1963

A Study of the Al27 (d,p) Al28 Reaction

Richard Heath Parker
College of William & Mary - Arts & Sciences

A STUDY OF THE $Al^{27}(d,p)\ Al^{28}$ REACTION

A Thesis

Presented to

The Faculty of the Department of Physics

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Master of Arts

By

Richard Heath Parker

October 1963

APPROVAL SHEET

This thesis is submitted in partial fulfillment of

the requirements for the degree of

Master of Arts

____
Author

Approved, October 1963:

____
Jag J. Singh, Ph.D.

____
Donald E. McLennan, Ph.D.

____
Herbert O. Funsten, Ph.D.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. Jag Jeet Singh, under whom this investigation was conducted, for his advice and encouragement; also the author wishes to thank Dr. Donald E. McLennan and Dr. Herbert O. Funsten for their careful reading and criticism of the manuscript and the staff of the William and Mary Physics Department for their interest. The author, in addition, is indebted to Mr. Emanuel Rind of N.A.S.A. for help in carrying out this work, to Dr. Gale Harris, Dr. Hans Hennecke, and the Van de Graaff staff of the Wright-Patterson Air Force Base for their tireless efforts in the actual running of the machine. Special thanks go to my wife, Diane, for her continued encouragement and for her patience in typing this manuscript.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF DIAGRAMS

ABSTRACT

The deuteron stripping reaction has been extensively used in nuclear spectroscopy. For incident deuteron energies well above the Coulomb barrier, well developed Butler stripping patterns are observed for protons and neutrons. However, for deuteron energies below the Coulomb barrier height, one does not normally expect simple stripping to occur. Also, it is this energy region for the deuterons where the finer details of the stripping reaction mechanism are more important in interpreting the data. In order to get this information, Al^{27} (d,p) reaction has been investigated at 1350 kev bombarding energy. The results of angular distribution measurements on proton groups leading to various excited states in Al^{28} are compared with the simple Butler theory. Even the mechanism of Coulomb effects fail to account for the marked back angle rise in intensity of the protons. It is well known that the back angle rise in intensity is characteristic of exchange stripping. But it is far from clear why exchange stripping should predominate over normal stripping in this reaction.

Experimental procedure and the results of the measurements are presented.

A STUDY OF THE Al^{27} (d,p) Al^{28} REACTION

INTRODUCTION

The (d,p) stripping reactions have been subject to extensive investigations,[1,2,3,4,5] due to their usefulness in nuclear structure analysis. S.T. Butler[6] supplied the first theory which gave a satisfactory picture of the stripping reaction. Butler's theory was later modified to include the Coulomb potential. This theory predicted cross section maximum in the first quadrant, progressing from low angles for low l values to higher angles for high l values. Toboman[7] recently introduced the D.W.B.A. (distorted wave Born approximation) theory which appears to be more

---

[1] H.A. Enge, N.W. Buechner and A. Sperduto, Phys. Rev., 88, 963, (1952).

[2] P. Shapiro, Phys. Rev., 93, 290, (1954).

[3] Jag Jeet Singh, "A Study of the $S^{32}(d,p)S^{33}$ Reaction", College of William and Mary (unpublished).

[4] Richard H. Stokes, Phys. Rev., 121, 613, (1961).

[5] Richard Zdanis, George E. Owens and L. Mandansky, Phys. Rev., 121, 854, (1961).

[6] S.T. Butler, Proc. Roy. Soc., (London), A 208, 559, (1951).

[7] W. Toboman, Phys. Rev., 115, 98, (1959).

successful.

Most stripping reaction investigations have been made using nuclear emmulsion techniques. It is a tedious and time consuming method. With recent improvements in solid state detectors, the study of charged particle reactions has become much simpler. We decided to make detailed investigation of (d,p) reactions in light/intermediate heavy nuclei using S.S.R. detectors for proton detection.

This report concerns Al^{27}(d,p) reaction at deuteron energies below the Coulomb barrier. describes the experimental procedure involved in the investigation and gives a brief discussion of the detectors used. Theoretical results are presented for pure Butler and Butler plus Coulomb. Due to the relatively low cross section of the reaction it was not possible to obtain the accuracy desired.

