THE DISINTEGRATION OF NEON BY FAST NEUTRONS

by

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ABSTRACT

A normal mixture of the stable neon isotopes, Ne^{20} 90.51%, Ne^{21} 0.28%, Ne^{22} 9.21%, has been bombarded with 2.68 Mev. neutrons from the reaction $H^{2}(dn)He^{3}$. A gridded ion chamber, with 1 litre sensitive volume, filled with neon to $6\frac{1}{4}$ atmospheres pressure, was used to detect disintegrations. Pulses from the ion chamber were amplified, and recorded on an 18-channel kicksorter.

The ground-state transition of $Ne^{20}(n\alpha)O^{17}$ was observed, with 1% counting statistics. The Q-value was measured as -0.77 ± 0.08 Mev., in fair agreement with previously reported results.

Careful search failed to reveal any evidence of excited states in O^{17}. A level at 0.87 Mev. is known, and one at 1.6 Mev. is suspected, but calculation of barrier penetrability for alpha particles corresponding to these levels indicates that they are not likely to be observed at the neutron energy used.

A second reaction, with disintegration energy corresponding to a Q-value of $+0.48 \pm 0.10$ Mev. was also observed. It was not clear whether this reaction was $N^{14}(np)C^{14}$ or $Ne^{21}(n\alpha)O^{18}$. This point is to be clarified by further investigation.

ACKNOWLEDGEMENTS

The author is pleased to express his thanks to Dr. J. B. Warren for the suggestion and direction of this research.

The assistance of Mr. F. C. Flack throughout the course of the experiments, and in the preparation of this thesis is deeply appreciated.

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ILLUSTRATIONS

THE DISINTEGRATION OF NEON BY FAST NEUTRONS

I. INTRODUCTION

A. KNOWLEDGE OF NUCLEI

It is much easier to speak with optimism regarding the future of Nuclear Physics than to discuss with satisfaction its present status. While the general principles and methods of quantum mechanics appear to be satisfactory for dealing with nuclear phenomena, yet the most fruitful approach, particularly in dealing with nuclear reactions and energy levels, is essentially a phenomenological one.

The main difficulties in attempting to formulate a theory of nuclei, comparable in scope to that of atomic structure, are twofold. Firstly, the nature and proper description of the short-range forces between the protons and neutrons of which the nuclei are composed are not understood, and secondly, even with a comprehensive knowledge of the short-range forces, the mathematical difficulty of dealing with such a many body problem accurately is still formidable. In this case even approximation methods make little headway--in the words of Gamow, "the theory of complex nuclei is difficult mathematically because everything is of the same order of magnitude, and nothing can be neglected." (GAMOW, 1937)

The problem has then been approached experimentally by collecting as much data as possible on all aspects of nuclear structure: excitation functions, energy levels, spin values, and phenomenological theory, such as the dispersion formula, deduced to fit the observed results.

Attempts to progress further have resulted in the proposal of various nuclear models. One example is the "alpha particle model", which pictures the nucleons as being grouped within the nucleus as alpha particles, the alpha in turn forming shells, with extra nucleons in outer orbits. Such a picture suggests exceptional stability for closed shells of alpha particles, as in C^{12} and O^{16}. It was hoped that some of this model's predictions for nuclei of the $4N+n$ type might be tested in the present experiment as one such nucleus, namely O^{17} ($4\alpha+n$) was a known disintegration product in the reaction $Ne^{20}(n\alpha)O^{17}$

The alpha particle model is by no means the only model postulated, and recently the "orbit model" has been extensively and successfully developed by MAYER, (1948). However, with light nuclei the alpha particle model has had some success in correlating experimental data. It is hoped that the present experiment will contribute another small fact to the ever increasing information about nuclear reactions.

B. ($n\alpha$) REACTIONS

Nuclear energy levels are usually excited by bombardment with nucleons, or other heavy particles. For neutron bombardment, capture adds about 8 Mev. to the nucleus, this energy being distributed among the nucleons. The compound nucleus so formed remains in this excited state until random fluctuations concentrate sufficient energy in one or more nucleons for their emission. Photon emission may also occur, but the levels for this process are sharper than for particle emission, and the latter process is much more probable, if energetically possible.

The most favoured transition is that which leaves the residual nucleus in the most stable configuration. Generally, neutron emission requires somewhat less excitation energy than proton or alpha emission, because of the Coulomb barrier for the charged particles. Alpha emission, however, commonly occurs for the light nuclei, in which the Coulomb barrier is relatively low, while the average energy per nucleon in the compound nucleus is high, due to the sharing of excitation energy between relatively few particles.

C. CHOICE OF EXPERIMENT

Much work has been done with fast neutrons, and the disintegration of certain nuclei, in particular those of carbon and nitrogen by such particles is well known. Neon however, has received little attention. Previous experiments, using neutrons of less than 3 Mev. energy, showed with rather poor statistics only one single-energy group of emitted alphas. This group was identified with the ground state transition of $Ne^{20}(n\alpha)\ O^{17}$. No evidence of excited states has been reported, but since a level in O^{17} at 0.87 Mev. is known, and another at 1.6 Mev. suspected, further investigation seemed worthwhile.

Neon is readily obtainable in pure form, and like the other noble gases is suited for use in an ion chamber (WILKINSON, 1950). With an 18 channel pulse amplitude analyser available in this laboratory, it was expected to obtain data more rapidly and hence more precisely than heretofore.

It was decided therefore to bombard neon with fast neutrons, using an ion chamber as a detector. The Q-value of the $Ne^{20}(n\alpha)\ O^{17}$ reaction was to be carefully measured, and a thorough search made for other groups of particles, particularly any associated with excited states of O^{17} . The remainder of this thesis discusses the details of this experiment, and the results obtained.

II. EXPERIMENTAL METHOD

A. THE EXPERIMENTAL PROBLEM

Since neon like the other noble gases has excellent electron collection properties, it seemed obvious to detect the reaction directly by ionization produced in a gas target. Among the various possible detectors, cloud chamber, proportional counter, etc., a gridded ion chamber was chosen as being a fast operating detector with excellent linearity between pulse-size and energy.

Three sources of fast neutrons were available for the experiment: a 50 millicurie Radium-Beryllium source, a 50 kev. ion accelerator, and a Van de Graaff generator, at present producing protons with energies up to 2 Mev. The Ra-Be source provides a reasonable yield of neutrons, but the straggling of alphas within the source produces a very broad spectrum of neutron energies. Neutrons can be generated in both the 50 kev. accelerator and the Van de Graaff by means of a nuclear reaction, such as $H^2(dn)He^3$ or $H^3(dn)He^4$. Since an intense, monoenergetic source was required, it was decided to start by using the $H^2(dn)He^3$ reaction with the 50 kev. ion accelerator and a thick target of heavy ice.

B. PRODUCTION OF FAST NEUTRONS

1. Fast Neutron Sources

Many nuclear reactions may be used as neutron sources. In particular, bombardment of light nuclei with protons or deuterons produces neutrons of a wide range of energies. The choice of a reaction depends on the yield, on the number of neutron energy groups produced, and on the energies required.

A few of the better known fast neutron sources are: (HANSON et al 1949; HORNYAK et al, 1950).

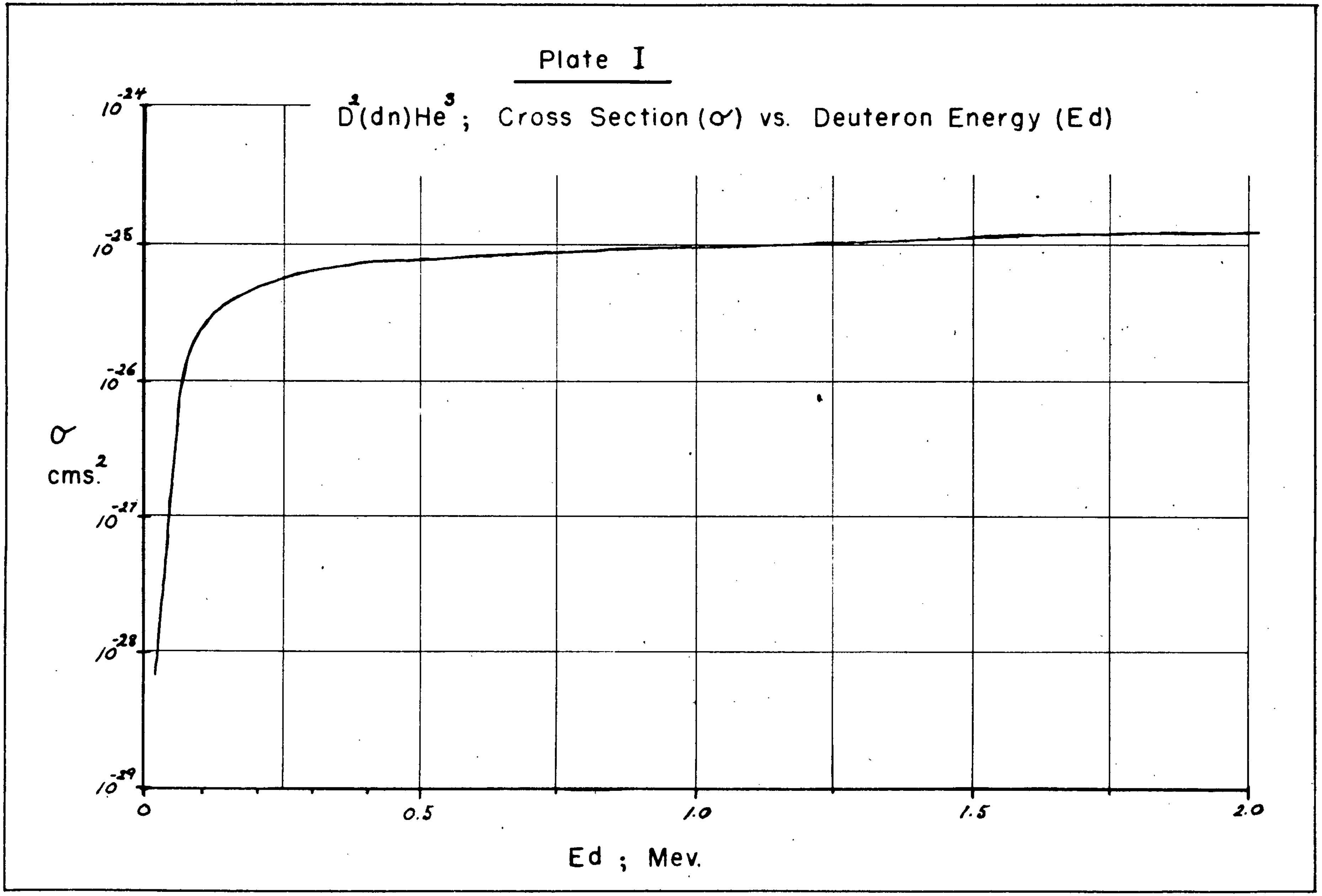

Plate I
$D^2(dn)He^3$; Cross Section (σ) vs. Deuteron Energy (Ed)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
σ
$cms.^2$
0
0.5
1.0
1.5
2.0
Ed ; Mev.

