THE DIRECT CAPTURE REACTIONS $T(\alpha, \gamma) L_{i}{ }^{7}$ AND $0^{16}(p, \gamma) F^{17}$ by

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## ABSTRACE

The differential cross section for the capture of tritium by alpha particles to form $\mathrm{Li}^{7}$ has been measured using a tritium-zirconium target and 1.64 mev. alpha particles. The differential cross section for the gama-ray transition to the ground state of $\mathrm{Li}^{7}$ was found to be $2.54 \pm .46 \times 10^{-31} \mathrm{~cm} .^{2}$ per steradian at $90^{\circ}$ to the incident alpha beam direction. At the same energy, the ratio of the differential cross section at $90^{\circ}$ for transitions to the first excited state to that for transitions to the ground state of $\mathrm{Li}^{7}$ was found to be approximately 0.40 .

The $T(\alpha, \gamma) L_{i}{ }^{7} 90^{\circ}$ differential cross section has been measured relative to the differential cross section at 1.64 mev. using alpha particles of energies $0.515,0.72,0.98,1.23$, and 1.94 mev. From the smooth change of the reaction cross section with energy it can be concluded that the reaction proceeds by direct radiative capture. At all energies, the ratio of the differential cross section at $90^{\circ}$ for transitions to the first excited state to that for transition to the ground state was approximately 0.4 .

Preliminary angular distribution measurements at $0^{\circ}$ and at $90^{\circ}$ to the incident alpha beam direction indicate that the angular distribution is not isotropic. The ratio of the yield at $0^{\circ}$ to the yield at $90^{\circ}$ was found to be $1.40 \pm 0.37$ at an alpha particle energy of 1.64 mev .

Differential cross section measurements for direct radiative capture of protons by 016 have been made relative to the cross section at $800 \mathrm{kev.}$, using a solid tungsten-dioxide target and protons of energies $0.618,0.823$, 1.13, 1.536 , and 2.04 mev. Absolute $90^{\circ}$ differential cross section values were based on the measurement of the $90^{\circ}$ differential cross section for transitions to the first excited state in Fl7 at 800 kev . of $10.4 \pm 1.3 \times 10^{-32}$ cm. ${ }^{2}$ per steradian made by Robertson. The differential cross section for the
gamma ray transitions to the first excited state of $\mathrm{F}^{17}$, at $90^{\circ}$ to the incident proton beam direction, was found to vary smoothly from $0.41 \times 10^{-31} \mathrm{~cm} .^{2}$ per steradian at 0.618 mev. to $11.9 \times 10^{-31} \mathrm{~cm} .^{2}$ per steradian at 2.04 mev . At all energies the ratio of the differential cross section at $90^{\circ}$ for transitions to the ground state to that for transitions to the first excited state was approximately 0.20 .

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FIGURE I LOW ENERGY LEVELS OF Li ${ }^{7}$

## CHAPTER I

## INTRODUCTION:

This thesis concerns the study of two reactions, both of the direct capture type but otherwise unrelated.
(a) THE REACTION $T(\alpha, Y) L_{i} 7$

Nuclear shell model theory considers the Li nucleus as comprising three nucleons (one proton and two neutrons) in the lp shell outside a closed ls shell. To first order, the ground state properties of $\mathrm{Li}^{7}$ should be determined by the odd proton in the $1 p$ shell, the angular moments of the two neutrons being coupled to zero. With the added concept of spin-orbit coupling, the ground state of $\mathrm{Li}^{7}$ should be a $\mathrm{P} 3 / 2^{-}$level, with the proton spin aligned parallel to its orbital angular momentum, and the first excited level should be a $\mathrm{Pl} / 2^{-}$level. There also should be a one-to-one correspondence between the energy levels, spins, and parity values of $\mathrm{Li}^{7}$ and those of its mirror nucleus, $\mathrm{Be}^{7}$, after correction for neutron and proton mass differences and coulomb binding effects.

The spin and parity of $\mathrm{Li}^{7}$ in the ground state have been measured and found to be $3 / 2$, of negative parity (J.E. Mack, 1950), in agreement with the above predictions. The first excited level of $\mathrm{Li}^{7}$ is now believed to be a $\mathrm{J}=1 / 2^{-}$ level. Evidence such as the superallowed nature of the beta-decays $\mathrm{Be}^{7}(\in) \mathrm{Li}{ }^{7}$, and $\mathrm{Be}^{7}(\epsilon) \mathrm{Li}^{7}$, indicate that the ground state and first excited states of $\mathrm{Be}^{7}$ are $3 / 2^{-}$and $1 / 2^{-}$states, confirming the one-to-one correspondence between lowlying states of $\mathrm{Li}^{7}$ and $\mathrm{Be}^{7}$. $\mathrm{Li}^{7}$ is more stable than $\mathrm{Be}^{7}$ by 0.863 mev. , in reasonable agreement with the calculated charge effect between the two nuclei.

However, the one-particle, or "Schmidt" description of the $\mathrm{Li}^{7}$ nucleus above predicts a magnetic moment of 3.79 nuclear magnetons, compared with the experimental value of 3.26 nuclear magnetons (J.E. Mack). To predict a magnetic moment closer to the experimental value, it is necessary to consider the vec-
torial addition of the angular moments of the three p-nucleons. In the threeparticle description $J=3 / 2$ can be obtained either with the angular moments of the neutrons coupled to zero, as in the one-particle description, or with the orbital part of the angular momentum of the two neutrons aligned parallel. This second state gives a magnetic moment of -0.77 nuclear magnetons (Mayer and Jensen, 1955); a suitable mixture of the two states could give the experimentally observed magnetic moment.

Both the one-particle and the three-particle nuclear shell-model descriptions of the $\mathrm{Li}^{7}$ nucleus predict a negative nuclear quadrupole moment. there has been considerable disagreement concerning the sign of the nuclear quadrupole moment of Li7, which now appears to be positive (see Chapter II) in direct disagreement with simple shell model predictions.

Thus, the single particle shell model predicts the angular momentum, parity, and approximate magnetic moment of the ground state of $\mathrm{Li}^{7}$ while a more accurate description of the ground state may be obtained in terms of three particles. Further refinements are required in order to explain the apparently positive sign of the nuclear quadrupole moment.

The present work is a study of the $T(\alpha, \gamma) L_{i}{ }^{7}$ reaction, which has not been previously reported. If an alpha-particle of energy less than (7/3 x 4.78) or approximately 11 mev. is used to bombard a tritium target, the $T(\alpha, \gamma) L i$ reaction is the only reaction energetically possible apart from scattering. Above 11 mev. the particle reaction $T\left(\alpha, L_{i}{ }^{6}\right)_{n}$ becomes possible. The $T(\alpha, \gamma) L_{i}{ }^{7}$ radiative transitions might occur either through direct radiative capture, similar to the $D(p, \gamma) \mathrm{He}^{3}$ and the $0^{16}(p, \gamma) F^{17}$ reactions, or through compound nucleus formation through the tails of resonances at $\mathrm{Li}^{7}$ excited levels at 0.477 mev. and above 4.6 mev . The energy dependence and cross section should thus be sensitive to the type of capture process. Since the levels at 0.477 mev, and at 4.61 mev. are not broad levels, the probability of radiative
capture with compound nucleus formation at an energy midway between these two levels is low.

If we consider the direct radiative capture process, a triton with spin $1 / 2$, and an alpha-particle with spin 0 can form initial $25,2 \mathrm{P}$, etc. states, depending on the orbital angular momentum of the alpha particle. $S$ wave capture, with electric dipole emission to the $J=3 / 2$ - ground state of Li? , would be expected to be the most probable capture process; the angular distribution, due to the S-wave capture, would be isotropic. Hence, the study of the $\mathrm{T}(\alpha, \gamma) \mathrm{Li}^{7}$ reaction should yield information concerning the type of capture process, and in particular it should show whether the above direct radiative S-wave capture, with subsequent electric dipole emission, occurs. A detailed study of the reaction may also yleld information concerning the structure of the ground state of $\mathrm{Li}^{7}$, about which there has been much interest and considerable disagreement.

The reaction $T(\alpha, \gamma) L_{i}^{7}$ is also of interest for comparison with the inverse reaction $L_{i}{ }^{7}(\gamma, \alpha) T$ on the basis of reciprocity. (See Chapter II.) An accurate comparison of the cross sections $r_{\alpha}$ to Far cannot be made, however, since values of $\sigma_{\gamma_{\alpha}}$ have not been reported below 4.7 mev ., and because of disagreement between the reported cross section values $\boldsymbol{P}_{\alpha}$ for higher energies. From a very approximate comparison, the cross section for $T(\alpha, \gamma) L i{ }^{7}$ should lie in the region from 3 microbarns to 0.1 microbarns at an alpha particle energy of 1.5 mev . With the relatively thin tritium target available and the limitation on beam current due to target heating, the counter used in the present investigation was sensitive enough to detect radiation with cross sections as small as 0.1 microbarns. This sensitivity proved to be adequate for an investigation of the $T(\alpha, \gamma) L_{i}{ }^{7}$ reaction.


FIGURE 2 LOW ENERGY LEVELS OF $F^{17}$
(b) THE REACTION $0^{16}(p, \gamma) F^{17}$

Shell model theory treats the $F^{17}$ nucleus as a single proton moving in the potential of the closed $0^{16}$ core. The ground states of both $F^{17}$ and its mirror nucleus $0^{17}$ are predicted to be D5/2 levels with the odd nucleon aligned with its spin parallel to its orbital angular momentum. Experimental measurements are consistent with D5/2 for the ground states of both nuclei. The first excited levels of $0^{17}$ and of $F^{17}$ appear to be $s \frac{1}{2}$ levels, again consistent with present shell model predictions.

Theoretical calculations for the cross section and angular distribution of the reaction $0^{16}(p, \gamma) F^{17}$ are being made by a California Institute of Technology group (private communication from N. Tanner). Similar calculations based on shell model predictions and on a direct radiative capture process, are being performed by Dr. G.M. Griffiths of this laboratory. Comparisons between theoretical predictions and experimental measurements should provide a check on the assumed theoretical models.

The $016(p, \gamma)$ Fl7 cross section at stellar energies is of interest in astrophysics. The conversion of protons into alpha particles via the carbonnitrogen cycle occurs as follows:

$$
\begin{aligned}
& \left.\begin{array}{l}
c^{12}(p, \gamma) N^{13} \rightarrow c^{13}+\beta^{+} \\
c^{13}(p, \gamma) N^{14} \\
N^{14}(p, \gamma) o^{15} \rightarrow N^{15}+\beta^{+} \\
N^{15}(p, \alpha) c^{12}
\end{array}\right\} \quad Q \sim 27 \text { Mev. } \quad \text {. } \quad \text {. } 1 .
\end{aligned}
$$

$N^{15}$, lost from the cycle by the competing reaction $N^{15}(p, \gamma) 0^{16}$, is replaced by the reactions $0^{16}(p, \gamma) F^{17} \rightarrow 0^{17}+\beta^{+}$, and $0^{17}(p, \alpha) N^{14}$.
For stars whose main source of energy is the carbon-nitrogen cycle, the $0^{16}(\mathrm{p}, \gamma) \mathrm{E}^{17}$ cross section ultimately determines the carbon-oxygen ratio in the
star as a function of the stellar temperature (Cameron, 57). It is not possible to measure the $0^{16}(p, \gamma) F^{17}$ cross section at stellar energies; however, information obtained at the energies available is essential for theoretical extrapolations of the reaction cross section to the stellar energies.

In order to check the theoretical calculations of cross section for the $0^{16}(p, \gamma)$ reaction, and because of the interest of this reaction in astrophysics, it was felt that more accurate cross section and angular distribution data would be of value. The $90^{\circ}$ differential cross section has been recently measured at 800 kev . by Robertson (57) of this laboratory. The present work was undertaken to provide a measurement of the $90^{\circ}$ relative differential cross section in the energy range from 0.6 to 2.0 mev .


## CHAPTER II

## THE $T(\alpha, Y) L_{i}{ }^{7}$ REACTION:

1. Apparatus -
(a) Target arrangement

A schematic diagram of the target arrangement is shown in Figure 3. A tritium-zirconium target, with tungsten backing material, was used. The target chamber, similar to one described by Alexander (1955), was that used by Robertson (1957) with tungsten oxide targets. Water cooling was applied to the target assembly in order to reduce target deterioration due to overheating. The target and support were insulated with a lucite ring to enable beam current measurements to be made; a positive potential of 90 volts was appied to the target system to reduce secondary electron error in the beam measurement. The beam current was measured with a current integrator, (Edwards, 1950). One integrator count corresponded to a charge of 107 microcoulombs to an accuracy of 1\%. Since it was found that charge leaked from the target on the water cooling hoses at a rate of from $14 \%$ to $20 \%$ of the observed rate of charging, the true number of integrator counts was $1.17-.04$ the observed number of counts.
(b) Gamma ray detector

The detector used for this experiment was a 2.5 inch diameter by 3.5 inch long cylindrical sodium iodide, thallium activated, (Harshaw) crystal mounted as described by Robertson (1957) on a Dumont 6363 photomultiplier. The efficiency of the counter for ganma rays, $\epsilon(E, E / 2)$ is defined as the ratio of the number of counts of a gamma ray of energy, $E$, above a bias energy of $E / 2$, to the number of gamma rays incident on the crystal. An efficiency of 0.612 . 009 has been measured by Larson (57) for 6.14 mev. radiation, using

gamma rays from the reaction $F^{19}(p, x, \gamma) 0^{16}$. The efficiency, $\in(E, E / 2)$ at 1.17 and 1.33 mev, has been measured by P. Singh and H. Dosso (1957) of this laboratory, using a $\mathrm{Co}^{60}$ source calibrated by the National Research Council of Canada. In order to extrapolate crystal efficiencies to other energies, the theoretical crystal efficiency has been calculated by P. Singh. Because the agreement between theoretical and experimental efficiencies at both 1.25 mev . and 6.14 mev. is within $5 \%$, theoretical estimates of crystal efficiency are considered accurate to within $10 \%$ in the energy range 3 mev , to 6 mev.

Since the detailed shapes of the separate gamma rays were not observed in this experiment due to overlapping of the spectra from two gama rays and the presence of a high "target dependent" background, the efficiency was defined only for the number of counts under the full energy peak of the $T(\alpha, \gamma) L_{i}{ }^{7}$ gamma ray spectrum. Comparison spectra from Rdth and from $C^{12}(\alpha, p, \gamma) C^{13}$ were used to compute full energy peak efficiencies for the crystal at 2.62 and 3.09 mev. The efficiency calculation for 2.62 mev. radiation is indicated by Figure 4. The full energy peaks of the $T(\alpha, \gamma) L_{i}{ }^{7}$ spectra were broader than those from the mono-energetic calibration gamma ray spectra because of the spread in $T(\alpha, r) L L^{7}$ reaction gamma ray energy from the finite target thickness. The crystal efficiencies $\in(E, E b)$ were consequently defined to a bias energy Eb . slightly below the base of the full energy peak for the calibration spectra. At 2.62 mev., $\in(E, E / 2)=(56 \pm 5) \%$ and at $3.09 \mathrm{mev} ., \in(E, E / 2)=(56.4 \pm 5) \%$ where the efficiences are theoeretical estimates of efficiency. At 2.62 and 3.09 mev., the full energy peak efficiencies for $T(\alpha, \gamma)$ Li ${ }^{7}$ spectra were $(14.1 \pm 2.1) \%$ and $(13 \pm 2) \%$ respectively.

