 8 \times 10^{-3} \text{ } \mu\text{barns for } E_d \text{ from } .5 \text{ to } 2.3 \text{ Mev}. \]

Again the cross section is extremely small compared to the \((d,p)\) channel. Also, the detectors are insensitive to neutron detection.

3) \(^{3}\text{He}(d,np)^{3}\text{He} : \]
\[ Q\text{-value} = -2.225 \text{ Mev} \]

This reaction is not energetically possible at the resonance energy for the \((d,p)\) channel.

4) \(^{3}\text{He}(d,pp)^{3}\text{He} : \]
\[ Q\text{-value} = -1.461 \text{ Mev} \]

As case 3) above.

Thus, no interference from competing reactions in the source target is to be expected.

3.1. Reaction kinematics.

The results of the computations for the non-relativistic two body breakup of \(^{3}\text{He}(d,p)^{4}\text{He}\) are plotted in Figures 3.3 to 3.8. The region of the reaction cross section resonance was covered by assuming \(^{3}\text{He}\) incident energies of 400, 600 and 800 kev as the free parameter in the calculations. It is evident in each of the first four graphs that there is a region in which the influence of the incident energy is minimum. These correspond to the intercept of the curves corresponding to the three different incident energies.
Figure 3.3: $^3\text{He}(d,p)^4\text{He}$ reaction kinematics
Figure 3.4: $^3\text{He}(d,p)^4\text{He}$ reaction kinematics
Figure 3.5: $^3\text{He}(d,p)^4\text{He}$ reaction kinematics
Figure 3.6: \(^3\text{He}(d,\alpha)\) Reaction Kinematics

PROTON ANGLE (°)

ALPHA ENERGY (MeV)

400 keV
500 keV
600 keV
700 keV
Figure 3.7: $^3\text{He}(d,p)^4\text{He}$ reaction kinematics
Figure 3.8: \( ^3\text{He}(d,p)^4\text{He} \) reaction kinematics
This is useful because it permits the use of thick source targets (by thick is meant an energy loss in the target comparable to the incident energy) without considerable change in the kinematics of the products of reactions taking place at different depths. The possibility of thick targets is important in order to obtain high counting rates in the associated beam.

We will now describe those properties of figures 3.4, 3.5, 3.6, 3.7, which are of relevance in later discussion. The range of parameters correspond to a change in $^3\text{He}$ incident energy from 400 to 800 kev.

CASE I (Figure 3.4): Intercept at $E_p = 14$ Mev; $^4\text{He}$ angle = $50^\circ$

Ranges $E_{^4\text{He}} = 4.75 \text{-} 5.2$ Mev; p angle = $117^\circ \text{-} 110^\circ$

This configuration facilitates the production of a well collimated $^4\text{He}$ beam associated with monoenergetic protons.

CASE II (Figure 3.5): Intercept at $E_{^4\text{He}} = 4.0$ Mev; $^4\text{He}$ angle = $75^\circ$

Ranges $E_p = 14.75 \text{-} 15.15$ Mev; p angle = $90^\circ \text{-} 82^\circ$

This configuration facilitates the production of a well collimated and monoenergetic $^4\text{He}$ beam.

CASE III (Figure 3.6): Intercept at $E_p = 14.5$ Mev; p angle = $98^\circ$

Ranges $E_{^4\text{He}} = 4.25 \text{-} 4.65$ Mev; $^4\text{He}$ angle = $67^\circ \text{-} 61.5^\circ$

This configuration facilitates the production of a well collimated, monoenergetic proton beam.
CASE IV (Figure 3.7): Intercept at $E_\text{He} = 3.3$ Mev; $p$ angle = $65^\circ$
Ranges $E_p = 15.45 - 15.9$ Mev; $^4\text{He}$ angle = $92^\circ - 100^\circ$

This configuration facilitates the production of a well collimated proton beam associated with monoenergetic $^4\text{He}$.

The two interesting cases that minimized variations of the secondary and associated beams at the same time are cases I and IV.

In CASE I the detection of $^4\text{He}$ at a "well defined" angle defines an associated beam of "monoenergetic" protons, at around $113.5^\circ$, for reactions taking place with incident $^3\text{He}$ energies between 400 and 800 kev. The angular divergency on the proton beam will be of $7^\circ$ but the energy will be defined to better than 100 kev for the specified range. The associated $^4\text{He}$ particles are assumed to be detected in a counter subtending an angle of $2^\circ$ and span an energy range of 450 kev.

In CASE IV the detection of $^4\text{He}$ within a "narrow energy" interval of 50 kev permits the "collimation" of an associated beam of $15.7 \pm 0.22$ Mev protons to the order of $1^\circ$ for reaction taking place for incident $^3\text{He}$ energies between 400 and 800 kev. The $^4\text{He}$ particles associated with the protons would be spread over an angular range of $8^\circ$.

3.2. Kinematical collimation of the associated proton beam.

From the considerations of section 3.1, Case IV will permit the use of thick source targets with their resulting higher counting rate, at the same time as a highly collimated
proton beam, if the secondary beam of $^4\text{He}$ is energy selected with good energy resolution. The spread in proton energies of 220 kev is sufficiently small that the corrections discussed in Chapter 2 section 4.1 (eq. 2.10) can be neglected.

The properties of Case IV amounts to a "Kinematical collimation" of the associated proton beam.

Figures 3.9 and 3.10 present an expanded view of the intercept area for Case IV. Here a primary target thickness of 100 kev has been considered, centred at the peak resonance energy of 650 keV.

Design of the present experiment represented a compromise between angular dispersion and particle flux in the associated beam. The case for an energy window of 100 kev in the $^4\text{He}$ channel is indicated in the expanded figures, centered at the intercept point. It involves $^4\text{He}$ energies between 3.17 and 3.27 Mev and associated protons emitted between $62^\circ$ and $65^\circ$. The proton energies involved are from 15.68 to 15.89 Mev and the angles for the secondary beam between $93.7^\circ$ and $98.6^\circ$ (center angle $96.2^\circ$ see figure 3.2).

In practice the proton beam will not be as sharply defined as mentioned in the previous paragraph due to the inherent energy resolution of the $^4\text{He}$ detection system. A value of 40 kev F.W.H.M. corresponds to the energy resolution that could be readily obtained with standard instrumentation in our laboratory. The effect of a 40 kev energy interval in the $^4\text{He}$ energies on the associated beam is indicated by the dotted lines in figures 3.9 and 3.10, centered at the intercept point just for illustration. It corresponds to an angular divergency in the
Figure 3.9: $^3$He(d,p)$^4$He reaction kinematics
Figure 3.10: $^3\text{He}(d,p)^4\text{He}$ reaction kinematics
proton beam of less than 1.2°.

3.3. **Source target angle.**

The particulars of the source-target itself will be discussed in section 2.3 of Chapter 4. Here we are concerned with choosing the orientation of the source-target plane.

The target was chosen to be a deuterium target in the form of solid D₂O, formed on a thin copper foil backing at liquid nitrogen temperatures.

For high particle fluxes in the associated beam a thick primary target is wanted; the use of kinematical collimation can be used to obtain nevertheless, a small angular divergency. As seen in section 3.2 this characteristic depends on detecting the ⁴He secondary beam with good energy resolution and small scattering effects on its original angle of emission. In other words, as little target material as possible is wanted in the direction of the selected ⁴He particles ( ξ = 96.2°). This will imply a primary target angle smaller than ξ, or β < 96.2°.

Due to the low thermal conductivity of ice, a low current density on the primary beam is desirable for stable targets. At 173°K the value for normal ice can be calculated to be 8 x 10⁻³ cal °C⁻¹ s⁻¹ cm⁻¹ (Po 65). If the temperature of the ice rises above 173°K it is vaporized at a fast rate. For a selected beam current, low current densities require a large beam spot. The geometrical effects of a large beam spot can be minimized by the use of "natural focusing" as described in Appendix II. The best angle for natural focusing to take place, as shown in the appendix, implies the transversal of more target
material in the direction of the secondary beam than in the direction of the incident beam.

In practice, choice of the primary target angle depends on the choice between "kinematical collimation" or "natural focusing".

Let us estimate the size of primary beam necessary. Beam densities in the order of $150 \mu \text{A cm}^{-2}$ for 200 kev deuterium beams on thick heavy ice layers (energy loss in the target comparable to the incident energy) have been found acceptable according to published information (Ma 63). From the stopping cross section curves given in Chapter 4 Section 2.3, the stopping power of D$_{2}$O ice for 650 kev $^3$He is a factor of three larger than for 200 kev deuterons. Thus, a current density of $50 \mu \text{A cm}^{-2}$ for an incident $^3$He beam will be considered acceptable. For 1 $\mu \text{A}$ of incident current a beam spot of at least $2 \times 10^{-2} \text{ cm}^2$, 0.16 cm in diameter, should be used.

It is clear then, that the effects of beam size can be practically minimized by locating the secondary beam detector at a sufficiently large distance from the primary target. Natural focusing is, then, a secondary consideration in choosing the primary target angle.

The primary target angle $\beta$ can then be chosen solely on the basis of the energy loss in the target by the primary and secondary beams. As indicated before, any angle smaller than $96.2^\circ$ will involve a thicker D$_{2}$O ice layer in the direction of the primary beam than for the secondary beam. The high energy protons will be required to go through the primary target backing metal foil, so a convenient angle is a perpendicular to the
proton angle $\psi$, or $\beta \approx 30^\circ$.

If 'L' is the $^2$H$_2$O target thickness in the direction then the target thickness in the directions of the secondary beam and primary beams is given by (See Figure 3.11):

úmero direction

$$L_{96.2^\circ} = \frac{L}{\cos(90^\circ + \beta - \xi)} = 1.1 \ L \quad (3.3)$$

úmero direction

$$L_{0^\circ} = \frac{L}{\cos(\beta - \frac{\pi}{2})} = 2 \ L \quad (3.4)$$

3.4. Expected yields.

In Section 3.2 a total angular divergency of $3^\circ$ was obtained for a target 100 kev thick and a 650 kev $^3$He beam, if an energy window of 100 kev is used on the secondary $^4$He beam. As will be seen in Section 4.1.1 of this chapter, this value of angular divergency is quite compatible with the accuracy desired in these experiments. In that section we shall also indicate that
the thickness of 100 kev in the primary target is also compatible with background considerations. We will, on this basis, calculate the expected yields from the source reaction.

The stopping power for protons, $^3$He and $^4$He on $D_2O$ ice as a function of energy is plotted in Figure 4.5 of the next chapter. From it we obtain:

$$\epsilon(^3\text{He})_{.65} = 64 \times 10^{-15} \text{ ev- cm}^2 / \text{molecule} \quad (3.5)$$

The molecular density of ice is:

$$N = 3.35 \times 10^{22} \text{ molecules cm}^{-3} \quad (3.6)$$

From (3.5) and (3.6):

$$dE/dx (^3\text{He})_{.65} = 2144 \text{ Mev cm}^{-1}$$

The 100 kev thickness of the $D_2O$ ice target will thus be equivalent to:

$$L = 4.66 \times 10^{-5} \text{ cm}$$

$$L_M = 1.56 \times 10^{18} \text{ Molecules cm}^{-2} \quad (3.7)$$

$$L_Q = 5.17 \times 10^{-5} \text{ g cm}^{-2}$$

We will assume a constant reaction cross section of 680 mb for the energy range of interest, and the yield will be calculated per $\mu$A-second,

For singly ionized helium

$$1 \mu\text{A} = 6.281 \times 10^{12} ^3\text{He s}^{-1} \quad (3.8)$$

The total yield of the reaction per $\mu$A and per second is given by:

$$M' = 2 N C_R L x 6.281 \times 10^{12} \mu\text{A}^{-1} \text{ s}^{-1} \quad (3.9)$$

$$M' = 1.33 \times 10^7 \mu\text{A}^{-1} \text{ s}^{-1}$$

where the factor 2 takes into account the presence of 2 deuterium atoms per each heavy water molecule.
Since the reaction cross section is isotropic in center of mass (Ku 52) (Bo 57) the reaction yield per unit of solid angle (center of mass) is,

$$M'_S = 1.06 \times 10^6 \ \ ^4\text{He} \ \mu A^{-1} \ \text{s}^{-1} \ \text{sr}^{-1} \quad (3.10)$$

Some anisotropy will be present in the laboratory system of coordinates arising from the solid angle transformation between them. The ratio of solid angles at 96.2° is, $R = 1.1$. Dividing (3.10) we get for the laboratory coordinates a value close to:

$$M_S = 1 \times 10^6 \ \ ^4\text{He} \ \mu A^{-1} \ \text{s}^{-1} \ \text{sr}^{-1} \quad (3.11)$$

From figure 3.10 the range of $^4\text{He}$ angles, defined by an energy range of 100 kev for any given value of the incident energy in the region of interest, is less than 3°; this corresponds to a solid angle of:

$$\omega_{D1} = 2\pi \left(1 - \cos \frac{\Delta \xi}{2}\right) = 2.15 \times 10^{-3} \ \text{sr} \quad (3.12)$$

From (3.12) and (3.11) the number of $^4\text{He}$ particles in the secondary beam with the wanted energy per $\mu A$ of current in the primary beam and per second is found to be:

$$M(D1) = M(^4\text{He}) = 2.15 \times 10^3 \ \mu A^{-1} \ \text{s}^{-1} \quad (3.13)$$

As the number of particles in the associated proton beam is the same, the number of coincidences is:

$$M(D1 \ D2) = 2.15 \times 10^3 \ \mu A^{-1} \ \text{s}^{-1} \quad (3.14)$$

If an attenuation of $5 \times 10^{-4}$ is to be measured, then the number of anticoincidences recorded will be:

$$M(D1 \ \overline{D2}) = 1.08 \ \mu A^{-1} \ \text{s}^{-1} \quad (3.15)$$

Using the approximation for $\delta << 1$, (eq. 3.1)

$$\delta = M(D1 \ \overline{D2}) / M(D1 \ D2)$$
and from (2.22) the relative error for the coincidence method is given by:

$$\eta_c = \left\{ \delta M(D1D2) \right\}^{-1/2}$$

For a 3% relative error and an attenuation of $5 \times 10^{-4}$, the number of coincidence counts $M(D1D2)$ should be at least $2.2 \times 10^6$. Using the rate given by (3.14) the time involved is of the order of $10^3 \mu$A s or approximately 17 $\mu$A min.

4. **Corrections**

In this section we will discuss the corrections to be applied to the experimental data in the case of coincidence attenuation methods.

The corrections will be divided into two categories: one including those related to "target-in" or "target-out" situations; and the other including those independent of the target. We will refer to the first as "Target corrections". The second type, which gives rise to anticoincidence counts without a target will be referred to as the "Anticoincidence background".

4.1. **Target corrections**

4.1.1. **Elastic scattering**.

As described in Section 4.1.2 of Chapter 2, knowledge of the differential elastic scattering cross section permits calculation of this correction. Its magnitude depends on the angle subtended by the full energy detector. In the case of lack of experimental data for the energy or nucleus under consideration, it is possible in most cases to estimate the correction by doing an optical model calculation, interpolating
the potentials obtained for other energies or nuclei, or using semiempirical potentials such as the "Perey potential".

A compound elastic decay will experimentally appear as a transmitted particle when it really arises from an absorption event. The measured total reaction cross section will then be smaller than the real one by the amount of compound elastic cross section into the transmitted particles detector. The problem of experimentally distinguishing the compound elastic scattering from the direct elastic scattering has been discussed in section 2.1, together with its energy dependence. The measurement for 10 Mev protons in $^{56}\text{Fe}$, using fluctuation analysis (Er 65), yielding the value of less than 2.5 mb sr$^{-1}$, is in support of considering the compound elastic contribution negligible for the range of energies concerned within the present work of 15.8 Mev.

4.1.2. Inelastic scattering.

The presence in the transmission detector of particles that suffered inelastic scattering in the target but can not be resolved, in energy, from the elastic contribution will give rise to a correction term in the experimental value of the reaction cross section. The correction will be given by the integral of the cross section for inelastic scattering over the angle subtended by the detector, and for energies of the scattered particle above a certain value $E_{\text{disc}}$ above which they will be interpreted by the system as elastic scattered ones. Thus

$$\sigma_{\text{IE}} = \int_{E_{\text{disc}}}^{\infty} \int_{\Omega} \sigma_{\text{IE}} (E, \theta) \, d\Omega \, dE \quad (3.16)$$
where $E_s$ is the energy of the scattered particle.