Reaction	Q-value	Threshold	Range of Neutron Energies #
H^2 (dn) He^3	+ 3.256 Mev.	< 0.015 Mev.	1.8 → 7.2 Mev.
H^3 (pn) He^3	- 0.764 "	0.98 "	0.001 → 4. "
H^3 (dn) He^4	+17.60 "	< 0.015 "	12. → 20. "
Li^7 (pn) Be^7	- 1.647 "	1.882 "	0.001 → 3. "
V^{51} (pn) Cr^{51}	- 1.50	1.53 "	0.002 → 0.020 Mev.

for bombarding energies up to about 4 Mev.

As mentioned, H^2 (dn) He^3 neutrons generated by the 50 Kev. ion accelerator were chosen for the initial investigation. It was hoped to extend the neutron energy up and down from the 2.68 Mev. value by using this reaction with faster deuterons, the H^3 (dn) He^4 reaction, and slower neutrons from the V^{51} (pn) Cr^{51} reaction.

2. The H^2(dn) He^3 Reaction

Since it was first reported by OLIPHANT, HARTECK and RUTHERFORD, (1934), this reaction has received the attention of many workers. The literature contains extensive information on the yield function (ROBERTS, 1937; AMALDI et al, 1937) the cross section (LADENBURG et al 1937) and the angular distribution (BONNER, 1937), for deuteron energies from 15 kev. (BRETSCHER et al, 1948) to 10 Mev. (LEITERS et al, 1950)

The reaction proceeds in two ways, with about equal probability:

$$H^2 \text{ (dn) } He^3 \qquad Q = +3.256 \pm 0.018 \text{ Mev.}$$

$$H^2 \text{ (dp) } H^3 \qquad Q = +4.036 \pm 0.022 \text{ Mev.}$$

These Q-values are magnetic spectrometer determinations (TOLLESTRUP et al, 1949). Exact relative yields of protons and neutrons have still not been established, but are known to be approximately equal.

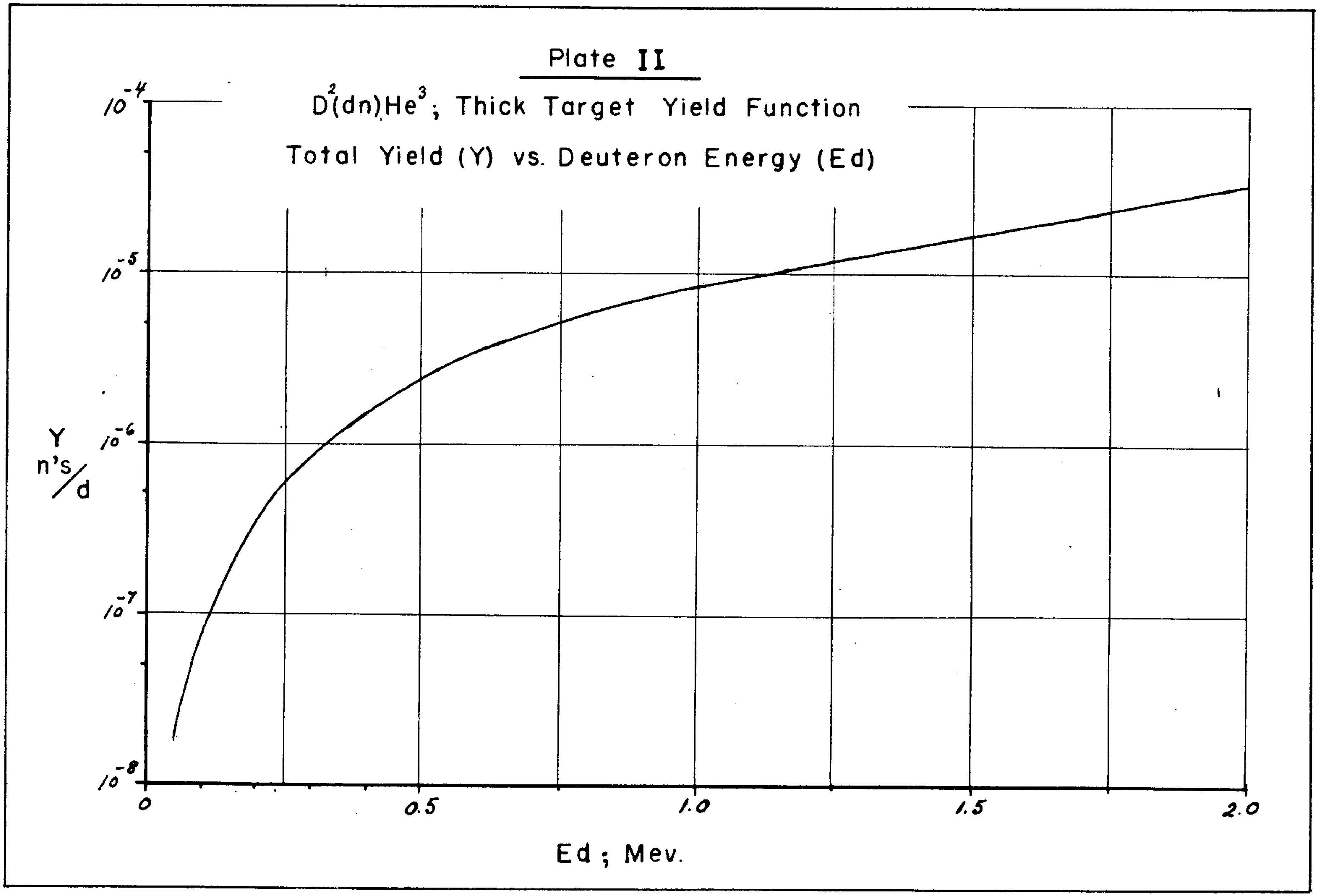
Plate II
$D^2(dn)He^3$; Thick Target Yield Function
Total Yield (Y) vs. Deuteron Energy (Ed)
Y n's/d
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
0.5
1.0
1.5
2.0
Ed ; Mev.

Curves of cross section and total yield for the reaction show smooth increases with the energy of the incident deuterons. These are illustrated in Plates I and II respectively, for deuteron energies up to 2 Mev. The former gives the integrated cross section, and the latter the total yield, over the whole solid angle, for a thick heavy ice target. These curves are based on several investigations, as listed by HORNYAK et al, (1950)

The angular distribution of neutrons is anisotropic. For deuteron energies of less than 500 kev., it is adequately described by a relation of the form $N(\phi) = B(1 + A\cos^2\phi)$ in the centre of mass system. (MANNING et al, 1942). At higher deuteron energies, more neutrons are observed in the forward direction than this relation predicts, and terms in higher powers of $\cos^2\phi$ must be added. The more extensive investigations of this aspect of the reaction include those of BENNETT et al, (1946) for deuterons of up to 1.8 Mev., HUNTER and RICHARDS, (1949), 0.5 to 3.7 Mev. deuterons, and ERICKSON et al (1949) for 10 Mev. deuterons.* In the present experiment, the angular distribution was calculated using the value of $A = 0.45$ for 50 kev. deuterons. (HUNTOON, 1940)

The neutron energy varies with the angle of emission measured relative to the deuteron beam, and is also a function of the deuteron energy. This dependence may be calculated from the masses and energies of the particles involved. HANSON et al (1949) have carried out these calculations for several of the reactions used as neutron sources, for a wide range of deuteron energies. Plate III shows the results of their calculations for deuterons up to 2 Mev. It is evident that if fairly high energy deuterons are available, as with a Van de Graaff generator, the reaction provides a wide and continuously variable range of neutron energies.

The extent to which the neutrons obtained are truly homogeneous depends on several factors. Variation in energy of the incident deuterons, and

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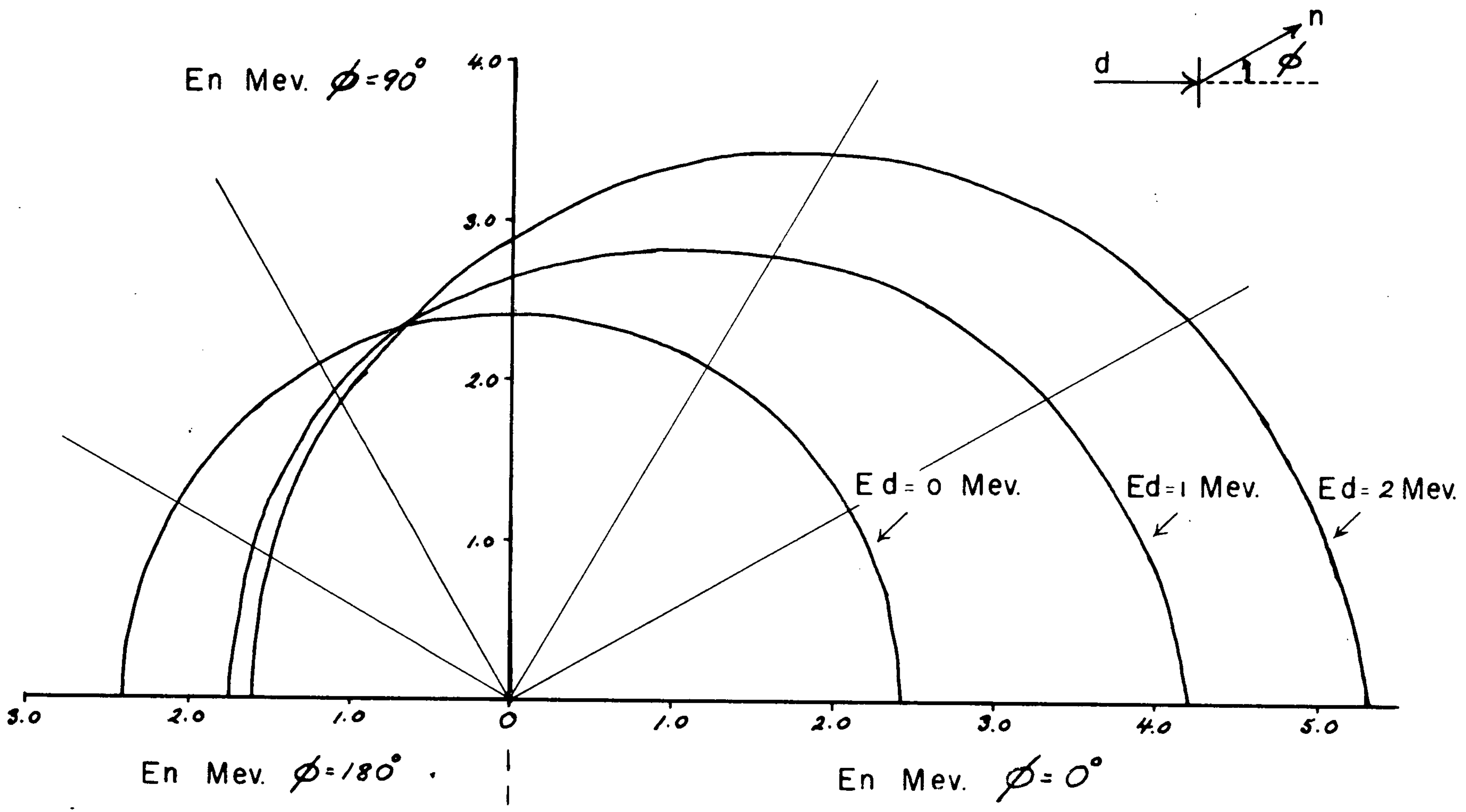
* note especially BRETSCHER et al(1948)for low energies.