All runs were made at a counter distance of 1.91 inches from the front of the crystal face to the centre of the target, the counter being pushed
as close to the target pot as the shielding would allow in order to obtain a large solid angle. The solid angle was determined using the experimental measurement of the effective centre of Robertson (1957). The distances from the crystal face to the effective centre for $0.51,1.28$, and 6.14 mev . radiation are respectively $1.43 \pm .08$ in., $1.47 \pm .10$ in., and $1.60 \pm .10$ in. All measurements are in agreement to within the experimental error. The effective centre distance used for all runs in the present experiment, extrapolated from the above data, was 1.52 in., again with a probable error of approximately 0.10 inches. The counter therefore subtended a solid angle of 0.418 steradians at the target, to a probable error of approximately $8 \%$.

Slight photomultiplier gain shifts were observed, the maximum gain shift being approximately $1 \%$. The photomultiplier gain shifts, a function of the photomultiplier counting rate, appeared less serious in the present work than in work where protons were used to bombard tungsten oxide targets (Robertson, 1957). A possible explanation is that high intensity radiation from the zirconium is much lower in energy (K X-ray from zirconium of 18 kev .) than radiation from tungsten (K X-ray of $66 \mathrm{kev} . ; 112 \mathrm{kev}$. Coulomb excitation line) and therefore causes less photomultiplier gain shift. However, the photomultiplier gain shift produced by alpha-particles on a tungsten target has not been investigated with the present counter.

## (c) Electronics

The high voltage supply for the photomultiplier dynode chain was 1100 volts, supplied by an Isotopes Development Limited Stabilized power supply. The preamplifier after the photomultiplier was a $6 J 6$ (parallel) cathode follower. The negative output pulses drove a Northern Electric wide band amplifier type 1444, which fed a "biased distorter" amplifier (see Appendix III). The "biased distorter" output was fed into a 30 channel Marconi kicksorter. The kicksorter
channel edges were set up by feeding pulses from an accurately linear mercury pulse generator (Robertson, 1957) onto the grid of the $6 J 6$ cathode follower. The mercury pulse generator pulses were also used to check the stability of the electronics except for the photomultiplier, which was then checked by means of sources.
2. Target -
(a) Target Tritium Content

The tritium-zirconium target kindly supplied by Oak Ridge National Laboratories consisted of 429 mcs . of tritium taken up in a very thin film of zirconium ( 1.33 mgms.; l - 1 atomic ratio of tritium to zirconium) evaporated onto tungsten backing material. The target was circular, of diameter ( $1 \pm 1 / 128$ ) inches, and of uniform thichness of (. $0239 \pm .0001$ ) inches. The target tritium content has been measured on June 20, 1956, 1.58 years before this experiment was carried out. The tritium content at the time of this experiment, therefore, was estimated from

$$
\begin{aligned}
& N=N o e^{-t / T} \\
& \text { where } T=\text { mean life } \\
& \text { where } T \frac{1}{2}=\frac{1}{2} \text { life }=12.26 \text { years, so that } T \text { mean }=17.69 \text { years } \\
& t=1.58 \text { years, } \\
& \text { and No }=429 \text { millicuries } \\
& \text { Therefore } N=429(.914)=392 \text { millicuries } \\
& \text { Then from } \mathrm{dN} / \mathrm{dt}=\mathrm{N} / \mathrm{T} \text { mean, where } \mathrm{dN} / \mathrm{dt}=392 \times 37 \times 10^{6} \text { dis. } / \mathrm{sec} . \\
& \mathrm{N}=8.09 \times 10^{18} \text { atoms of tritium }
\end{aligned}
$$

The target area was $5.07 \mathrm{~cm} .^{2}$; therefore, on the assumption that the tritium was distributed uniformly over the target, the target tritium content was
$1.60 \times 10^{18}$ atoms of tritium per $\mathrm{cm} .^{2}$
After the $T(\alpha, \gamma) L^{7}$ work had been completed, the tritium content of the tritium target used was checked approximately, assuming the $90^{\circ}$ differential cross section for $T(p, \gamma) H^{4}$ reaction as measured by Perry and Bame (1955). The target was bombarded with 830 kev , protons, and the gamma ray flux was measured. $n_{t}$, the number of tritium atoms per square centimeter of target, was then computed from
$n_{t}=\frac{1}{\left(\frac{d r}{d \omega}\right)} \cdot \frac{1}{\alpha_{r}} \cdot \frac{N_{r}}{\epsilon} \cdot \frac{r^{2}}{A} \cdot \frac{1}{n_{p}}$
where $\epsilon$ is the efficiency of the counter
$r$ is the target to effective centre distance
$A$ is the area of the face of the counter
$\alpha_{\gamma}$ is the transmission coefficient for 20 mev. radiation through the $1 / 16$ in. brass walls, $=0.958$
$n_{p}$ is the number of protons incident on the target
$\frac{d \sigma}{d \omega}$ is the $90^{\circ}$ differential cross section for $T(p, \gamma) \mathrm{He}^{4}$ The target arrangement and gamma ray detector for the $T(p, \gamma) \mathrm{He}^{4}$ runs were the same as those used in the $T(\alpha, \gamma) L i^{7}$ work. However, no target water cooling was used in the $T(p, \gamma) \mathrm{He}^{4}$ work. The following changes in the electronics were made; first, the voltage for the photomultiplier dynode chain was 880 volts, as this voltage gave a convenient gain with no apparent loss in resolution; second, a 100 channel Computing Devices of Canada kicksorter was used instead of the 30 channel Marconi kicksorter. It was therefore possible to count the whole 20 mev. wide spectrum at one time with reasonable dispersion.

The crystal efficiency for 20 mev . radiation was computed from absorption coefficients given in Siegbahn (1955) for Na and Iodine. $\mu$ was calculated to be $0.1613^{\circ}$ per centimeter for 20 mev. radiation for sodium iodide. Then $t=\left(1-e^{-\mu l}\right)=0.74$. d $\omega$ efficiency was then obtained from $\mu x \frac{A}{r^{2}}$
where $A=$ area of the face of the crystal, and
$r=$ distance from the target to the effective centre of the crystal. The distance from the crystal face to the effective centre, $x$, has been measured by Robertson (1957), and has been found to disagree with the theoretical value predicted from

$$
x=\frac{-\ln \left[0.5\left(1+e_{x p}-\mu l\right)\right]}{\mu}
$$

However, theoretically, $\frac{x_{20 \text { mev. }}}{x_{6} .14 \mathrm{mev} .}=0.88$
And if we use the experimental value of 1.60 lin. for $x_{0} .14 \mathrm{mev}$. the $x_{20}$ mev. $=1.41$ in. $\pm .10$ in.

However, since $x$ for a particular crystal varies only with $\mu$, then for the crystal used $\mathrm{x}_{20} \mathrm{mev}$. should $=\mathrm{x}$ for 1.7 mev . radiation. From Robertson's measurements, $x_{1.7 \mathrm{mev} .}=1.48 \pm .1$ inches. Within the probable error, the two values for $x$ are the same; the value of $x=1.48 \pm .10$ inch was used for this experiment.

The above estimation of $d \omega x$ efficiency is an approximation of the calculation of $d \omega x$ eff. $=\int_{v} \frac{\exp _{p}(-\mu l / \cos \phi)}{r^{2}} \mu d v$ as performed by Perry and Bame, and is justified because the inverse square relationship between the counting rate and distance does hold for distances measured to the effective centre.

Currents of 5 microamperes were used at a bombarding energy of 830 kev. Time dependent background was negligible over most of the energy range studied. The count rate between 10 and 20 mev . being 20 counts per minute, the bombarding energy was chosen below 1 mev. to avoid neutron pulses from the $T(p, n) \mathrm{He}^{3}$ reaction.


Since the efficiency calculation was based on the total absorption coefficient, it was necessary to count the total number of pulses produced by the gamma rays in the crystal. Fluorine was found to be present in the target; consequentiy, the low energy pulse spectrum from $T(p, \gamma) \mathrm{He}^{4}$ was obscured by the 6.14 mev. fluorine gamm rays. However, the pulse distribution from $T(p, f) \mathrm{He}^{4}$ was extrapolated smoothly to zero pulse height from above 6 mev. The pulse spectra, Figure 5, is similar to that observed by Perry and Bame. $n_{t}$, the number of tritium atoms per $\mathrm{cm}^{2}$, was calculated from the following data:
$r=3.48 \mathrm{in}$.
$\mathrm{A}=4.91 \mathrm{in}$ ?
$\mathrm{N}_{\mathrm{F}}=35,300$ counts.
$n_{p}=\frac{50 \text { integrator counts } \times 107 \text { microcoulombs }}{1.602 \times 10^{-13}}$
$\epsilon=0.74$
$\gamma=0.958$ for 20 mev. radiation through $1 / 16$ in. brass
$\frac{\mathrm{d} \sigma}{\mathrm{d} \omega}{ }_{90^{\circ}}=2.96 \times 10^{-30} \mathrm{~cm}^{2} /$ steradian for $\vec{E}_{p}=812 \mathrm{kev}$.
The target thickness, $\mathbf{A}$, has been computed from Whaling (1954) to be $36 \mathrm{kev} .$, computed so that $\bar{E}_{p}=830-\Delta / 2=812 \mathrm{kev}$.
$n_{t}$ is therefore computed to be $1.25 \times 10^{18}$ atoms $/ \mathrm{cm}^{2}$ which compares with the value of $2.03 \times 10^{18}$ atams $/ \mathrm{cm}^{2}$ calculated on the basis of a 429 millicurie target tritium content.

Errors are as follows:

$$
\begin{aligned}
r^{2} & =8 \% \\
\frac{d \sigma}{d \omega} & =7 \% \\
N_{\gamma} & =5 \% \\
\epsilon & =10 \%
\end{aligned}
$$

For the $T(\alpha, \gamma) L^{7}$ cross section calculations, a target tritium content of $2.03 \times 10^{18}$ atoms $/ \mathrm{cm}^{2}$ rather than $1.60 \times 10^{18}$ atoms $/ \mathrm{cm} .^{2}$, was assumed, since the $T(p, \gamma) \mathrm{He}^{4}$ check was run on only one portion of the target. Further, the $T(p, \gamma) \mathrm{He}^{4}$ check was done after the $T(\alpha, \gamma) L_{i} 7$ work and there may have been some target deterioration during the $T(\alpha, \gamma) L \mathrm{Li}^{7}$ runs.
(b) Target Thickness

The theoretical target thickness was computed from tables collected by Whaling (1957), which define the stopping cross section $\epsilon_{\alpha}\left(E_{\alpha}\right)$ in terms of ev-cm. ${ }^{2} /$ atom. From the mass of 0.00133 grams of zirconium in the target, the number, $\mathrm{n}_{\mathrm{Zr}}$, $=1.734\left(10^{18}\right)$ atoms per $\mathrm{cm}^{2}$ of target; a uniform layer of zirconium metal over the target surface was assumed. Then the Zr target thick ness, $\Delta$, in kev. at an $\alpha$-particle energy $E_{\alpha}$, is given by

$$
\Delta=\quad \epsilon_{\alpha}\left(E_{\alpha}\right) \times n_{Z r} \times\left(10^{-3}\right) \quad \text { kev }
$$

Values of $\epsilon_{\alpha}\left(E_{\alpha}\right)$ for alpha particles in zirconium (Z of 40) were extrapolated from values given for $G e\left(Z\right.$ of 32) and for $\mathrm{Ag}\left(2\right.$ of 47). $\epsilon_{\alpha}$ ( $E_{\alpha}$ ) was assumed to vary linearly with $Z$, i.e.

$$
\left(\epsilon_{\alpha}\right)_{\mathrm{Zr}}=\left(\epsilon_{\alpha}\right)_{\mathrm{Ge}}+0.53\left[\left(\epsilon_{\alpha}\right)_{\mathrm{Ag}}-\left(\epsilon_{\alpha}\right)_{\mathrm{Ge}}\right]
$$

The probable errors quoted for $\left(\epsilon_{\alpha}\right)_{\mathrm{Ag}}$ and $\left(\epsilon_{\alpha}\right)_{G e}$ were $10 \%$, the error therefore expected for $\left(\epsilon_{\alpha}\right)_{\mathrm{Zr}}$ is expected to be approximately $15 \%$. $\left(\epsilon_{\alpha}\right)_{\mathrm{Zr}}$ could not be estimated for energies below 1 mev. by this method owing to lack of data.

A second, less accurate estimate of $\left(\epsilon_{\alpha}\right)_{Z_{r}}$ was used for energies below 1 mev. Tables of $\epsilon_{\alpha} / \epsilon_{p}$ (Whaling, 1957) were used to give $\epsilon_{\alpha}$ from the relationship

$$
\epsilon_{\alpha}\left(E_{\alpha}\right)=\left(\epsilon_{\alpha} / \epsilon_{p}\right) \mathbf{x} \quad \epsilon_{p}\left(E_{p}=\frac{E_{\alpha}}{3.97}\right)
$$

where $\epsilon_{p}=$ the stopping cross section for protons in zirconium at an energy


Ep, where Ep is evaluated for $\frac{E_{\alpha}}{3.97}$.
To obtain $\epsilon_{\rho}$ (Ep) it was necessary to extrapolate from $\epsilon \mathrm{p}$ for $\mathrm{Cu}(\mathrm{Z}$ of 29) to $\in p$ for $A u(Z$ of 79). A linear dependence of $\epsilon p(E p)$ on $Z$ was assumed. The probable error in $\frac{\epsilon_{\alpha}}{\epsilon p}$ was given as $20 \%$. If the probable error in the extrapolation error is approximately $20 \%$, then the standard error in $\epsilon_{\alpha}$ as computed by this method should be approximately $30 \%$. The approximate stopping power of the tritium in the target was similarly computed from

$$
\epsilon_{\alpha}=\frac{\epsilon_{\alpha}}{\epsilon_{p}} \times \epsilon p \quad\left(E p=\frac{E_{\alpha}}{3.97}\right)
$$

where $\epsilon_{\alpha}\left(E_{\alpha}\right)$ was the stopping cross section for alpha particles in hydrogen gas. The standard error in $\epsilon_{\alpha} / \epsilon_{p}$ is again $20 \%$; there is presumably also some error in assuming that $\left(\epsilon_{\alpha}\right)_{H_{2}}=\left(\epsilon_{\alpha}\right)_{t}$.

The computed stopping cross sections are shown plotted in Figure 6. To within the probable error, there is no change in the total stopping cross section for the target in the energy range 0.5 to 2 mev . At 1.64 mev. ,

$$
\Delta=\left[\left(\epsilon_{\alpha}\right)_{\mathrm{Zr}} \times \mathrm{n}_{\mathrm{Zr}}+\left(\epsilon_{\alpha}\right)_{\mathrm{t}} \times \mathrm{n}_{\mathrm{t}}\right] \times 1.27 \times 10^{-3} \mathrm{kev}
$$

where the factor 1.27 is introduced because the target is oriented at $52^{\circ}$ to the $\alpha$-beam. Then $\Delta=\left[(1.734)(97) \times 10^{3}+(9.24)(1.60) \times 10^{3}\right] \times 1.27 \times 10^{-3}$ $=232 \mathrm{kev}$.

## 3. Experimental -

(a) Backgroumd

Since a low reaction jield was expected, considerable care was taken to reduce interfering radiation. The walls of the target chamber in the vicinity of the target, and the stops in the side arm were gold plated to reduce couiomb excited gama radiation. A liquid nitrogen trap was used in front of
the target chamber to reduce the formation of carbon deposits on the target from cracked diffusion pump oil vapors. Before the experiment was performed, the target chamber, stops, and other side arm components were thoroughly cleaned to remove carbon deposits. The magnet box of the $90^{\circ}$ deflection magnet was also removed and thoroughly cleaned with steel wool and hot dilute nitric acid.