When the detection system is not particle sensitive, identical considerations apply for reactions yielding charged particles as final products, different than the incident one.

The importance of this correction term depends largely on the energy resolution of the full energy detector.

4.1.3. Lattice effects.

From equation (2.9) once the attenuation, $\delta$, of the beam is measured the value of the reaction cross section, $\sigma_R$, is obtained from:

$$\sigma_R = \delta (N_L)^{-1}$$

where $N_L$ is the number of nuclei per square centimeter in the sample.

The implicit assumption involved here, is that the nuclei are randomly distributed in the sample.

The possibility of significant ordering of the distribution of target nuclei within a sample may require modification of this expression for particular experimental situations.

Recently, during the last three years, detailed analysis of lattice effects from both an experimental and theoretical point of view have been performed. It is found that for some situations they can yield significant effects, although they were previously considered negligible.

"Channeling" is used to indicate when an incident charged particle is focused, in a crystal, by Coulomb interactions into some lattice interspacing. The pattern of interaction will then be changed, since the particle will travel through regions
of the crystal removed from the nuclei of the crystal atoms and thus will suffer collisions only with the electrons filling the interspacing.

"Shadowing" indicates the effect that once a particle suffers scattering from a repulsive potential, there is an area defined behind the scattering center where the probability of finding the incident particle is very low. In other words, the incident particle can no longer interact effectively with nuclei, or atoms, within the shadowed area.

The experimental results are very remarkable and, as expected, lattice effects manifest themselves more strongly when single crystals are used, either as samples or particle detectors. For a wide review of experimental results and their consequences for measurements in nuclear physics reference should be made to the recent article by Bergstrom and Domeij (Be 66).

In general, the importance of lattice effects is governed not only by the presence of ordering in the material but also by the angular divergency of the incident beam and its direction with respect to some lattice internal axis.

For the theoretical treatment of the subject reference should be made to the article by J. Lindhard (Li 65).

Since nuclear processes take place only when the particles are within a distance of the order of nuclear radii of each other, they are expected to be very sensitive to the presence of lattice effects. Their consequence is to keep the particles from the incoming beam away from possible interaction with a certain fraction of the sample nuclei.

These effects have been experimentally observed.
"Channeling" effects are found in the measurements of stopping power and reaction yields for single crystals. "Shadowing" effects are present in the angular distribution of decay products emitted from radioactive nuclei located in crystal lattice.

Such lattice effects, associated with ordered matter, are not present in gaseous or liquid samples. Thus, experiments involving single crystals should be carefully analysed to determine the importance of these effects. The use of polycrystalline samples will decrease the importance of such corrections when the range of the particles of interest is much larger than the microcrystals dimensions. Furthermore one can not just assume that the microcrystals are randomly oriented. A certain degree of alignment can be present after such processes as rolling, evaporation etc. Even for a polycrystalline sample these effects can not be, then, assumed to be small until the ordering is checked by, for example, X-ray analysis or by rotating the sample with respect to the incident beam and counter in the experimental set up (Be 66).

4.2. The attenuation background.

Applying (3.1) we can measure the attenuations with and without the sample in the proton beam, as before we will refer to these attenuations as $\delta_{IN}$ and $\delta_{OUT}$. The mechanical system for inserting the sample is described in detail in Section 2.4 of Chapter 4. As indicated before the attenuation due to the sample is:

$$\delta = \delta_{IN} - \delta_{OUT} \quad (3.17)$$

To this value the target corrections discussed in
Section 4.1 should be applied. $\delta_{\text{OUT}}$ arises from the presence of an anticoincidence background. In the next subsections we will discuss the contributions to it and their influence in the design of the present experiment.

4.2.1. Background due to the backing foil.

Due to the geometry chosen for the source target the protons are emitted through the backing foil of the heavy ice target. A certain amount of attenuation will be introduced both from those particles reacting in the foil, and so absorbed, and those elastically scattered into an angle larger than that subtended by the detector for transmitted particles.

This contribution can be minimized by using very thin backing foils and by subtending a larger solid angle with the proton detector. In choosing the thickness of the foils a compromise has to be made with the thickness required to conduct away the beam power dissipated by the primary beam. When choosing the angle subtended by the proton detector a compromise must be made between the large angle desired, as indicated above, and the maximum acceptable counting rate to the proton detector.

The proton detector is then exposed not only to the associated proton beam, but also to those protons coincident with $^4\text{He}$ of different angles and energies. If we assume a maximum allowable proton rate of about $1 \times 10^5$ s$^{-1}$, then from (3.10) we can evaluate the maximum solid angle, per $\mu A$ of primary beam current, that the proton detector can subtend,

$$\Omega = 9.4 \times 10^{-2} \mu A \text{s} r$$  \hspace{1cm} (3.18)

And for the actual maximum angle $|\Omega_m = \Delta \xi / 2$ of eq. (3.12)
\[ \cos \alpha_M = 1 - \frac{\Omega_M}{2\pi} = 1 - (0.015 \mu A) \quad (3.19) \]

for the special case of 1 \( \mu A \), \( \alpha_M = 10^\circ \).

The contribution to the anticoincidence background from the backing foil is given by:

\[ \delta_{BF} = \delta_{R}^{BF} + \delta_{E}^{BF} \quad (3.20) \]

where \( \delta_{R}^{BF} \) represents the attenuation due to absorption in the backing foil and \( \delta_{E}^{BF} \) the attenuation due to elastic scattering from the backing foil into angles greater than that subtended by the detector,

\[ \delta_{R}^{BF} = N \cdot L \cdot \sigma_{BF}^{R} \]

\[ \delta_{E}^{BF} = N \cdot L \cdot 2\pi \int_{0}^{180^\circ} \sigma_{E}^{BF}(\theta) \, d\Omega \quad (3.21) \]

where 'L' is the thickness of the backing foil, \( \sigma_{BF}^{R} \) the total non-elastic cross section and \( \sigma_{E}^{BF}(\theta) \) the differential elastic scattering cross section for its nuclei. If we expect to measure attenuations of the order of \( 5 \times 10^{-4} \) then we would like

\[ \delta_{BF} < 5 \times 10^{-5} \quad (3.22) \]

On the other hand if the temperature of the ice layer rises above 173°K the target will vaporize relatively fast (Ma 63 p. 685). If the foil is attached to a reservoir at liquid nitrogen temperatures (78°K) this requirement restricts the temperature rise in the primary target to approximately 100°K.

The temperature rise at the target center was calculated in order to determine the necessary thickness of the backing foil for a given incident current. The details of the calculations
are given in Appendix I, and are plotted in figure A1.3 as the temperature rise in °K per μA of incident beam as a function of the thickness of the copper backing foil. The cases for two different beam diameters were considered. CASE I corresponds to a diameter of .318 cm (1/8 inches) and CASE II to .16 cm (1/6 inches).

The attenuation given by (3.20) can be calculated as a function of the thickness "L" using the angle \( \alpha \) as a parameter,

\[
\delta_{BF} = NL \left( \sigma_R^{BF} + 2\pi \int_0^{\alpha} \sigma_e^{BF}(\theta) \, d\Omega \right)
\]

(3.23)

The integral was performed by generating the differential elastic scattering cross sections with the SCAT 4 optical model program. The following potentials were used (p on Cu at 15 Mev):

\[ V = 50.0 \] (as given by the Perey potential), \( W = 7.5 \) Mev, \( \sigma_{SO} = 7.5 \) Mev, \( a = .5 \) f, \( r_o = 1.25 \) f. (See chapter I).

The results are indicated in Table 3.1 and plotted in Figure 3.12 as a function of the thickness 'L'.

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( \sigma_R ) (mb)</th>
<th>( \int_{\alpha}^{180^\circ} \sigma_e ) (mb)</th>
<th>( \sigma_R + \int_{\alpha}^{180^\circ} \sigma_e ) (mb)</th>
<th>( L^1 \delta_{BF} ) (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>891</td>
<td>7023</td>
<td>7914</td>
<td>.669</td>
</tr>
<tr>
<td>20°</td>
<td>891</td>
<td>1383</td>
<td>2274</td>
<td>.192</td>
</tr>
<tr>
<td>30°</td>
<td>891</td>
<td>606</td>
<td>1497</td>
<td>.127</td>
</tr>
</tbody>
</table>

Finally in Figure 3.13 we have indicated the counting rate in the proton detector, per μA of incident beam, as a function of the detector angle \( \alpha \).
Figure 3.12: Attenuation background due to the backing foil thickness, as a function of the thickness and the angle subtended by the proton detector.
Figure 3.13: Counting rate at the proton detector as a function of subtended angle.
The Figures 3.12, 13, and AI.3 enable us to obtain a good compromise for the thickness of the backing foil.

If the attenuation of the backing foil was the main source of the anticoincidence background then the choice should allow $S < 5 \times 10^{-5}$ (for target attenuation measurements of $5 \times 10^{-4}$). It would seem to be reasonable then to use a foil around $10^{-4}$ cm thick. Self-supporting Copper foil can be obtained down to $50 \times 10^{-6}$ inches or $1.27 \times 10^{-4}$ cm. This would represent a of approximately $2.5 \times 10^{-5}$ for $\alpha = 20^\circ$. From Figure AI.3 we obtain a maximum primary beam current of around $1/4 \mu A$ for $\Delta T$ less than $100^\circ K$ and 1/8 inches collimators. The counting rate from Figure 3.19 will be of the order of $10^5$ s$^{-1}$.

4.2.2. Background due to the proton detector.

An important contribution to the anticoincidence background arises from nuclear interactions taking place in the full energy detector itself.

Using stopping cross sections to determine the amount of detector material per fraction of energy loss, $dE$, and total reaction cross section data, the total expected attenuation of the incident beam, in the detector, can be calculated:

$$dS = N \sigma_R d\xi = N \sigma_R(E) \xi^{-1} dE$$

$$d = \int_0^E N \sigma_R(E) \xi^{-1} dE$$

(3.24)

where $E$ is the incident energy and $\xi$ the stopping power of the detector material.

The best choice of detector should be the one that provides the lowest attenuation, or anticoincidence background.

A second consideration is the extent to which the
inelastic channels of the reactions that take place in the detector nuclei will give rise to counts of the lower energy region of the proton spectrum, since a large background of this type would hamper the inelastic target corrections.

The third consideration related to the full energy detector is given by its timing characteristics or speed of response. A fast rise time is convenient for good time resolution when performing coincidences and anticoincidences. At high counting rates for good energy resolution it is important that the proton pulse is not distorted by an immediately preceeding one. This can be achieved with a short fall time of the detector pulse; short such that the probability of another proton being detected during the fall time of the first one is very low at the given counting-rate. This restriction can be made less strict by electronically assuring that analysis of pulses is done only when a proton is detected without being preceeded by a previous one during a certain period of time. This method was employed in the experiment here concerned using the "Dead time generator" described in Section 3.4 of Chapter 4.

These considerations must be taken into account when selecting the particular type of full energy detector. The case of a plastic scintillator can be used to illustrate the point. Even though advantageous for timing purposes the 4.4 Mev and 7.6 Mev excited levels of its carbon nuclei produces a significant low energy tail to the full energy peak that can mask completely the inelastic contributions arising from the target.

When a nuclear reaction takes place in the detector the energy recorded can be divided into two different contributions:
a) the energy deposited in the detector until the reaction takes place,
b) the energy deposited in the detector by the products of the reaction.

When a (p,n) reaction takes place in the detector the contribution given by b) is negligible. For inelastic scattering and events characterized by emission of charged particles, contributions a) and b) will total an amount equal to the full energy of the particle incident on the detector minus the Q-value associated with the channel being considered.

It is clear then that the recorded number of anticoincidences will depend on the sensitivity or threshold of the proton system. It will increase as the threshold is moved towards the elastic peak. With the threshold set above the inelastic contributions, so that only full energy events are recorded, attenuation arising from the anticoincidences so recorded can be compared with the expected values calculated from equation (3.24). In general, however, due to the finite energy resolution of the detector some non-elastic events are always lost into the full energy peak.

Except for the case of plastic scintillators other detector materials to be chosen will be used in single crystal form. This is the case for CsI and NaI scintillators or the case of either Ge or Si solid state detectors. The possibility of lattice effects, which has been discussed in Section 4.1.3, should be taken into account. Their importance can arise from the fact that, in general, the angular distribution of the particles incident on the detector will change for target-out to
target-in position. This contribution to the change in the anticoincidence background could be checked by either rotating the detector with respect to the incident beam direction, or by knowing that the angular divergency of the beam is much greater than the critical angle for these effects. For accurate experiments a rotation of the detector provides the best check for the importance of the lattice effects.

The integration described by equation (3.24) was performed for Si, Plastic NE102, NaI(Tl), and CsI(Tl) in order to choose the detector with the lowest background contribution. The results for 15.8 and 14.8 Mev protons and the references for the data used are listed below.

**SILICON**:
\[ \delta (15.8 \text{ MeV}): 50.0 \times 10^{-4}; \delta (14.8 \text{ MeV}): 44.0 \times 10^{-4} \]
\[ \text{dE/dx} \]
(St 59) (W1 62a)

Atomic density
5.0 \times 10^{22} \text{ cm}^{-3}

Reaction Cross Section
Data for aluminum was used. At 5.5 Mev agrees with \( ^{28}\text{Si}(p,p')^{28}\text{Si*} \) (Ya 58)
Compilation by Pollock and Schrank
(Po 65a) and (Po 61) (Bu 65) (Be 65a)
(Me 60) (Pi 65).

**PLASTIC NE 102**:
\[ \delta (15.8 \text{ MeV}): 39.0 \times 10^{-4}; \delta (14.8 \text{ MeV}): 34.0 \times 10^{-4} \]
\[ \text{dE/dx} \]
(Wh 58)

Atomic density
H = 5.4 \times 10^{22} \text{ cm}^{-3} ; \ C = 4.8 \times 10^{22} \text{ cm}^{-3}

Reaction Cross Section
(Bu 59) (No 62) (Ma 65) (Wi 62) (Po 65a).

**NaI (Tl)**:
\[ \delta (15.8 \text{ MeV}): 32.0 \times 10^{-4}; \delta (14.8 \text{ MeV}): 27.0 \times 10^{-4} \]
\[ \text{dE/dx} \]
Assumed \( \text{dE/dx(I)} = \text{dE/dx(Xe)} ; \text{dE/dx(Na)} = \text{dE/dx(Ne)} \) (Wh 58)
Atomic density 1.48 x 10^{22} \text{ cm}^{-3}

Reaction Cross Section

$^{23}\text{Na}$ Charged particle Cross Sections (La 61), and data for $^{27}\text{Al}$ as listed for Si.

$^{127}\text{I}$, data was interpolated from a collection of data from other nuclei including the (p,n) for Cs and I by BLASER et al (Bl 51).

$\text{CsI (Tl)}$: $\delta$ (15.8 MeV): $19.2 \times 10^{-4}$; $\delta$ (14.8 MeV): $15.9 \times 10^{-4}$

dE/dx

Assumed dE/dx(Cs) = dE/dx(I) = dE/dx(Xe); (Wh 58).

Atomic density 1.04 x 10^{22} \text{ cm}^{-3}

Reaction Cross Section

As above, assuming same values for Cs as for I. The low energy following values for $^{103}\text{Rh}$ (Ha 62).

The data used in these calculations is also presented in graphical form. Figure 3.14 is a plot of the energy loss, in Mev cm^{-1}, versus the proton energy for each detector material considered.

Figure 3.15 displays the values for total reaction cross sections for the different nuclei as a function of the proton energy.