Plate III



$D^2(dn)He^3$ Neutron Energy (En) vs. Angle of Emission (ϕ) straggling of deuterons in thick targets will produce a spread in neutron energies. Unless the solid angle subtended by the detector is very small, a range of neutron energies will be observed, due to the angular dependence of the reaction.

Variations in deuteron energy may be controlled by magnetic analysis of the ion beam. Deuteron straggling in thick targets is difficult to determine, as the rate of energy loss, (dE/dx) is not well known. In the present experiment, the effect of this mechanism on the homogeneity of the neutron energy will be small. In the region of deuteron energies used (50 kev.), the yield function of the reaction rises very rapidly. Therefore, for deuterons of even slightly less than average energy, the neutron yield drops very sharply. Thus relatively few low energy neutrons will result from straggled deutrons.

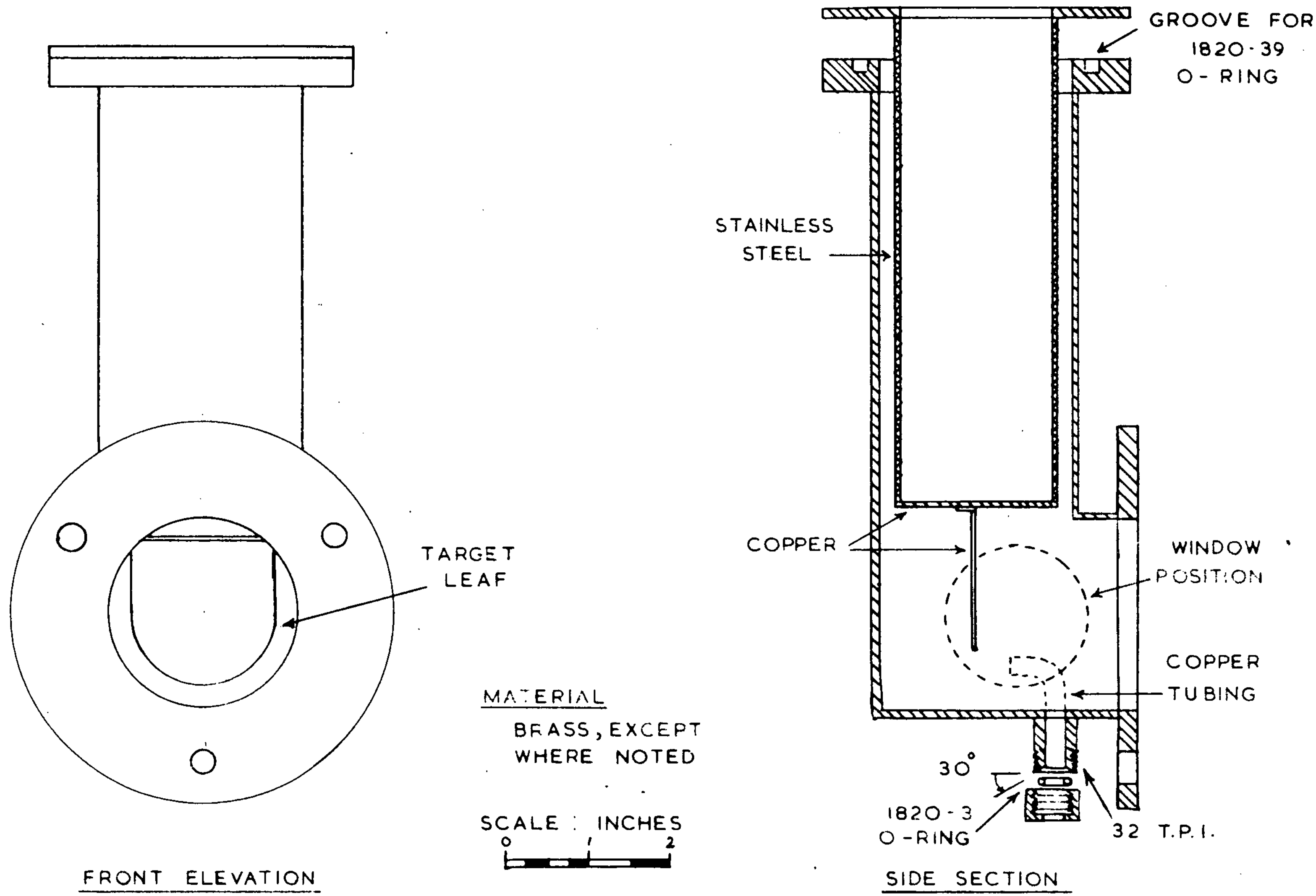
3. <u>The 50 kev. Ion Generator</u>

The accelerating voltage of the 50 kev. generator was supplied by a commercial half-wave transformer-rectifier set, (FERRANTI X-RAY) with condenser filtering. Ion voltage was monitored by observing the current through a calibrated oil immersed resistance stack. Ripple voltage was stated to be much less than 1 %. Construction of the unit is described elsewhere (KIRKALDY, 1951).

The ion beam was produced by a radio-frequency ion source, of a type developed in this department. (KIRKALDY, 1951; WOODS, 1952). Energy spread in the discharge is less than 100 volts. Provision is included for magnetic analysis of the ion beam.

Deuterium gas was obtained from heavy water in this laboratory. The heavy water (99^{+} %) was electrolysed in a closed system, which included a cold trap and phosphorous pentoxide drier. The gas was passed into the ion

PLATE IV HEAVY ICE TARGET



source through a Palladium leak, thereby eliminating most contamination, with the exception of hydrogen.

Beam currents were measured by metering the target current to ground. The target was biased to +300 volts to prevent back electron current. Beams of 100 to 200 μ-amp. resolved H^{2+} ions were obtained.

4. Heavy Ice Target

The first targets used consisted of heavy water adsorbed on Phosphorous Pentoxide but the neutron yields obtained were low. A heavy ice target, as shown in Plate IV was then constructed.

The target was attached to the ion generator by a two inch Pyrex pipe and flare fittings. After evacuation, the inner chamber of the target was filled with liquid air. Heavy water vapour was then admitted to the body of the target via a needle valve and the copper tube, indicated in Plate IV. The vapour froze to the copper target-leaf, forming a layer of heavy ice. The O-ring seal on the copper tube allowed it to be moved out of the way of the beam after the target was formed.

Formation of the target was first observed by looking into the target body through the Pyrex pipe. This view proved to be rather restricted, and the target was later modified by cutting a circular part in the side of the body, (position indicated in Plate IV), and attaching a glass window by means of an O-ring seal.

The Pyrex pipe effectively insulated the target from the ion generator, and allowed the beam current to be metered. It was found initially that the interior of the glass pipe became charged, causing serious defocussing of the beam and so a great reduction in the useful beam current. A sleeve of wire gauze on the interior of the pipe, connected to the target, overcame the difficulty.

The inner chamber of the target accomodated about 200 cc. of liquid air. With a normal beam of 150 μ-amp. on the target, i.e. 7.5 watts beam-power, this was sufficient for a maximum of one hour's operation. Normally it was topped up every half hour.

A beam of 150 amp. corresponds to 9.36×10^{14} deuterons per second, and from the yield curve for the reaction, (Plate II), the yield for 50 kev. deuteron energy is approximately 2×10^{-8} neutrons per deuteron, so that the total yield was about 2×10^{7} neutrons per second.

5. Background Radiation from Neutron Source

It was necessary to consider the possibility of other penetrating radiations originating in the heavy ice target, i.e. other (dn) reactions. The light nuclei exposed to the deuteron beam were H^1, H^2, O^{16}, O^{17}, O^{18} from the heavy water, and traces of C^{12} and C^{13} from pump oil contamination. The only reactions to be considered were:

$O^{16}(dn)F^{17}$	$Q = -1.6$ Mev.	(NEWSON, 1935; HEYDENBURG, 1948)
$O^{17}(dn)F^{18}$	$Q = +3.5$ Mev.	(WELLES, 1946) (isotopic abundance 0.04 %)
$C^{12}(dn)N^{13}$	$Q = -0.26$ Mev.	(BONNER et al 1949) (threshold 0.328 Mev.)

The high thresholds eliminate the $C^{12} + O^{16}$ reactions, while both C^{13} and O^{17} have too few atoms present to be significant.

Soft (50 kev.) γ-rays will be present from the ion generator, but would not be expected to penetrate the 1/4 inch steel walls of the ionization chamber. Additional protection was given by a 1/4 " sheet of lead wrapped around the chamber.

There is expected to be a background of scattered neutrons from the concrete walls of the laboratory, and from such massive objects in the vicinity as the analysing magnet. Tests with a cadmium absorber would indicate whether thermal neutrons were producing any effects, such as $(n\gamma)$

reactions in the walls of the ion chamber. Scattered neutrons with somewhat less energy than those from the heavy ice target would be expected to cause some spreading of pulse distributions.

C. MEASUREMENT OF ALPHA PARTICLE ENERGIES

1. Choice of Detectors

As mentioned previously, such difficulties as straggling in windows can be avoided by detecting the ionization of the products of the reaction in the target gas itself.

The Wilson Cloud Chamber has often been used for such observations--the first records of Neon disintegrations were so obtained, (HARKINS, 1933). However, there are several drawbacks in using it for accurate measurement of particle energies. Unless special high-pressure chambers are used, there will be relatively few target atoms, and correspondingly few disintegrations will be observed. Fairly accurate energy determinations from cloud chamber photographs are possible, but both the collection and analysis of the data are tedious.

Proportional counters are capable of fast and accurate energy determinations. Most difficulties arise in maintaining stability of the device. For detecting energetic particles, the gas pressure must be high in order to confine the particle range to the gas volume. High voltages are then required to obtain gas-amplification. For consistant results, the gas-amplification must remain constant, and this requires well-stabilized high voltage. The amplification is also very sensitive to slight changes in the constitution of the filling gas, and the release of even small amounts of occluded gases from the walls of the chamber can be very troublesome. Background is fairly high in proportional counters, because of their sensitivity to stray radiations, such as soft x-rays. Such an increase in "noise" will raise the useful lower limit of the device, making the detection of low energy events difficult. Finally, the pure noble gases are unsuited for use in proportional counters, chiefly because of their tendency to form metastable states. Addition of a quenching gas is necessary to de-excite these states, and so prevent spurious pulses. (WILKINSON, 1950)