The target, target chamber, and gamma ray detector were surrounded on all sides by approximately four inches of lead in order to reduce background from secondary cosmic radiation, radiation from radioactive salts in the concrete, and machine X-ray background. With this shielding, the time dependent counting rate in the energy range from 2.0 to 3.5 mev, was 8 counts per minute.

Lead and paraffin blocks were placed between the magnet box and the counter to reduce background from any $(d, n)$ and ( $\alpha, n$ ) reactions in the magnet box. To estimate the total background from sources other than from contaminants in the target itself, a sheet of zirconium metal was placed on the reverse side of the target holder to the target, and the target holder reversed to run the "beam dependent" background. The beam dependent background was approximately 12 counts per minute in the energy region 2.0 to 3.5 mev. for energies below 1.6 mev.; that is, $50 \%$ higher than the time dependent background. If it is assumed that radiation is readily detectable if it is twice as intense as background, with the above background and a beam current of 10 microamperes, it would be possible to detect a cross section of $10^{-31} \mathrm{~cm} .^{2}$ with the target thickness used in the present work of $1.60 \times 10^{18}$ atoms per cm. ${ }^{2}$

The beam dependent background increased above 1.6 mev., and by 1.9 mev. had increased to 68 counts per minute in the energy range from 2.0 to



$a$ on Zr - "BEAM DEP." BACKGROUND


FIGURE 7 a ON T SPECTRA, SHOWING RISE IN TGT-DEP. BACKGROUND AT LOW ENERGY (ALL RUNS ARE OF $30 \times 107 \mu$ COULOMBS)
3.5 mev. The increase in background is believed to be caused largely by ( $d, n$ ) reactions from the base of the Van de Graaff accelerator tube. Any molecular deuterium in the alpha beam would be a prolific source of neutrons from $c^{12}$ $(d, n)$ and $c^{13}(d, n)$ reactions. The $c^{13}(\alpha, n) 0^{16}$ reaction cross section should also increase with energy. Considerable radiation from the zirconium backing is also possible for energies above 1.6 mev.

However, at all energies the beam dependent background was small compared with "background" from the target itself; that is, a large number of counts remained below the characteristic gamma ray spectrum counts attributed to $T(\alpha, \gamma)$ reaction gamma rays after subtraction of beam dependent background. The spectrum shape of the "target dependent" background indicated that it was caused by neutrons; apart from the small irregularities the background decreased monotonically with increasing pulse energy. In the alpha particle energy range from 0.7 to 1.6 mev., this "target dependent" background yield was from. 4 to 7 times the beam dependent background yield. The target, dependent background increased markedy at $E_{\alpha}=1.9$ mev., and also at energies below 0.7 mev. At 0.5 mev., the background was higher by a factor of 2 than at 0.7 mev., and at 0.4 mev., was higher by another factor of 2. Figure 7 shows this increase in target dependent background at low Van de Graaff energies.

Neutrons were observed with a neutron counter at 1.9 mev., but not at $300 \mathrm{kev} .$, although it is possible that the bias of the neutron counter was incorrect. The NaI crystal radiation at 300 kev . did not have significant $1 / 2$ hour half-life of the $\left(I^{128}, n\right)$ reaction characteristic of the absorption of neutrons in a $\mathrm{NaI}(\mathrm{T} A)$ crystal; counting stopped when the beam was removed. No characteristic gamma ray spectrum was observed in the background spectrum
in the energy interval from 0.7 mev . to 6.2 mev . Further, since the number of target-dependent background counts above 6.2 mev. was approximately equal to the number of time-dependent counts, the high target dependent background was not caused by gamma rays of energy greater than 6.2 mev.

Neutrons were expected through $H^{3}(t, \alpha) 2 n$ and $H^{3}(t, n) \mathrm{He}^{5}$ reactions from "mock-on" tritons in the target. The neutron yield, however, should increase monotonically (Ajzenberg and Lauritsen, 1955). The reaction $T(d, n) \mathrm{He}^{4}$ has a maximm near Ed $=107 \mathrm{kev}$., with a cross section of 4.95 barns (Argo et al., 1952), and therefore should be a prolific source of neutrons at low energy if molecular deuterium were present in the alpha beam. Cross sections for higher deuterium energies are as follows:

| Ed (kev.) | cross section (barns) |
| :--- | :---: |
|  |  |
| 107 | 4.93 |
| 109 | 4.44 |
| 190 | 2.78 |
| 243 | 1.85 |
| 270 | 1.50 |
| 384 | 0.77 |
| 653 | 0.38 |

Since the target used in the present $T(\alpha, \gamma) \mathrm{Li}^{7} 7$ work was reasonably thick (approximately 50 kev. for protons), the high target dependent background at low bombarding energies could be caused by the $T(d, n) \mathrm{He}^{4}$ reaction. However, the present work was done with no deuterium source bottle present in the Van de Graaff accelerator; deuterium contamination of the alpha beam was therefore not expected. Further measurements are still required to determine the source of the target dependent background.

At all energies the target dependent background introduced uncertainty in the yield measurement from $T(\alpha, \gamma) L i$. Because the yield from the reaction gamma rays decreased with decreasing energy, it was not possible to estimate
the reaction cross section at alpha particle energies below 0.50 mev.
(b) Procedure

The target was bombarded with singly charged alpha particle beams of from 3 to 5 microamperes supplied by the University of British Columbia electrostatic generator. The target was positioned at $38^{\circ}$ to the beam tube to avoid attenuation of the radiation by the target holder. The $38^{\circ}$ orientation was chosen, rather than the more usual $45^{\circ}$ position, because of a convenient mark for target alignment at $38^{\circ}$. To check for target uniformity, spectra were recorded on four different portions of the target. No significant differences in yield were so obtained, indicating reasonable target uniformity. It was also hoped to reduce target dependent background by changing the target position. Prolonged bombardment changed the target surface from a light mottled-grey to a dark smudged-grey colour, indicating the presence of contaminants such as carbon, probably from the break-down of pump oils and vacuum grease.
1.6 mev. was chosen as the energy for an absolute determination of yield because of a relatively high ratio of $T(\alpha, \gamma) L_{i}{ }^{7}$ reaction yield to background at this energy. Runs at other energies were preceded and followed by runs at 1.6 mev . in order to check more easily for target deterioration. Runs were kept short ( 30 integrator counts of 107 microcoulombs each), also in order to check more easily for target deterioration. Deterioration was observed only once, following a run at 1.2 mev. The beam current of 5 microamperes, is believed to have been too high or else the beam was not sufficientiy defocussed, thereby heating a small section of the target too intensely. Spectra were recorded of transition directly to the ground state of $\mathrm{Li}^{7}$, indicated by $\gamma_{1}$, and of transitions to the first excited level of $\mathrm{Li}^{7}$,

indicated by $\gamma_{2}$. Transitions from the first excited level of $L_{2}{ }^{7}$ to the ground state, $\gamma_{3}$, were observed. However, no cross section measurements were made using $\gamma_{3}$ transitions. Figure 8 is a pulse distribution spectrum for $T(\alpha, \gamma)$ radiation showing $\gamma_{1}, \gamma_{2}$ and $\gamma_{3}$. Measurements were made on $\gamma_{1}$, and $\gamma_{2}$ at bombarding energies of $.515, .720, .980,1.64$, and 1.94 mev. The linearity and calibration of the Van de Graaff energy scale measured by the generating voltmeter were determined by measuring the positions of the $.340, .8735$, and 1.372 mev . resonances of $F^{19}(p, \alpha, \gamma) 0^{16}$. All runs were made with the same energy dispersion, and because the change of gamma ray energy is only $3 / 7$ of the change of alpha particle energy, most of the spectra were recorded over the same energy range also. The energies of the gamma ray spectra in the 3 mev . region were measured by using RdTh as a calibration point for the mercury pulse generator amplitude scale. The linearity of the pulse height versus gamma ray energy scale was approximately 1\%. Frequent checks were made on the kicksorter channel positions. 4. Variation in gamms ray energy with alpha particle energy -

In order to check that the observed radiation really originated from $T(\alpha \gamma) L_{i}{ }^{7}$, careful measurements were made on the variation in gama ray energy with alpha particle energy.

The gamma ray energy for the transition to the ground state from the capturing state in the reaction $T(\alpha / \gamma) L i$ is given by

$$
E_{r_{1}}+\frac{\left(E_{r_{1}}\right)^{2}}{2 M_{i} C^{2}}=2.465+\frac{M_{t}}{\left(M_{t}+M_{\alpha}\right)} \bar{E}_{\alpha}
$$

where Ef, is the gama ray energy in mev., and $\bar{E}_{\alpha}$ is the average energy of the alpha particle in the target. The effect of doppler shift is neglected. Since measurements were made with the counter at $90^{\circ}$ to the incident alpha beam, doppler shift was eliminated, and the above expression is correct. Neglecting the small effect of recoil,


$$
E_{\gamma_{1}}=2.465+3 / 7 \bar{E}_{\alpha}
$$

The observed values of $\mathrm{E}_{\gamma 1}$ are shown plotted in Figure 9.
Changes in $E \gamma_{1}$ follow closely

$$
\Delta E_{\gamma 1}=3 / 7 \quad \Delta E_{\alpha}
$$

where $\Delta_{\alpha} E=$ change in energy of the incident alpha beam, which are the changes we expect in E $\mathrm{C}_{1}$ since the target thickness remains approximately constant at all energies used. This seems excellent evidence that this reaction is being observed. However, $\mathrm{E}_{\gamma_{1}}$ is 105 kev . less than $2.465+3 / 7 \mathrm{E}_{\alpha}$ where $\mathrm{E}_{\boldsymbol{\alpha}}$ is the energy of the incident alpha beam.

The theoretical estimate of the target thickness was 232 kev . We therefore expect from $\bar{E}_{\alpha}=E_{\alpha}-\Delta / 2$, where $\Delta$ is the target thickness, that the average alpha-particle energy in the target is 116 kev . less than the incident alpha particle energy. Since

$$
\Delta E_{\gamma}=3 / 7 \Delta E_{\alpha}
$$

$\mathrm{E}_{\gamma 1}$ should be 50 kev . less than $2.465+3 / 7 \mathrm{E}_{\alpha}$.
The observed value of Erl is therefore 55 kev . too low. However, this 55 kev . energy discrepancy could be caused either by a concentration of tritium near the back of the target, or by the presence of more zirconium in the target than is indicated.

An approximate check on the target thickness was made by measuring the width of the fulleenergy peak of $\gamma_{1}$. If the full width at $1 / 2$ maximum height of the full-energy peak for a line source is $\Gamma_{R} k e v$, , and the target thickness is $\Delta$ kev., then the resultant width $\Gamma$ of the full energy peak is given approximately by $\Gamma=\sqrt{2+\Gamma_{R^{2}}}$ kev. If we approximate the full energy peak by a Gaussian, at any energy in the target the full energy peak for reaction gamma rays can be represented by a Gaussian. The observed full energy peak of the spectrum represents an infinite sum of small

Gaussians spread over the target thickness. For target thicknesses A less than or approximately equal to the resolution width $\Gamma_{R}$ the observed full energy peak is approximately Gaussian in shape and of width as given above. The mean value of $\Delta$ computed from $\Delta=\sqrt{\Gamma^{2}-\Gamma_{R}^{2}}$ is 100 kev. , in agreement with the estimated target thickness of 232 kev . for alpha particles. The above calculation is not an accurate calculation of target thickness because of fluctuations of counter resolution; the probable error is estimated to be 20 kev. A concentration of tritium near the back of the target should cause the target to appear thinner; the presence of extra zirconium would cause the target to appear thicker. The above measurement of the gamm ray peak width therefore does not explain the discrepancy in ganma ray energy.

Because the full energy peak of $\gamma_{2}$ coincided with the (full-energy $m_{0} c^{2}$ ) peak of $\gamma_{1}$, the energy $E_{\gamma 2}$ was not accurately determined. $\gamma_{3}$ was also observed of energy approximately 0.5 mev ; however, precise energy and yield measurements were not attempted.
5. Cross section determination -
(a) Background

Because of the high target dependent background, the beam and timedependent background measurements were of little use in determining the true background level. The background level was estimated from the appearance of the spectra; counts recorded below the base of the full-energy peaks were considered as background.

The number of counts in the full-energy peak of $\gamma_{2}$ was determined by subtracting from the full-energy peak of $\gamma_{2}$ the contribution from the (full-energy - $m_{0} c^{2}$ ) peak of $\gamma_{1}$. This (full-energy $-m_{0} c^{2}$ ) contribution was determined by assuming the spectrum shape for $\gamma_{1}$ to be the same as the spectrum

shape for the $c^{12}(d, p, \gamma) c^{13} 3.09 \mathrm{mev}$. gamma ray, shown in Figure 10. Again, counts below the full-energy peak were considered to be background.
(b) Determination of the absolute cross section

The counts attributed to $\gamma_{1}$ transitions during five runs over forr different sections of the target were sumed. The differential cross section for transitions at a bombarding energy of 1.64 mev . was calculated as follows:

$$
\left({ }^{( } \gamma_{1}\right)_{\text {per steradian }}=\frac{(d \sigma)}{(d \omega)} n_{\alpha} \times n_{T}
$$

from which,

$$
\frac{(d \sigma)}{(d \omega)}=\frac{1}{} \quad N_{r_{1}} r^{2} \quad 1 \quad 1 \quad 1
$$

where $\epsilon=0.13$ is the full energy peak efficiency of the counter,
$\mathbf{r}=3.43$ inches is the target to effective centre distance,
$A=4.91$ inches $^{2}$, is the area of the face of the counter,
$\alpha_{\gamma_{1}}=0.956$ is the transmission coefficient for 3.06 mev. radiation through
the $1 / 16$ inch brass walls,
$n_{\alpha}=\frac{140 \text { integrator counts } \times 107 \text { microcoulombs } \times 1.17}{1.602 \times 10^{-13}}$ is the number of
alpha particles incident on the target,
$n_{T}=1.60 \times 10^{18} \times 1.27=2.03 \times 10^{18}$ atoms per $\mathrm{cm} .^{2}$, where 1.27 was introduced because the target was at $52^{\circ}$ to the alpha beam,
$N_{\gamma_{1}}=2956$ counts, after background subtraction.
Then $\frac{(\mathrm{d} \sigma)}{(\mathrm{d} \omega)} \frac{2956}{.956} \times \frac{(3.43)^{2}}{0.13 \times 4.91} \times \frac{1}{1.095 \times 10^{17}} \times \frac{1}{2.03 \times 10^{18}}$
$=2.54 \times 10^{-31} \mathrm{~cm}$. per steradian.
The ratio of the differential cross section for $\gamma 2$ transitions compared with the value computed above for $\gamma_{1}$ transitions was calculated from

$$
\left.\frac{\frac{(d \sigma)}{(d \omega)} \gamma_{2}}{\frac{(\mathrm{~d} \sigma)_{\gamma_{1}}}{(\mathrm{~d} \omega)_{1}}}\right|_{90^{\circ}} ^{\epsilon_{2}} \times \frac{\epsilon_{1}}{\mathrm{~N}_{2}} \times \frac{\alpha_{1}}{\alpha_{2}}
$$