THEORY

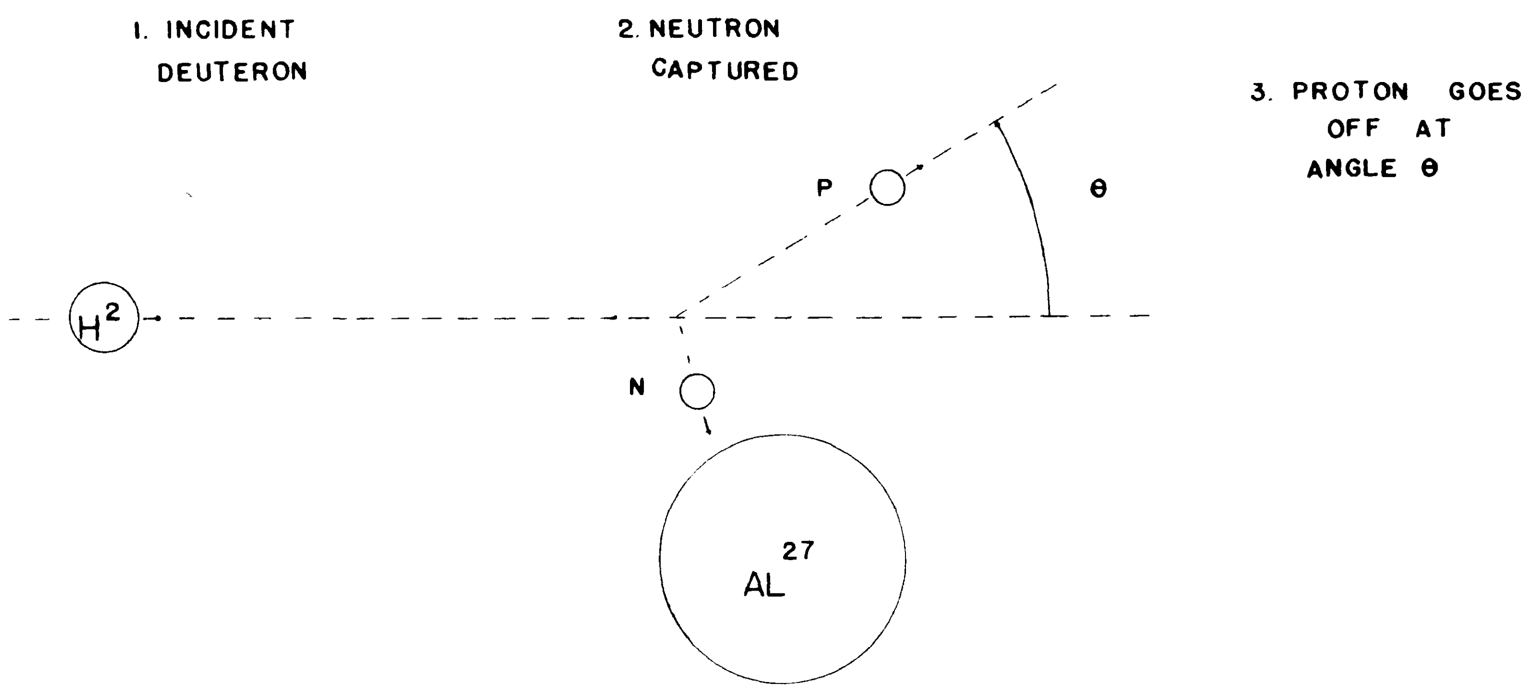
Two general classes of nuclear reactions are available for the study of a final nuclear state; those proceeding through a compound nuclear state and the direct reactions. The cross section of reactions going through a compound state is not only dependent on the initial and final states but also on the particular intermediate state involved. This complication is not prevalent in stripping reactions, which are direct reactions.