Figure 3.16 is a plot of the calculated attenuation, per Mev of energy loss in the detector material, as a function of the proton energy. The attenuations quoted for 15.8 and 14.8 Mev when describing the data used corresponds to the integrals of these curves from zero to the indicated energy.
Figure 3.14: Energy loss curves for different detectors
Figure 3.15: Proton total reaction cross sections, coulomb barriers and \((p,n)\) thresholds for nuclei of different detectors.
Figure 3.16: Calculated attenuation per MeV of energy loss in different detectors.
Since it presented the lowest expected attenuation of the different detectors considered, CsI (Tl) was chosen as the proton detector. In addition, also Cs and I have the lowest energy threshold for the production of neutrons and the highest Coulomb barrier of the detector nuclei considered. These values are indicated in the upper part of Figure 3.15. Because neutron emission is then favoured for Cs and I with respect to the other detector's nuclei, the intensity of the competing elastic channels could be expected to be correspondingly lower. This will produce a cleaner energy spectrum below the full energy peak, an important consideration when estimating the inelastic target corrections.

As discussed before in this Section, when a (p,n) reaction takes place in the detector, only the energy deposited until then is recorded. Due to Coulomb effects the reaction cross section decreases for decreasing proton energy. Thus counts arising from the (p,n) reactions will be mainly located in the low energy part of the pulse height spectrum, with the number of counts decreasing for increasing pulse height. On the other hand inelastic events which take place in the detector give rise to counts corresponding to an energy $Q$ Mev below the full energy peak, where $Q$ is the excitation energy of the level involved.

In figure 3.17 we have plotted the dependence of the attenuation background on pulse height threshold level for 15.8 and 14.8 Mev protons incident in a CsI scintillator when assuming that all compound nuclei formed in the detector decay via neutron emission. If the pulse height threshold level is adjusted for an energy of 0.5 Mev an attenuation background of the order of $15 \times 10^{-4}$ is to be expected. This value is a low limit of background, being
Figure 3.17: Calculated attenuation in CsI as a function of the discrimination level.
impractical to consider threshold levels below the one indicated above because the system may become too sensitive to noise.

The amount of anticoincidences detected for a target-out measurement will depend on the threshold setting and the incident proton energy in the manner indicated by Figure 3.17. On the other hand, when the target-in measurement is performed the inelastic correction to the target attenuation varies with the pulse height threshold level in the opposite way. The lower the setting the larger the inelastic correction (see Section 4.1.2.) It is clear that the choice of this level will arise from a compromise of these two effects, and that this compromise will depend on the particular sample being considered.

We will discuss the two extreme cases: CASE I, the threshold level is set just below the elastic full energy peak; CASE II, the threshold level is set at the lowest pulse height compatible with the noise of the system.

CASE I: In this case all inelastic events, either due to the detector nuclei or the sample nuclei, are recorded as anticoincidences with the only exception of a small correction arising from the finite energy resolution of the detector. The target-out attenuation will then be large and dependent on the energy of the incident beam. Since $\delta_{\text{OUT}}$ is larger than the target attenuations to be measured, a large number of counts are required for good statistics on the anticoincidence background. Knowledge of the background dependence with incident energy is necessary to account for the energy loss in the sample. This case can be illustrated with the CsI scintillator,
Figure 3.17. For a level setting equivalent to 12 Mev and for 15.8 Mev incident protons the expected attenuation is $19.2 \times 10^{-4}$, and a change in the proton energy of 1 Mev, down to 14.8 Mev, produces a change of 20% in $S_{\text{OUT}}$.

**CASE II:** Most of the inelastic events are recorded as coincidences. Thus $S_{\text{OUT}}$ decreases to its lowest limit. When $S_{\text{IN}}$ is measured, all the inelastic contributions from the sample are recorded as transmitted particles, and a much larger inelastic correction than in Case I is necessary. On the other hand since $S_{\text{OUT}}$ is lower, the number of counts to be recorded is greatly diminished, and the dependence of the anticoincidence background on the incident energy is greatly decreased. With what accuracy the inelastic correction can be made, depends on the previous knowledge of the inelastic scattering differential cross section for the sample considered. The case is also illustrated in figure 3.17 for the CsI scintillator; the anticoincidence background for a threshold level of 6.5 Mev is $1.5 \times 10^{-4}$ and practically independent of the incident energy.

4.2.3. Background due to energy degraded protons

The high energy protons emitted from the primary target in directions other than that of the proton detector, will in general, be scattered within the chamber. These scattered protons will give rise to the presence of backgrounds in both detectors.

To decrease its intensity the inside of the chamber was lined
with .042 inches thick polyethylene. The polyethylene thickness being greater than the expected range of 16 Mev protons.

Although reduced in intensity, a low energy proton background was still observed. Of particular concern was the fact that many of these protons had energies of the order of the selected $^4$He energies. Since these events are not associated with any full energy protons, they therefore generate background anticoincidence events.

A similar effect could be produced from slit edge scattering in the collimator defining the alpha angle. Thus, the high energy protons would be degraded in energy during grazing collisions with the collimator while on route to the $^4$He detector.

To eliminate these effects from contributing to the anticoincidence background, particle identification was employed by choosing an appropriate depletion thickness for the surface barrier alpha detector. Values lower than 70 microns will provide a clear distinction between $^4$He particles of the order of 3.5 Mev, typical of those in the experiment, and a background of protons of all energies. In this case, the proton spectrum is actually a distribution which folds over at the energy corresponding to a proton with a range equal to the depletion depth. For the case of 70 microns of silicon this occurs at 2.5 Mev. This is clearly seen in Figure 4.4, a typical solid state detector spectrum obtained during one of the runs. In fact, for good particle identification depletion layers of approximately 40 microns were used. Since such small depletion depths require very low biasing voltages, (e.g. 10 V, for 700
ohm-cm), and since these low voltages result in poor charge collection, specially manufactured detectors of silicon with resistivities of 200 ohm-cm and 35 ohm-cm were used in the experiment.

4.2.4. Background due to source target thickness.

Another source of anticoincidence background may arise from $^4$He particles originally emitted in directions other than that of the secondary beam detector. In leaving the primary target they could be scattered into the angle subtended by the detector, and with energies in the range of the selected $^4$He energy. For not being associated with protons emitted necessarily into the proton detector angle, they therefore generate background anticoincidence counts. As the primary target is a thin layer of heavy ice, the main source of $^4$He scattering will be the $^{16}$O nuclei from the D$_2$O molecules. The details of the calculation performed to estimate this background are presented in Appendix I. The contribution obtained for a source target thickness of 100 kev (for 650 kev $^3$He), a source target angle of 30°, a selected energy range of 100 kev and an angle subtended by the proton detector greater than 10° can be neglected.

There are two other effects whose importance depends on the source target thickness. These are multiple scattering effects and energy stragglng in the secondary beam when leaving the source target. Their effect is to distort the spacial definition of the associated beam by changing the direction and energy of the secondary beam. These calculations are also presented in Appendix I. The results for the target thickness
assumed of 100 kev for 650 kev $^3$He are:

a) From multiple scattering a mean square angle with respect to the initial direction of emission of

$$\left| \langle \Delta \hat{\alpha}^2 \rangle \right|^{1/2} = 0.3^\circ$$

(3.25)

b) From energy straggling a standard deviation for the energy loss in leaving the target of

$$\left| \langle \Delta \hat{E}^2 \rangle \right|^{1/2} = 3.6 \text{ kev}$$

(3.26)

We will therefore neglect the contributions to the anticoincidence background arising from the source target thickness.

5. Electronic requirements.

In this section the "design requirements" for the electronic system to apply the associated particle technique to the measurements of total reaction cross sections will be discussed. The essential feature of these requirements is the prevention of "accidental" anticoincidence counts, arising from electronic effects and thus not correlated with real anticoincidence events. The occurrence of such "accidental" anticoincidence counts would result in an artificial increase of the anticoincidence attenuation count.

The detailed description of the different electronic units used in the experiment is presented in Section 3 of Chapter 4. In this section we will derive the criteria applied either to their design or to their selection from commercially available ones.

In the rest of this section we will refer to the $^4$He detector as D1, to the proton detector as D2, to their respective counting rates as $M(D1)$ and $M(D2)$ and to the coincidence and anticoincidence rates as $M(D1D2)$ and $M(D1\overline{D2})$ respectively.
An anticoincidence gate will be referred to as AC and a coincidence gate as C. Random anticoincidence and coincidence rates are indicated as \( M(RAC) \) and \( M(RC) \) respectively.

We will consider the situation for \( 1 \mu A \) of incident \(^3\text{He}\) beam current, as discussed in section 3.4 and 4.1. In addition we will assume (as also discussed in 3.4) a half angle \( \alpha \) subtended by detector D2 of \( 10^\circ \) and a half angle subtended by the D1 detector of \( \Delta \xi / 2 = 2.5^\circ \).

Since the primary reaction is essentially isotropic the total rates observed in detectors D1 and D2 are proportional to their respective solid angles subtended at the center of the primary target. As will be seen in Section 2 of Chapter 4, detector D1 is sensitive to both \(^4\text{He}\) and protons, whereas detector D2 is shielded from the \(^4\text{He}\) particles. We can then write down:

\[
M(D1)/M(D2) = 2 \times \Omega_1/\Omega_2 = 2 \times (1-\cos 2.5^\circ)/(1- \cos 10^\circ) = .12
\]

If the maximum acceptable counting rate for the D2 detector is taken to be:

\[
M(D2) = 10^5 \text{ s}^{-1}
\]

we obtain:

\[
M(D1) = 1.2 \times 10^4 \text{ s}^{-1}
\]

Of all these counts, the number of coincidence counts between detectors D1 and D2 is given by 3.14 as:

\[
M(D1D2) = 2 \times 10^3 \text{ s}^{-1}
\]

The basic components of the electronic equipment are an AC gate and a C gate. These are used to select, out of the
non-coincident background, the \( M(D1D2) \) and the \( M(D1D2^-) \) rates and thus determine the attenuation factor according to equation (3.1).

From equation (3.1) a relative error present in the number of coincidences \( M(D1D2) \) will mean the same relative error in the experimental value obtained for the attenuation. If attenuation values are wanted to an accuracy of a few per cent we will restrict the number of possible random coincidence counts \( M(RC) \) to less than .5% of the true coincident rate (3.29). The resolution time \( \tau \) necessary in the C gate would be given by:

\[
\tau = \frac{M(RC)}{M(D1) M(D2)} \tag{3.30}
\]

A factor should be applied to the value of \( M(D1) \), to be used in (3.30), due primarily to the fact that an additional energy restriction is imposed on those pulses from D1 which can contribute to real coincidences or anticoincidences. This energy restriction is required in order to obtain the desired angular collimation of the associated proton beam. From the ratio of (3.29) to (3.28), this reduction amounts to a factor of 1/6 for the case considered. Then from (3.30) we obtain:

\[
\tau = 50 \text{ ns} \quad \tag{3.31}
\]

this will require D1 and D2 pulses approximately 25 ns wide, and pulse timing to better than 5 ns. This value (50 ns) of the resolving time was then obtained on the basis that the D1 pulses are first energy selected with the required resolution of 40 kev (Section 3.2) before going into the C gate. If an RC amplifier is used in connection with the D1 pulses, differentiation and integration time constants of the order of 1 \( \mu \text{s} \) are required if the above mentioned resolution is to be attained. Pulse timing
to within 10 ns is not a simple matter with pulses of this type. For this reason, a "Fast-Slow" coincidence system was employed. In this method, fast coincidences are first obtained for all pulses without energy selection. Then the output of the "Fast C" gate is checked in coincidence with the output of a single channel analyser that selects those D1 pulses in the selected energy range. In this second C gate the pulse rates are much lower due to the first fast selection, thus longer resolving times and less precise timing are permissible.

Resolving times in the order of 50 ns can be readily achieved with the transistor techniques standard in this laboratory. Adopting this as the resolving time for the fast C gate, $\tau_1 = 50$ ns, from (3.30) we obtain for the random coincidence rate at the output of the fast C gate:

$$M(RC)_{\text{Fast}} = 50 \text{ s}^{-1} \quad (3.32)$$

The random coincidence rate at the final output of the "Fast-Slow" system is given by random coincidences between (3.32) and the rate of particles selected in energy, assumed equal to $M(D1D2)$. If, as before, a final random coincidence rate of 0.5% of (3.29) is wanted, from equation (3.30) the resolving time at the second coincidence gate must be less than:

$$\tau_2 = 100 \text{ \mu s} \quad (3.33)$$

This allowed resolving time is sufficiently large, it allows amplification and selection of the pulses from detector D1, using a single channel analyser, in a slow system with high energy resolution. It is convenient to adopt pulses in the order of 1 \mu s long for the second, slow coincidence, gate. This will
result in a final random coincidence rate much less than 5% of the true coincidence rate. Also, the same form of "Fast-Slow" selection is convenient for the counting of the anticoincidence events.

The considerations required for determining the effects of random pulse coincidences and system dead times on the anticoincidence rate are of an entirely different nature, since the true rates involved $M(D_1D_2)$ are about $10^4$ times smaller than $M(D_1D_2)$, and they will be considered later on.

The problem of how to obtain the necessary timing pulses to satisfy the conditions required for the fast selection, in the "Fast-slow" coincidence system, is directly related to the discussion of the origin of "accidental" anticoincidences and is discussed next.

The occurrence of wrong timing on either of $D_1$ or $D_2$ pulses, that is the occurrence of the electronic pulse within a different time of the particle detection than normally, could result in false information recorded at the output of the fast C or AC gates. (For example, a real coincidence being recorded as an anticoincidence). As the anticoincidence rate is a factor of $10^4$ lower than the coincidence rate, even if only few coincidences are missing due to wrong timing the appearance of "accidental" anticoincidences could result in a much larger apparent attenuation than the correct one.

Two different ways of obtaining timing signals from a detector were considered, "Leading Edge Threshold" and "Zero Crossover Methods". A complete discussion of these methods is available in an article by C.W. Williams (Wi 67).

Due to the large range of amplitudes recorded at the
detector D1 (from 470 kev for the high energy protons to 3.5 Mev for the \(^4\)He particles of interest) it seemed convenient to adopt a zero crossover timing system, since such methods present a better anti-walk behaviour (change of timing as function of pulse amplitude) compared to leading edge triggering.

Two considerations led to the selection of leading edge triggering in association with detector D2. One is the presence of the large non-coincident background 100 times larger than the coincident rate itself. The second is the large dead time effects resulting from the same non-coincident background.

A convenient zero crossover time for a CsI(Tl) pulse is of the order of .5 to 1 \(\mu\)s. If another pulse occurs before the zero crossover has taken place, the crossover point and thus the timing pulse itself is delayed by the time difference between the two pulses. The probability of at least one pulse arriving before the crossover time "\(t\)" for a counting rate \(M(D2)\) is:

\[
p = 1 - \exp (-M(D2) \times t)
\]
and for .5 \(\mu\)s,

\[
p = 5 \times 10^{-2}
\]

This result is the probability that a coincident proton pulse gives rise to a delayed timing pulse. This value is much larger than the expected attenuation in the proton beam of 5 \(\times 10^{-4}\), and thus would lead to an excessive rate of false anticoincidence counts.

Similar considerations apply to the case of detector D1 but due to the lower counting rates the probability of delay timing is correspondingly smaller. It is convenient then to
operate the fast C and AC gates in a different way. For the fast C gate short, fast pulses 25 ns wide are used to prevent a large contribution from random coincidences. At the AC gate, on the other hand, a fast proton pulse longer than the zero crossover time in the $^4$He channel is desirable in order to prevent the appearance of "accidental" anticoincidences arising from delayed triggering of D1 pulses.

The final effect to be taken into account is the presence of dead time in the detectors. If a particle arrives at one of the detectors within the paralysis time following a preceding pulse, either the event fails to produce a pulse at all, or the pulse amplitude is severely degraded.

Loss of a small fraction of D1 pulses due to dead time effects does not lead to any major effects since it reduces both the coincidence and anticoincidence counts by the same factor. If the D1 pulse is produced with degraded amplitude, the event will be disregarded when the energy selection is performed.

On the other hand the disappearance of a pulse from the proton detector, D2, will result in the recording of an "accidental" anticoincidence count. If the event corresponds to a degraded D2 pulse it would be interpreted as an inelastic proton. Since these dead time effects are enhanced in the proton detector due to the large background of non-coincident protons, it is desirable to incorporate in the system additional circuitry to prevent the recording of pulses when they follow previous pulses too closely. That is, the dead time effects described can be efficiently prevented if pulse analysis is performed only when the time interval between proton pulses is greater than a
preset time, $\tau_D$, the effects of pulse degrading can be drastically reduced.