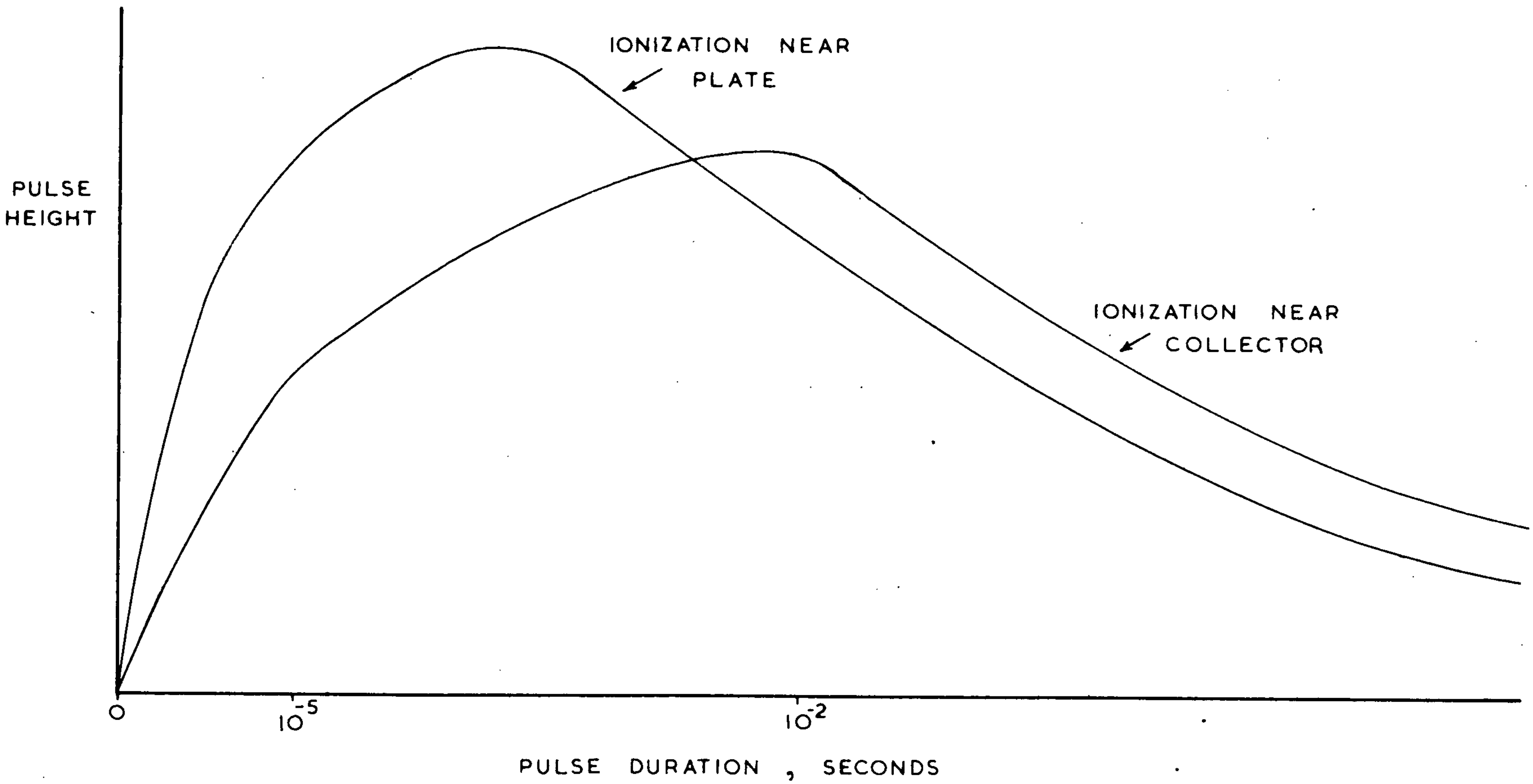
Ionization chambers, and particularly gridded ion chambers, are well suited to these investigations. They require very stable amplifiers, but modern circuits meet these demands. Ion chambers are less sensitive to variations in collecting voltage than proportional counters, are much less sensitive to background radiations, and are relatively unaffected by slight changes in the composition of the filling gas.

The speed with which data may be collected depends on the recording equipment available. Frequently the voltage pulses are displayed on an oscilloscope and photographed. This method yields accurate results, but the rate of collecting data is usually limited by the photographic equipment, and analysis of the data is a bit tedious. Greatest speed is attained with a pulse-amplitude analyser, or "kicksorter". Such a device was available for the present experiment.

2. The Gridded Ion Chamber

Measurement of particle energies with an ion chamber requires that the ionization produced be proportional to the particle-energy, and that the voltage pulses from the chamber be proportional to this ionization. Events of a single energy may in practice

PLATE V   PULSE FORMATION IN UNGRIDDED ION CHAMBER



produce a distribution of pulse-heights. The spread of this distribution depends on several factors--source thickness, in the case of solid sources placed in the chamber, straggling of ionization, non-ionizing excitation of the filling gas, noise in the associated electronic circuits, and the influence of positive ions on pulse-formation.

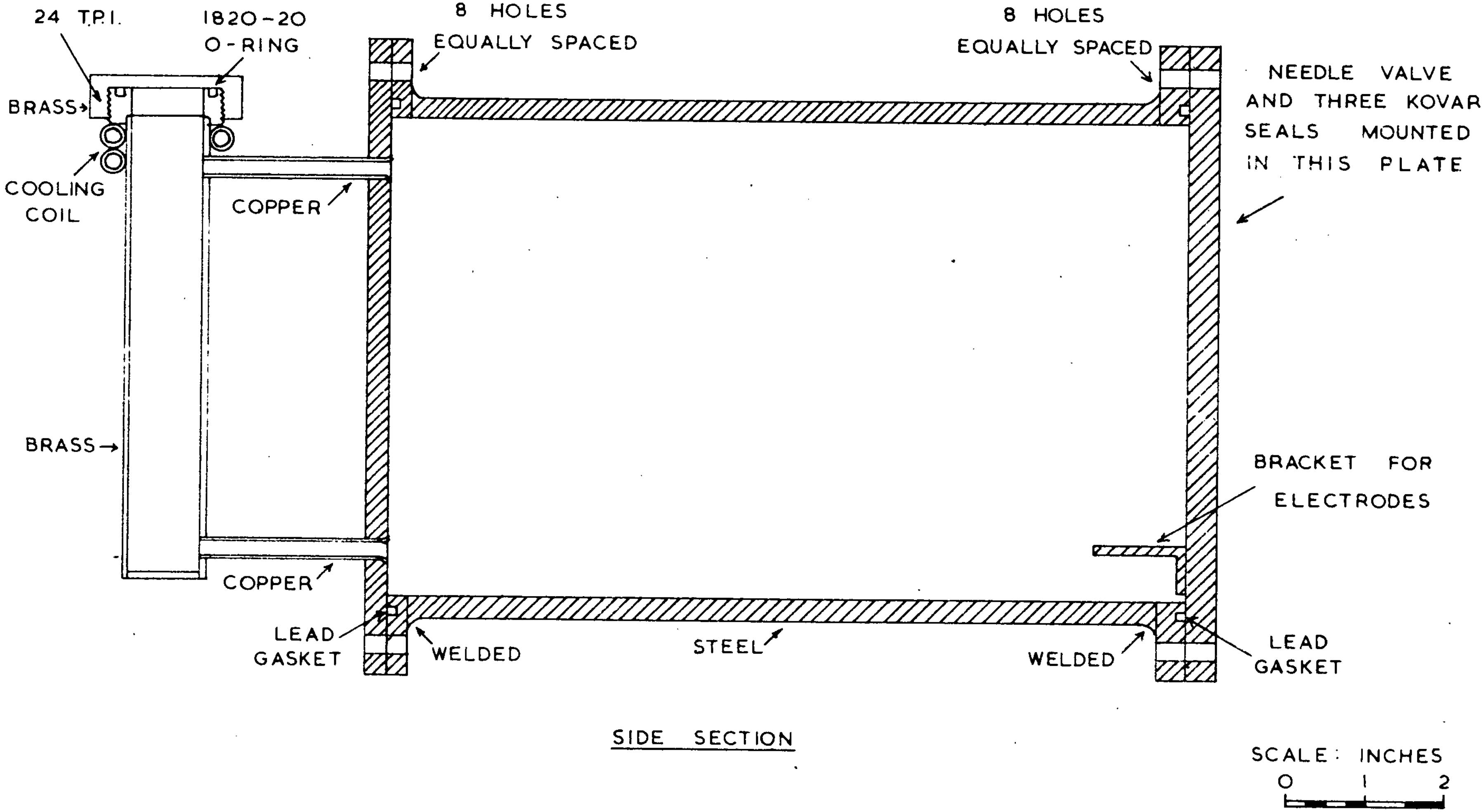
In a gridded ion chamber, the effect of the positive ions is eliminated. How this is achieved may be understood by considering pulse-formation in an ungridded chamber. We assume that electron-attachment does not occur in the filling gas, and that the collecting field is sufficient to prevent recombination of the ions.

An ionizing event occurs between the electrodes, and the electrons are attracted to the positive collector. Electron collection requires 10^{-5} seconds or less, and results in a sharply rising voltage pulse on the collector (see Plate V). The positive ions, whose mobility is about 1000 times less than that of the electrons, do not move appreciably before electron collection is completed. While the positive ions are being collected, the potential of the collector continues to rise, and reaches its maximum when all positive ions have been collected (at the negative electrode). The pulse then decays as the charge leaks away through the resistance and capacity of the electrode system.

Not only is such pulse-formation slow, but the height and duration of the portion resulting from the collection of positive ions depends on the orientation of the ions at the time of formation. In many experiments this will be a fairly random matter, and the resulting spread of the pulse-height distribution will be correspondingly widened. An amplifier to reproduce such slow pulses requires a low low-frequency cut-off, thus introducing the additional problem of microphonics.

PLATE VI

GRIDDED ION CHAMBER



SIDE SECTION

The difficulty is completely overcome by placing a grid between the electrodes, near the collector. The grid shields the collector electrostatically from the field of the positive ions. When an ionizing event occurs, the collector potential remains constant until the electrons have diffused past the grid, then rises rapidly to its maximum value as electron collection occurs. The pulse then decays as the charge leaks from the electrode system. Much faster amplifiers may be used for such pulses, improving the signal-to-noise ratio. The faster pulses also allow shorter resolving time and much higher counting rates. Suitable choice of the grid voltage prevents electron collection by the grid.

Some fraction of the ionizing events will occur in the portion of the sensitive volume between the grid and the collector. This region will behave as an ungridded chamber, with collection of positive ions at the grid. Such pulses will have random heights, and will cause some spreading of the distribution.

For some events, only a portion of the ionization will occur in the sensitive volume, the particles either striking an electrode, or passing out of the sensitive region. This effect will cause an asymmetry of the low-energy side of the distribution of pulses from single energy ionizing events. The degree of asymmetry will depend upon the range of the ionizing particles in the chamber.

3. Description of the Ion Chamber

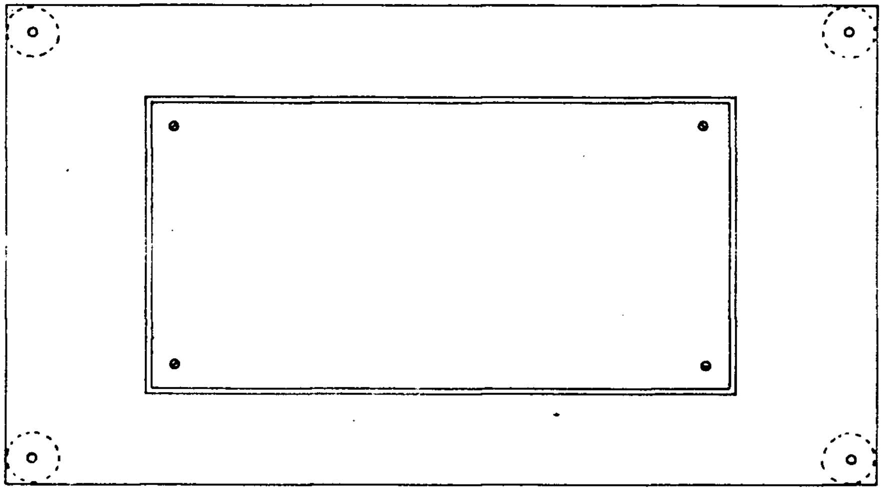
Plate VI shows the gridded ion chamber used in the experiment. The body of the chamber was steel tubing, with welded flanges. The end-plates were sealed with lead gaskets, thus avoiding the exposure of the filling gas to rubber, a common source of contamination.