The reaction mechanism in pure Butler stripping can be understood best with the aid of the simple diagram on page 5. In this reaction, the deuteron approaches the target nucleus X, is stripped of one nucleon (neutron or proton) to form nucleus Y, while the other passes far enough away from X that at most it interacts weakly with X or Y. The reaction, with the above assumptions, can be represented by plane waves. This method has been quite successful with stripping reactions where the incident deuteron energies are large compared to the Coulomb barrier. Later the pure Butler theory was modified to include the Coulomb effects and nuclear effects.

Tobocman and Kalos[8] have given an expression which will

---

[8] W. Tobocman and M.H. Kalos, Phys. Rev., 97, 132, (1955).



(D,P) STRIPPING

reduce to pure Butler, Butler plus Coulomb and also account for other mechanisms. Their cross section is given by

$$\sigma_L(\theta_P)=\gamma_L \frac{(2J+1)\hbar^3 \epsilon^{\frac{1}{2}}(1+M_N/M_I)(1+M_D/M_I)^{-1}(1+M_P/M_F)^{-1}\sum_{m=-L}^{L}|B^{Lm}|^2}{(2I+1)R|E_N|E_D^{3/2}E_P^{\frac{1}{2}}M_N M_D^{\frac{1}{2}}} \qquad (1)$$

$$B^{Lm}=\sum_{l=0}^{\infty} P_l^{|m|}(\cos\theta_P)\sum_{\lambda} f_{l\lambda}^{L}\Gamma_{l\lambda}^{Lm}\exp\{i[\sigma_l(\eta_P)+\sigma_\lambda(\eta_D)+\tfrac{\pi}{2}(\lambda-l)]\}$$

$$\Gamma_{l\lambda}^{Lm}=\frac{(2\lambda+1)(2l+1)}{(2L+1)}\left[\frac{(l-|m|)!}{(l+|m|)!}\right]^{\frac{1}{2}}(l\lambda 00|l\lambda L0)(l\lambda m0|l\lambda Lm)$$

$$f_{l\lambda}^{L}=\frac{|K_N|}{h_L^{(1)}(i|K_N|R)}\int_{R(1+M_N/M_I)}^{\infty} dr\, h_L^{(1)}(i|K_N|r)[F_\lambda(\eta_D,K_D r)-\alpha_\lambda H_\lambda(\eta_D,K_D r)]$$

$$X\ [F_l(\eta_P,\frac{K_P r}{1+M_N/M_I})-\beta_l H_l(\eta_P,\frac{K_P r}{1+M_N/M_I})]$$

The symbols used are from the article by Tobocman and Kalos and are explained in detail in their paper.

Pure Butler theory, without Coulomb corrections, corresponds to Z = 0, $\beta_1 = 0$ and $\alpha_\lambda = 0$. When the above simplifications are introduced, the expression for

$$B^{Lm}=-\delta_{m0}\frac{i^L R^2 K_P K_D(1+M_N/M_I)}{|K_N|(1+|K_N|^{-2}\kappa^2)}\left[\frac{d}{dr}j_L(\kappa r)-j_L(\kappa r)\frac{d}{dr}\ln h_L^{(1)}(i|K_N|r)\right]_{r=R(1+M_N/M_I)} \qquad (2)$$

Where

$\kappa=K_D-(1+M_N/M_I)^{-1}K_P$, (ρ)= *the spherical Bessel function and* $h_L^{(1)}$ = *the spherical Hankel function of the first kind.*

In order to include the Coulomb effect, set Z = Z, $\beta_1 = 0$ and $\alpha_\lambda = 0$.

Both of these cases predict a cross section which peaks in the forward direction. The Coulomb correction has the effect of shifting the peak to slightly higher angles, while spreading the peak and filling in the valleys.