A practical way of paralysing the system during the artificial dead time $\tau_D$ is to generate a "Dead Time Pulse", of length $\tau_D$, each time a proton is detected, and use it to block the D1 pulses prior to the fast C and AC portion of the system. Thus, neither coincidence nor anticoincidence counts are recorded during the period of the "Dead Time Pulse". It is convenient to choose the length of the dead time pulse, $\tau_D$, longer than the pulse recovery time of the slowest part of the system.

The fact that a dead time pulse must be generated after each detected proton means that if a dead time pulse is already present, it must be extended in length by $\tau_D$.

The blocking of the D1 channel with the dead time pulse must, however, follow transmission to the fast gates of any associated D1 pulse. This means that the "dead time anticoincidence gate" must close approximately 25 ns after the fast AC closes.

A resume of these design requirements is illustrated in Figure 3.18. The different electronic units have been separated into blocks according to their function.
Figure 3.18: Block diagram of electronic requirements.
4. EXPERIMENTAL SET-UP.

1. General introduction.

In Chapter 3 the applicability of the reaction $^3\text{He}(d,p)^4\text{He}$ to total reaction cross section measurements was discussed. Parameters affecting the flux and kinematics of the associated beam and the anticoincidence background were also analysed. In this Chapter a description of the actual experimental set-up used is provided. The description is subdivided into two parts, that concerning the chamber and mechanical parts on one hand and that concerning the electronics on the other.

2. The chamber.

Figure 4.1 is a schematic drawing of the chamber.

It is attached to one of the beam lines on the University of British Columbia Van de Graaff generator. A singly ionized $^3\text{He}$ beam is fed to the chamber via two sets of focusing electrostatic quadrupoles and steering magnets. The beam enters the chamber through the collimators assembly A.

The chamber has its own pumping system to permit good vacuum on both sides of the collimators. It also prevents $\text{D}_2\text{O}$ vapour from going into the accelerator vacuum system when building the heavy ice target.

The inside walls of the chamber contain a .042 inches polyethylene lining as described in Section 4.2.3. of Chapter 3.

The heavy water vapour enters the chamber through the inlet B.

The solid state detector assembly C is an integral part of the chamber's bottom cover.
Figure 4.1: Schematic diagram of the Chamber

A = Incident Beam
B = D₂O Inlet
C = Si Counter
D = D₂O Ice Backing (L.N.)
E = Targets and Collimators
F = CsI Counter
G = Light Pipe
The backing foil on which the heavy ice target is formed, is located at D at the center of the chamber.

The proton detector assembly is fixed at 63° 50' with respect to the incident beam direction. The system indicated by E allows the insertion of collimators and/or different targets on the associated proton beam. The CsI scintillator F is connected to the photomultiplier via the light pipe G.

2.1. The collimator assembly.

The collimator assembly is comprised of two defining apertures and a skimmer.

Two sets of apertures and the corresponding skimmers were available. One set corresponding to a beam diameter of .160 cm (1/16 inches) and the other set to a beam diameter of .318 cm (1/8 inches). The diameters of the apertures and skimmers were machined to .001 inches. A piece of gun barrel was used as a holder for the collimators in order to align them concentrically to better than .001 inches.

The maximum angular divergency in the incident $^3$He beam, as defined by the collimator assembly was:

- .16 cm apertures ........... $75° \pm .02°$
- .318 cm apertures ........... $1.50° \pm .02°$

The collimator assembly was aligned with the incident beam direction, defined by the two sets of electrostatic quadrupoles, by means of a laser beam.

No strong focusing was used in order to keep the incident $^3$He beam on the collimators assembly as parallel as possible, and with a cross section larger than that of the apertures in use. The uniformity of the current density on the
beam region facing the collimators was checked by observing the beam in a quartz chopper.

2.2. The solid state detector assembly.

As mentioned above this assembly forms part of the chamber's bottom cover. The angular position with respect to the incident beam direction, and the vertical position relative to the plane defined by the primary beam direction and the center of the proton detector, can be adjusted without breaking the vacuum.

To center the solid state detector, with respect to the corresponding secondary beam, a small collimator of .2 inches in diameter subtending approximately 1.75° half angle from the center of the source target, was installed at the center of the proton detector. Then the anticoincidence background was measured as a function of the angular and vertical position of the solid state detector assembly. A minimum in the measured ratio of anticoincidence to coincidence count rates between the two detectors thus defines the required kinematical relationship. When this is done the solid state detector is fixed at the angle and vertical position corresponding to the minima and the small collimator in front of the proton detector removed. Typical curves are reproduced in Figures 4.2 and 4.3.

The origin of the low energy proton background was described in Chapter 3, Section 4.2.3. The contribution from the wall lining was reduced by enclosing the region between the solid state detector and the collimator with polyethylene tubing. To reduce the contribution from the collimator edge scattering, the detector-collimator spacing was made as large as possible.
Figure 4.2: Attenuation as a function of the horizontal position of a detector.

Figure 4.3: Attenuation as a function of the vertical position of a detector.
A typical pulse height spectrum from the surface barrier detector is shown in figure 4.4 for a detector depletion depth of approximately 70 microns. The continuous proton spectrum folded about the "proton edge" is observed in the center part of the spectrum with the edge well resolved from the alpha peak. The peak at lower energies corresponds to the high energy protons going through the depletion layer, leaving only a fraction of their energy in it (470 kev). The areas under the alpha peak and the low energy peak contain roughly the same number of counts as expected if these count rates are determined simply by the detector solid angle.

To prevent the 650 kev primary $^3$He beam scattered from the heavy ice target assembly from reaching the solid state detector a Nickel foil $20 \times 10^{-6}$ inches thick was installed against the detector face. This foil introduces an energy loss of 240 kev for 3.3 Mev $^4$He and 50 Kev for 15 Mev protons. Since it is mounted against the detector the fraction of secondary beam lost due to scattering from it is negligible.

2.3. The deuterium target.

The copper backing foil is in thermal contact with a liquid nitrogen reservoir which is an integral part of the top chamber cover. The container is electrically insulated from the rest of the chamber so that the primary beam current can be measured. It can also be rotated so that the angle between the source target and the incident beam can be varied.

After the backing foil has cooled, the heavy ice target is formed by letting into the chamber a measured amount of heavy water vapour. The vapour inlet has a diffusor, made with glass
Figure 4.4: Typical solid state detector spectrum
wool, to prevent nozzle effects in the incoming vapour jet.

The primary target thickness was calibrated against the amount of vapour allowed into the chamber. This amount was measured by the vapour pressure measured with respect to the chamber pressure, in a glass container of a fixed volume, and so will be quoted in centimeters of Silicon oil of differential pressure. The actual D\textsubscript{2}O target thickness was measured using the 873 kev resonance in the reaction \textsuperscript{19}F (p,\textsuperscript{4}He)\textsuperscript{16}O\textsuperscript{*} ( \sigma = 540 mb, \Gamma = 5 kev, E\gamma = 6 Mev). A fluorine target, approximately 10 kev thick, was deposited onto one side of the backing foil and the \gamma-ray yield measured as a function of the energy of the bombarding protons. Successive amounts of D\textsubscript{2}O were then let into the chamber and the energy shift of the yield curve measured in each case. The energy shifts are due to the proton energy loss in the ice layers formed on top of the fluorine target. The results are plotted in Figure 4.5.

The energy loss for \textsuperscript{3}He ions was determined from the measured energy loss for protons (Nu 60, p. 18)(We 52) (Wh 58), and illustrated in Figure 4.6.

The thin backing foils were attached to the holder by a simple, convenient technique. The backing foil holder frame was covered with a layer of indium, and the foils attached to it by a simple cold solder under pressure. This method permitted copper foils of a few microinches thickness to be attached with good thermal and electrical contact, quickly and easily.

When the target was exposed to beam currents of .2 \mu A through a 1/8 inches collimator, the \textsuperscript{3}He(d,p)\textsuperscript{4}He reaction yield deteriorated at the rate of approximately 5 \times 10\textsuperscript{-2} per hour (relative
Figure 4.5: Calibration of heavy ice target thickness.

Figure 4.6: Stopping power of D$_2$O for different particles.
change of yield per hour) for a 120 x 10^{-6} inches thick copper backing foil.

The presence of $^{16}O$ in the ice target would give rise to competing reactions arising from decays of the compound system ($^3\text{He} = ^{16}O$). The cross sections for such reactions are, however, very small due to the Coulomb barrier (of the order of 3 Mev for $^3\text{He}$ on $^{16}O$).

Secondary reactions between the high energy protons and the ice target do not contribute significantly to the anticoincidence background due to the very small thickness and hence low reaction rate in the heavy ice layer.

The distortion of the $^4\text{He}$ secondary beam in leaving the ice target is considered in detail in Appendix I and the results discussed in Section 4.2.4 of Chapter 3.

2.4. The final target assembly.

The mechanical design of the final target system was chosen to facilitate the insertion of one of several target foils in front of the detector while at the same time enabling selection of one of several different collimators situated immediately prior to the target. These items could be changed without breaking vacuum or altering the mechanical configuration of any other part of the chamber.

Figure 4.7 is a schematics of the cross section of the final target assembly. It is mounted at the end of the proton detector assembly and consists of two fixed collimators and two sliding holders. The fixed collimators can not be changed from outside the chamber, collimator #1 defines the angle $\alpha$ referred
Figure 4.7: Schematic diagram of the final target assembly.

Figure 4.8: Schematic diagram of the rotary assembly.
to in Section 4.2.1. of Chapter 3. When the sample is inserted, shown in holder number 2, the angle $\theta$ subtended by the proton detector at the center of the sample is determined by collimator #2 and remains fixed at $83^\circ$.

The two sliding holders, #1 and #2, move in a direction perpendicular to the plane of the drawing. Each of them has two target, or collimator positions available. In one position of holder #1 the .2 inches diameter collimator is usually kept, in order to align the secondary beam detector as described in section 2.2.

2.5. The rotary assembly.

In Sections 4.2.2 of Chapter 3 reference was made to the possibility of lattice effects in the attenuation background when the detectors in use are single crystals. This is the case for a CsI(Tl) scintillator.

The angular divergency of the proton beam is larger than the critical angle for channeling (Li 65) of 15.8 Mev protons in CsI of only $3^\circ$. It is desirable, nevertheless, to know if the change in the angular divergency of the proton beam due to the insertion of the sample alters the anticoincidence background.

In order to perform such measurements the final target assembly could be replaced by the rotary assembly, a schematic drawing of which is presented in Figure 4.8.

The rotary holder indicated by A is designed to hold the CsI crystal and can be rotated on its plane around the direction $k$, with respect to the rest of the proton detector assembly B attached to the chamber. This rotation can be performed from
outside the chamber via a 100:1 reduction. The angle between the holder A and the proton beam direction can be varied only by disassembling the proton detector.

Using a crystallographic method, like Laue's back reflection method, the angle that a principal axis \([a,b,c]\) of the crystal forms with its face can be found. If the angle \(\kappa\) of figure 4.8 is made equal to the axis angle, when the crystal is rotated around \(k\), one is effectively changing the angle between the proton beam and the \([a,b,c]\) axis from \(0^\circ\) to \((180^\circ - 2\kappa^\circ)\)

The assembly is, then, used to measure the dependence of the attenuation in the crystal on the lattice orientation with respect to the incident beam. The same assembly can be used to check the target samples for lattice effects; since relative measurements are involved no problem arises from the lack of facilities for inserting or removing the samples.

2.6. The proton detector assembly.

A 2 milimeter thick and 2 inches in diameter CsI(Tl) crystal scintillator is coupled with optical silicon grease to a 2 inches diameter light pipe made out of solid "Lucite" rod. The vacuum seal is made to the light pipe so that the photomultiplier tube, its shielding and electronics, are situated outside the chamber, at atmospheric pressure.

The first runs were done using an RCA 6342 phototube. It was later replaced by a CBS 7817 because of its superior electron transit time spread characteristics, which enabled better time resolution to be obtained.

The assembly is connected to the chamber at the port
indicated in Figure 4.1, located at 63° 50' from the direction defined by the primary beam collimators, corresponds to the angle providing kinematical collimation as described in section 3.2 of Chapter 3.

In order to reduce the low energy non-coincident background count rate in the proton detector due to detection of the 4He particles produced by the source reaction into the angle subtended by the detector, the window for light reflection on the open face of the scintillator was made of aluminum foil 18. x 10^-4 cm thick. This thickness allows it to stop up to 4.5 MeV 4He, the energy of the alpha particles emitted at 63°. This thickness of aluminum is only expected to contribute an anticoincidence background of about 6.6 x 10^-5, a value that is much less than the background from the detector itself.

3. **Electronics.**

The overall electronic requirements were discussed in Section 5 of Chapter 3.

Most of the electronics was designed and built in the laboratory at a time when such instrumentation was not readily available commercially. As the experiment progressed, many of these locally manufactured units were replaced with more flexible commercial units when they became available. The details of the locally manufactured units still in use is presented in Appendix 3. Special attention will be given in this section, however, to the "paralysable dead time generator" since it is the main component to eliminate the appearance of "accidental" anticoincidences due to random effects.
The block diagram of the electronics is presented in Figure 4.9. This is an "expanded" version of Figure 3.18 used to illustrate the basic system. The fast and slow circuits are clearly distinguished. In agreement with the design requirements previously discussed, the fast circuitry is composed of units having rise times of less than 10 ns. The slow units have rise times of over 100 ns.

Description of the system will be presented in three subsections, one being the solid state detector channel and associated units, one describing the CsI scintillator channel and related equipment and the third being the "Paralysable dead time generator".

3.1. The solid state detector channel.

The solid state detector signal is fed into a charge sensitive amplifier. The output of the preamplifier is fed into both a "slow" channel for energy selection of the $^4$He particles, and also a "pulse shaper" circuit to obtain the bipolar pulse necessary for the zero cross over triggering. A zero cross over unit detects the zero cross over time of the "pulse shaper" output and triggers a pulse 25 ns wide.

The energy selection is performed with the "slow" unit consisting of an ORTEC 410 Multimode Amplifier, with differentiation and integration time constants of 1 μs, an ORTEC 408 Biased Amplifier and a COSMIC 901 SCA Single Channel Analyser. The biased amplifier and the single channel analyser were set to select $^4$He particles in the energy range 3.17 to 3.27 MeV for appropriate "Kinematical collimation" of the associated protons.
Figure 4.9: Block diagram of the electronics.
as described in Section 3.2 of Chapter 3. The solid state detector used possessed an overall resolution of 40 KeV as measured with a $^{241}$Am alpha source.

A 512 channel pulse amplitude analyser NUCLEAR DATA ND120 at the output of either the multimode amplifier, or the biased amplifier, was used in coincidence mode with the single channel analyser output to help in setting the desired energy. The output of the single channel analyser also fed a scaler to monitor the number of $^4$He particles of the desired energy selected.

3.2. The photomultiplier channel.

The photomultiplier was supplied with negative high voltage, and the anode signal fed through an ORTEC 260 Time Pickoff unit into the base of the first transistor of the pre-amplifier.

The time pickoff unit provided the "Leading edge trigger" for this channel. The threshold level, mentioned in Section 4.2 of Chapter 3, was controlled with an ORTEC 403 Time Pickoff Control unit that permitted continuous adjustment of the triggering level of the time pickoff unit.

The preamplifier delivers bipolar pulses, used to eliminate problems associated with DC shifts due to the high counting rates characterizing this channel. The time from threshold to the zero crossover point can be varied by changing the length of a delay line. When using a CsI crystal it was adjusted to approximately 500 ns. When a plastic scintillator was employed (for the test runs described in Chapter 5) it was adjusted to about 100 ns.
The output of the fast leading edge trigger unit was fed into a passive variable delay unit used to balance the delays in the two channels prior to the fast coincidence gate. This time delay unit was also useful in determining the time resolution of the fast coincidence gate.

The fast pulse is also used to trigger the "Paralysable Dead Time Generator" whose design will be discussed in section 3.4. This generator produces a pulse 16 μs long, with rise and fall times of less than 10 ns, each time a fast proton pulse arrives. (as required by Section 5 of Chapter 4 for the Dead Time Pulse). The Dead time pulse is delayed by an additional 50 ns before being fed into the "Dead time Gate" used to paralyse the alpha channel.