Using 0.14 as the full energy peak efficiency for 2.62 mev. radiation,

$$
\left.\frac{\frac{(\mathrm{d} \sigma)}{(\mathrm{d} \omega) \gamma_{2}}}{\frac{(\mathrm{~d} \sigma)}{(\mathrm{d} \omega) \gamma_{1}}}\right|_{90^{0}}=\frac{1260}{2956} \times \frac{.13}{.14} \times \frac{0.956}{0.954}=0.40
$$

Adding the contributions from both transitions, the $90^{\circ}$ differential cross section at a bombarding energy of 1.64 mev . is $3.54 \times 10^{-31} \mathrm{~cm}{ }^{2}$ per steradian. Assuning an isotropic angular distribution, the total reaction cross section is therefore $4.4 \times 10^{-30} \mathrm{~cm} .^{2}$

If the tritium is distributed uniformly throughout the zirconium layer, the average energy of the alpha particles in the target at a bombarding energy of 1.64 mev. is ( 1.74 - . 116 ) mev. However, if the tritium is concentrated near the back of the zirconium layer, as the observed gamma ray energies indicate, the average energy of the alpha particle beam in the target is (1.64 - .23) mev.
(c) Errors

Sources of error in the differential cross section measurement for transitions at a bombarding energy of 1.14 mev. are as follows:

Source
r, effective centre and beam position
$\epsilon$, counter efficiency $\quad 15 \%$
$\mathbf{n}_{\alpha}$, number of incident alpha particles


FIGURE 11 VARIATION $\mathbb{N}^{\top} T(a, y) \mathrm{Li}^{7}$ DIFFERENTIAL CROSS SECTION WITH VAN DE GRAAFF ENERGY

$$
\begin{aligned}
& \left.N Y_{1}, \text { from counting statistics }-5 \%\right) \\
& \text { from background error }-7 \%)=1.7 \% \\
& \left.\left(\sum(\text { error })^{2}\right)^{1 / 2}\right)
\end{aligned}
$$

For $\gamma_{2}$ transitions, the probable error in the estimation of $N \gamma_{2}$ was $22 \%$, caused by counting statistics (5\%), background error (15\%), and subtraction error (15\%). The standard error in the estimation of $(d \sigma) /(d \omega) \gamma_{2}$ is therefore 28\%. No attempt has been made to allow for possible error in the tritium content of the target; this could introduce a considerably larger error into the cross section measurements.
(d) Determination of the Excitation Function

Differential cross section measurements relative to the measurement at 1.64 mev, were made at bombarding energies of $1.94,1.23,0.98,0.72$, and 0.515 mev. For $\gamma_{1}$ transitions, whose energy varied from 3.18 to 2.59 mev., the counter efficiency was assumed to vary linearly between $\epsilon_{3.09 \text { mev. }}=.13$, and $\epsilon_{2.62 \text { mev. }}=$.14. For $\gamma_{2}$ transitions, whose energy varied from 2.1 to 2.7 mev., , the efficiency was assumed to be constant at $\epsilon_{2.62 \mathrm{mev}}=.14$. The probable error in all cases was considered to be $15 \%$.

The slight changes in transmission coefficient for the brass target pot walls were neglected. Relative cross sections were computed from

$$
\frac{(d \sigma)}{(d \omega)}=\frac{(d \sigma)}{(d \omega) \gamma_{1}, 1.64 \mathrm{mev} .} \frac{\mathrm{N} \gamma}{\left(N \gamma_{1}\right)_{1.64} \mathrm{mev} .} \quad \times \frac{\left.\epsilon_{1}\right)}{\epsilon} 1.64 \mathrm{mev} .
$$

The resulting differential cross sections, all measured at $90^{\circ}$ to the incident alpha particle beam, are tabulated below, and are shown plotted in Figure 11.


| 1.23 | 517 | 38 | 2.08 | .39 | 200 | 70 | .74 | .26 |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: | ---: | :--- |
| 0.98 | 344 | 28 | 1.31 | .25 | 140 | 50 | .52 | .19 |
| 0.72 | 240 | 40 | 0.89 | .21 | 140 | 50 | .52 | .19 |
| 0.515 | 173 | 41 | 0.64 | .19 | 60 | 40 | .22 | .15 |

The probable error in cross section values for $\gamma_{2}$ transitions is larger than the probable error for $\gamma_{1}$ transitions because of the added uncertainty in $N \gamma_{2}$ caused by the subtraction of the contribution of the (full energy $-m_{0} c^{2}$ ) peak of $\gamma_{1}$ from the full energy peak for $\gamma_{2}$ transitions.
6. Angular Distribution Measurements -

Angular distribution measurements were made at $0^{\circ}$ and at $90^{\circ}$ at 1.64 mev. on $\gamma_{1}$ transitions. The same counter, a $2.5 \times 3.0$ inch sodium iodide crystal mounted on a 6363 Dumont photomultiplier, was used as in the cross section measurements. A 1.75 in. diameter by 2.0 in. long sodium iodide (thallium activated) crystal, mounted on an R.C.A. 6342 photomultiplier, was set at $90^{\circ}$ to the incident alpha beam and used as a monitor counter. All pulses from the monitor counter greater than 2, mev. triggered a discriminator and were subsequently recorded by a scaler.

The target was oriented at $45^{\circ}$ to the incident alpha beam so that the gamma rays were attenuated by the target equally in the $0^{\circ}$ position and in the $90^{\circ}$ position.

The counter was moved farther from the target than in the cross section measurements in order to reduce the solid angle subtended by the counter. The yield was reduced by a factor of approximately 5 to the gield in the cross section measurements; at this reduced yield the time dependent background was comparable with the target dependent background.

The yields at $0^{\circ}$ and at $90^{\circ}$ were compared by assuming a constant flux per unit solid angle. Integrating a $\sin ^{2}$ yield over the counter at the effective centre for the distance used ( $r=6.66$ inches) gives a result differing
by approximately $1 \%$ from that of an isotropic distribution; integrating a $\sin ^{2}$ yield over the counter at the effective centre for the distance used in the cross section measurements ( $r=3.43$ inches) gives a result differing by approximately $3 \%$ from that of an isotropic distribution. At both distances the error in assuming a constant flux per unit solid angle is small. The angular distribution could therefore be more accurately measured with the counter closer to the target, that is, with an effective centre distance of approximately 3.5 rather than 6.6 inches, because of the lower background to jield ratio at the larger solid angle.

From the above measurements,
$\frac{\left(\frac{(\mathrm{d} \sigma)}{(\mathrm{d} \omega)} 90^{\circ}\right.}{\frac{(\mathrm{d} \sigma)}{(\mathrm{d} \omega)} 0_{0}^{0}}=\frac{1}{1.39}(1 \pm .37)$

The yields at $0^{\circ}$ and at $90^{\circ}$ differ only by a little more than the probable error of the measurement, but it would appear that the angular distribution is definitely not isotropic.

## 7. Summary of Experimental Results -

From the smooth change of the $T(\alpha, \gamma) L_{i}{ }^{7}$ cross section with energy it can be concluded that the reaction proceeds by direct radiative capture. The $90^{\circ}$ differential cross section for transitions directly to the ground state of $\mathrm{Li}^{7}$ is $2.54 \times 10^{-31} \mathrm{~cm}^{2}$ per steradian at a bombarding energy of 1.64 mev . Adding the contributions from the ground state transitions, $\gamma_{1}$, and from transitions through the first excited level of $\mathrm{Li}^{7}, \gamma_{2}$, gives a $90^{\circ}$ differential cross section at 1.64 mev . of $3.54 \times 10^{-31} \mathrm{~cm} .^{2}$ per steradian, which corresponds to a total reaction cross section of $4.4 \times 10^{-30} \mathrm{~cm} .^{2}$ if we assume
an isotropic angular distribution. The mean alpha-particle energy in the target is believed to be between 116 and 230 kev . less than the bombarding energy as measured by the Van de Graaff generating voltmeter.

Relative cross section measurements have been made at bombarding energies from 0.5 to 1.9 mev . At all energies the ratio


Assuming an isotropic angular distribution, the total $T(\alpha, \gamma) L_{i} 7$ reaction cross section in the energy range studied can be expressed approximately by $\sigma=3 \overline{\mathrm{E}} \alpha$, where $\overline{\mathrm{E}}_{\alpha}=$ (bombarding energy $=.116$ ) mev.

Preliminary measurements indicate that the angular distribution is not isotropic, as would be expected from a purely s-wave capture process, the yield at $0^{\circ}$ to the incident alpha beam being larger than the yield at $90^{\circ}$.


## CHAPTER III

## DISCUSSION:

1. Comparision of $T(\alpha, \gamma) \mathrm{Li}^{7}$ with the mirror reaction $\mathrm{He}^{3}(\alpha, \gamma) \mathrm{Be}^{7}$ -

After the present $T(\alpha, \gamma) L_{i} 7$ work had been performed, it was learned that similar work had been done on the mirror reaction $\mathrm{He}^{3}(\alpha, \gamma) \mathrm{Be}^{7}$ at the U.S. Naval Research Laboratory. Cross section values obtained for the $\mathrm{He}^{3}(\alpha, \gamma) \mathrm{Be}^{7}$ reaction are given below. (Private communcation from R. L. Johnson for H.D. Holmgren) The third column gives comparable cross section values for the $T(\alpha, \gamma) L i=^{7}$ reaction, where to allow for target thickness, $E$ is taken as (Evan de Graaff -116 kev .)

| Average $\alpha$-particle energy $_{\mathrm{E}_{\alpha}}$ in target | $\begin{gathered} \mathrm{He}^{3}(\alpha, \gamma) \mathrm{Be}^{7} \\ \text { microbarns } \end{gathered}$ | $\underset{\text { microbarns }}{T(\alpha, \gamma) L_{i}{ }^{7}}$ | $\begin{aligned} & \text { Ratio } \\ & \sigma \mathrm{T}, \alpha \\ & \sigma \mathrm{He}^{3}, \alpha \end{aligned}$ |
| :---: | :---: | :---: | :---: |
| 1.3 mev. | $1.30 \pm .08$ | 3.9 | 3.0 |
| 1.1 mev. | $0.76 \pm .06$ | 3.4 | 4.5 |
| 0.9 | $0.40 \pm .02$ | 2.7 | 6.7 |
| 0.7 | $0.19 \pm .02$ | 2.0 | 10.5 |
| 0.5 | $0.04 \pm .02$ | 1.6 | 40 |

To compare the $\mathrm{He}^{3}(\alpha, \gamma) \mathrm{Be}^{7}$ cross sections with the $\mathrm{T}(\alpha, \gamma) \mathrm{Li}^{7}$ cross sections, the penetrabilities $(1 / A O)^{2}$, for swwave capture, and (1/Al) ${ }^{2}$, for p-wave capture, were plotted for the two reactions, as shown in Figure 12. Values of $(1 / A)^{2}$, where $A^{2}=F^{2} \quad G$, where $F(\rho)$ and $G(\rho)$ are the regular and irregular Coulomb fractions, were taken from "Graphs of Coulomb Functions", (Sharp, Gove, and Paul, 1953). In these graphs, (A) is plotted versus por specific values of $\log _{10} \eta$,

$$
\begin{aligned}
& \text { where } \rho=\frac{\mathrm{Z} \mathrm{Z}^{\prime} \mu_{\mathrm{R}}}{29.05 \eta} \\
& \text { and } \eta=0.1574 \mathrm{Z} \mathrm{Z}^{\prime}\left(\frac{\mu}{\epsilon}\right)^{\frac{1}{2}} \\
& Z \text { and } Z^{\prime} \text { are the atomic numbers of the colliding particles, }
\end{aligned}
$$

$\mu$ is the reduced mass in atomic mass units,
$R$ is the nuclear radius, which was taken to be $1.45\left(3^{1 / 3}+4^{1 / 3}\right)$ Fermis
$\epsilon$ is the kinetic energy of the relative motion of the two particles.

From the known values of alpha particle bombarding energy, values of $\eta$ and then values of $\rho$ were obtained. From Figure 12, the values of the ratio of $(1 / \mathrm{AO})^{2}$ for $\alpha$ on T to $(1 / \mathrm{AO})^{2}$ for $\alpha$ on $\mathrm{He}^{3}$ are respectively $2.8,3.8,5.8$, 11 , and 30 for the alpha particle energies $1.3,1.1,0.9,0.7$, and 0.5 mev . The ratios of the observed cross sections for the two reactions are approximately equal to the ratios of the penetrabilities for the two reactions over the whole energy range. The agreement between the two sets of cross section data is therefore considered to be good.
2. Comparison of $T(\alpha, \gamma) L_{i}{ }^{7}$ with the inverse reaction $L_{i}^{7}(\gamma, \alpha) T$ -

The expected cross section for the photodisintegration reaction $\mathrm{Li}^{7}(\gamma, \alpha) \mathrm{T}$ can be calculated from the measured cross section for $T(\alpha, \gamma) \mathrm{Li}^{7}$ using the principle of reciprocity. From reciprocity,
where

$$
\begin{aligned}
& \left(2 I_{A}+1\right)\left(2 I_{a}+1\right) \mathrm{Pa}^{2} \sigma_{a b}=\left(2 I_{B}+1\right)\left(2 I_{b}+1\right) P_{b}^{2} \sigma_{b a} \\
& \left(2 I_{A}+1\right)=\left(2 I_{T}+1\right)=2 \\
& \left(2 I_{a}+1\right)=\left(2 I_{a}+1\right)=1 \\
& \left(2 I_{B}+1\right)=\left(2 I_{L i}+1\right)=4 \\
& \left(2 I_{b}+1\right)=\left(2 I_{\gamma}+1\right)=2 \\
& \mathrm{~Pa}_{\mathrm{a}}=\mathrm{P}_{\alpha}=\sqrt{2 m_{\alpha} \varepsilon_{\alpha}} \\
& E_{\alpha}=\text { centre of mass } \alpha \text {-particle energy }=9 / 49 E_{\alpha_{L}} \text { ab. } \\
& P_{b}=P_{\gamma}=\frac{h b r}{c}
\end{aligned}
$$

Then

$$
\frac{\sigma_{\alpha} \gamma}{\sigma_{\gamma \alpha}}=4^{\left(P_{\gamma}\right)^{2}}\left(P_{\alpha}\right)^{2}
$$

$$
\text { For } E_{\alpha}=1.6 \text { mev., } \frac{\sigma_{\gamma_{\alpha}}}{\sigma_{\alpha} \gamma}=56
$$

The cross section $\sigma_{\alpha}$ measured in the present work is approximately 4 microbarns at 1.6 mev. Thus, $\sigma_{\gamma \alpha}=240$ microbarns for $E_{\gamma}=3.2 \mathrm{mev}$.