The usefulness of the stripping reaction lies in the fact that there are strong restrictions on the orbital angular momentum, l, of the nucleon captured by the target nucleus. If we let J_o represent the initial nuclear spin and J_f the final nuclear spin, then

$$\bar{J}_f = \bar{J}_o + \bar{l} + \bar{s}$$

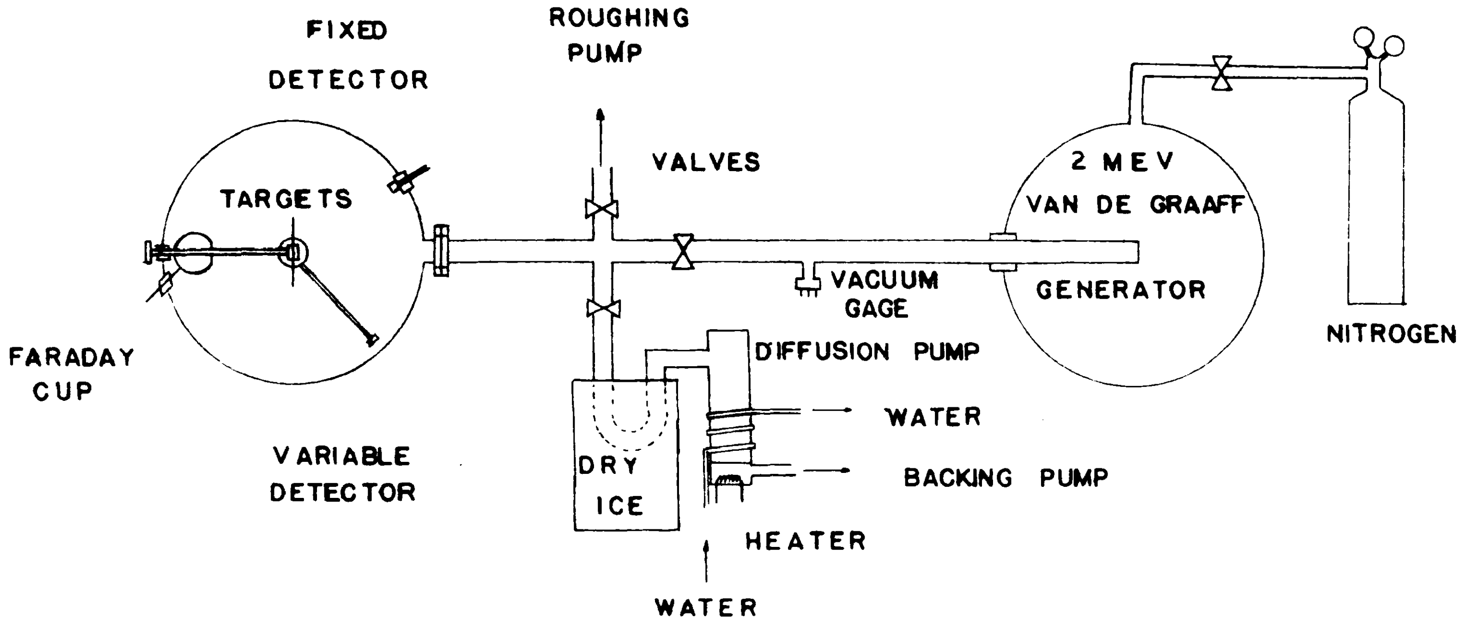
Also conservation of parity restricts l to even or odd values. From the expression for the cross section, one can see that the angular distribution determines l and the parity $(-1)^l$, and thus the final nuclear spin J_f.

However at deuteron energies comparable to or lower than the Coulomb barrier, this theoretical angular dependence fails to predict the back angle peaking observed in experiments. The introduction of the D.W.B.A. theory has been successful even at low incident energies and also is more reliable in separating different l contributions. The D.W.B.A. theory differs from the pure Butler in that it accounts for the effect of the target nucleus on the incident deuteron and the outgoing nucleon after stripping.