It was found convenient to use as a proton gating pulse in the fast AC gate the non-delayed output of the dead time generator, instead of employing an extra pulse stretcher unit, as illustrated in Figure 3.18.

The output of the preamplifier was fed via a passive variable delay unit into a LeCROY 1086 Fast Linear Gate operated in coincidence mode. The gating pulse was obtained from the output of the "transmission" slow coincidence unit. Thus, this gate selects only those proton pulses corresponding to the alpha particles selected in the alpha channel before amplification by a "slow" system, for high energy resolution. The gate pulse width is adjusted to be approximately equal to the zero crossover time in use in the channel, so that the output pulses of the gate are essentially unipolar.

The slow unit following the fast linear gate was composed of a CAMBERRA 1410 Multimode Amplifier operated with integration
and differentiation time constants of 1 μs and a NUCLEAR DATA 160 multichannel pulse height analyser operated in single parameter mode and in subgroups of 256 channels.

Due to the high counting rate in this channel, an electronic counter was preferred over a scaler for monitoring the transmitted proton rate. The "instantaneous" rate instead of the total number of counts accumulated over the long counting time interval, as obtained from such a unit, was found very useful for detecting deterioration of the heavy ice target.

3.3. Coincidences and anticoincidences.

The system of coincidences and anticoincidences as required by the design considerations of Section 5 of Chapter 3, is essentially a standard "Fast-Slow" system, applied to both the coincidence and anticoincidence channels.

The fast coincidence gate was fed with fast pulses from both the $^4$He and proton channels.

As mentioned in Section 3.2, the non-delayed output of the Paralysable Dead Time Generator was used as gating pulse for the Fast Anticoincidence unit. The fast alpha pulses were delayed by 200 ns to ensure that the gate was completely closed in those cases where the alpha pulse was accompanied by a coincident proton pulse.

The fast anticoincidence gate used as the "Dead time gate" differs from the Fast Anticoincidence unit only in that a 50 ns delay for the dead time gating pulse is incorporated. This results in different DC levels at the gating inputs. Both anticoincidence gates were, however, DC connected to the gating
pulses (the reasons for this requirement are presented in section 3.4, where reference is also made to the different DC levels mentioned above).

The outputs of the fast gates were fed into two separated "slow" coincidence units named the "Transmission Coincidence Gate" and the "Absorption Coincidence Gate". Here the slow selection of the design requirements was satisfied. The second input to each slow coincidence unit was connected to the output of the alpha channel Single Channel Analyser described in section 3.1.

The slow coincidence gate outputs were fed into two different scalers, a "Transmission Scaler" which provides a measurement of \(M(D_1D_2)\), and an "Absorption Scaler" used to record the number of absorbed protons or \(M(D_1D_2^-)\).

3.4. The paralysable dead time generator.

Figure 4.10 is a simplified schematic drawing indicating the essential components of the paralysable dead time generator. The detailed unit actually used is illustrated in Figure 4.11.

The short input pulse, (the timing proton pulse), is fed via C1 into a "pulse stretcher" formed by T1, R2, R3 and C2. T1 is an emitter follower used to charge C2 to the value \(V_i + V_l\), where \(V_i\) is the amplitude of the input pulse and \(V_l\) is the DC level at the emitter of T1. This operation, of course, requires the duration of the input pulse, \(t_i\), to be:

\[
t_i \gg R_3 \cdot C_2
\]  

(4.1)

Following the pulse, T1 is cut-off, and the stretch capacitor, C2, discharges towards ground via R2 and R3. When the
Figure 4.10: The paralysable dead time generator (essential components).
Figure 4.11: Circuit diagram of the paralysable dead time generator.
voltage at the emitter of $T_1$ returns to $V_I$, $T_1$ comes into conduction again, and the discharge ceases. For $V_i \ll V_I$ the discharge is approximately linear, and the discharge time (or stretch interval) is given by:

$$t_s = C_2 \cdot \frac{V_i}{I_I} \quad (4.2)$$

where $I_I$ is the DC current in transistor $T_1$.

For long $t_s$, of the order of $\mu$s, and $I_I$ equal for example to 1 mA and $V_i$ of a few volts, $C_2$ is of the order of $10^3$ pF. Since the input pulses are only 25 ns wide, an intermediate stretcher prior to the $T_1$-$C_2$ stretcher discussed here was employed in the complete circuit shown in Figure 4.11.

$T_2$ is an emitter follower used to buffer the discharge waveform (B) from the rest of the circuit.

The DC conditions following the stretcher capacitor $C_2$ are set as follows. $T_3$ is held in saturation with the tunnel diode $T_D$ in its low stable state, so that $V_3 = V$. Due to the $V_{BE}$ voltage drop in $T_1$, $V_2 < V_3$ and $T_2$ is off. Following an input pulse $V_2$ rises, and when $V_2 > V_3$, $T_2$ goes into conduction causing $T_3$ to be turned off. This forces the current $I_4$ through the tunnel diode $T_D$, which switches into the upper stable condition. This situation persists until the value of $V_2$, now controlled by the discharge of $C_2$, falls below $V$. $T_3$ then goes back into the saturation mode and the $T_D$ switches back to its DC condition.

$\Delta V$ is a variable voltage supply that allows $V_2$ to be adjusted with respect to $V_3$ thus permitting the width of the square pulse at (D) to be varied. The situation is illustrated by the waveform diagrams (A) to (E) of Figure 4.10. The dashed
line in waveform (B) indicates the switching level set by V+ΔV. The tunnel diode is used to produce a pulse with short rise and fall times. This pulse is used to drive T4 into saturation, thus defining the output pulse.

If a second pulse occurs before V2 has recovered to its DC condition, C2 is recharged and the output pulse width is extended for an additional discharge period. Since the circuit is completely DC coupled, the operation as described was found to apply even for pulse rates so large that 100% paralysis resulted.

The matching of DC levels with the anticoincidence gates is provided by T7 in the complete diagram of Figure 4.11.

4. **Electronics performance.**

The performance of the electronic system was checked with artificially generated pairs of coincident alpha and proton pulses. High rates of "proton" pulses, produced by a pulse generator randomly triggered with a β-source, were superimposed on the coincident pairs. The system could then be tested for the appearance of "accidental" anticoincidence events due to high background rates.

For a coincident count rate of 2 x 10^3 s⁻¹ and random rates up to 120 x 10^3 s⁻¹, much above experimental values, not a single anticoincidence was observed.

4.1. **The paralysable dead time generator.**

The same set-up of artificially generated pulses also permitted a detailed examination of the performance of the "Paralysable dead time generator". When the random proton rate
is superimposed on the coincident rate, a certain fraction of the coincident pulses are eliminated at the dead time gate. This gate, as discussed before, remains closed for a length of time \( \tau_D \) after each detected proton. \( \tau_D \) was chosen to be 16 \( \mu s \).

The probability of having no counts appearing in a time interval \( \tau_D \), for pulses with a Poisson distribution corresponding to rate \( 'n' \) is given by:

\[
P_0 = \exp \left( -n \tau_D \right) \quad (4.3)
\]

If a coincident pair of alpha and proton pulses appears after a period \( \tau_D \) in which no protons were detected, a coincident count is recorded. Then, the recorded coincidence rate \( M(C) \) is given by the true coincident rate \( M(D_1D_2) \) multiplied by the probability of no random protons [of rate \( M(D_2) \)] occurring during the preceding \( \tau_D \) interval, or:

\[
M(C) = M(D_1D_2) \exp \left[ -M(D_2) \tau_D \right] \quad (4.4)
\]

The fraction of coincidences lost at the dead time gate, \( \Delta M(C) \), is then given by:

\[
\Delta M(C) = M(D_1D_2) \left[ 1 - \exp \left\{ -M(D_2) \tau_D \right\} \right] \quad (4.5)
\]

From (4.4) we obtain:

\[
\ln \left[ M(C)/ M(D_1D_2) \right] = -M(D_2) \tau_D \quad (4.6)
\]

The number of coincidence counts, corresponding to \( M(C) \) are obtained directly at the "Transmission Scaler" (See Figure 4.9). The true number of coincidence counts \( M(D_1D_2) \) is recorded at the \("^4\text{He Monitor Scaler}". The proton rate \( M(D_2) \) is given by the electronic counter in the proton channel.
In Figure 4.12 the result of the "Paralysable dead time generator" check is presented. The ratio between the true and detected coincidence counts is plotted against the proton rate. The full line is the expected behaviour as obtained from equation (4.6), assuming a $\tau_D$ of 16 $\mu$s.

4.2. Proton channel threshold triggering and calibration.

With the experimental configuration used, two difficulties were experienced with the setting of the proton channel discrimination level. One involving the operation of the Time Pickoff Unit at low discrimination levels, and the other arising from the use of high count rates;

1) the unit (ORTEC model 260) tended to multitrigger when the discrimination was set below a level corresponding to about 3 Mev for our experimental configuration. In this case, for each incoming pulse or particle detected, a train of pulses of decreasing amplitude was produced.

2) a number of spurious counts were produced below the "cut-off" setting of the discrimination level when high proton rates were used, their total number being less than $10^{-3}$ of the counts in the full energy peak. For the measurements presented in Section 4 of Chapter 5 the total number of counts in this region for the different targets used (Au, Cu, Fe) agreed within statistics.

Since the operation of the "time pickoff" units is dependent on the rise time of the current pulse at the anode of the phototube, it was difficult to calibrate the discriminator settings as a function of energy with a fast pulser. The calibra-
Figure 4.13: Time pickoff unit calibration.

Figure 4.12: Paralyzable dead time generator performance.

Fraction of counts lost at the dead time gate
tion was therefore obtained by producing a continuous proton energy distribution. A number of aluminum foils, $12 \times 10^{-3}$ cm thick, stacked in a "wedge" arrangement were placed in front of the proton detector. Enough clear area was left so the 15.8 Mev peak could be seen, in order to define the energy scale. The foils produced a reasonable counting rate of protons with energies distributed between very low energies and the full energy peak.

A multichannel analyser was gated in coincidence with the output of the "Time pickoff" unit so that the cut-off at the discriminator level could be seen in the energy spectrum.

The result is presented in Figure 4.13. The lack of linearity was characteristic of all the "Time pick-off" units used in our laboratory. The error bars in the energy values correspond to the uncertainty in the experimental determination of the channel at which the discriminator cut-off occurred.
5. PERFORMANCE & CONCLUSIONS.

1. General introduction.

The details of the method of applying the "Associated particle technique" to the measurements of proton total reaction cross sections were discussed in Chapter 3. In Chapter 4 the actual experimental set-up was described. In this chapter the performance of the system is presented, together with the discussion of measurements for particular targets.

Measurements were performed for readily available targets of natural copper, natural iron and gold, with the aim of testing the usefulness of the technique.

2. The associated beam profile.

Knowledge of the angular distribution of the associated beam of protons, or beam profile, is necessary to determine if geometrical corrections are required in the elastic correction of the type described in section 4.1.1 of Chapter 3.

Measurements of the attenuation as a function of the angular and vertical positions of the solid state detector assembly were, as mentioned in Section 2.2 of Chapter 4, used to position it. These measurements were also used to obtain the angular profile of the associated proton beam.

A change in the angular position of the $^4$He detector can be translated (using the data of Figure 3.7) into the corresponding shift in the angular position of the proton beam. A similar technique can be employed for the vertical position. The observed ratio: $f = \frac{M(D1D2)}{\text{(number $^4$He)}} = \frac{M(D1D2)}{M(D1D2) + M(D1D2)}$ or $f = (1 + \delta)^{-1}$ (5.1)
Figure 5.1: Associated proton beam profile.
obtained from the data of Figures 4.2 and 4.3 is therefore a measure of the associated proton beam intensity over an angular interval of approximately 3.4° (as defined by the proton collimator size). These results are presented in Figure 5.1, and show that more than 90% of the coincident proton beam is contained in the region between 0° and 4° from the center of the beam. (The asymmetry observed in the figure for the horizontal profile was produced by a change of heavy ice target thickness during that particular run). This angular spread was found to be sufficiently small so that no significant correction was required in the target elastic scattering correction. For this reason a detailed quantitative measurement of the profile shape was not performed.

An example of the extent of such a correction for the case of protons in copper where the elastic correction is of the order of 53 mb (83° to 180°) would lead for a 4° change in the direction of incidence and assuming Rutherford scattering for simplicity, to a modification in this value of the order of 1 mb. This value is negligible as compared to the cross sections measured of the order of 900 mb.

3. The anticoincidence background.
3.1. The primary beam parameters.

To check for possible effects of very short period 3He beam instabilities that were not detected by observing the beam periodically, measurements were made under extreme focusing conditions. By means of the quadrupole lenses and steering magnets the beam was focused into either a sharp horizontal or
a sharp vertical line and moved across the collimator apertures. Within the 10% statistical errors, the anticoincidence background was independent of the focusing conditions.

Normally the beam was focused so as to have a cross section larger than the collimating apertures and a roughly uniform current density across it.

The anticoincidence background was also measured for two different collimator aperture diameters (1/8 and 1/16 inches). The larger aperture, as described in Appendix I, permitted larger beam currents, and so higher counting rates. No dependence was found in the anticoincidence background, again within the statistical errors of 10%.

3.2. The heavy ice thickness.

No dependence, to 10%, was found in the anticoincidence background as a function of the heavy ice target thickness for the range of thicknesses employed in the measurements. Only when the thickness exceeded about 3 times that used during the measurements, did a rise in the anticoincidence background occur.

3.3. The plastic scintillator.

Since plastic scintillators have been used by other workers, a measurement of the total attenuation background, using our system, was performed for this scintillator as a further check of the overall operation. Pollock and Schrank (Po 65a) for example, obtained an attenuation value of:

$$\delta = 5.00 \times 10^{-3}$$  (5.2)
for 17 Mev protons when their discrimination level was set in the valley at approximately 3.3 Mev below the elastic peak. This is in the region between the low energy tail of the elastic peak and the contributions from inelastic scattering to the 4.43 Mev level of $^{12}\text{C}$. For our measurements a plastic scintillator was substituted for the CsI crystal and the attenuation measured for the 15.8 Mev associated protons. The discrimination level was chosen to be in the same energy region as that used by Pollock and Schrank. The value obtained for the attenuation was: 

$$\delta' = (5.00 \pm .13) \times 10^{-3}$$  \hspace{1cm} (5.3)

The higher bombarding energy used by Pollock and Schrank would be expected to increase this value by: 

$$\Delta \delta = (.60 \pm .05) \times 10^{-3}$$  \hspace{1cm} (5.4)

This estimate is based on the total reaction cross section for carbon obtained by Pollock and Schrank.

Adding the values given by (5.3) and (5.4) we obtain: 

$$\delta = (5.60 \pm .18) \times 10^{-3}$$  \hspace{1cm} (5.5)

Since Pollock and Schrank did not assign any experimental error to their value, the agreement of (5.2) and (5.5) within 10% is considered a satisfactory check of the overall operation of our system.

3.4. The CsI detector.

As previously discussed in Section 4.2 of Chapter 3, of the readily available scintillators, CsI is the most convenient due to its low background contribution.
The dependence of the attenuation in the CsI as a function of the discriminator level was estimated for 15.8 and 14.8 Mev protons from total reaction cross section data for neighbouring nuclei, assuming that the (p,n) reactions dominate. These results were presented in Figure 3.17.

For the experimental configuration used, the energy of the protons incident on the CsI scintillator is 14.8 Mev after traversing the sample. Since the attenuation in the CsI is a function of the proton energy an accurate measurement of the sample attenuation requires either an accurate knowledge of the dependence of the CsI attenuation as a function of energy, or the use of a comparison target of the same energy thickness as the sample under investigation, whose cross sections are well known.

For the reference sample a gold foil was chosen because it contributes an attenuation lower than most other foils and was readily available in the desired thickness.