An excitation function for $\mathrm{Li}(\gamma, \alpha)$ T was first measured by Titterton and Brinkley (1953) for energies up to 24 mev. using bremsstrahlung radiation from a synchrotron. Titterton and Brinkley (1953) also carried out absolute cross section measurements for $\mathrm{Li}^{7}(\mathrm{\gamma}, \alpha) \mathrm{T}$ at 6.14 mev. using fluorine radiation, and at 14.8 and 17.6 mev. using radiation from the 440 kev . resonance in $\mathrm{Li}^{7}(\mathrm{p}, \gamma) \mathrm{Be}^{8}$. The observed cross section at 6.14 mev . was 15 micro barns was found at 6.14 mev. by Stoll and Wachter (1953), also using fluorine radiation. Erdos, Stoll, Wachter, and Wateghin (1954) investigated the reaction $\mathrm{Li}^{7}(\gamma, \alpha) \mathrm{T}$ using radiation from a 31 mev. betatron. Excited levels in $\mathrm{Li}^{7}$ were found at $4.7,5.5,6.8,8.3$, and 9 mev. The first three levels (4.7, 5.5 , and 6.8 mev.) had a relative intensity of $1: 0.75: 0.75$. The absolute cross section for $\mathrm{Li}^{7}(\gamma, \alpha) \mathrm{T}$ obtained from known $\mathrm{C}^{12}(\gamma, 3 \alpha)$ cross sections was approximately 190 microbarns at 4.7 mev. The cross section for $\mathrm{Li}^{7}(\gamma, \alpha) \mathrm{T}$ calculated from the cross section for $T(\alpha, \gamma) L i 7$ observed in the present work is apparently in reasonable agreement with the measurements of Erdos, Stoll, Wachter and Wateghin, but in marked disagreement with the cross section values observed by Titterton and Brinkley, and by Stoll and Wachter. It would be interesting to investigate the photodisintegration of $L i A^{7}$ at lower energies than has been done, where the reaction cross section could be expected to depend more on the ground state wave function, and less on the characteristics of higher excited levels.

It has been shown by Peaslee and Telegdi (1953) that comparison of
the yields from $\mathrm{Li}^{7}(\gamma, \alpha) \mathrm{T}$ and $\mathrm{Li}{ }^{7}(\gamma, n) \mathrm{Li}{ }^{6}$ provides a way of identifying the $T=3 / 2$ levels of $\mathrm{Li}^{7}$. When $\mathrm{Li}^{7}$ is bombarded with gamma rays, excited states of $T=3 / 2$ and $T=1 / 2$ result from the selection rule $\Delta T=1$, 0 . $L i^{6}$ has both $T=0$ and $T=1$ low-lying levels; $\mathrm{He}^{4}$ has only $T=0$ low-lying levels. Neutron and triton emission is therefore allowed from $T=\frac{1}{2}$ states. From $T=3 / 2$ excited states, neutron emission is allowed to the $T=1$ state, but triton emission is forbidden from the selection rules. More levels in the neutron yield curve from $\operatorname{Li}^{7}(\gamma, \mu) L i^{6}$ above 9 mev. (Katz and Goldenberg, 1954) than in the triton yield curve from $\mathrm{Li}^{7}(\gamma, \alpha) \mathrm{T}$ in the same energy region, support the above argument. However, the argunent is of no concern in the present work, since the very low levels of $\mathrm{Li}^{7}$ are $\mathrm{T}=\frac{1}{2}$ states. Presumably, at high energies, the $T(\alpha, \gamma) L_{i}{ }^{7}$ reaction cross section would not show resonances at $T=3 / 2$ levels of $\mathrm{Li}^{7}$.

## 3. The Ground State of $\mathrm{Li}^{7}$ -

There has been much interest in, and speculation on, the $\mathrm{Li}^{7}$ nucleus. From Shell Model considerations the ground state wave function of $\mathrm{Li}^{7}$ is uniquely defined in a $J J$ configuration as having $J=3 / 2, T=\frac{1}{2}$ (Mayer and Jensen, 1955). The ground state configuration is

$$
(\nu \mid s)^{2}(\nu \mid p 3 / 2)^{2}(\pi \mid s)^{2}(\pi \mid p 3 / 2)
$$

where $V$ indicates a neutron state, and $\pi$ indicates a proton state. The configuration, (r|p $3 / 2)^{2}(\eta 1 p 3 / 2)$ which makes up the wave function, contains levels with $\mathrm{J}=7 / 2,5 / 2,3 / 2$, and $1 / 2$, i.e. the two neutrons and one proton combine in JJ coupling as is indicated below, where negative values of $M_{J}$ are not indicated.

| $(\pi / p 3 / 2)$ | $(\nu / p 3 / 2)$ | (*) 1 , 3/2) | $\mathrm{MJ}_{J}$ | J |
| :---: | :---: | :---: | :---: | :---: |
| 3/2 | 3/2 | 1/2 | 7/2,5/2,3/2,1/2 | 7/2 |
| 1/2 |  | -1/2 | 5/2,3/2,1/2 | 5/2 |

$-1 / 2$
$-3 / 2$
$1 / 2$
$-3 / 2$
$-1 / 2$
$-3 / 2$
$\begin{array}{rr}3 / 2,1 / 2 & 3 / 2 \\ 3 / 2,1 / 2 & 3 / 2 \\ 1 / 2 & 1 / 2\end{array}$

The desired wave function is therefore of the form

$$
\begin{aligned}
\psi_{3 / 2}^{3 / 2} & =a\left|\left(\pi^{3 / 2}\right)\left(\nu^{3 / 2} \psi^{-3 / 2}\right)\right|+b \mid\left(\pi \psi^{3 / 2}\right)\left(\nu^{1 / 2} \psi^{-2}\left(\nu^{-1 / 2}\right) \mid\right. \\
& +c\left|\left(\nu \psi^{3 / 2}\right)\left(\hat{\pi} \psi^{-1 / 2}\right)\left(\nu \psi^{-1 / 2}\right)\right|+d\left|\left(\psi^{3 / 2}\right)\left(\psi^{\frac{1}{2}}\right)\left(\pi^{-1 / 2}\right)\right|
\end{aligned}
$$

where the bars indicate that the term is a totally anti-symmetrized Slater determinant. The desired eigenfunction with $J=3 / 2, T=1 / 2$, fulfills the two conditions that

$$
\begin{aligned}
& T_{+} \psi_{3 / 2}^{3 / 2}=\sum_{i=1}^{3} t_{+}^{(i)} \psi=0 \\
& J_{+}+\psi_{3 / 2}^{3 / 2}=\sum_{i=1}^{3} j^{(i)} \psi=0
\end{aligned}
$$

and
which follow from the relationships

$$
\begin{aligned}
& J_{+} \psi_{L}^{M}=\sqrt{J(J+1)-M(M+1)^{\prime}} \quad L^{M+1}, \text { and } \\
& T_{+} \psi_{T}^{T_{3}}=\sqrt{T(T+1)-T z(T z+1)} \phi_{T}^{T z+1}
\end{aligned}
$$

The two conditions

$$
\begin{aligned}
& T_{+} \psi_{3 / 2}^{3 / 2}=0 \\
& J_{+} \psi_{3 / 2}^{3 / 2}=0
\end{aligned}
$$

are sufficient to determine the three ratios of the coefficients. The normalized eigenfunction obtained is

$$
\begin{aligned}
\psi_{3 / 2}^{3 / 2}(T=1 / 2)= & \sqrt{\frac{1}{15}}\left[\frac{1}{15}\left|\left(1 \psi^{3 / 2}\right)\left(\nu \psi^{3 / 2}\right)\left(\nu \psi^{-3 / 2}\right)\right|-2\left|\left(\pi^{3 / 2}\right)\left(\psi^{1 / 2}\right)\left(\psi-\frac{1}{\psi}\right)\right|\right. \\
& +\left|\left(\nu \psi^{3 / 2}\right)\left(\pi \psi^{2}\right)\left(\nu-\frac{1}{\psi} / 2\right)\right|+\left|\left(\psi^{3 / 2}\right)\left(\nu \psi^{1 / 2}\right)\left(\pi \psi^{-1 / 2}\right)\right|
\end{aligned}
$$

Mayer and Jensen compute the magnetic moment of this eigenfunction to be 3.03
nuclear magnetons, in reasonable agreement with the observed value of 3.257 . The nuclear quadrupole moment is calculated to be negative, equal to $-11 / 15 \times$ $2 / 5\left\langle\mathrm{r}^{2}\right\rangle \mathrm{cm} .^{2}$

There has been much disagreement concerning the sign of the nuclear quadrupole moment of $\mathrm{Li}^{7}, \mathrm{Q}$, largely because of the difficulty in calculating the magnitude of the electric field gradient, $q$, at the nucleus in the $\mathrm{Li}_{2}$ molecule; the product eqQ has been measured accurately for $\mathrm{Li}^{7}$ by the nuclear resonance method. After measurement of the product eqQ, Kusch (1949) reported the nuclear quadrupole moment of $\mathrm{Li}^{7}$ to be positive, in direct disagreement with simple shell model predictions as discussed above. The electric field gradient, q, was subsequently recalculated by Harris and Melanoff (1952) using both a Heitler London function and a 12 term variational (James) function, for the molecular wave functions for $\mathrm{Li}_{2}$. The results of the two calculations of $q$ differed in sign; however, the James function, which was considered the more accurate, gave a negative $q$, and so a negative $Q$. Recent calculations by Ishiguro et al. (1957) lead to a positive $Q$ for $\mathrm{Li}^{7}$, of magnitude $9.6 \times 10^{-26} \mathrm{~cm}^{2}$, neglecting Sternheimer correction, (Sternheimer, 1950) or of magnitude $10.8 \times 10^{-26} \mathrm{~cm}^{2}$ (including Sternheimer correction). It therefore appears likely that the nuclear quadrupole moment of $\mathrm{Li}^{7}$ is positive; the charge distribution for $\mathrm{Li}^{7}$ is then apparently prolate.

A negative nuclear quadrupole moment for $\mathrm{Li}^{7}$ is also predicted in the first approximation of Wigner's coupling scheme (Present, 1950). In this coupling scheme, the orbital wave function is characterized by a definite symmetry with respect to permutations of the nucleons. Instead of the 2valued spins $T$ and $S$, Wigner introduces the 4 -valued spin $\eta$; the representations of the 4 -dimensional unitary group than characterize the multiplet
system (Wigner, 1937). In terms of the partition numbers $\left[\lambda_{1}+\lambda_{2}+\lambda_{3}\right]$ the partitions for $L i A^{7}$ are [3], $[2+1]$, and $[1+1+1]$, in the order of decreasing symmetry of the orbital wave function. For symmetry [3], the orbital part of the wave function is completely symmetric under permutations of the three nucleons; for symmetry $[1+1+1]$, completely antisymmetric. The ground state configuration is $\left(15^{4}{ }_{2 P}{ }^{3} \mathrm{P}_{3} / 2\right)$, of symmetry [3].

Present (1950) explains the positive nuclear quadrupole moment of $\mathrm{Li}^{7}$ by configuration interaction. The ground state configuration consists of $2_{P}$ functions of symmetry [3] from the low odd parity excited configurations $\left(15^{4} 2 \mathrm{P}^{2} 3 \mathrm{P}\right.$ ) and ( $15^{4} 2 \mathrm{P}^{2} 4 \mathrm{f}$ ) mixed with the ( $15^{4} 2 \mathrm{P}^{3}$ ) configuration. Present finds that all data are adequately explained without the breakdown of L-s coupling or a large departure from partition symmetry. The argument appears reasonable, since the configuration interaction need not be large to produce a positive nuclear quadrupole moment.

Avery and Blanchard (1950) have attempted to explain the positive nuclear quadrupole moment of $\mathrm{Ij}^{7}$ on the basis of a combination of spin-orbit interaction (breakdown of L-S coupling), and the breakdown of partition symmetry. A $\left(s^{4}{ }^{3}{ }^{3}\right)$ configuration is assumed. The angular momenta of the 3 p nucleons can be combined to give 10 linearly independent eigenfunctions, 8 of which have $J=3 / 2$. I-S coupling is assumed; i.e. the two neutrons can combine to form $l_{S}, 3_{P}$, and $l_{D}$ states. These can combine with the p-proton in I-S coupling as is indicated by the table below:

 "(neutron state, proton state) combined state", can therefore be formed. In addition, the three p-nucleons can form the following states:

$$
\begin{aligned}
& \left(1_{S}{ }^{2}\right)^{2}{ }^{2} \\
& (3 \mathrm{p} 2 \mathrm{p}) 2_{p} \\
& (3 p 2 p) 4 p \\
& \left(3_{P} 2_{p}\right){ }^{2} D \\
& \left(3_{p}{ }^{2} p\right) 4 D \\
& \left(3_{p}{ }^{2} p\right) 4 s \\
& \left(3 p 2^{2}\right) 2_{S}
\end{aligned}
$$

The $\left(3_{P} 2_{p}\right) 2_{S}$ and the $\left(1_{D} 2_{p}\right) 2_{F}$ states are rejected since they do not have $J=3 / 2$. The above eight states are expressed in terms of their symmetry proparties as follows:

$$
\begin{array}{ll}
\psi_{1}={ }^{22} \mathrm{P}[3] & \psi_{5}={ }^{22} \mathrm{D}[2+1] \\
\psi_{2}={ }^{22_{\mathrm{P}}[2+1]} & \psi_{6}={ }^{24_{\mathrm{D}}[2+1]} \\
\psi_{3}={ }^{24_{\mathrm{P}}[2+1]} & \psi_{7}={ }^{42} \mathrm{D}[2+1] \\
\psi_{4}={ }^{42} \mathrm{P}[2+1] & \psi_{8}={ }^{44^{2}}[1+1+1]
\end{array}
$$

where the functions $\psi$ are linear combinations of the first set of eight eigenfunctions, such that the symmetry properties given by $\left[\lambda_{1}+\lambda_{2}+\lambda_{3}\right]$ are satisfied. The set $\psi$ was obtained by Avery and Blanchard by the usual rules for combining angular momenta. The notation for the $\psi$ functions is

$$
(2 S+1)(2 T+I) L\left[\lambda_{1}+\lambda_{2}+\lambda_{3}\right]
$$

In the first approximation of Wigner's the ground state of $\mathrm{Li}^{7}$ consists of the function $\psi_{1}={ }^{22} \mathrm{P} \quad[3]$
where $\psi_{I}=\frac{\sqrt{5}}{3}\left(1_{S} 2_{p}\right)^{2} P+2 / 3\left(1 D^{2} p\right)^{2} P$

However, Avery and Blanchard, under the assumption that $\psi_{G}=\sum_{J=1}^{8} a_{j} \psi_{j}$ find a positive quadrupole moment for $\mathrm{Li}^{7}$, as well as reasonable agreement with magnetic moment and $\mathrm{Be}^{7} \mathrm{~K}$-capture data, if the ground state wave function is almost all of symmetry $\left[\begin{array}{ll}2 & + \\ \text { not }\end{array}\right]$, with the largest contribution from the D states. $L$ and $S$ are therefore/good quantum numbers; the data suggest that $\tau$ may be a good quantum number.

The above ground state configuration, since it involves large departures from shell model theory, does not seem as reasonable as the configurations deduced by Present to explain the positive quadrupole moment of $\mathrm{Li}^{7}$.

Most recent work concerns the intermediate coupling models for $\mathrm{Li}^{7}$, for which the nuclear quadrupole moment is negative, in agreement with simple shell model predictions (Inglis, 1953). In pure L-S coupling, the lowest states of $\mathrm{Li}^{7}$ are the maltiplets ${ }^{2} \mathrm{P},{ }^{2} \mathrm{~F},{ }^{4} \mathrm{P}$, etc., in order of increasing energy. Inglis takes the multiplet separations from interaction energies computed from the direct and exchange integrals $L$ and $K$, as evaluated by Feenberg and Wigner (1937). Inglis specializes the interaction for the operator $O_{i j} V\left(r_{i j}\right)$, where

$$
0_{i j}=0.8 P+0.2 Q
$$

$P$ is the Majorana operator and $Q$ is the spin exchange operator. The multiplet splittings, defined by $H^{\prime}=\{$ a $1 . s=A$ L.S , are obtained from trace invariance. In $J-J$ coupling the ground configuration is ( $\mathrm{P} 3 / 2)^{3}$. The spin-orbit energy is $3 a / 2$, and the separations between states of different $J$ have been calculated. Inglis finds the best fit between experimental energy levels and theory at $a / K=0.7$, where $a$ is a measure of the L-S multiplet splittings, and $K$ is the multiplet separations. The coupling $a / K=0.7$ is very close to pure L-S coupling.