PLATE VII

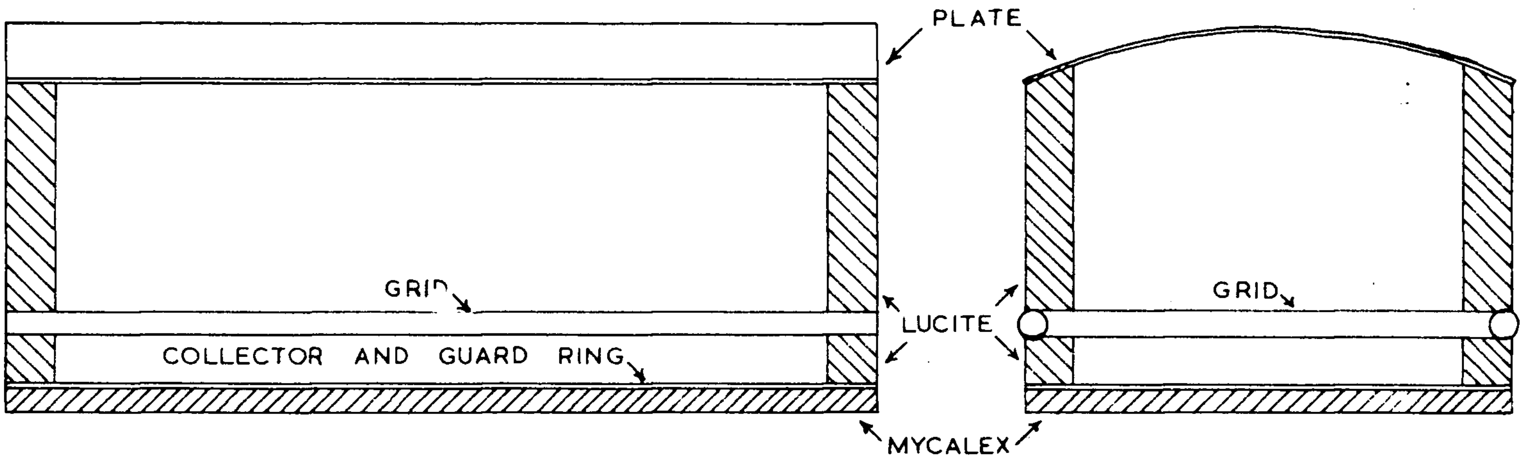
ELECTRODE SYSTEM FOR GRIDDED ION CHAMBER

SCALE : INCHES 0 1 2

MATERIAL:
BRASS, EXCEPT WHERE NOTED



COLLECTOR AND GUARD RING



SIDE ELEVATION

END ELEVATION

The volume of the chamber was 4.64 litres. All interior surfaces were coated with "aquadag" colloidal graphite, to reduce the background from natural alpha-activity in the steel.

One end plate carried the gas purifier, constructed of brass and copper tubing. An electric heating coil of about 30 ohms (cold) resistance was wound about the centre of the purifier, and insulated with glass wool and asbestos paper. 75 volts across the heater produced a temperature of about 300°C. at the interior. A copper cooling coil at one end aided in convection of the gas, and protected the O-ring seal on the filling cap. The most common impurities are oxygen, nitrogen, and water vapour. Calcium metal is known to be effective in removing all of these, and so was used as the purifying agent. (REIMANN, 1934; WILKINSON, 1950)

The opposite end-plate carried a needle-valve for filling the chamber, and three kovar terminals. The electrode system was also mounted on this plate, and the electrodes connected to the kovars.

The chamber was designed by Mr. F. Flack, and the electrode system constructed by Dr. S. B. Woods. Its use in other experiments has been described elsewhere (WOODS, 1952)

4. Electrode System

The design of grids for such chambers has been carefully investigated, both in theory and experiment by BUNEMANN, CRANSHAW, and HARVEY, 1949. The electrode system of the present chamber was designed largely according to their recommendations.

The electrodes were constructed of brass, with Mycalex and Lucite insulation. Plate VII shows the arrangement. The grid was wound from # 36 Coppel wire, spaced 1 mm. centre-to-centre. Grid-collector spacing was 1.52 cms. and grid to plate 7.6 cms. For such an arrangement, the "grid inefficiency", i.e. the extent to which the number of lines of force ending on the collector is dependent upon the field due to positive ions, is 0.01, indicating very efficient shielding of the collector.

The curvature of the high-voltage plate is a slight modification to the design of Bunemann et al. Field plots have shown that the curvature increases the number of lines of force ending on the collector, and insures that the sensitive volume approximates to the actual volume above the collector.

The sensitive volume was estimated to be about 1 litre. About 15% of this volume constitutes the unshielded region between the grid and the collector. To a first approximation, we may assume that the ionizing events are distributed uniformly throughout the sensitive volume, and so about 15% of the events will contribute to the spreading of the pulse-distribution.

5. Filling Gas

Like all noble gases, neon is well suited to use in an ionization chamber . Electron attachment does not occur, and electron collection can be achieved, even at high pressures, with reasonable collecting voltages.

Although the purest obtainable gas was used, the purifier on the chamber was still necessary, because of occluded gases on the chamber walls. Outgassing of such a chamber is very difficult, though some attempt was made by evacuating the chamber while baking it under a heat lamp, prior to filling.

The manufacturers # of the neon used stated the limits of

The Matheson Co., East Rutherford New Jersey; private communication

impurity to be

Helium	0.2%
Nitrogen	0.02%
Other less than	0.02%

The three stable neon isotopes were present in the normal ratios:

Ne^{20}	90.51%
Ne^{21}	0.28%
Ne^{22}	9.21%

(MATTAUCH and FLAMMERSFELD, 1949)

It was desirable to have as high a pressure of neon as possible, for two reasons. First, high pressure increased the number of target atoms, making disintegrations more probable. Second, the higher pressure shortened the tracks of the ionizing particles, so increasing the number of events which are completely confined to the sensitive volume, relative to those which are only partially in this region. The pressure may be limited if the electrostatic field is not sufficient to achieve electron collection, but this consideration did not affect the present experiment.

After evacuation, the chamber was filled by equalizing pressures between the chamber and the neon storage cylinder. The gas was passed through a liquid nitrogen cold-trap during filling. The final pressure was 473.5 cms. mercury (at 22°C) and hence the range of the alpha particles produced in the $Ne^{20}(n\alpha)O^{17}$ reaction with 2.68 Mev. neutrons would be 0.2 cms., a relatively small distance compared to the dimensions of the sensitive volume, (roughly $7.5 \times 9 \times 15$ cms.)

6. Operating Conditions

In the present chamber, the voltage was limited by sparking at the high-voltage kovar seal inside the chamber, which occurred at about -950 volts. This was more than adequate to achieve saturation, i.e. complete electron collection, without recombination. In operation, a plate voltage of -800 volts and grid voltage of -200 volts was used. The plate voltage was obtained from a Dynatron Radio Type 200 regulated supply, and the grid voltage was supplied from the plate by a resistor network.

The chamber was stationed with its centre-line about 5 1/2 inches from the heavy ice target. In this position the sensitive volume received about 1/35 of the total yield of neutrons, i.e. about 5×10^{5} neutrons per second for a 150 μ-amp. beam.

The range of neutron energies received by the sensitive volume was determined by the half-angle subtended at the target by the sensitive volume, in this case about 45 degrees. A value for the average neutron energy was obtained as follows.

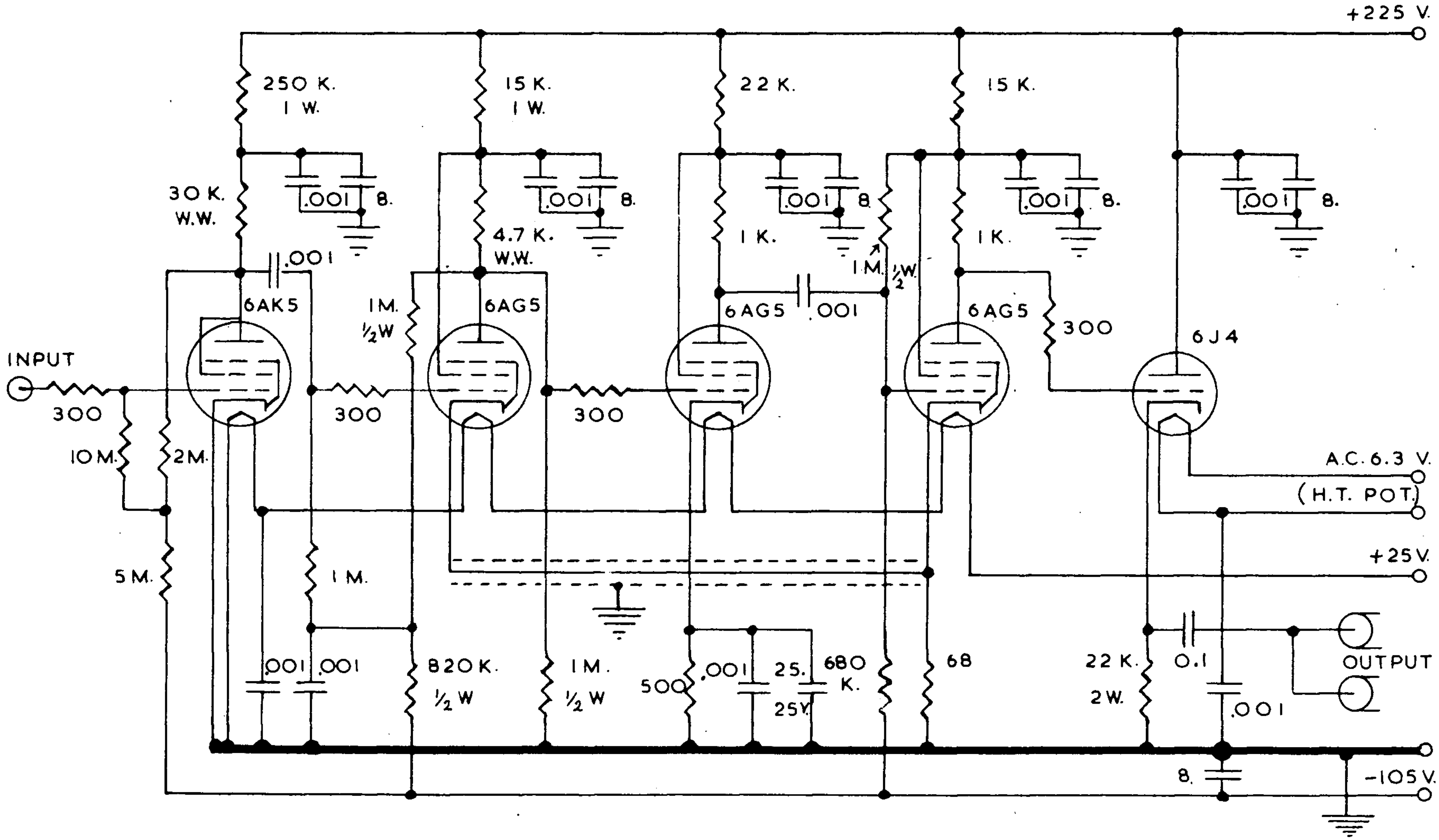
The solid angle was treated in three regions: 0-15, 15-30, and 30-45 degrees. A value of neutron energy for each region was calculated from the general formula for the angular energy dependence in collision processes (HANSON et al, 1949). Substituting appropriate masses and energies for 50 kev. deuterons bombarding deuterium, the expression for neutron energy is:

$$E_n = (0.0125)\left[\cos^2\theta + 196 + \cos\theta\sqrt{\cos^2\theta + 392}\right]$$

Neutron energies for the three regions were obtained from this formula with $\theta = 7.5$, 22.5, and 37.5 degrees.