Attenuation measurements were performed for both the bare CsI scintillator (15.8 Mev protons) and with the gold foil (3.617 x 10^-3 cm thick) in front of it (14.8 Mev protons), yielding the following values:

\[ \Delta_{\text{CsI}}(15.8 \text{ Mev}) = (19.7 \pm .5) \times 10^{-4} \]  \hspace{1cm} (5.6)

\[ \Delta_{\text{CsI}}(14.8 \text{ Mev}) + \Delta_{\text{Au}} = (18.97 \pm .23) \times 10^{-4} \]  \hspace{1cm} (5.7)

For both measurements the discriminator level was set on the flat region of the curves in Figure 3.17, at approximately 10 Mev.
(5.6) can be compared with the estimated value from Figure 3.17 of:

\[ \delta_{\text{theo}}^{\text{CsI}} (15.8 \text{ Mev}) = 19.2 \times 10^{-4} \]  

(5.8)

for 15.8 Mev protons in CsI. The agreement between (5.6) and (5.8) (in the 2.5% order) is certainly better than is warranted by the assumptions involved in the estimated value.

Direct comparison of the experimental value (5.7) with the estimated attenuation for 14.8 Mev protons in CsI cannot be directly performed. The experimental value includes the contribution arising from the elastic scattering and reactions that take place in the gold foil.

The close agreement between (5.6) and (5.8) is felt to justify the use of the estimated values for the dependence of the attenuation in CsI on the proton energy to an accuracy of 5%, over the small energy range (15.8 to 14.8 Mev) involved.

With the gold foil in position the attenuation was measured as a function of the discrimination level as illustrated in Figure 5.2. A determination of the attenuation in CsI for 14.8 Mev protons as a function of the discrimination level can be obtained by subtracting from this curve the contribution arising from the gold foil.

As is indicated in Table 5.1 of this Chapter the estimated change in the attenuation for CsI between 15.8 Mev protons and 14.85 Mev (as defined by the energy thickness of the gold foil) is:

\[ \Delta \delta_{\text{theo}}^{\text{CsI}} = (3.17 \pm .16) \times 10^{-4} \]  

(5.9)
Figure 5.2: Attenuation background as a function of the discrimination level.
where the uncertainty is given by the 5% level determined above.

The use of (5.6), (5.7) and (5.9) enables us to estimate the attenuation arising from the gold foil. That is,

\[ \delta_{Au} = \Delta \delta_{CsI} - \Delta \delta' \]  

(5.10)

where:

\[ \Delta \delta' = \delta_{CsI} (15.8 \text{ MeV}) - \left\{ \delta_{CsI} (14.8 \text{ MeV}) + \delta_{Au} \right\} \]  

(5.11)

from (5.6) and (5.7) we obtain:

\[ \Delta \delta' = (0.73 \pm 0.55) \times 10^{-4} \]  

(5.12)

Thus,

\[ \delta_{Au} = (2.44 \pm 0.58) \times 10^{-4} \]  

(5.13)

If one assumes that the major contribution to the reaction cross section in Gold arises from (p,n) reactions, then the measured attenuation for gold would be independent of the discrimination level. Thus the attenuation contributed by the CsI (at 14.85 Mev) as a function of the discriminator level would, on this basis, be obtained by subtracting the constant value \((2.44 \pm 0.58) \times 10^{-4}\) given by (5.13). In this way the points shown as triangles in Figure 5.2 were obtained. The experimental error bars have been assigned to the measured values minus the contribution from gold, in order to compare them with the estimated curve shown by the full line. This curve is the same as that presented in Figure 3.17.

In general the agreement is good, with the experimental points slightly above (approximately 8%) the estimated values.

Two regions of large discrepancies with the measured values are observed, one for discrimination levels below 3 Mev
and the other for settings above 11 Mev. The sharp increase in the experimental values above 11 Mev corresponds to the low energy tail of the elastic peak starting to be included below the setting of the discriminator.

The possibility of an increase in the attenuation at low energies arising from backscattering in the CsI detector was considered. A fraction of the protons incident on the detector will be backscattered out of the detector leaving in it only a portion of their total energy. A computer program was written to perform this calculation by assuming Rutherford scattering from the Cs and I nuclei. The energy spectrum arising from backscattering was then calculated and found to yield a peak at about 3 Mev, but with an attenuation of at least an order of magnitude too low (\(1 \times 10^{-4}\)) to explain the divergency between the measured and estimated attenuations at 3 Mev.

This discrepancy, at 3 Mev, appears in the same energy region of discrimination settings as that of multitriggering of the "Time Pickoff" unit for a single input pulse (See Section 4.2 of Chapter 4). It is assumed that in this region the unit fails to trigger properly for the low energy protons and so gives rise to a constant detected attenuation for decreasing discrimination level.

The tendency of the experimental points to lie above the estimated values, in the region from 4 to 9 Mev, could reflect the presence of a significant contribution to the total reaction cross section for gold from other than \((p,n)\) processes.

For all subsequent measurements, the discrimination
level was set at around 10 Mev, in the flat portion of the curve of Figure 5.4. The reasons for this setting are discussed in Section 4.

3.4.1. Lattice effects.

The "Rotary Assembly" described in Section 2.5 of Chapter 4 was employed to measure the anticoincidence background as a function of the CsI crystal orientation with respect to the associated proton beam.

Using Laue's back reflection method (Cu 60) the orientation of the [1,1,1] axis of the CsI crystal lattice was found to be at an angle of 14° with the crystal surface. X-Ray radiation from molybdenum was used.

Referring back to Figure 4.8, the angle \( \kappa \) was made equal to 14° and the crystal rotated 360°, in 36° steps, around the axis \( k \).

The anticoincidence background was independent of the orientation of the CsI lattice within a 10% statistical error.

Thus, for the experimental arrangement used during attenuation measurements, the attenuation background due to the proton detector is assumed to be independent of changes in the angular distribution of protons incident on the CsI crystal scintillator.

No quantitative measurements of the microcrystal sizes, or lattice effects were performed for the samples used.

4. Total proton reaction cross section measurements.

In Section 4.2.2 of Chapter 3 two different possibilities for performing attenuation measurements were discussed. The
first involved setting the discrimination level in the proton channel as low as is compatible with the noise of the system. This method essentially eliminates the problem of correcting for the variation in attenuation with energy in the full-energy detector. On the other hand it requires detailed knowledge of inelastic scattering and \((p,q)\) cross sections for the sample to be measured.

A modification of this method employing an additional counter to yield an improved geometry and better energy resolution has recently been described by Dicello et al (Di 66). They are capable by these means of achieving measurements of total proton reaction cross sections to \(2\% - 3\%\).

In the second case, using high settings of the discrimination level (below the elastic peak) detailed knowledge of \((p,p')\) and \((p,q)\) cross sections for the sample are less important, but require a background correction due to the change in incident energy of the protons into the CsI detector.

The geometry used in the present experiment is imposed by the nature of the proton beam inherent to the technique. Its angular divergency requires a large angle to be subtended by the proton detector in order to make an accurate elastic scattering correction for the sample to be measured. The large angle is also required in order to have a low contribution to the attenuation background due to proton scattering in the heavy ice backing foil. Significant inelastic corrections in the sample attenuation will only occur for this large angle when a low discrimination level is used.

Because of lack of detailed experimental data on angular
distributions of non-elastic cross sections the discrimination level was set just below the elastic peak. As mentioned before, this introduces the necessity of correcting the attenuation background for the change in the proton energy occurring at the proton detector when a sample is inserted.

By normalizing the measurements to a comparison target of the same energy thickness as the sample, i.e. "difference" measurements, the values so obtained are independent of the energy dependence of the attenuation in the CsI detector.

In addition, the comparison target can be chosen to be a material of large dE/dx (e.g. gold) for which the attenuation resulting for the same energy thickness is approximately half of that for Copper, Iron, etc. Therefore if accurate "difference" measurements are performed, the uncertainties in the absolute values characterizing the various samples would be approximately half of the uncertainty in the absolute determination of the comparison target.

Measurements were performed for readily available targets of natural copper and natural iron in addition to those for gold that were discussed in Section 3.4.

The characteristics of the targets used are presented in Table 5.1. In row #1 the thickness is given as determined by weighing the targets, the quoted error arises from determining the surface area for the targets (targets dimension : 2 inches diameter). Row #6 gives the estimated change in the CsI attenuation due to the decrease in proton energy (from 15.8 Mev) by the energy loss given in row #5. The uncertainties assigned in row #6 correspond to the 5% value discussed in Section 3.4.
TABLE 5.1

Characteristics of the different targets

<table>
<thead>
<tr>
<th>#</th>
<th>TARGET</th>
<th>GOLD</th>
<th>COPPER</th>
<th>IRON</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thickness $10^{-3}$ cm</td>
<td>3.617 ± .002</td>
<td>4.998 ± .0025</td>
<td>5.674 ± .003</td>
</tr>
<tr>
<td>2</td>
<td>Molecules $\cdot$ cm$^{-2}$ x $10^{19}$</td>
<td>21.340</td>
<td>42.283</td>
<td>48.124</td>
</tr>
<tr>
<td>3</td>
<td>Stopping Power $\times 10^{-15}$ ev-cm$^2$</td>
<td>4.45 (Wh 58)</td>
<td>2.1 (Wh 58)</td>
<td>1.95 (Wh 58)</td>
</tr>
<tr>
<td>4</td>
<td>Stopping Power MeV cm$^{-1}$</td>
<td>262.6</td>
<td>177.9</td>
<td>165.4</td>
</tr>
<tr>
<td>5</td>
<td>Energy loss by 15.8 MeV protons MeV</td>
<td>.950</td>
<td>.889</td>
<td>.939</td>
</tr>
<tr>
<td>6</td>
<td>Estimated $\Delta\delta$ in CsI ($\times 10^{-4}$)</td>
<td>-3.17 ± .16</td>
<td>-2.97 ± .15</td>
<td>-3.13 ± .16</td>
</tr>
</tbody>
</table>
4.1. Summary of results for gold.

The value of the attenuation obtained for gold (5.13) 
(2.44 ± .58) x 10^{-4} is an absolute measurement of its attenuation. The large uncertainty arises from the uncertainty in the dependence of the CsI attenuation with energy.

The high settings of the discriminator assure a value for gold practically independent of non-elastic contributions. For the same geometry the inelastic correction for copper and iron presents an attenuation of the order of .15 x 10^{-4}. Since the larger Coulomb barrier for gold would be expected to further inhibit charged particle emission in favor of neutron emission, giving rise to a smaller contribution than that of copper or iron, which is already of such magnitude to be within the experimental uncertainty, a more quantitative estimate for gold was not attempted.

The correction arising from elastic scattering outside the detector angle was calculated by generating the angular distribution using the Optical Model program SCAT 4 mentioned in Chapter 1. Experimental values for the scattering of protons from gold is available for 17 Mev protons (Da 56). This data has been fitted with Optical Model potentials by a number of authors. The potentials obtained by Glassgold and Kellog (Gl 57) were chosen because they fit the large angle elastic scattering data. These angles, between 83° and 180°, are the ones required for the correction. In order to account for the lower proton energy the real potential was increased by the energy dependence of the "Perey potential" (See Chapter 1 eq. (1.4), .55 E). The imaginary part was decreased according to the general trend of
this potential with incident proton energy for heavy nuclei. (Ho 63, p. 105).

The values of the parameters used for the potential were:

\[ V = 61.3 \text{ MeV} \quad a = 0.55 f \]
\[ W = 7.2 \text{ MeV} \quad r_0 = 1.23 f \]

with both the real and imaginary parts having the same Saxon-Woods radial dependence. The cross sections obtained were:

Elastic scattering; \( \sigma_{E}^{\text{theo}} \) (83 - 180) = 242 mb \[ (5.14) \]
Reactions; \( \sigma_{R}^{\text{theo}} \) = 768 mb

For the thickness of gold used this gives rise to theoretical attenuations of:

\[ \delta_{E}^{\text{theo}} = 0.52 \times 10^{-4} \]
\[ \delta_{R}^{\text{theo}} = 1.64 \times 10^{-4} \]

or a total value of:

\[ \delta^{\text{theo}} = 2.16 \times 10^{-4} \]

The value so obtained is 13% smaller than the experimental value but within the experimental error.

The final result for gold is presented together with the results for copper and iron in TABLE 5.2.

4.2. Measurements for copper and iron.

A summary of results is presented in TABLE 5.2. Measurements were obtained by alternating either copper or iron with the gold comparison target. In this way all values could be checked for consistency with each other during the run and
### TABLE 5.2

Experimental results

<table>
<thead>
<tr>
<th>#</th>
<th>TARGET</th>
<th>GOLD</th>
<th>COPPER</th>
<th>IRON</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measured $\delta \times 10^{-4}$</td>
<td>18.97</td>
<td>21.05</td>
<td>21.09</td>
</tr>
<tr>
<td></td>
<td>± .23</td>
<td></td>
<td>± .25</td>
<td>± .28</td>
</tr>
<tr>
<td>2</td>
<td>$\delta \text{Cs}_1(15.8\text{MeV}) - \Delta \delta \times 10^{-4}$</td>
<td>16.53</td>
<td>16.73</td>
<td>16.57</td>
</tr>
<tr>
<td></td>
<td>± .53</td>
<td></td>
<td>± .53</td>
<td>± .53</td>
</tr>
<tr>
<td>3</td>
<td>Sample attenuat. $\times 10^{-4}$</td>
<td>2.44</td>
<td>4.32</td>
<td>4.52</td>
</tr>
<tr>
<td></td>
<td>± .58</td>
<td></td>
<td>± .58</td>
<td>± .58</td>
</tr>
<tr>
<td>4</td>
<td>Measured cross section $\text{mb}$</td>
<td>1143</td>
<td>1022</td>
<td>939</td>
</tr>
<tr>
<td></td>
<td>± 272</td>
<td></td>
<td>± 137</td>
<td>± 121</td>
</tr>
<tr>
<td>5</td>
<td>Elastic correction $\text{mb}$</td>
<td>242</td>
<td>53</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>± 24</td>
<td></td>
<td>± 5</td>
<td>± 5</td>
</tr>
<tr>
<td>6</td>
<td>Inelastic correction $\text{mb}$</td>
<td></td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>± 7</td>
<td></td>
<td>± 7</td>
<td>± 7</td>
</tr>
<tr>
<td>7</td>
<td>Total reaction cross section $\text{mb}$</td>
<td>901</td>
<td>1003</td>
<td>925</td>
</tr>
<tr>
<td></td>
<td>± 274</td>
<td></td>
<td>± 138</td>
<td>± 122</td>
</tr>
<tr>
<td>8</td>
<td>Uncertainty %</td>
<td>30</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>
systematic deviations, if present, detected.

The anticoincidence counting rate was 20 per minute for $^3$He beam currents of the order of .15 $\mu$A. This represents a counting time between 3 and 4 hours for the approximately 1% statistical uncertainty in the total attenuation obtained (sample plus background).

The elastic corrections were calculated by interpolating, with the help of the optical model, the experimental elastic scattering data of Dayton and Schrank (Da 56) for copper and iron at 17 Mev; that of Koike et al (Ko 65), for 14.6 Mev protons in copper; and that of Kikuchi et al (Ki 59) for 14.6 Mev protons in iron. An uncertainty of 10% was assigned to the resulting corrections.

The inelastic corrections were calculated from the results of Cohen et al (Co 59) for 14.6 Mev protons in copper and iron. From the measured cross section at 90° the contribution into the angles between 83° and 180° was obtained by assuming isotropy in the angular distribution. From the same reference, using the relative intensity of the inelastic protons as a function of their energy, the fraction of the cross section for inelastic scattering into the detector angle with energies above the discrimination level of 9.5 Mev was obtained. An uncertainty of 20% was assigned to these values.

No corrections arise from such processes as (p,d), (p,t) or (p,$^3$He). Their large negative Q-values result in the final particle of any of these reactions, if present, being detected with energies below the discrimination level and, thus recorded as an anticoincidence count. On the other hand (p,$^4$He)
reactions have a positive Q-value but their cross sections are estimated to be only 20% of those for inelastic scattering on the basis of measurements at 10 Mev (Be 61) and were not considered in detail.

Based on the discussion of Section 4.1.1 of Chapter 3, corrections due to compound elastic scattering were considered negligible.

4.3. "Difference" measurements.

The large errors associated with the reaction cross section measurements listed in TABLE V.2 arise mainly from the uncertainty in the correction involved in the CsI attenuation.

It is possible, nevertheless, to obtain from the experimental data, values for the "differences" in attenuations between samples. For samples of the same energy thickness differences between measured attenuations are independent of the CsI attenuation.