Aeurback and French (1955) have determined the intermediate coupling parameter. $P=a / K=1.4$ from consideration of the reaction $L i^{7}(p, d) L i^{6}, L i^{6} \notin$ in reasonable agreement with the predictions of Inglis. They obtain $\rho=$ approximately 2.5 from the reaction $\mathrm{Li}^{6}(\mathrm{~d}, \mathrm{p}) \mathrm{Li}^{7}$, $\mathrm{Li}{ }^{7}$. ${ }^{\mathbf{\#}}$
D. Kurath (1956) finds the intermediate coupling parameter $a / K$ approximately $=2$.

Since the $T(\alpha, \gamma) \operatorname{Li}^{7}$ reaction, in the low energy region studied here, occurs through direct radiative transitions, and therefore is sensitive to the properties of the ground state and of the first excited state of $L \mathrm{Li}^{7}$, it is hoped that the reaction cross section and angular distribution will be of use in determining the ground state and first excited state wave functions.

## CHAPTER IV

THE $0^{16}(p, \gamma) F^{17}$ REACTION:

1. Previous Measurements -

The $0^{16}(p, \gamma) F^{17}$ reaction was first observed by Dubridge et al (1938) by measuring the annihilation quanta from the decay of $\mathrm{F}^{17}$. Laubenstein et al (1951) measured the relative cross section from 1.4 to 4.1 mev. by measuring the yield of annihilation radiation. Warren et al (1954), in this laboratory, observed the gamma radiation directly and attributed the non-resonant character of the cross section for gamma emission in the region 0,8 to 2.1 mev. to a direct radiative capture process. The $0^{16}(p, \gamma) F^{17}$ cross section was found to be $6 \pm 3 \times 10^{-30} \mathrm{~cm}_{0}^{2}$ at 1.90 mev. The angular distribution for the $\gamma_{2}$ transitions, which go via the first excited level of $\mathrm{F}^{17}$, was approximately $1+(5 \pm 1) \sin ^{2} \theta$ at 1.9 mev . The angular distribution for the $\gamma_{1}$ transitions, which go directly to the ground state of $F^{17}$, was believed to be isotropic. Recently, the differential cross section has been measured at 800 kev . by Robertson (1957) in this laboratory. The differential cross section at $90^{\circ}$ to the incident proton beam for $\gamma_{2}$ transitions was found to be $10.4 \pm 1.30 \times$ $10^{-32} \mathrm{~cm} .^{2}$ per steradian, and the ratio, at $90^{\circ}$ of the yield for $\gamma_{1}$ transitions to the yield for $\gamma_{2}$ transitions was found to be $1.4 \pm .03$. Using the angular distribution of the gama rays found by Warren et al at 1.9 mev. for the angular distribution at 800 kev ., Robertson estimated the $0^{16}(\mathrm{p}, \gamma) \mathrm{F}^{17}$ cross section to be $9.3 \times 10^{-31} \mathrm{~cm} .^{2}$ at 800 kev . for transitions to the first excited state of $\mathrm{F}^{17}$, and $1.8 \times 10^{-31} \mathrm{~cm}_{0}^{2}$ for transitions to the ground state.
2. Apparatus -
(a) Target and Target Arrangement

For reasons as described by Robertson (1957), solid oxidized tungsten targets, approximately $0.02 \times 1 \times 0.75$ inches, were used for this work. The
tungsten was oxidized by suspending it in a heater coil of nickel wire inside a bell jar. Heating was continued in the presence of commercial grade oxygen for approximately 10 minutes until a dark blue grey tungsten oxide layer was formed over the surface of the tungsten.

The target chamber and target arrangement were as described in Chapter II. A sheet of clean tungsten was placed on the reverse side of the target holder for beam-dependent background measurements. No heating was applied to the target assembly; after prolonged bombardment the target changed to a deeper blue colour, presumably due to the formation of cracked oil deposits.

The first tungsten plates used were cleaned in potassium hydroxide solution, etched, and rinsed in distilled water before oxidation. Since Robertson had found traces of $\mathrm{Na}^{23}$ in tungsten oxide targets, the targets were checked for $\mathrm{Na}^{23}$. Gamma rays from $\mathrm{Na}^{23}$ are a 0.45 mev . gamma ray from $\mathrm{Na}^{23}\left(\mathrm{p}, \mathrm{p}^{\prime}, \gamma\right) \mathrm{Na}^{23}$ and a 1.60 mev . gamma ray from $\mathrm{Na}^{23}(\mathrm{p}, \alpha, \gamma) \mathrm{Ne}^{20}$. The checks for $\mathrm{Na}^{23}$ contamination were made by running an excitation curve over the resonance at $1287.5 \mathrm{kev} .$, which decays by proton emission giving the 0.45 mev. gamma ray. A significant increase of 0.45 mev . radiation at the resonance energy confirmed the presence of $\mathrm{Na}^{23}$ in the target. $\mathrm{Na}^{23}$ was also found in significant quantities on clean, unoxidized tungsten, indicating the possibility of $\mathrm{Na}^{23}$ contamination through the cleaning in potassium hydroxide, which contains traces of sodium. The tungsten plates were therefore only heavily etched (approximately 4 amperes for 5 minutes), and then boiled in distilled water for $1 / 2$ hour before oxidation. At no time were the plates touched by hand. This procedure reduced the sodium content such that the $\mathrm{Na}^{23}$ gamma ray yield was estimated to be 60 counts per 100 microcoulombs of
beam above a 300 kev . bias at the resonance energy of 1287.5 kev . proton energy for the counter-target arrangement used in this work. Excitation functions are given for gamma rays from the proton bombardment of $\mathrm{Na}^{23}$ by Stelson and Preston (1954) and by Burling (1941). The yield of gamma rays from the sodium contamination of the target in the energy region of the fullenergy peaks of the $0^{16}(p, \gamma) F^{17} \gamma_{1}$ and $\gamma_{2}$ transitions was estimated to be negligibly small for all energies used in the present work.

## (b) Ganma Ray Detector

Preliminary runs were made at 830 kev . and 1.64 mev . with the large $2.5 \times 3.5$ inch crystal described in Chapter II. A positive photomultiplier gain shift of $4 \%$ was observed at 1.64 mev. after bombardment of 70 integrator counts at a beam current of 5 microamperes. Because gain shifts distorted the full energy peaks of $\gamma_{1}$ and $\gamma_{2}$, it wes decided to use a $1.75 \times 2.0$ inch sodium iodide (thallium activated) crystal mounted on a Dumont two-inch photomultiplier tube. With this smaller counter, a positive gain shift of $6 \%$ was observed at 1.64 mev . after bombardment of 100 integrator counts at a beam current of 6 microamperes. This gain shift was reproduced by flooding the counter with radiation from a $\mathrm{Eu}^{155}$ source (strong lines at 87 kev . and at 330 kev .) for $1 / 2$ hour. The Dumont photomultiplier tube was therefore replaced with an R.C.A. 6342 two-inch photomultiplier tube, code number 8-4-246.

The above counter arrangement, consisting of an R.C.A. 6342 photomultiplier mounted on a $1.75 \times 2.00$ inch crystal, was used for all $0^{16}(p, Y) F^{17}$ measurements reported in the present work. Flooding the counter with a $\mathrm{Eu}^{155}$ source (count rate of 30,000 per second) produced no apparent gain shift when calibration runs were made before and immediately after flooding. It was necessary to remove the Eu before calibration because of interfering high
energy radiation from Eu. When $\mathrm{Cs}^{137}$ was used to flood the counter, and a calibration made simultaneously with RdTh, a negative gain shift of $6 \%$ was observed, similar to the negative gain shift observed by Robertson with the large counter. The gain shift disappeared inmediately the Cs source was removed.

During the oxide runs, a positive gain shift of $4 \%$ with a decay time of a few hours was observed after bombardment at 2.0 mev. for 20 minutes with a beam current of 3 microamperes. Calibrations were made with the beam off; the negative gain shift was therefore not observed. However, the reaction spectrum from the oxide target was displaced upwards on the kicksorters, indicating a net positive gain shift. It is not understood why flooding the counter with a Eu source did not produce a similar positive gain shift. Possibly the oxide runs produced a higher intensity of very low energy radiation (112 and 66 kev.) than came from the Eu source.

For accurate energy determination, it is necessary to avoid intense Low energy radiation, as from tungsten irradiated with protons of energy above 2 mev., and to calibrate with the beam on the target. The calibration radiation must then, of course, be much less intense than normal radiation to avoid extra gain shifts. When intense low energy background radiation cannot be avoided, as in the present work, a thin absorber could be placed in front of the counter. This was not done during the present $0^{16}(p, \gamma) F^{17}$ runs.

The average of five determinations of resolution gave a counter resolution of $8.9 \pm 1 \%$ for 0.662 radiation from a Cs ${ }^{137}$ source, where the resolution is defined as the full width at one-half maximum amplitude of the full-energy peak. Between 960 and 1200 volts, the resolution was independent of the voltage supplied to the dynode chain; 1200 volts was used for the
present work.
The energies of the $0^{16}(p, \gamma) F^{17}$ gamma rays, $\gamma_{2}$ and $\cdot \gamma_{1}$, are 0.66 mev. and 1.16 mev . at a proton energy of 600 kev ., and 2.48 mev . and 1.98 mev . at a proton energy of 2.00 mev . The efficiency of the crystal for gamma rays, $\in(E, E / 2)$, where $E / 2$ is a bias energy of $1 / 2$ the incident gamma ray energy, has been obtained for the energy region 0.60 to 2.5 mev . (Appendix I.). Since the detailed shapes of the $\gamma_{1}$ and $\gamma_{2}$ spectra below the full-energy peaks were not accurately observed in this experiment, comparisons were made with the spectra from $\mathrm{Cs}{ }^{137}, \mathrm{Zn}^{65}, \mathrm{Na}^{22}$, and RdTh sources, and the efficiency. $\in(E, E-.20)$ defined to a bias of 200 kev . below the incident gamma ray energy.
(c) Electronics -

The electronics were set up as described in Chapter II. The stability of the electronics during the runs was better than 0.1\%. The kicksorter was set to cover a 1 mev. energy region in the vicinity of the full energy peaks of $\gamma_{1}$ and $\gamma_{2}$ transitions; most runs were made without altering the kicksorter dispersion.

## 3. Experimental -

(a) Background

The target and target chamber were surrounded by approximately 4 inches of lead to reduce background radiation. The time dependent background was approximately 50 per minute in the energy region $1 / 2$ to 3 mev. At proton energies below 1.1 mev., the beam dependent background, on clean tungsten, was approximately the same as the time dependent background. Above 1.1 mev., the beam dependent background rose steadily. At 2 mev . the beam dependent background in the energy region 1.8 to 3 mev. was 110 counts per minute, compared with the time dependent counting rate of 8 counts per minute in this

energy range. Part of the rise in background with energy can be attributed to ( $\mathrm{d}, \mathrm{n}$ ) reactions in the magnet box. 2.37 mev. gama rays could be expected from carbon contamination of the target and beam stops; however, the background spectrum showed no significant gammay reak, but decreased uniformly over the energy range studied. The walls of the target chamber had been gold plated to reduce fluorine contamination; it is possible that the plating is insufficiently thick, or impure. Background radiation could also come from impurities in the tungsten backing; some radiation could come from the tungsten itself.
(b) Procedure

Protons of $0.618,0.823,1.13,1.54$, and 2.04 mev., supplied by the university electrostatic generator, were used to bombard a tungsten oxide. The beam energy, governed by the sniffer separation, was known to approximately 1\%. The counter face was positioned as close as possible to the target chamber in order to obtain a maximum counting rate, the distance from the counter face to the target being 1.63 inches for all the runs. Since preliminary runs showed target deterioration for beams of 6 to 7 microamperes, beam currents were from 3 to 4 microamperes. The target was checked for deterioration by frequent checks of the yield at 1.54 mev. No target deterioration was observed during the experiment. Spectra were recorded of the fullenergy peaks of $\gamma_{1}$ and $\gamma_{2}$. A typical spectrum, at a bombarding energy of 1.13 mev., is shown in Figure 13.

## 4. Target Thickness -

The target thickness was necessary in order to obtain the mean proton energy in the target. The target thickness was calculated from Robertson's ice target results. For an ice target containing $1.118 \times 10^{19}$ molecules
of water $/ \mathrm{cm}^{2}$, Robertson observed 92 counts per integrator in the 2 full energy peak. The number of oxygen atoms $/ \mathrm{cm} .^{2}$ in the oxide target used in the present work is then given by
where $N_{\gamma}$ are the number of full-energy peak counts per integrator,
$\Omega$ are the solid angles, and
$\epsilon$ are the efficiencies of the two counters used.
Then $n_{0}=\frac{48}{92} \times \frac{0.377}{0.753} \times \frac{0.31}{0.27} \times 1.118 \times 19^{10}$
From Robertson's calculations, the stopping cross section, $\mathrm{WO}_{2}$, of tungsten dioxide for 800 kev . protons is

$$
\sigma_{\mathrm{WO}_{2}}=35 \times 10^{-15} \mathrm{e} . \mathrm{v} \cdot-\mathrm{cm} . / \text { molecule }
$$

and since $(\Delta E)_{W_{2}}=\sigma_{W_{2}} \times n_{0} \times 1 / 2$, where $(\Delta E)_{W O_{2}}$ is the target thickness, Then $(\Delta E)_{W_{2}}=59 \mathrm{kev}$. at a proton energy of 800 kev . The target thickness at other energies is then given by

$$
(\Delta E)_{W_{2}}=(\Delta E)_{W_{2}} 800 \times \frac{\sigma \mathrm{WO}_{2}}{\left(\sigma \mathrm{WO}_{2}\right)_{800}}
$$

Where $\sigma_{W_{2}}$ was computed from atomic stopping power data diven by whaling (1957). The following values of target thickness were obtained:

| Ep (mev.) |  | $\sigma\left(\mathrm{WO}_{2}\right)$ |  |
| :--- | :--- | :--- | :--- |
| 0.600 | $40.5 \times 10^{-15}$ | $(\Delta \mathrm{E})_{\text {kev. }}$ |  |
| 0.800 | 35 | 11 | 68 |
| 1.10 | 29 | 11 | 59 |
| 1.50 | 25 | 11 | 49 |
| 2.00 | 21 | 11 | 42 |
|  |  |  |  |

The target thickness was also computed directly from the observed
energy. Since the counter was at $90^{\circ}$ to the incident proton beam,
and
$E_{\gamma_{2}}=0.10+16 / 17 \mathrm{Ep}$,
$E p-\overline{E p}=\Delta / 2$,
where Ep is the bombarding proton energy,
$\overline{E p}$ is the mean proton energy in the target, and
$\Delta$ is the target thickness.
At a bombarding energy of 0.823 mev., $E \gamma_{2}=0.840$ mev., consistent with a target thickness of 62 kev ., in good agreement with the above computation of 59 kev. However, at 1.53 mev., and also at 2.04 mev., E $\gamma_{2}$ was consistent with a target thickness of 100 kev . An explanation for the apparent discrepancy is the presence of a negative gain shift with a short decay time constant, as was observed by flooding the counter with a $\mathrm{Cs}^{137}$ source. Calibrations were made with the beam off; consequently, the apparent energy E $\gamma_{2}$ was decreased.