The relative number of neutrons in each region was then

PLATE VIII WIDE-BAND LOW NOISE HEAD AMPLIFIER



calculated from the angular distribution function $N(\phi) = B(1+A\cos^2\phi)$, which is valid for 50 kev. deuterons, using $A = 0.45$ (HUNTOON, 1940). In this relation, ϕ is measured in centre-of-mass co-ordinates. The angle θ in the laboratory system is related to ϕ by the expression

$$\tan\theta = \frac{\sin\phi}{\cos\phi + \gamma} \qquad \text{(SCHIFF, 1949)}$$

For the present reaction, $\gamma = 0.0504$, and at 45 degrees the correction is 2 degrees, which was considered negligible.

Finally, adjustment was made for the number of target atoms exposed to each of the three neutron groups, i.e. for the fraction of the sensitive volume included in each of the angular regions.

The final value obtained for the average neutron energy was 2.68 ± 0.07 Mev. The error on this figure makes allowance for slight variations in deuteron energy, chiefly due to straggling in the heavy ice target.

7. Pulse Amplification and Measurement

A wide band, low noise head amplifier with an approximate gain of 100 was mounted directly on the chamber. Plate VIII gives the circuit diagram. Gain of the first tube was about 10. The tube itself was selected as having the lowest noise of those available. The input capacity of the collector and first grid was measured by observing the reduction in height of standard pulses when a known capacity was connected in parallel and was found to be 100 $\mu\mu$ farads. The plate voltage was obtained from a Lambda Model 28 regulated supply, and stabilized DC was used for the filaments of the first tube and the ring-of-three.

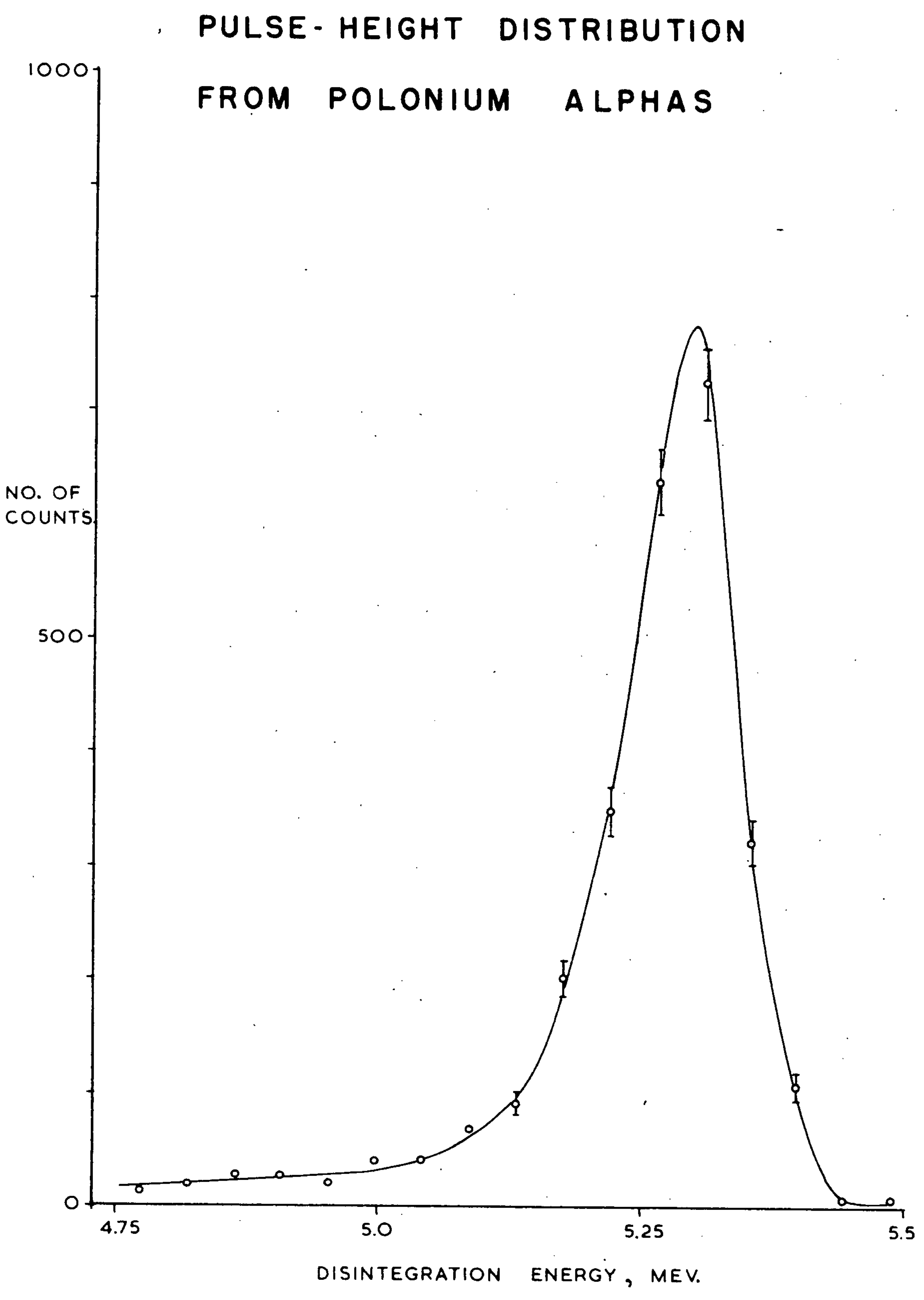
The output pulses were fed from the cathode follower through 120 feet of co-axial cable to a Northern Electric Type 1444 Linear Amplifier. This amplifier has a gain of about 10^4, and gain stability better than 1% over long operating periods. Provision is included for up to 33 db. attenuation, variable top and bottom cuts, and variable duration of output pulses. For optimum signal-to-noise ratio, the amplifier was operated with both top and bottom cuts set at 5μ-seconds.

The amplified pulses were fed to an 18 channel Marconi Type * 155-935 pulse-amplitude analyser, or "kicksorter", (CHALK RIVER design). Amplitude stability of the kicksorter discriminators is stated as approaching 0.02 volts under the existing operating conditions. The kicksorter has a maximum input voltage of 40 volts, and incorporates a stabilized amplifier with a gain of 5, so that maximum input to the discriminator is 200 volts.

The kicksorter channels were set up using pulses from a Standard Pulse Generator. The amplitude of these pulses was stable to about 0.01 volts over long periods. These pulses were fed through the kicksorter amplifier when adjusting the channels.

The minimum practical channel-width was found to be 0.2V in terms of the Standard Pulse Generator amplitude. This channel width corresponded to about 0.045 Mev. disintegration energy, which provided adequate resolution for the present experiment.

PLATE IX



PULSE-HEIGHT DISTRIBUTION
FROM POLONIUM ALPHAS
1000
NO. OF COUNTS
500
0
4.75
5.0
5.25
5.5
DISINTEGRATION ENERGY, MEV.

8. Energy Calibration

A series of ionizing events of the same energy in the chamber should, within statistical limits, produce voltage pulses of the same amplitude. Moreover, the pulse amplitude is expected to depend linearly on the disintegration energy. The energy scale was calibrated by a Po^{210} source in the chamber. This source was attached to the inner surface of the high voltage plate, and covered with a thin aluminum collimator. The alphas from Po^{210} have 5.3 Mev. energy, and an air-range of 3.842 cms. This corresponds to a range of about 1 cm. in 6 1/4 atmospheres of neon. Since it requires 29.3 ev. per ion pair in neon (STETTER, 1943), such particles should produce about 290μvolt pulses on the 100μμfarads capacity of the collector and first grid. The signal-to-noise ratio for those polonium alphas was about 20:1. All polonium alphas are stopped in the sensitive volume, and none reach the unshielded region between the grid and the collector.

Plate IX shows a typical distribution of pulses from the polonium alphas. The half-width of this distribution is 68 kev., or 1.3% of the total energy.

Ionization produced by disintegrations in the filling gas differs somewhat from that produced by alpha particles from radioactive sources in the chamber. In the case of a neon disintegration, the reacion energy is shared between an alpha particle and a recoiling oxygen ion, both of which will produce ionization in the filling gas.

For the alpha particles, the relation between ionization and energy is linear down to low energies (region of 100 kev.) after which the proportionality may break down, due to electron attachment and inelastic non-ionizing collisions. The variations in total ionization produced will however be rather small, so that the determination of alpha particle energies is quite accurate.

In the case of the larger fragments, the mechanism of ionization is not clearly understood, though some investigations have been made on recoil particles in cloud chambers; (see WRENSHALL, 1940) and discussion and references given by WILKINSON (1950)). Two points must be considered with regard to energy determination for such particles. First, the energy loss may be less uniform than for alpha particles, so that the amount of ionization released by single energy events is somewhat more random than for alphas. In this case, the result would be a spreading of the pulse-height distribution.

Secondly, the energy calibration is based on the energy loss of Po alphas in neon, i.e. 29.3 ev. per ion pair. If the energy loss per ion pair for oxygen ions has some other value, the apparent disintegration energy will be in error.

The linearity of the detecting system was tested by the following method. Pulses from the Standard Pulse Generator were attenuated and fed into the head amplifier through the grid-collector capacity. After amplification, they were displayed on the kicksorter, where they appeared in not more than two channels. Pulses of the same amplitude, without attenuation, were then fed directly into the kicksorter amplifier, with the same discriminator settings. This procedure was carried out for a range of pulse amplitudes. Comparison of the two sets of kicksorter readings showed the system to be linear to within 1%.