For the case of equal energy thickness, the measured attenuation difference between targets A and B is given by:

\[ D = \delta_A - \delta_B = N_A \sigma^A - N_B \sigma^B \]  

(5.18)

where \( N_A \) is the number of atoms per cm\(^2\) of target A, and \( \sigma^A \) indicates the cross section for target A as measured, without corrections. We will consider target B as being a comparison target. By adding and subtracting \( \sigma^B \) from the first term of equation (5.18):

\[ D = N_A (\sigma^A - \sigma^B) + \sigma^B (N_A - N_B) \]  

(5.19)
From here, an expression for the difference between the measured cross sections of sample A and B is obtained. Thus,

\[(\sigma^A - \sigma^B) = D N_A^{-1} + \sigma^B (N_A N_B^{-1} - 1)\] (5.20)

The error associated with this value has two different origins. The first term contributes a certain error arising from the attenuation measurements for the two samples A and B. The error contributed by the second term depends on the uncertainty in \(\sigma^B\) for the given experimental geometry multiplied by the value of the factor between brackets. If the comparison target is chosen so that the factor in the second term is less than unity the uncertainty transmitted to the "difference" value will decrease accordingly.

We must emphasize here that the value of \(\sigma^B\) used in equation (5.18) is the cross section appropriate to the sample B for the geometry used in the \(\sigma_A\) and \(\sigma_B\) measurements.

The results of applying equation (5.18) to the measured attenuations for gold, copper and iron are presented in TABLE 5.3.

The effect of removing the uncertainty in the change of the CsI attenuation can be seen. Although large relative errors are present, they are smaller than for the differences obtained directly from the absolute values of TABLE 5.2. These differences are presented for comparison purposes in row #4 of TABLE 5.3.

In the differences (Cu - Au) and (Fe - Au) the major contribution to the error arises from the large error in the measurement for gold. A direct comparison of the differences with the work of other authors is limited by the lack of an
### TABLE 5.3
Measured differences

<table>
<thead>
<tr>
<th>#</th>
<th>DIFFERENCE</th>
<th>Copper - Gold</th>
<th>Iron - Gold</th>
<th>Iron - Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$D \times 10^{-4}$</td>
<td>1.88 ± .34</td>
<td>2.08 ± .36</td>
<td>.20 ± .38</td>
</tr>
<tr>
<td>2</td>
<td>Measured difference mb</td>
<td>-121 ± 157</td>
<td>-204 ± 169</td>
<td>-83 ± 81</td>
</tr>
<tr>
<td>3</td>
<td>Corrected difference mb</td>
<td>102 ± 160</td>
<td>24 ± 172</td>
<td>-78 ± 82</td>
</tr>
<tr>
<td>4</td>
<td>Differences from TABLE 5.2 mb</td>
<td>102 ± 307</td>
<td>24 ± 300</td>
<td>-78 ± 185</td>
</tr>
<tr>
<td>5</td>
<td>$\sigma_B^B$ of comparison target mb</td>
<td>901 ± 274</td>
<td>901 ± 274</td>
<td>1003 ± 138</td>
</tr>
</tbody>
</table>

### TABLE 5.4
Total reaction cross sections generated from differences

<table>
<thead>
<tr>
<th>#</th>
<th>TARGET</th>
<th>GOLD</th>
<th>COPPER</th>
<th>IRON</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>mb</td>
<td>768 ± 77</td>
<td>936 ± 126</td>
<td>866 ± 125</td>
</tr>
<tr>
<td>2</td>
<td>Uncertainty %</td>
<td>10</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>
accurate measurement for gold in this energy range.

For the purpose of comparison, absolute values for copper and iron were generated from the measured differences by using as the cross section for gold that obtained from an optical model fit to the elastic scattering data, as described in Section 4.1. In general, when an optical model potential is optimized for a particular target, bombarding energy and particle, an overall fit to better than 10% is obtained. Thus, a 10% uncertainty was assigned to the theoretical cross sections quoted in (5.15). The value for $\sigma^B$ in equation (5.18) is then taken as $(1010 \pm 101)$ mb. To the resulting corrected differences the theoretical value for the reaction cross section for gold was added, $(768 \pm 77)$ mb. These results are presented in Table 5.4. In this case both contributions to the uncertainties, the error in the experimental determination of the attenuation differences and that of the absolute value in $\sigma^B$ are comparable in magnitude.

5. Conclusions.

The results listed in Table 5.2 have been plotted in Figure 5.3 together with measurements by other authors in the same energy range. The values for single isotopes by Dicello et al (Dl 66), are presented as a function of their mass numbers. The results of Pollock et al (Po 65a) and of the present work are plotted at the mass values corresponding to the natural targets. Although the agreement is good, the large experimental errors in our results make this comparison less significant.
Figure 5.3: Comparison of the results for iron and copper with other measurements in the same energy range.
The values obtained from the "difference" measurements (Table 5.4) are not more significant than the absolute values (Table 5.2) due to their comparable errors. If an experimental value for the cross sections for gold becomes available in this energy range with a relative error of 5%, the errors quoted in Table 5.4 will decrease to the 10% level. The remaining uncertainty is due to the statistical errors in the experimental determination of the attenuation differences, and could, of course, be reduced with longer running times or improvements in counting rate.

A useful application of the "difference" measurements is to the study of isotopes of the same nucleus. In this case, and for targets of the same energy thickness, the second term in equation (5.20) becomes negligible. Thus, the sole source of error in the measured "difference" value is the statistical uncertainty in the determination of D. In addition, the elastic correction to the measured value, to obtain the real "difference", will be very similar for all isotopes. Therefore, accurate measurements of the differences between the total proton reaction cross section of different isotopes of the same nucleus would be readily obtainable from the experiment. These measurements are expected to provide useful information on the dependence of the optical model potential with the number of neutrons.

The problem of decreasing the experimental errors of the absolute values by this technique is different. A more complete knowledge of the dependence of the CsI attenuation with energy will be required.
With the present experimental arrangement the limit to the counting rate is imposed by the large background of non-coincident protons present in the proton detector. As can be inferred from Figure 4.12 the maximum counting rate after the "dead time gate" ($\tau_D = 16 \mu s$) occurs for an incident proton flux of about $70 \times 10^3$ s$^{-1}$.

The ratio of coincident to non-coincident proton rates is determined by the angle subtended by the proton detector at the center of the heavy ice target. This angle is chosen so that the scattering of the associated proton beam in the heavy ice backing foil does not contribute significantly to the attenuation background (Section 4.1 Chapter 3). As mentioned in Section 1 of Appendix I, we were unsuccessful in using self-supporting films of deuterated polyethylene instead of the heavy ice target. This would have resulted in elimination of the backing foil and thus in a large reduction of the scattering suffered by the associated proton beam.

Recent developments in our laboratory in connection with deuterated polyethylene targets provide the possibility of primary targets with practically no backing foil. (Olivo, priv. comm.) If the scattering of the associated proton beam can be reduced by removing the backing foil, the angle subtended by the proton detector can be reduced accordingly. In addition, for an energy thickness of 100 keV for 650 keV $^3$He, approximately 2.5 times more deuterium atoms would be available at the source target than in the case of heavy ice.

The angle subtended by the proton detector could, then, be reduced to an angle compatible with the inherent angular
divergency of the associated proton beam of approximately 3° for 100 Kev range of selected $^4\text{He}$ energies. (Figure 3.10).

The increase in the ratio of coincident to non-coin- cident protons plus the larger number of deuterium atoms available at the primary target could provide an increase by at least a factor of 4 in the coincident counting rate transmitted through the dead time gate. This increase in counting rate will result in half the experimental errors of the difference measurements for the same running time. As mentioned before, if absolute measurements to 5% become available for a comparison target the increase in accuracy would result in final errors for the absolute values obtained from the difference measurements of about 5%.

For the improvement of the accuracy in the direct measurement of absolute values, a more detailed analysis would have to be made of the experimental set-up. In order to use low discrimination levels, for which measurements will be independent of the variations of the CsI attenuation with energy, an improvement in the geometry of the system will be required. Although a geometry as the one employed by Dicello et al (Di 66) would help to decrease the otherwise large inelastic corrections, the inherent angular divergency of the associated proton beam makes its use difficult. This angular divergency could be reduced to approximately 1.5° by decreasing the range of selected $^4\text{He}$ energies with the consequent loss in counting rate.

An alternative approach would involve a more complete investigation of the CsI scintillator. A direct measurement of the proton reaction cross sections for CsI, using thin crystals
commercially available, could be attempted. The lack of scattering data will nevertheless make difficult the extraction of the cross section from the raw experimental data.

Complementary information could be obtained from the dependence of the anticoincidence background in CsI as a function of low discrimination levels. In this region the shape of the curve is sensitive to the (p,n) cross sections.

The results presented in this thesis indicate the usefulness of the technique described. Although the errors characterizing the measurements performed in this work are larger than those quoted by other workers in this field, the ever present possibility of systematic errors for any technique means that measurements by a variety of techniques is particularly important for assessing the overall accuracy of such a measurement. In addition, a number of improvements are suggested, by means of which it should be possible to decrease the experimental error associated with this technique to about 5%.
APPENDIX I CONSIDERATIONS IN THE DESIGN OF THE HEAVY ICE TARGET

1. The target.

In order to obtain in the laboratory the reaction $^3\text{He}(d,p)^4\text{He}$ it is clearly more convenient to employ an incident $^3\text{He}$ beam on a deuterium target. It is difficult to make a $^3\text{He}$ target of the thickness required in this experiment and, in addition, the neutron background associated with deuteron beams makes working in the experimental areas unnecessarily difficult.

A review of the different types of deuterium targets used for neutron production is available in the literature (See Ma 63, Chapter 4.D). They are: $^2\text{H}_2\text{O}$ ice, $^2\text{H}_2$ occluded in metals (Zr or Ti) and gas targets. As far as this experiment is concerned the $^2\text{H}_2\text{O}$ ice targets seem to be the more advantageous. The occluded targets present the problem of the thick metal layer, of high Z, that would produce large scattering in the secondary beam. A similar situation arises from the windows in a gas target, plus the fact that the density of deuterium nuclei for $^2\text{H}_2$ gas (NTP) is three orders of magnitude smaller than for ice.

Even more convenient than the heavy ice thin layer, that requires a good thermal conductor backing, are the self-supporting films of "deuterated" polyethylene. The main contribution to scattering from the target itself will then arise from the $^{12}\text{C}$ nuclei in the polyethylene. The preparation technique of these targets has undergone some development in our laboratory (Tr 67). Trial runs in the system described in Chapter 4, have shown that targets of the desired thickness, (i.e. 100 KeV for 650 KeV $^3\text{He}$), can not however, withstand the
beam currents necessary to obtain cross sections measurements in a reasonable running time.

2. **Power dissipation.**

As a result of the considerations of Section 1 the target was chosen to be a thin layer of heavy ice. If the D$_2$O ice temperature rises above 173°K, however, the target vaporizes relatively quickly (Ma 63 p. 685). It is therefore convenient to build the ice layer on a good heat conductor held at liquid nitrogen temperatures. We will refer to the target backing as to the "backing foil".

The ability to conduct away the incident beam power and still maintain the heavy ice temperature below 173°K is not the only requirement for the backing foil, however. As discussed in Section 4.2.1. of Chapter 3, the thickness of the backing foil must also be chosen taking into account the anticoincidence background.

The heat to be dissipated by the backing foil is given by the 100 KeV energy loss in the ice layer plus the energy loss in the foil itself. In order to estimate a maximum value for the temperature rise of the heavy ice target, the following approximate model was considered. It is assumed that the first 100 Kev of energy loss are deposited at the front of the ice layer. This energy is then conducted away as heat, in the direction of the incident beam, across the layer of ice and into the backing foil. From there, this heat plus that deposited in the foil itself is radially dissipated towards the liquid nitrogen container. This is schematically illustrated in Figure
where a beam of diameter 'd' is incident at the center of a backing foil of diameter 'D' and thickness 'L' held in contact with a liquid nitrogen reservoir at its outer edge. The arrows indicate the assumed direction for the heat flow. Conduction through the thin ice layer parallel to the beam direction only, and not radially in the ice, is justified by the much larger thermal conductivity of the foil.

The calculation will be divided into three different parts: the temperature rise across the ice layer $\Delta T_1$, the radial dependence of the temperature for radii smaller than the beam radius $\Delta T_2$, and the temperature rise between the beam diameter and the backing foil outer diameter $\Delta T_3$.

The equation for heat conduction is:

$$Q = -\Delta T \lambda a t L^{-1}$$  \hspace{1cm} \text{(AI.1)}

where $\Delta T$ is the temperature rise across a material with thermal conductivity $\lambda$, area 'a', thickness 'L', and 'Q' the heat in calories conducted in time 't'.

The conversion factor from Mev to calories and for 1 $\mu$A is:

$$1 \text{ MeV } \mu\text{A}^{-1} \text{s}^{-1} = 0.2399 \text{ cal s}^{-1} \mu\text{A}^{-1}$$  \hspace{1cm} \text{(AI.2)}

In the calculations two incident beam diameters will be considered:

**CASE I**: $d = 0.318 \text{ cm (1/8 inches)}$; **CASE II**: $d = 0.16 \text{ cm (1/16 inches)}$

$$\pi d^2/4 = 8 \times 10^{-2} \text{ cm}^2 \hspace{1cm} \pi d^2/4 = 2 \times 10^{-2} \text{ cm}^2$$

The value for the thermal conductivity, $\lambda$, for normal ice can be calculated at 173 K to be: $8 \times 10^{-3} \text{ cal deg}^{-1} \text{s}^{-1} \text{ cm}^{-1}$
Figure AI.1: Source target power dissipation.

Figure AI.2: Energy deposited in backing foil.
(Po 65). From (AI.1) and (AI.2), we get the temperature rise across the ice layer in the direction of the incident beam using the value of 'L' given by 3.7:

\[ T = 2 \times 10^{-2} \text{ deg } \mu A^{-1} \quad \text{(AI.3)} \]

\[ T = 8 \times 10^{-2} \text{ deg } \mu A^{-1} \quad \text{(AI.2)} \]

CASE I: \[ T = 2 \times 10^{-2} \text{ deg } \mu A^{-1} \]

CASE II: \[ T = 8 \times 10^{-2} \text{ deg } \mu A^{-1} \]

In order to calculate \( \Delta T_2 \), we define a heat density:

\[ q = \frac{Q}{\tau}  \frac{d^2}{t} \quad \text{(AI.4)} \]

that is, the heat deposited by the beam per unit of area, and assumed constant across the beam diameter.

In calculating the values for \( \Delta T_2 \) and \( \Delta T_3 \) the amount of heat to be dissipated, \( Q/t \), now includes the energy losses in the foil. It will of course depend on the foil material and its thickness.

Copper was chosen as a backing material because of its high heat conductivity, \( \lambda = 1.097 \text{ cal deg}^{-1} \text{ s}^{-1} \text{ cm}^{-1} \), at 113 K (Ha 60 p. 2433). Aluminum is almost as good, having a conductivity of half this value, and is better from the point of view of scattering of the proton beam. However the presence of an aluminum oxide layer makes the conduction of heat into the aluminum more difficult.

For 'L' values smaller than the \( ^3 \text{He} \) range in Cu at 550 KeV, \( Q/t \) is a function of 'L'. The amount of energy, per incident \( ^3 \text{He} \), dissipated in the target as a function of 'L' is plotted in Figure AI.2. For \( L = 0 \) the value of 100 KeV corresponds to the \( \text{D}_2\text{O} \) ice thickness. This data is obtained from the energy loss for protons in Cu (Wh 58). Thus, in the expression (AI.4) for the heat density, \( Q/t \) is a function of
'L' and will be indicated in the following by the notation q(L).

Equation (AI.1) may be rewritten as:

\[ dT = - \frac{r}{a} \frac{dQ}{dt} \tag{AI.5} \]

where 'r' is the radial distance to the center of the target, and \( a = 2 \pi rL \).