The approximate target thicknesses were also estimated from the observed with the full energy peaks for $\gamma_{2}$ transitions. The mean value of the target thickness, $\Delta$, was computed from

$$
\Delta=\sqrt{\Gamma^{2}-\Gamma_{R^{2}}}
$$

where $\Gamma$ and $\Gamma_{R}$, as defined previously, are respectively the width of the full-energy peak for $\gamma_{2}$ transitions, and the width of the full-energy peak for a mono-energetic gamma ray source. Target thicknesses were found to be 66 kev. for $\mathrm{Ep}=0.84 \mathrm{mev}$. , and 46 kev . for $\mathrm{Ep}=1.13 \mathrm{mev}$. , in reasonable agreement with above estimates. Values of target thickness computed from the widths of the full-energy peaks are not, however, considered accurate because of fluctuations in counter resolution between runs.
5. Determination of the Excitation Function -

Relative cross sections were computed from the following data:

| Ep mev. | $\Delta$ kev. | $\begin{aligned} & \overline{E p} \\ & \text { mev. } \end{aligned}$ | Xtal effy. Erl | Xtal effy. $\epsilon_{Y}$ | No. of integrator counts | Gamma $\mathrm{N}_{\gamma_{1}}$ |  | ts per $\mathrm{N}_{\gamma_{2}}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.618 | 69 | 0.583 | - | 0.345 | 100 | - |  | 20.2 | 2 |
| 0.823 | 60 | 0.793 | 0.17 | 0.30 | 30 | 5.50 | . 4 | 45.2 | 2 |
| 1.13 | 49 | 1.11 | 0.13 | 0.21 | 50 | 12.2 | . 2 | 90.9 | 5.5. |
| 1.536 | 41 | 1.52 | 0.10 | 0.145 | 50 | 20.4 | . 9 | 135.5 | 8 |
| 2.04 | 35 | 2.02 | 0.078 | 0.10 | 50 | 22.9 | 2.8 | 175 | 9 |

Cross sections were estimated relative to the cross section for $\gamma_{2}$ transitions at $800 \mathrm{kev} .$, by means of

where $N_{\gamma 2,800}$ is the observed number of gamma ray counts per integrator for $\gamma_{2}$ transitions at a proton energy of 800 kev , , $\epsilon_{\gamma 2,800}$ is the counter efficiency for $\gamma_{2}$ transitions at a proton energy of 800 kev ., and
$\alpha$ is the transmission coefficient through the $1 / 16$ inch brass target pot walls.

The values of absolute cross section were based on the measurement of the $90^{\circ}$ differential cross section for $\gamma_{2}$ transitions at 800 kev of $10.4 \pm 1.3 \times 10^{-32}$ $\mathrm{cm} .^{2}$ per steradian by Robertson. The following values of $90^{\circ}$ differential cross section, in units of $\mathrm{cm}^{2}{ }^{2}$ per steradian, were obtained:

| Ep <br> mev. | $\frac{\left(d^{\sigma}\right)_{\gamma 1}}{(d \mu)_{\gamma 1}}$ | $\frac{\left(d^{\sigma}\right)}{(d \mu)_{\gamma 2}}$ | $\frac{\left(d^{\sigma}\right)}{(\alpha \mu)_{\gamma}}$ |
| :--- | :--- | :--- | :--- |
| $\frac{(\alpha \sigma)}{(d \mu)_{\gamma}}$ |  |  |  |
| 0.583 | -- | $0.412 \times 10^{-31}$ | - |
| 0.793 | $0.214 \times 10^{-31}$ | $1.04 \times 10^{-31}$ | 0.205 |



FIGURE 14 VARIATION IN $O^{16}(p y) F^{17} 90^{\circ}$ DIFFERENTIAL CROSS. SECTION WITH PROTON ENERGY

| 1.11 | $0.642 \times 10^{-31}$ | $2.96 \times 10^{-31}$ | 0.217 |
| :--- | :--- | :--- | :--- |
| 1.52 | $1.39 \times 10^{-31}$ | $6.38 \times 10^{-31}$ | 0.217 |
| 2.02 | $2.23 \times 10^{-31}$ | $11.9 \times 10^{-31}$ | 0.188 |

The crystal efficiencies are believed accurate to within $12 \%$, giving a probable error of $17 \%$ in the ratio of the two efficiencies. The probable error in the number of reaction counts per integrator is approximately $5 \%$. The probable error in the ratio of the differential cross sections is therefore approximately l8\%.

Yields were estimated on the basis of a constant solid angle, since the distance from the crystal face to the effective centre has been shown not to vary significantly with energy in the energy region studied (Appendix I). The ratio of $\frac{(d \sigma)}{(d \mu)_{\gamma_{1}}}$ to $\frac{(\alpha \sigma)}{(d \mu)_{\gamma 2}}$ of $.205 \pm .037$ at 0.793 mev. is higher than the ratio found by Robertson of $0.14 \pm .03$ at 800 kev ., although to within the probable error the results are in agreement. The effect of angular distribution was not considered in estimating the yields. In the present work the counter subtended a solid angle of 0.669 steradians at the effective centre. $A \sin ^{2} \theta$ distribution over this solid angle yields approximately $4 \%$ less than an isotropic distribution with the same $90^{\circ}$ differential cross section. Since the angular distribution for $\gamma_{2}$ tramisitions is nearly $\sin ^{2} \theta$, the ratio of $\frac{(d \sigma)}{(d \mu)_{\gamma_{1}}}$ to $\frac{(d \sigma)}{(d \mu)_{\gamma_{2}}}$ found above may therefore be consistently high by nearly $4 \%$.

To summarize, the $0^{16}(p, \gamma) F^{17} 90^{0}$ differential cross section for $2^{\text {transitions varies smoothly from } 0.41 \times 10^{-31} \mathrm{~cm} .^{2} \text { per steradian at a }}$ proton energy of 0.58 mev . to $1 . .9 \times 10^{-31} \mathrm{~cm} .^{2}$ per steradian at a proton energy of 2.02 mev . The ratio of the $90^{\circ}$ differential cross sections for
$\gamma_{1}$ transitions to $\gamma_{2}$ transitions is approximately 0,20 in this energy region. Using the angular distribution for $\gamma_{2}$ transitions found by Warren et al (1955)
as being proportional to $1+5 \sin ^{2} 0$, the total cross section for $\gamma_{2}$ transitions is given by $\sigma_{\gamma 2}=\frac{4 \pi(1+2 / 3 \times 5)}{6} \times \frac{(d \sigma)}{\left(d_{\omega}\right)} 90^{\circ}=8.98 \times \frac{(d \sigma)}{(d \mu)} 90^{\circ}$
On this basis, $\sigma_{\gamma}=0.37$ microbarns at 0.583 mev , and 10.7 microbarns at 2.02 mev . Adding the contribution from $\gamma_{1}$ transitions, assumed to have an isotropic angular distribution, gives an $0^{16}(p, \gamma) F^{17}$ total reaction cross section of 0.44 microbarns at 0.583 mev., and 13.5 microbarns at 2.02 mev. If we assume the above angular distributions, the ratio of the cross sections, ${ }^{\sigma_{\gamma 1}}=0.28$. However, in order to establish this ratio, more accurate angu${ }^{\sigma_{\gamma 2}}$
lar distributions need to be measured.

## APPENDIX I

## GAMMA RAY EFFICIENCIES FOR THE $1.75 \times 2.00$ INCH CRYSTAL

The efficiency of the 1.75 by 2 inch crystal has been measured for the 6.14 mev. gamma rays from the 340 kev . resonance of $\mathrm{F}^{19}(\mathrm{p}, \mathrm{x}, \gamma) 0^{16}$ by Larson. The efficiency for gamma rays, $\in(E, E / 2)$, where the bias energy was chosen as $1 / 2$ the incident gamma ray energy was found to be $0.388 \pm .019$. The effective centre distance used was $2.18 \pm .71 \mathrm{~cm}$. , as determined by an inverse square plot.

For the $0^{16}(p, \gamma) F^{17}$ measurements described in Chapter IV, it was necessary to determine the efficiency of this counter for gamma rays in the energy region from 0.6 mev , to 2.5 mev . The efficiency for radiation from co 60 has been determined with a $\mathrm{Co}^{60}$ source whose strength was measured by the National Research Council to be 0.134 millicuries to an accuracy of $5 \%$. The present crystal efficiency measurements were made 1 year, $71 / 2$ months after the source calibration, so that taking $\mathrm{T}_{\frac{1}{2}}$ for $\mathrm{Co}^{60}$ to be 5.24 years, the strength at the time of the efficiency measurements was 0.1094 millicuries.

Measurements were made with the source 80 cm . from the face of the crystal, with the source holder axis perpendicular to the counter axis. From kicksorter spectra, the number of counts were recorded to a bias of 0.625 mev.; i.e. it was assumed that the mean efficiency for the 1.17 mev . and 1.33 mev . radiation was equal to the efficiency for 1.25 mev. radiation. The efficiency to $\frac{1}{2}$ - energy bias, was given by

$$
\epsilon(2.25,0.625)=\frac{N_{\gamma}}{2 N_{0}} \frac{r^{2}}{A} 4 \pi
$$

With $N \gamma$ the number of observed counts above background,
2 No the number of gamma rays emitted per second by the source, and $\mathrm{A} / \mathrm{r}^{2}$ is the solid angle subtended by the area of the counter face
positioned at the effective centre of the crystal. The value of $2.18 \pm .72 \mathrm{~cm}$. was used for the effective centre distance. Since a large source to counter distance ( 80 cm .) was used, any error in the effective centre distance is negligible.

An efficiency for the total number of counts recorded in the pulse spectra to zero energy, $\epsilon(1.25,0)$ was also computed. A low energy peak at approximately $220 \mathrm{kev} .$, believed due to back-scattered radiation from the mu-metal shield, aluminum and brass casings, and the lead counter shielding, was neglected. From the formula for Compton scattering of photons,

$$
\mathrm{hr}=\mathrm{hr} /[1+(1-\cos \theta)]
$$

where $h r_{0}=$ energy of initial photon in units of $m c^{2}$, $\mathrm{hr}=220 \mathrm{kev} .$, for $\mathrm{h} r_{0}=1.25 \mathrm{mev} .$, corresponds to a scattering angle $\theta$ of 155 ${ }^{\circ}$, approximately the angle expected for back-scattered radiation. The flat Compton spectrum tail was extrapolated horizontally down to zero pulse energy to obtain the total spectrum counts.

Runs were made both with the sides of the counter shielded with a lead castle and unshielded. The flat Compton tail of the pulse spectrum was $12 \%$ higher with the lead castle than without it; the efficiency was consequently higher when using the castle.

The calculated efficiencies are as follows:

$$
\begin{aligned}
& \epsilon(1.25,0.662)=(40.5 \pm 2) \% \text { with the lead castle shielding, and } \\
& \epsilon(1.25,0.662)=(37.9 \pm 2) \% \text { without the lead castle shielding. }
\end{aligned}
$$ The two efficiencies differ significantly because most of the probable error comes from uncertainty. in the source strength. The total crystal efficiencies were

$$
\begin{aligned}
& \epsilon(1.25,0)=(72.0 \pm 7) \%, \text { with the lead castle shielding, and } \\
& \in(1.25,0)=(63.8 \pm 7) \%, \text { with the counter unshielded. }
\end{aligned}
$$

Again the two efficiencies differ significantly. $\in(1.25,0)=61.5 \%$, computed from ( $1-\exp -\mu l$ ), in reasonable agreement with the measured value when not using the shielding. Because of the smaller dependence of $\epsilon(1.25,0.662)$ than $\epsilon(1.25,0)$ on the shielding used, and the necessity of extrapolating below the back-scattered gamma ray peak in estimating $\in(1.25,0)$, both theoretical and experimental efficiencies were calculated to a bias energy of one-half the incident gama ray energy. Theoretical efficiencies were estimated by means of a method developed by P. Singh of this laboratory. The efficiency is defined by

$$
\epsilon(E, E / 2)=\left(\frac{A \tau+B \sigma C \pi}{\mu}\right)[1-\exp -\mu l]
$$

where $\mu$ is the total absorption coefficient,
$\tau, \tau$ and $\pi$ are the theoretical photo-electric, Compton, and pair-production coefficients respectively. $\mathbb{L}$ is the length of the crystal, so that ( 1 - exp. $-\mu($ ) is the total fraction of the gamma rays absorbed in the crystal.
$A, B$, and $C$ are the relative probabilities for the respective absorption processes to produce spectrum counts above the $1 / 2$ energy bias; that is, for more than $1 / 2$ of the gamma ray energy to be absorbed by the crystal. In the energy region from 0.6 to 3 mev ., where the most important absorption process is Compton Scattering, most uncertainty is in the estimation of the probability of further absorption by the crystal of secondary photons whose energy is still greater than E/2 following a single Compton event. If such a secondary absorption process occurs, it is assumed that the resulting spectrum pulse from both events lies above the $1 / 2$ energy bias.

Theoretical efficiencies were calculated for 1.25 mev . and 6.14

mev., and compared with the experimental efficiencies. Efficiencies were also calculated energies of $0.6,2.0$, and 3.0 mev. The results are as follows:

| $E$ | $E(E, E / 2)$ Theoretical | $E(E / E / 2)$ Expt. |
| :--- | :---: | :---: |
| 0.6 | 0.58 | $0.392 \pm .03$ |
| 1.25 | 0.43 |  |
| 2.0 | 0.384 |  |
| 3.0 | 0.378 |  |
| 6.14 | 0.42 | $0.388 \pm .019$ |

Since only the upper part of the spectra of $\gamma_{1}$ and $\gamma_{2}$ were observed in the $0^{16}(p, \gamma) F^{17}$ work, the efficiencies were estimated to a bias of 200 kev., which fell slightly below the bottom of the full energy peak. Spectra from $\mathrm{Cs}^{137}, \mathrm{Zn}^{65}, \mathrm{Na}^{22}$, and RdTh were used to estimate $\in$ ( $\mathrm{E}, \mathrm{E}-200$ kev.). Efficiencies are shown plotted in Figure 15.

## Effective Centre Measurement:

The distance from the crystal face to the effective centre was determined experimentally for gamma ray energies of 1.25 with a $\mathrm{Co}^{60}$ source, and for 0.51 mev. with a $\mathrm{Na}^{22}$ source. The distances, obtained from a distance vs. $1 / \sqrt{\text { counting rate }}$ plot, were $2.40 \pm .20$ and $2.50 \pm .20 \mathrm{~cm}$. for the 0.51 and 1.25 mev. radiation respectively. The distance measured by Larson at 6.14 mev. for the effective centre was $2.18 \pm .72 \mathrm{~cm}$. The effective centre distances for the three energies are equal to within the probable errors, as was observed by Robertson for the $3.0 \times 2.5$ inch crystal.

The simple theoretical calculation of the effective centre distance of

$$
x=\frac{-\ln (0.5(1 \text { exp. }-\mu l)}{\mu}
$$

gives a distance of 2.12 cm . for $6.14 \mathrm{mev} ., 1.95 \mathrm{~cm}$. for 1.25 mev ., and 1.55 cm. for 0.51 mev. radiation. As in the case of the large crystal, the theore-
-53-
tically predicted distances are significantly different from the observed effective centre distances.


## APPENDIX II:

## THE BIASED DISTORTER

The biased distorter, which replaced an older biased amplifier, accepts negative pulses from a high gain Northern Electric Linear Amplifier and provides variable gain and cut before driving the Marconi Kicksorter. A block diagram of the distorter circuit is shown in Figure 17 and a detailed circuit diagram in Figure 18. The chief advantage of the present biased distorter over the older biased amplifier is that the output pulses of the distorter are shaped to have a constant rate of rise, rate of fall, and a constant width from the beginning of the pulse to the back edge of the pulse, independent of the shape of the input pulse. Dependence of kicksorter channel edges on pulse shapes (especially rate of rise of the pulses), are therefore minimized by means of the biased distorter.