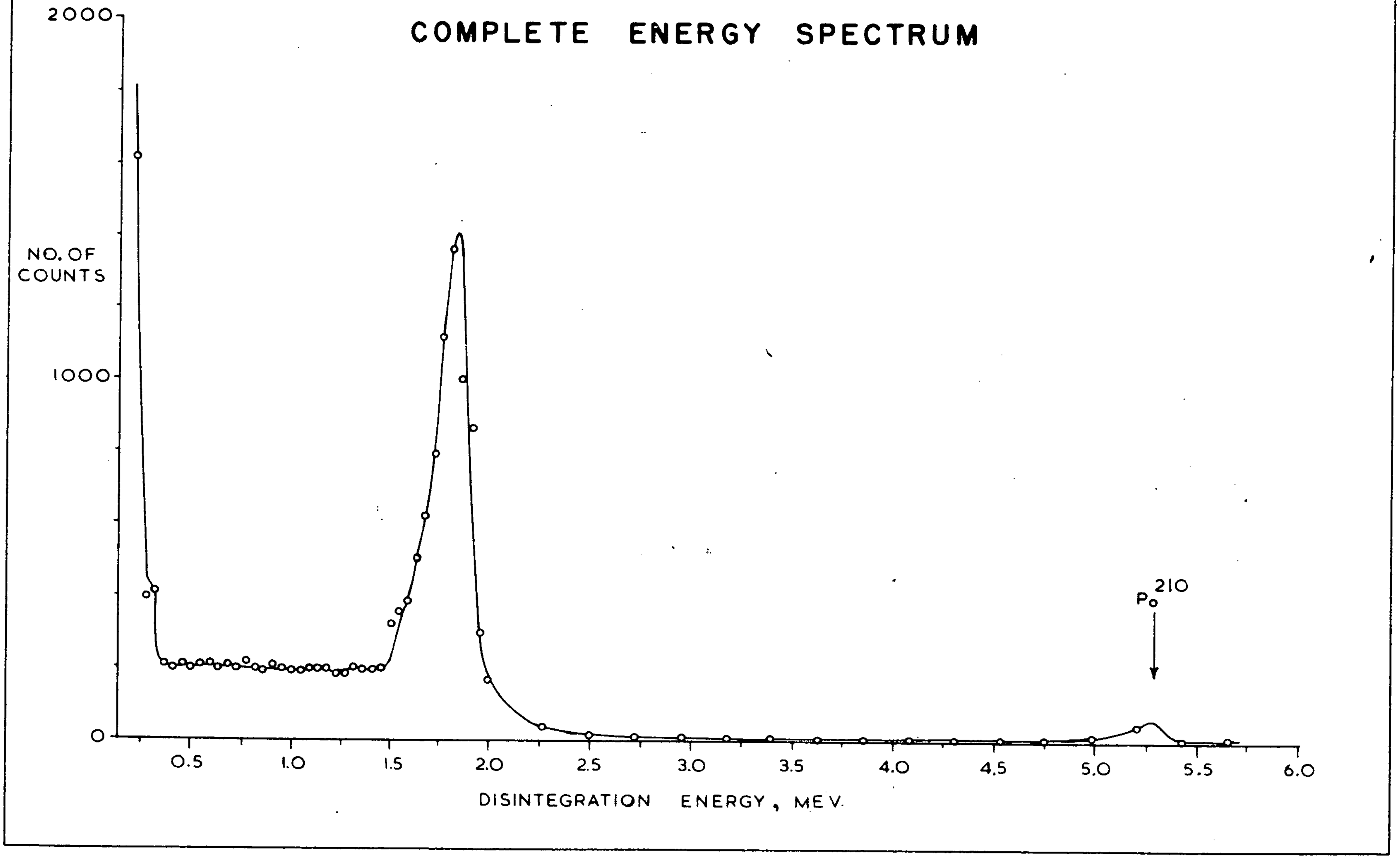
9. Experimental Procedure

Except when shut-downs of several days duration were anticipated, all electronic equipment, with the exception of the collecting voltage on the chamber, ran continually, thus maintaining the greatest stability.

The polonium alphas were observed for at least an hour at the beginning of each run. A fresh target of heavy ice was then prepared, and the kicksorters set to cover the desired part of the energy spectrum. At the end of the run a second polonium alpha-peak was taken to ensure that the gain of the amplifiers, and conditions within the chamber were unchanged.

The calcium purifier was heated for several hours at intervals of a few weeks. The filling gas was thus kept free of contamination, such as occluded gases from the walls of the chamber.

PLATE X



COMPLETE ENERGY SPECTRUM
2000
1000
0
NO. OF
COUNTS
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
DISINTEGRATION ENERGY, MEV.
Po210

III. RESULTS AND DISCUSSION

A. EXPERIMENTAL RESULTS

Plate X shows the complete energy spectrum. The spectrum was examined in sections, and in moving the kicksorter from one section to another, an overlap region of six channels was allowed. The data shown in Plate X was taken from a number of runs, normalized to approximately the same average number of counts per channel in the overlap regions. It would have been preferable to normalize on the basis of integrated neutron flux, but a neutron monitor was not available at the time this data was collected.

The position of the large peak corresponds to a disintegration energy of 1.91 ± 0.01 Mev. Examination of the low energy side of this peak showed no evidence of further structure, down to the onset of electronic noise at about 450 kev.

The background over this region is due mainly to scattered neutrons from the walls of the laboratory and massive objects in the vicinity of the ion chamber. Neon recoils from neutrons scattered in the chamber have a maximum energy of about 490 kev. Some contribution may also come from disintegrations in the unshielded region between the grid and collector of the chamber.

Investigation of the high energy side of the main peak disclosed a second peak of about 100 times less intensity. This region of the spectrum is shown in greater detail in Plate XI. Position of this peak corresponds to a disintegration energy of 3.16 ± 0.03 Mev.

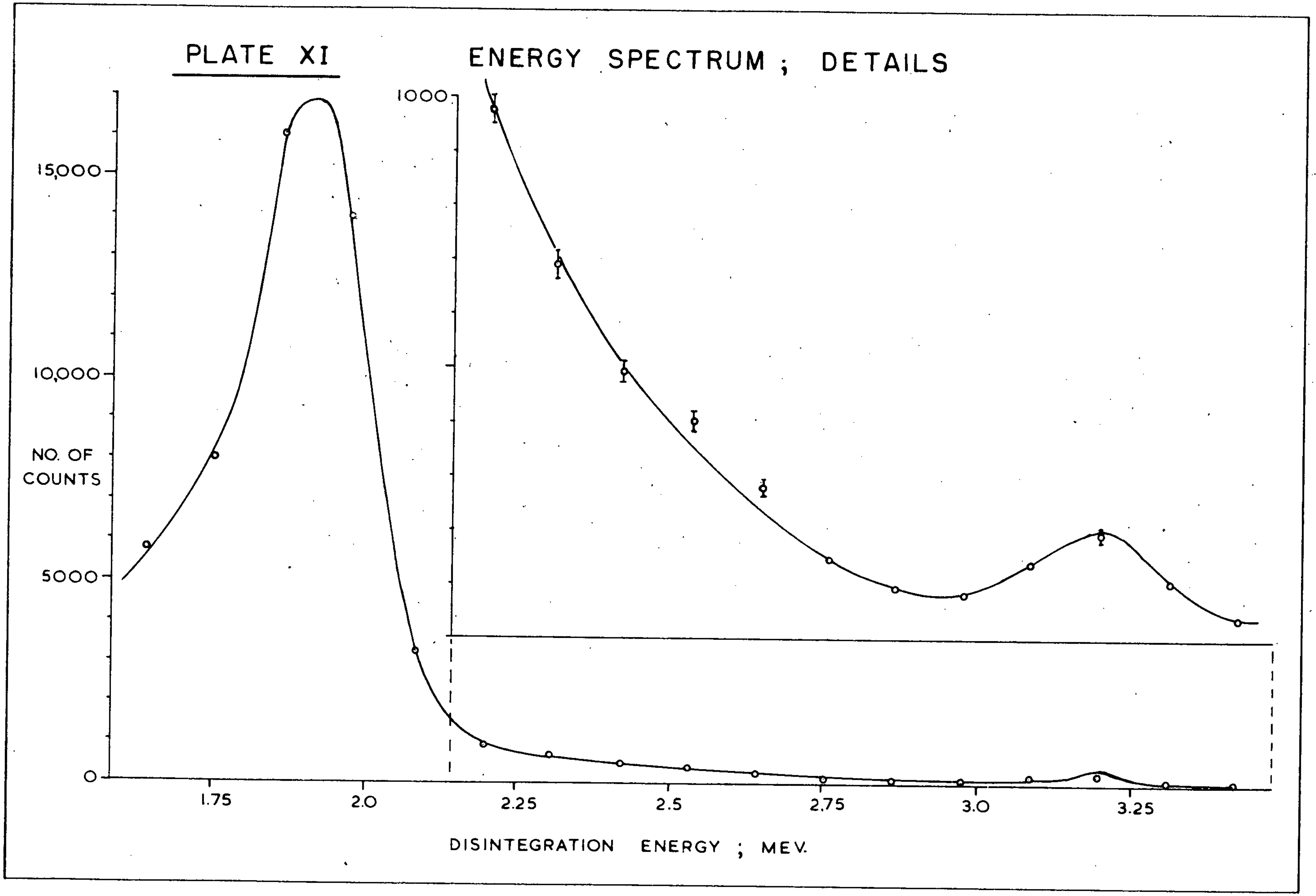


PLATE XI
ENERGY SPECTRUM ; DETAILS
15,000
10,000
5000
0
1000
NO. OF COUNTS
1.75
2.0
2.25
2.5
2.75
3.0
3.25
DISINTEGRATION ENERGY ; MEV.

No other structure was observed at energies below those of the polonium alphas, and no pulses of energies greater than these were observed.

B. DISCUSSION

1. Threshold Energies for Fast Neutron Disintegration of Neon

The gridded ion chamber might be expected to detect any $(n\alpha)$ and $(n\ p)$ reactions arising from the disintegration of neon nuclei. The following disintegrations must then be considered:

Isotope	Reactions	Calculated Q-Value
Ne^{20}	$(n\ \alpha)$	− 0.54 Mev.
	$(n\ p)$	− 6.14 "
Ne^{21}	$(n\ \alpha)$	+ 0.71 "
	$(n\ p)$	—
Ne^{22}	$(n\ \alpha)$	− 5.06 "
	$(n\ p)$	—

These Q-values have been calculated from the mass tables of MATTAUCH and FLAMMERSFELD (1949). Such values are only approximate, due to uncertainties in the masses, but are useful in estimating the thresholds of reactions.

2. Interpretation of the Main Peak

There is no question but that the main peak is due to the reaction $Ne^{20}(n\,\alpha)\,O^{17}$. From the measured energy release, $Q = -0.77 \pm 0.08$ Mev. This reaction has previously been reported as follows:

(a) GRAVES and COON (1946), using an ion chamber, and photographing pulses displayed on an oscilloscope, obtained a value of $Q = -0.6$ Mev., and estimated the cross section to be about 5 millibarns. No information was given on the number of events recorded. Their Q-value was later revised to -0.8 to -0.85 Mev. in a private communication to JOHNSON et al (see below).

(b) SIKKEMA (1950) used a large proportional counter filled with 2 atmospheres of neon, and recorded pulses on a photographic strip. The reaction energy was observed as -0.6 Mev. The published curves show peaks 200 counts or less high, with a background as high as 75 counts.

(c) JOHNSON, BOCKELMAN and BARSCHALL (1951) used a proportional counter containing 30 atmospheres of neon, and operating at a gas amplification of about 5. They obtained the values $Q = -0.75 \pm 0.05$ Mev. and cross section about 20 millibarns. The published curves show peak about 100 counts high.

It is of interest to recall the considerations of WILKINSON (1950) mentioned previously, regarding the use of pure noble gases in proportional counters. The formation of metastable states in these gases, and the emission of photo-electrons from the cathode of the counter may produce an objectionably high background. Such an effect was observed by SIKKEMA, though he attributed it to hydrogen or helium contamination in the ion chamber.