In the region for '2 r' less than 'd', \( Q/t \) is also a function of 'r'. The amount of heat dissipated in a ring 'dr' at the radius 'r' is:

\[ dQ = 2\pi r q(L) \, dr \tag{AI.6} \]

Replacing in (AI.5),

\[ dT = q(L) \frac{r \, dr}{a \, Lt} \tag{AI.7} \]

\[ \Delta T_2 = \int_{T_d}^{T_c} \frac{dT}{dt} = q(L) \frac{d^2}{2 \pi L t} \tag{AI.8} \]

where \( T_c \) is the temperature at the center of the target and \( T_d \) the temperature at \( r = d/2 \). If we replace the value given by (AI.4) for \( q(L) \) in (AI.7):

\[ \Delta T_2 = \left[ \frac{Q(L)/t}{2 \pi L \lambda} \right] \tag{AI.9} \]

For the region \( D/2 \gg r \gg d/2 \) the amount of heat to be conducted is just \( Q(L) \). Rewriting (AI.1) as:

\[ dT = - \frac{Q(L)}{a t 2 \pi L \lambda} \tag{AI.10} \]

\[ \Delta T_3 = \int_{T_d}^{T_c} dT = \frac{Q(L)}{t} \frac{1}{2 \pi L} \frac{\ln D}{d} \]

The maximum temperature rise will be at the center of the beam spot, on the front face of the ice layer, and is given by adding up (AI.3), (AI.8) and (AI.9),

\[ \Delta T = \Delta T_1 + \frac{Q(L)}{t} \frac{1}{2 \pi L \lambda} \left( 1 + \ln \frac{D}{d} \right) \tag{AI.10} \]
The second term of equation (AI.10) was solved for D = 1.27 cm (1/2 inches) and for the two cases of 'd' mentioned above. The values for Q(L)t⁻¹ are obtained from Figure AI.2. The results of the calculations are presented in Figure AI.3. The temperature rise at the center of the heavy ice target per \( \mu A \) of incident beam current, is given as a function of the Cu backing foil thickness 'L' for the two incident beam diameters CASE I: \( d = 0.318 \) cm; CASE II: \( d = 0.16 \) cm.

3. Energy straggling and multiple scattering.

The particles corresponding to the associated and secondary beam, arising from reactions taking place in the primary target, will suffer interactions with target material in traversing it.

The importance of these effects on the proton beam were discussed in Section 4.2.1. of Chapter 3.

Their results on the secondary beam were presented in section 4.2.4 of Chapter 3. Here the derivation of the results is described for an assumed target thickness of 100 KeV for 650 Kev incident \(^3\)He.

3.1. Energy straggling.

The variance \( \sigma_o \) of the energy transfer per unit of path length is given by (Bo 15):

\[
\sigma_o = 4 \sigma_\perp z^2 e^4 N Z
\]

(AI.11)

where \( z \) and \( Z \) are the atomic numbers of the incident particle and target nuclei and \( N \) is the number of atoms per cm\(^3\) in the target. In the case of D\(_2\)O ice the main contribution to the
Figure AI.3: Temperature rise at the center of the heavy ice target.

Beam collimators diameter

CASE II: .318 cm
CASE I: .160 cm

Temperature rise at the target center (deg. x \(\mu\text{A}^{-1}\))

Copper backing foil thickness (\(x 10^{-5}\) cm)
energy loss arises from the $^{16}_0$ atoms. For $^4\text{He}$ particles and
the value of $N$ given in (3.6) the value for $^{16}_0$ is:

$$P_0 = .28 \text{ MeV}^2 \text{ cm}^{-1}$$  \hspace{1cm} (AI.12)

For the $D_2O$ ice thickness assumed, $4.66 \times 10^{-5}$ cm, (see eq, 3.7):

$$P = 1.30 \times 10^{-5} \text{ MeV}^2$$  \hspace{1cm} (AI.13)

Thus the standard deviation in the energy loss by the $^4\text{He}$ beam
is:

$$(P_0)^{1/2} = 3.6 \text{ KeV}$$  \hspace{1cm} (AI.14)

a value much less than the intrinsic resolution of the $^4\text{He}$
detection system thus, small enough to be neglected.

3.2. Multiple scattering.

The effect of multiple scattering is characterized by
the mean square spatial angle, which in the approximation of
assuming a Gaussian distribution in angles is given as (Di 53)
(Ma 66):

$$\langle \theta^2 \rangle = \frac{B Z \ln (E_i/E_f)}{4 (M/m) \ln (2\pi \beta Z \gamma^{1/2})} \text{ rad}^2$$  \hspace{1cm} (AI.15)

where $E_i$ and $E_f$ are the initial and final energies of the
scattered particle, $(M/m)$ is the ratio of the mass of the
scattered particle to the mass of the electron, $Z$ is the atomic
number of the scattering nuclei, $B$ is defined by the transcen-
dental equation:

$$e^8 B^{-1} = \frac{6710 \, Z^{4/3} \, z^2}{A \, \beta^2 \, (1 + 3.33 \, \gamma^2)}$$  \hspace{1cm} (AI.16)

and

$$\gamma = Z z / 137 \beta \quad \beta = \nu \text{ c}^{-1}$$
A is the atomic weight of the scattering nuclei, \( \delta \) the thickness of the scattering media in g cm\(^{-2} \).

Calculating for \(^4\)He particles in \(^{16}\)O, \( E_1 = 3.22 \) MeV, \( E_f = 3.12 \) MeV and \( \delta = 5.17 \times 10^{-5} \) g cm\(^{-2} \), we obtain:

\[
\beta = 4.15 \times 10^{-2} ; \quad \delta = 2.82
\]

\[
e^B \bar{B} = 26.6 \quad . \quad B = 4.86
\]

And for the mean square angle:

\[
\langle \Theta_m^2 \rangle = 2.75 \times 10^{-5} \text{ rad}^2
\]

and for the standard deviation:

\[
\langle \Theta_m^2 \rangle^{1/2} = 5.2 \times 10^{-3} \text{ rad} = 0.29^\circ \quad (A1.17)
\]

Since this standard deviation from the original direction of emission is much smaller than the angular range of \( 5^\circ \) defined by the energy window settings and the target thickness, (Section 3.2 Chapter 3) this multiple scattering effect can also be neglected.

4. **Anticoincidence background due to \(^4\)He scattering.**

In Section 4.2.4 of Chapter 3 was discussed the possible contribution to the anticoincidence background from those \(^4\)He particles originally emitted in directions other than the secondary beam detector, but scattered into it with energies in the selected range.

This problem was analysed using the Van de Graaff PDP-8 computer, as outlined in the following.

It was assumed that all the scattering arises from the \(^{16}\)O nuclei of the \( \text{D}_2\text{O} \) molecules. Experimental data for the elastic scattering of \(^4\)He by \(^{16}\)O is available for incident
energies between 2.4 and 3.9 Mev (Ca 53) and 3.7 to 5.6 Mev (Mc 66).

The secondary beam detector, the solid state detector, was assumed to be at 96.2° with respect to the incident \(^3\)He beam direction, the center angle for the secondary beam in the case of "kinematical collimation" of the associated proton beam.

\(^4\)He particles emitted with angles greater than 96.2° will already have energies below the selected energy range of 3.17 to 3.27 Mev. Energy loss in leaving the target or due to recoiling \(^{16}\)O nuclei will further degrade them in energy. Thus, calculations were performed for \(^4\)He emitted with angles smaller than 96.2°, angles for which the energy of emission is above the selected range. Background events arise from those particles scattered into the secondary beam detector which lose sufficient energy while traversing the target to be accepted by the energy window.

To obtain an upper limit for this background contribution it was assumed that all \(^4\)He particles were produced in reactions taking place on the back face of the ice target. This is justified by the fact that an energy loss by the \(^4\)He greater than the one provided by the thickness of ice in the direction of the secondary beam detector is necessary for them to fall in the selected energy range.

The angle of \(^4\)He emission was varied in steps, and for each angle the laboratory energy of it was calculated from the kinematics of the \(^3\)He(d,p)\(^4\)He reaction. With the data of Figure 4.6 the energy loss by the \(^4\)He in traversing the ice
target was calculated. The energy of the $^4\text{He}$ particle emerging in the direction of the secondary beam detector was checked to see if it fell into the selected energy range. If it did, the fraction of all the particles originally emitted into that angle of emission, incident in the detector was obtained.

In order to obtain an upper limit for the background contribution, the normalization factor for each angle of emission was taken to be the solid angle defined by the angular increment (in the emission angle) into the same hemisphere of the source target plane where the detector was located.

The results are presented in Figure AI.4, for the selected energy range from 3.13 to 3.31 Mev. This energy range is that corresponding to the kinematical collimation considered earlier plus 40 Kev in each extreme in order to take into account possible indeterminations arising from the energy resolution in the alpha detection system. The plot shows the upper limit of the anticoincidence counts per $\mu$A and per second arising from the scattering into the detector of $^4\text{He}$ originally emitted in other directions than that one of the secondary beam.

The results indicate contribution to the background for values of the angle of $^4\text{He}$ emission in the range:

$$91.2^\circ \leq \xi \leq 96.2^\circ$$

The proton detector subtends at least $10^\circ$ to each side of the associated beam direction to the $^4\text{He}$ emitted into $96.2^\circ$, in order to prevent background due to the source target backing foil. This causes the detection of the protons associated with the $^4\text{He}$ particles emitted into $91.2^\circ \leq \xi \leq 93.7^\circ$, even though they do not belong to the wanted secondary beam. No contribution
Figure AI.4: Anticoincidence background due to $^4$He scattering.
to the anticoincidence background will then arise from this scattering effect.
APPENDIX II  NATURAL FOCUSING.

Even though this effect was not used in the present experiment it will be briefly discussed here.

It can be seen in Figure 3.7 that a change $\Delta \xi$ in the angle of emission of the secondary beam corresponds, due to the $^3$He incident energy being much less than the Q-value of the reaction, to a change of angle for the associated beam given by:

$$\Delta \psi = - \Delta \xi$$  \hspace{1cm} (AII.1)

This is true for $\psi = \xi = 80^\circ$.

The correlation between the angular increments of the reaction products described by (AII.1) could be used to produce focusing of the associated beam in cases when a large primary beam spot will normally give rise to a dispersed associated beam. A large size of the primary beam is convenient to achieve low density currents on the primary target, for reasons mentioned when discussing the deuterium target (See Appendix I). The effect of a large size on the primary beam is illustrated in Figure AII.1, case A-A'. The source target is assumed to be perpendicular to the incident beam direction, and the beam size is purposely augmented to illustrate the point. For a point size secondary beam detector, A, located at $\xi = 45^\circ$ from the incident beam direction, the corresponding associated beam, A', is widely dispersed.

By observing Figure AII.1, the effects of the angular correlation (AII.1) can be easily seen. The particles of the secondary beam emitted from different sectors of the primary beam
Figure AII.1: Natural focusing effect.

Figure AII.2: Natural focusing in conjunction with kinematical collimation.
spot into the secondary beam detector form different angles $\xi$. For each one of these angles, a different angle, $\psi$, of emission for the associated particle will be selected. The change in angle $\psi$ given by the change in $\xi$ can either contribute to further dispersion of the associated beam or to give a tendency to focusing. Which one of these effects is present, is given by whether both reaction products are emitted into the same hemisphere defined by the source target plane, for focusing, or into different ones.

From Figure 3.7 can be seen that a source target angle $\beta$ that satisfies the focusing condition can be found for all values of $\xi$.

We will refer to this focusing effect as "natural focusing". Best "natural focusing" will occur for a source target angle such that the angle formed by its plane with the directions defined by the angle $\xi$ and the corresponding angle $\psi$ are the same.

In Figure AII.1, case B-B' illustrates the focusing effects for $\psi = \xi = 80^\circ$. For this case equation (AII.1) is exact, and for a target angle of $\beta = 90^\circ$ best focusing occurs. Thus, in this particular case, the associated beam will be focused at a distance $L'$ from the source target center equal to the distance $L$ from that center to the secondary beam detector.

If best "natural focusing" is to be used in conjunction with "kinematical collimation" occurring for $\xi = 96.2^\circ$ (Section 3.2 of Chapter 3), then the source target angle must be $\beta = 106.5^\circ$. This case is illustrated in Figure AII.2.
Natural focusing is inconsistent with small angular divergency. It tends to cancel the effects of the finite size of the primary beam by appropriate change in the angle of emission for the associated particle. Small angular divergency, on the other hand, means that all associated particles are emitted with approximately the same angle with respect to the incident beam direction. A parallel associated beam, with no angular divergency arising from the finite size of the primary beam, could be obtained for a detector angle equal to the source-target angle, as suggested by the diagrams. It is, of course, impossible experimentally to detect the secondary beam under such conditions.

Nevertheless, the angular divergency of the associated beam due to the finite size of the primary beam can also be minimized by decreasing the angular spread on the secondary beam. This can be achieved by locating the secondary beam detector, when possible, at a distance from the primary target center much larger compared with the primary beam size.

One of the difficulties in making practical use of "natural focusing" effects in the present experiment is that, in order to be used in conjunction with "kinematical collimation" the incident beam must go through the backing foil of the primary target.
APPENDIX III ELECTRONIC CIRCUITS.

In this appendix the detailed circuits of the locally manufactured electronic units, still in use in association with the experimental set-up described in Chapter 4, are presented. The different units are mentioned in the same order as that of Section 3 of Chapter 4.

The Solid State Detector Preamplifier is a charge sensitive one, an improved design of one described by T.K. Alexander (Al 63). The circuit diagram is presented in Figure (A3.1). The cascode input is a combination of two 8056 nuvistors (Vi, V2) connected in parallel, and a 2N709 transistor (T1). The unit is bipolar and can deliver up to ± 3 volt pulses into a 50 ohms load. The equivalent noise is approximately given by:

\[ \text{FWHM} = (5.4 + 3.68 \times 10^{-2} C_1 \text{ pF}^{-1}) \text{ KeV} \quad (A3.1) \]

where \( C_1 \) is the capacitance in pF connected at the input of the preamplifier. Equation (A3.1) does not take into account noise due to possible leakage current in the detectors. These results were measured as described by E. Fairstein (Fa 61) using an RC amplifier with integration and differentiation time constants set at .8 \( \mu \)s. The rise time of the preamplifier is approximately given by:

\[ t_r = (4.5 + .19 C_1 \text{ pF}^{-1}) \text{ ns} \quad (A3.2) \]

The Pulse Shaper circuit used to obtain from the output of the preamplifier the bipolar pulse necessary for the zero crossover triggering is illustrated in Figure A3.2, with a zero crossover time of 500 ns.
Figure A3.1: Circuit diagram of the low noise charge sensitive preamplifier.
Figure A3.2 : Circuit diagram of pulse shaper.
The Zero Crossover Unit which is based on a design by T.K. Alexander (Al 63) is illustrated in Figure A3.3. The zero crossover point is detected with a Schmitt trigger (T1, T2) with "hysteresis" compensation. P1 is adjusted so that minimum "walk" is obtained. Optimum adjustment corresponds to a walk of less than 10 ns for a 10:1 range of input signals. The back edge of the output (which occurs at the crossover time) is used to trigger a "Fast trigger circuit" which produces a pulse 25 ns wide. The "Fast trigger" is based on a design by G. Jones (Jo 63) and the circuit is illustrated in Figure A3.4. This short "timing pulse" is used in the fast gates to be described below.

The circuit diagram of the Photomultiplier Preamplifier is illustrated in Figure A3.5. It delivers a 10 ns rise time and a bipolar linear output up to ± 6 volt into a 50 ohm load.

The circuit diagram of the Fast Coincidence gate is presented in Figure A3.6. The time resolution for the 25 ns wide input pulses was measured as 50 ns. The output of the fast coincidence gate consists of a pulse 1 μs long generated by a trigger circuit of the type indicated in Figure A3.4 with a value of C = .005 μF.

The circuit diagram of the Fast Anticoincidence gate is illustrated in Figure A3.7. The output again consists of a 1 μs wide pulse obtained as indicated for the fast coincidence circuit.

The circuit diagram of the two slow coincidence gates is illustrated in Figure A3.8.
Figure A3.3: Circuit diagram of zero crossover trigger.

Figure A3.4: Circuit diagram of fast trigger.
Figure A3.5: Circuit diagram of photomultiplier preamplifier.
Figure A3.6: Circuit diagram of fast AC gates.
Figure A3.7: Circuit diagram of fast C gate.
Figure A3.8: Circuit diagram of double slow C gates.
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