The distorter has the following characteristics:

1. Accepts negative input pulses from 0 to 50 volts. It will tolerate appreciable positive overshoot without overloading. The input pulse length should be between 0.2 microseconds and 6 microseconds, from the beginning of pulse rise to the start of the fall of the pulse. The pulse should have recovered completely in 10 microseconds, since otherwise extreme lengthening of the distorter output pulse results. (See amplifier and pulse shaper.)
2. The output pulse size is from 0 to 50 volts, and is linear from 1 to 50 volts. The rate of rise, when driving 200 pf . of cable capacity, is 14 volts per microsecond. The rate of fall is 9 volts per microsecond, and the width from the beginning of the rise of the pulse to the beginning of the fall of the pulse is 6 microseconds.
3. A fixed dead time of 15 microseconds, beginning 1 to 2 micro-
seconds after the input pulse, is available during anti-coincidence operation by means of a switch located at the back of the biased distorter chassis.
4. The distorter has possible gains of $1,1.5,2,3,4$, and 5 , and a continuously variable bias level from approximately $1 / 2$ to 50 volts.
5. The distorter can be gated either by coincidence pulses, or by anti-coincidence pulses. 5 volt coincidence gate pulses of from 1 to 2 microseconds in width are supplied by a coincidence gate pulse generator, or they may be fed directly into the gate from external equipment. The gate pulses may be of either positive or negative polarity, since two coincidence inputs, connecting to the primary of a step-up pulse transformer, are provided. A shorted input connector is used to ground the mused side of the primary transformer coil. These gating pulses should not be longer than 3 microseconds, since the pulse transformer differentiates longer pulses. To drive coincidence gate pulses into the 100 ohm input impedance of the pulse transformer, the pulse source should be approximately 15 . volts, into a step-down pulse transformer.

12 volt, 15 microsecond anti-coincidence gate pulses are fed directly into the gate by an anti-coincidence gate-pulse generator, which also supplies dead-time pulses. The generator is driven by 6 volt positive pulses, fed into a step-up pulse transformer. To drive the 100 ohm input impedance of the pulse transformer, the 6 volt input pulses should come from a 20 volt source, fed into a step-down transformer. A slight change in the circuit would enable anticoincidence pulses to be fed directly into the gate from external equipment if so desired.
6. Curves A to $F$ in Figure 16 show the dependence of the distorter output pulse height on pulse repetition rate. Two pulse generators were used

simultaneously; "calibration" pulses were provided by a 60 -cycle mercury relay pulse generator (Robertson), and pulses of a high repetition rate were supplied by a General Radio Co. "Unit pulser", type number 1217-A. The curves show the percentage fall in distorter output pulse heights, for constant amplitude input "calibration" pulses, with increasing pulse repetition rates from the mit pulser. For all tests, the distorter output pulse height, for input "calibration" pulses, was approximately 30 volts.

For curve A, the distorter was operated on coincidence. The coincidence gate pulse generator was synchronized with the "calibration" pulses; pulses from the unit pulser were rejected by the distorter gate. Up to a pulse repetition rate of 20,000 per second of amplitude 14 volts, the output amplitude was constant.

For curves B to F, the gate was operated on anti-coincidence. Curves $B$ and $C$ show the gate response to a high pulse repetition rate. Low-amplitude (10 volt) pulses from the unit pulser were removed after the gate by a high cut setting; only "calibration" pulses reached the distorter amplifier. For curves $D$ to $F$, since zero cut setting was used, all input pulses reached the amplifier. For curves D and F, low amplitude pulses (10 volts for gain 1, and 2 volts for gain 5) were used from the unit pulser together with high amplitude "calibration" pulses from the mercury relay pulse generator. For curres $E$ and $G$, high amplitude pulses from the unit pulser only were fed into the distorter.

The curves show that for accurate pulse-height measurements, a high pulse repetition rate should be avoided during anti-coincidence operation of the distorter. If the low-amplitude palse rate is high, a high cut setting should be used to reduce the pulse rate into the amplifier. The amplifier itself should be used in a low gain position when accepting a high pulse rate.

FIGURE 17 BLOCK DIAGRAM OF BIASED DISTORTER CIRCUIT


Large input pulses produce a slightly larger fall in the distorter output at high repetition rates than do small ones; however, all pulses larger than a few volts into the amplifier produce significant decreases in the distorter output pulse height for repetition rates greater than 5000 per second. For most accurate pulse height measurements, the fall of the distorter output pulse height at high pulse repetition rates can be avoided by running the distorter on coincidence operation, and using pulses only in the required energy range to trigger the gate.

Descriptions of sections of the biased distorter as shown by the block diagram of Figure 17 are given below.

## Linear Gate:

Input pulses are fed into a gate circuit (V1 and V2). A constant d.c. current is produced in VI anode by d.c. anode following, (Farley, page 7) which holds the anode of VI at (390/470) $\times 150$ volts $=120$ volts. The 56 k . plate resistor sets the plate current at 3 milliamperes. V2 is normally held off by a 7 volt grid-cathode bias. When suitably gated, this section acts as a White cathode follower (Farley, 1955, page 105) when driven by negative input pulses. V2 is turned on hard by a positive grid signal from the plate of V1. This unclamps the $1 N 200$ diode, D2, from ground, allowing the negative input pulses to be transmitted to the bias circuit. For positive input pulses, or for positive overshoot after negative pulses, V2 remains off, and V1 acts as a cathode follower with a "long tail", carrying 5.5 milliamperes. The 1 N100 diode, Dl , is biased off, and the cathode of Vl follows the grid, allowing V1 to maintain a constant current ( 5.5 milliamperes) during the pulse. The output signal is eliminated through strong attenuation by the diodes D1 and D2. When the gate is closed V2 does not turn on in response to a negative
input pulse, since its grid is clamped at $(-150+9)$ volts by the cathode of V3. Vl is turned off by the negative input pulse since its cathode is clamped via diode Dl to approximately ground potential. A small output pedestal ( $\sim 1 / 4$ volt) is produced as a result of switching current in the diodes $D 1$ and D2. To protect the diodes D 4 and D 5 at the grid of V 2 , the anode of V 1 is prevented from rising above 150 volts when V1 is turned off by the diode D3 to the 150 volt line.

Coincidence and anti-coincidence pulses are fed onto the grid of the cathode follower V3. During anti-coincidence operation the grid of V3 is held at $(-150+17)$ volts, which biases off D5. The grid of V2 thus follows the plate of V1, since D4 is held in conduction by the 1.5 milliamperes supplied through the 100 k . resistor. The cathode of V 2 is always held at ( $-150+16$ ) volts by the two Zenner diodes. During coincidence operation, the cathode of V3 is held at $(-150+9)$ volts; the grid of V2 is therefore clamped to $(-150+9)$ volts via D5 by the low impedance ( $\sim 100$ ohms) of the cathode follower. A positive signal from V1 cannot raise the grid voltage of V2, since D4 cuts off, and therefore no output pulse is obtained. The two diodes, D4 and D5, form a simple coincidence circuit (Farley, page 131;: Figure d), transmitting to V2 the minimum of the voltage pulses at the plate of V1 and at the cathode of V3. Anti-coincidence gate pulses lower the cathode of V3 from ( $-150+17$ ) to $(-150+9)$ volts, thereby closing the gate. Coincidence pulses raise the cathode potential of $V 3$ from $(-150+9)$ to $(-150+17)$ volts, opening the gate. A pulse transformer input is used for the short coincidence pulses, allowing the use of either positive or negative input pulses.

Cút Circuit:
The output of the gate is fed into a $1 / 2$ to 50 volt cut circuit,
similar in design to a diode discriminator circuit described by Moody (1950), and used in the Marconi kicksorter. Only that part of the input signal greater than the bias voltage is transmitted. The bias level is set by a 15 turn helipot. The total 50 volt drop across the helipot coil is set by a 20 k . trimpot mounted on the top of the distorter chassis, which regulates the current in the helipot coil.

## Amplifier:

The amplifier is a cathode-coupled amplifier, with a boot-strap circuit (Farley, page 107) in the plate of V6 to provide a high effective load and so a high gain. Anode following (a.c. and d.c.) via V8 tends to maintain a constant current in V6. A signal is therefore generated at the grid of V6 equal in magnitude to the input signal at the cathode of V6. This signal is an attenuated version of the signal appearing at the cathode of V8, the low impedance output point.

V7 provides a high-impedance, high-current cathode load for V5 and V6; stray capacities in this cathode load limit the rise time of the amplifier to 0.2 microseconds. The input pulse width from the beginning of the pulse to the beginning of the fall of the pulse should consequently be greater than 0.2 microseconds. 2 series $1 N 100$ diodes limit the amplitude of the output pulse to 50 volts.

## Pulse Shaper:

(a) Diode stretcher -

The output from the amplifier is fed into a White Cathode follower (V12 and V13), which drives a diode stretcher (Farley, page 18) consisting of V14 B and the 220 pf. capacitor. On the back edge of the input pulse to the diode stretcher, the anode of V14 B is held negative by the charge on the 220
pf. capacitor. A 9 microampere current from the 300 volt line, fed into 220 pf., restores the grid of V 15 to ground potential at the rate of $\mathrm{dv} / \mathrm{dt}=9 / 220$ $=.05$ volts per microsecond. This leak is required to restore the grid of V15 to ground for pulses too small to trigger the d.c. restoring section of the circuit.

## (b) Linear Rise Circuit -

The output pulse is taken from the cathode follower V15, whose cathode load is the constant current pentode Vl6 (Farley, page 32). Because of the capacity loading on the cathode of V15, V15 turns off during the rise of the pulse. The rate of rise of the output pulse is given approximately by $\mathrm{dv} / \mathrm{dt}=\mathrm{i} / \mathrm{c} \sim 7\left(10^{-3}\right) / 250\left(10^{-6}\right)=28$ volts per microsecond. Additional loading by approximately 200 pf . of cable feeding the pulses to the kicksorter reduces this rate of rise to the observed rate of 14 volts per microsecond.

6 microseconds after the front edge of the input pulse, a restoring current of 3 milliamperes from the plate of V19 discharges the 220 pf. capacitor in the diode stretcher. The back edge of the output pulse falls at the rate of 9 volts per microsecond, in reasonable agreement with $\mathrm{dv} / \mathrm{dt}=\mathrm{i} / \mathrm{c}$ $=3\left(10^{-3}\right) / 220\left(10^{-6}\right)=14$ volts per microsecond. V15 is being turned on during the back edge of the pulse, and so can provide sufficient current to cathode follow. The output pulse has a positive overshoot of approximately 1 volt since the anode of $V 14 B$ rises to $l$ volt above ground before $V 14 B$ conducts the excess 3 milliampere discharge current away.

The input pulse should be shorter (completely restored by some 10 microseconds) than the output distorter pulse since unless the back edge of the input pulse remains smaller than the output pulse, the 3 milliampere discharge current is short-circuited through V14B. If this occurs for a slowly
falling input pulse, the output pulse then falls with the input pulse for the duration of the discharge current (a few microseconds). After the discharge current, the output pulse falls at the .05 volt per microsecond rate governed by the 9 microampere current flow from the 300 wolt line; i.e. extreme lengthening of the tail of the output pulse results.

## Kandiah discriminator and Restoring-current pulse circuitry:

The 6 microsecond delay of the restoring current is provided by a Kandiah discriminator (Journal of the Institute of Electrical Engineers, June 1954, page 239), V17 and V18, which is triggered by a positive pulse (approximately $1 / 2$ volt) from the plate of V8. A positive 40 volt, 6 microsecond, square output pulse is taken from the plate of V18, and differentiated. The positive edge of the pulse charges the 150 pf . capacitor through a 1 N 100 diode, which shorts the signal to ground; the negative edge unclamps the $1 N 100$ diode so that the 150 pf . capacitor is discharged in approximately 10 microseconds by the 0.5 milliampere current from the 270 k . resistor. V19 is therefore held off for some 10 microseconds; during this time its plate current is switched through the $1 N 96$ and V14A diodes into the 220 pf. of the diode stretcher.

## Kandiah Triggering Pulse: Capacity Compensating Pulse:

A positive pulse from the plate of $V 8$ triggers the Kandiah discriminator and provides a capacity compensating pulse for the diode stretcher. Negative overshoots in the coupling circuit are short-circuited to ground through the 1 N 96 diode. Positive pulses from the diode stretcher are strongly attenuated by the back resistance of the 1 N 100 diode; pulses from the grid of V17 are similarly attenuated.

Since approximately a $1 / 2$ volt signal is required to trigger the

Kandiah discriminator, and this corresponds to output pulses from the distorter of approximately 1.5 volts, for output signals of less than $11 / 2$ volts the Kandiah discriminator does not trigger. The rate of fall for smaller output pulses is therefore .05 volts per microsecond set by the 9 microampere current into the diode stretcher.

Dead-Time and Anti-Coincidence Pulse Generator:
A diode mixing circuit is used to introduce either or both of the two trigger pulses (anti-coincidence or dead-time) to the input of the univibrator (V20 grid), enabling the generator to be used in anti-coincidence and dead-time operation simultaneously. Dead-time input pulses are integrated before reaching the grid of V2O. A variation in the time of triggering of the generator is provided by a trimmer capacitor in the integrator, mounted on the back of the distorter chassis, which allows the generator to be triggered from approximately 1 to 2 microseconds after the input to the gate. Dead-time pulses, being identical to anti-coincidence pulses, can only control the gate during anti-coincidence.

The pulse generator itself (V20 and V21) is a cathode-coupled univibrator, with the first tube (V20) held off by a 15 volt grid bias in the d.c. state. As described earlier, the anti-coincidence trigger pulses are 6 volt positive pulses, fed in through a step-up pulse transformer. Coincidence Gate Pulse Generator:

The coincidence gate pulse generator, which is mounted in a separate chassis from the rest of the biased distorter, provides approximately 5 volt negative pulses of length from 0.5 to 2 microseconds. The pulse generator (V9 and V10) is a modified Scarrott oscillator, (Farley, page 43) operating in the fashion described by Kandiah, with a cathode follower output. The
generator input pulses are approximately $1 / 4$ volt, fed in through a step-up transformer. The input pulses should be shorter than the 1 to 2 microseconds length of the generator output pulses. As with the coincidence input to the gate, the coincidence generator input pulses may be of either polarity, since two coincidence inputs, connecting to the primary of a step-up transformer, are used. A shorted input connector is used to ground the unused side of the primary transformer coil.

## Power Supplies:

The distorter 300 volt power supply is a Model 32, Lambda regulated power supply "300 MA" series, rated at 200 to 325 volts d.c. at a current of from 0 to 300 milliamperes. The -150 volt power supply is a Model C-281 Lambda, "Com-Pak Series 200" power supply, rated at 125 to 325 volts d.c. at a current of from 0 to 200 milliamperes. The 150 volt supply is taken from the plate of a voltage reference OA2 tube, V22 connected (with a series plate resistor) across the 300 volt line.

All co-axial cables, except for the two specified below, are Telcon KIG-M (ICB) ( 50 ohm characteristic impedances).

The output cable and the input cable to the anti-coincidence generator are Telcon AS48 (100 ohm characteristic impedance, $12 \mathrm{l} / 2 \mathrm{pf}$. per foot capacitance) cables.


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