In the present experiment, the Q-value was obtained with 1% counting statistics, much better than previously reported.

The mass spectrograph data of EWALD (1951) gives the isotopic masses:

$$O^{17} = 17.004,507 \pm 0.000,015$$
$$Ne^{20} = 19.998,771 \pm 0.000,012$$

The O^{17} mass is fairly well agreed upon, and from the above value, and the observed Q-value in the present experiment, the mass of Ne^{20} is calculated to be 19.998,628 ± 0.000,045.

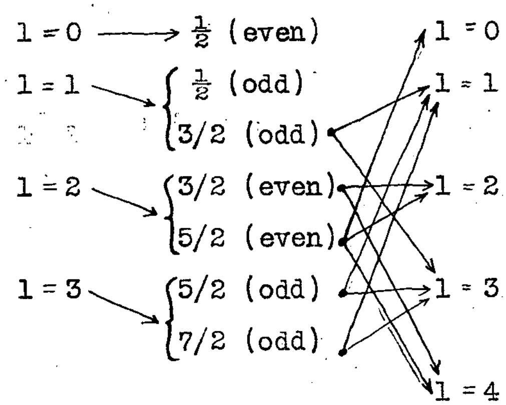
BUECHNER et al (1949) have observed the protons from $O^{16}(dp)O^{17}$ in a magnetic spectrometer and measured an excited state of O^{17} at 0.876 ± 0.009 Mev. The gamma ray from this level to ground has been reported by ALBURGER (1949). POLLARD and DAVIDSON (1947) have observed the same level through the reaction $N^{14}(\alpha p)O^{17}$, and in addition a second particle-group, which may indicate a second level at 1.6 Mev. However, it is possible that the particles observed were deuterons from $N^{14}(\alpha d)O^{16}$.

It is generally assumed that the ground-state of Ne^{20} has zero spin and even parity, (HORNYAK, 1950). BUTLER, (1950) in an analysis of the work of BURROWS et al (1950) on the angular distribution of protons from $O^{16}(dp)O^{17}$ concludes that the ground-state of O^{17} is 5/2 or 3/2., even, and that the first excited level is 1/2, even. The spin value of 5/2 for the ground state has been confirmed by the nuclear resonance experiments of ALDER and YU, (1951), and by GESCHWIND et al, (1952) from microwave spectroscopy.

Assigning these values of spin and parity, the ground-state transition of $Ne^{20}(n\alpha)O^{17}$ may be viewed as follows:

	Ne^{20}	+	n	→	Ne^{21*}	→	α	+	O^{17}
Spin:	0		½				0		5/2
Parity:	even								even

Angular momentum:

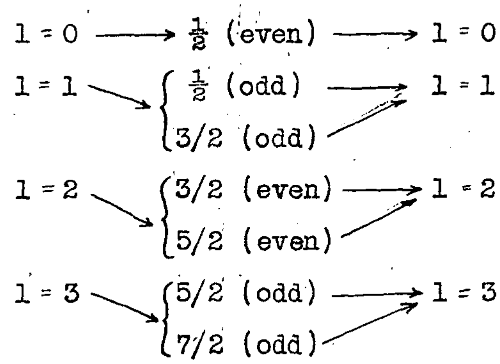


The arrows indicate the possible transitions for neutrons up to l = 3 and alpha particles up to l = 4 . In view of the cross section of the reaction, it seems unlikely that larger l-values need be considered.

The transition to the excited level in O^{17}, which was not observed with the 2.68 Mev. neutrons, has the possibilities:

	Ne^{20}	+	n	→	Ne^{21*}	→	α	+	O^{17*}
Spin:	0		½				0		½
Parity:	even								even

Angular momentum:



Thus, assuming up to F-wave neutrons, (l = 3) , leads to seven possible states for the compound nucleus, Ne^{21*}. Of these the the ground state transition is forbidden for the ½ even and ½ odd states.

It was hoped that the lack of excited levels of O^{17} in the present experiment would give some indication as to which state of Ne^{21*} appeared. However, the penetrability of the potential barrier for the alpha particles must also be taken into account. Calculation of the penetrability # indicates that the intensity of the excited-state transition would be approximately 10^{-4} times that of the ground-state transition. A reaction of such low intensity would not have been detected. Therefore, the non-observance of excited levels of O^{17} yields no information regarding the state of the compound nucleus, Ne^{21*}.

3. Interpretation of the Minor Peak

No such subsidiary peak has been reported by other workers. This is not surprizing in view of its low intensity, and the statistics which they obtained on the $Ne^{20}(n\alpha)O^{17}$ reaction.

There are three possible causes for this peak:

(a) A group of neutrons of higher energy than the main group from $H^{2}(dn)He^{3}$.

(b) A charged-particle reaction in Ne^{21} or Ne^{22}.

(c) A charged-particle reaction in some impurity in the filling gas.

The possibility of higher energy neutrons has been previously

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see for example BETHE, H. A. R. M. P. 9-164--1937

discussed, and shown to be most unlikely.

The only energetically possible reaction in Ne^{21} or Ne^{22} for the neutrons used is $Ne^{21}(n\,\alpha)\,O^{18}$. For this reaction, the observed energy release gives $Q = +0.48 \pm 0.10$. EWALD (1951) gives the mass values:

$$O^{18} = 18.004,875 \pm 0.000,013$$

$$Ne^{21} = 21.000,393 \pm 0.000,022$$

The above Q-value corresponds to a mass of

$$Ne^{20} = 21.000,339 \pm 0.000,068$$

Using the cross section of JOHNSON et al (1951) of 20 millibarns for $Ne^{20}(n\,\alpha)\,O^{17}$, the intensity of this peak would indicate a cross section of about 65 millibarns for $Ne^{21}(n\,\alpha)\,O^{18}$.

The limits of impurity for the neon were stated as 0.2% helium and 0.02% nitrogen, while nitrogen, oxygen and water vapour may have been present in the chamber prior to filling. The energetically possible reactions for these elements are

$N^{14}(n\,p)\,C^{14}$	$Q = +0.63$	Mev.
$N^{14}(n\,\alpha)\,B^{11}$	$Q = -0.28$	"
$O^{16}(n\,\alpha)\,C^{13}$	$Q = -2.31$	"
$O^{17}(n\,\alpha)\,C^{14}$	$Q = +1.73$	"

The first of these reactions is well known, and its Q-value has been carefully established as $+0.630 \pm 0.006$ Mev. (FRANZEN et al, 1950; HORNYAK et al 1950). This value lies close to that of the minor peak, although outside the probable error, which is believed to be generous. For 2.8 Mev. neutrons, the cross section for $N^{14}(n\ p)C^{14}$ is 40 millibarns (BALDINGER and HUBER, 1939). This would indicate more than 0.4% nitrogen in the chamber, though such an estimate is very approximate, as this cross section may not hold for 2.68 Mev. neutrons. This amount of nitrogen should be accompanied by about 0.1% oxygen. WILSON et al (1950) have stated that 5 parts per million of oxygen in 6 atmospheres of deuterium will prevent electron collection entirely. It would be expected therefore that 0.1% oxygen would have noticeable effects in $6\frac{1}{4}$ atmospheres of neon. The calcium purifier is expected to remove both nitrogen and oxygen.

If nitrogen were present in the chamber, the reaction $N^{14}(n\ \alpha)B^{11}$ should also be observed. The cross section is 160 millibarns for 2.8 Mev. neutron, and so a second small peak should be observed at a disintegration energy corresponding to Q = -0.28 Mev. Some irregularities have been noted in this region of the spectrum, but at the time of writing, sufficient data was not available to determine whether such a peak exists.

4. Summary of Results

This table shows the Q-values for $Ne^{20}(n\ \alpha)O^{17}$ from various experimental investigations, and from calculations based on mass spectrograph data.

	Q-values
GRAVES and COON (1946)	-0.80 to -0.85 Mev.
SIKKEMA (1950)	-0.6 "
JOHNSON et al (1951)	-0.75 ± 0.05 "
Present experiment	-0.77 ± 0.08 "
Mass Spectrograph	
MATTAUCH and FLAMMERSFELD (1949)	-0.54 ± 0.12 "
EWALD (1951)	-0.64 ± 0.05 "

C. FURTHER INVESTIGATIONS

The extension of this investigation is now being actively pursued in the following ways:

(a) Reaction energies are to be determined more exactly by reducing the error on the neutron energies. This will be done by moving the ion chamber away from the target, thus reducing the solid angle subtended by the sensitive volume, and so decreasing the angular variation of neutron energy.

(b) The region of the spectrum corresponding to a reaction energy of -0.28 Mev. is to be carefully re-examined. If the presence of a second small peak is established, it would seem to indicate that both small peaks are due to nitrogen in the ion chamber. This would however raise two interesting points. First, how could this amount of nitrogen appear in the ion chamber, and remain in spite of the calcium purifier? Second, if the minor peak is due to $N^{14}(np)C^{14}$, why is the reaction energy not closer to the accepted value?

(c) Investigations are to be carried out with thermal neutrons, by moderating the $H^{2}(dn)He^{3}$ neutrons with paraffin. This should eliminate the main peak, and move the minor peak to the low-energy end of the spectrum, just above the noise. Some increase in the intensity of this peak would be expected, if the reaction cross section follows the 1/v law. The shift in the position of this peak will give an additional check on the linearity of the amplifier system.

(d) Some initial attempts to thermalize the neutron flux were not completely successful in that the main peak still appeared, though with much lower intensity. If the moderation cannot be improved, it is proposed to use neutrons from the $V^{51}(pn)Cr^{51}$ reaction, which are below the threshold for $Ne^{20}(n\alpha)O^{17}$.

(e) The reactions will be examined at higher neutron energies, using neutrons from $H^{2}(dn)He^{3}$ and $H^{3}(dn)He^{4}$, with deutrons accelerated by the UBC Van de Graaff Generator, which at present is operating at energies up to 2 Mev.

(f) It would be of interest to introduce some 2% of nitrogen in the chamber and repeat the observations.

For all these experiments, a neutron monitor is desirable. A neutron counter, of the type designed by HANSON and McKIBBEN (1947) is at present under construction in this laboratory.

IV. CONCLUSIONS

The Q-value of the reaction $Ne^{20}(n\alpha)O^{17}$ has been measured as -0.77 ± 0.08 Mev. The 1% counting statistics obtained are considerably better than those reported in previous investigations of this reaction.

Careful search of the energy spectrum gave no evidence for the appearance of excited states of O^{17}, using 2.68 Mev. neutrons. At least one such state is known, (0.87 Mev.) . Calculation of the penetrability of the potential barrier for the alpha particles corresponding to this level indicates an intensity approximately 10^{-4} times that of the ground-state transition, at this neutron energy. A reaction of such low intensity would not have been detected in the present experiment.

A subsidiary peak was observed at a reaction energy corresponding to a Q-value of +0.48 ± 0.10 Mev. There is some evidence that the reaction is $Ne^{21}(n\alpha)O^{18}$, but the reaction $N^{14}(np)C^{14}$ may also be responsible, if nitrogen is present in the ion chamber. Further investigation is necessary to clarify this point.

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