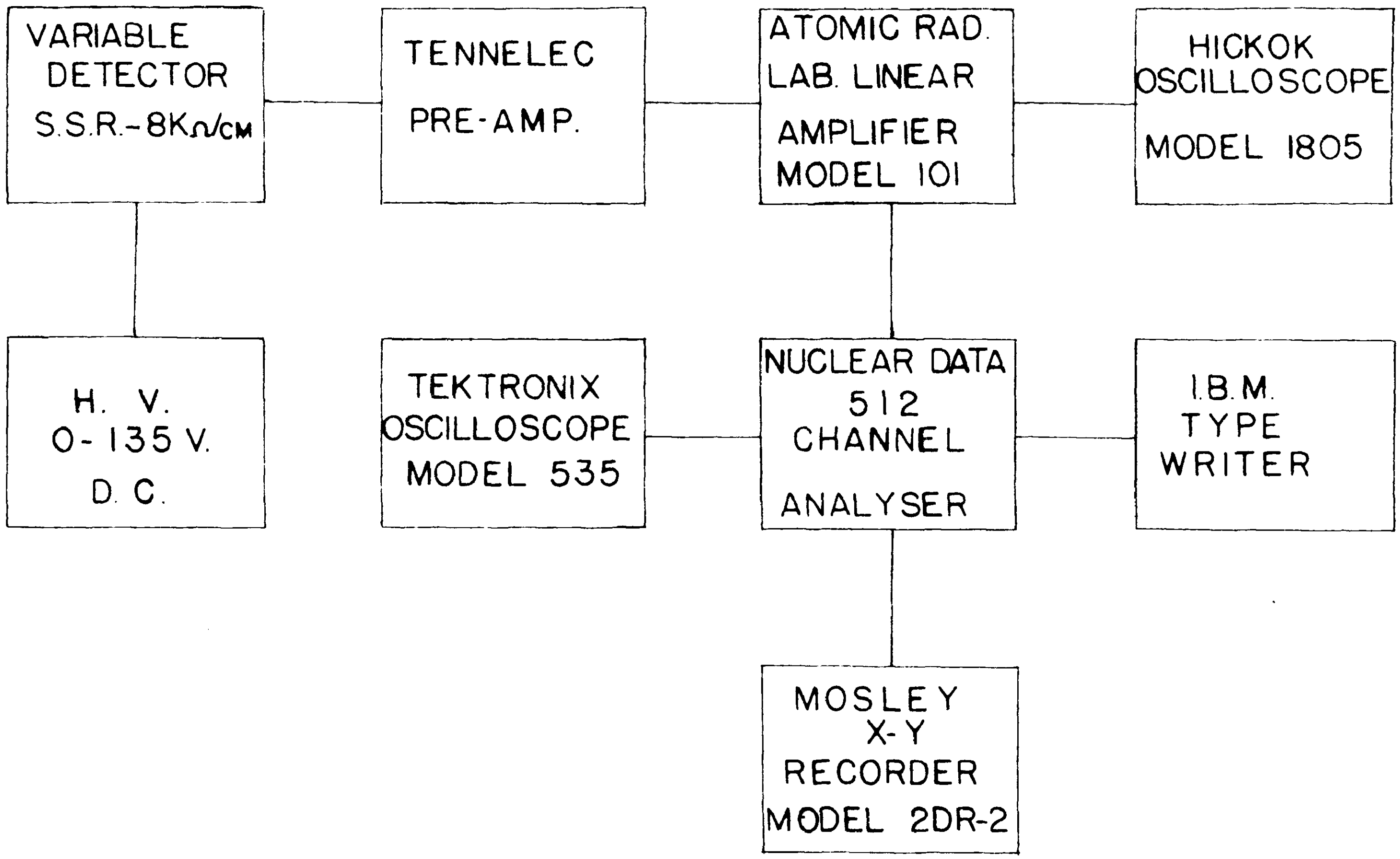
In some cases a slightly different situation may occur, in which the target nucleus instead of capturing a nucleon loses one. This is the so called exchange or heavy particle stripping reaction.[9] This leads to back angle peaking.

---

[9] L. Madansky and George E. Owens, Phys. Rev., 99, 1608L, (1955).


FIXED
DETECTOR
TARGETS
FARADAY
CUP
VARIABLE
DETECTOR
ROUGHING
PUMP
VALVES
DRY
ICE
VACUUM
GAGE
DIFFUSION PUMP
WATER
BACKING PUMP
HEATER
WATER
2 MEV
VAN DE GRAAFF
GENERATOR
NITROGEN

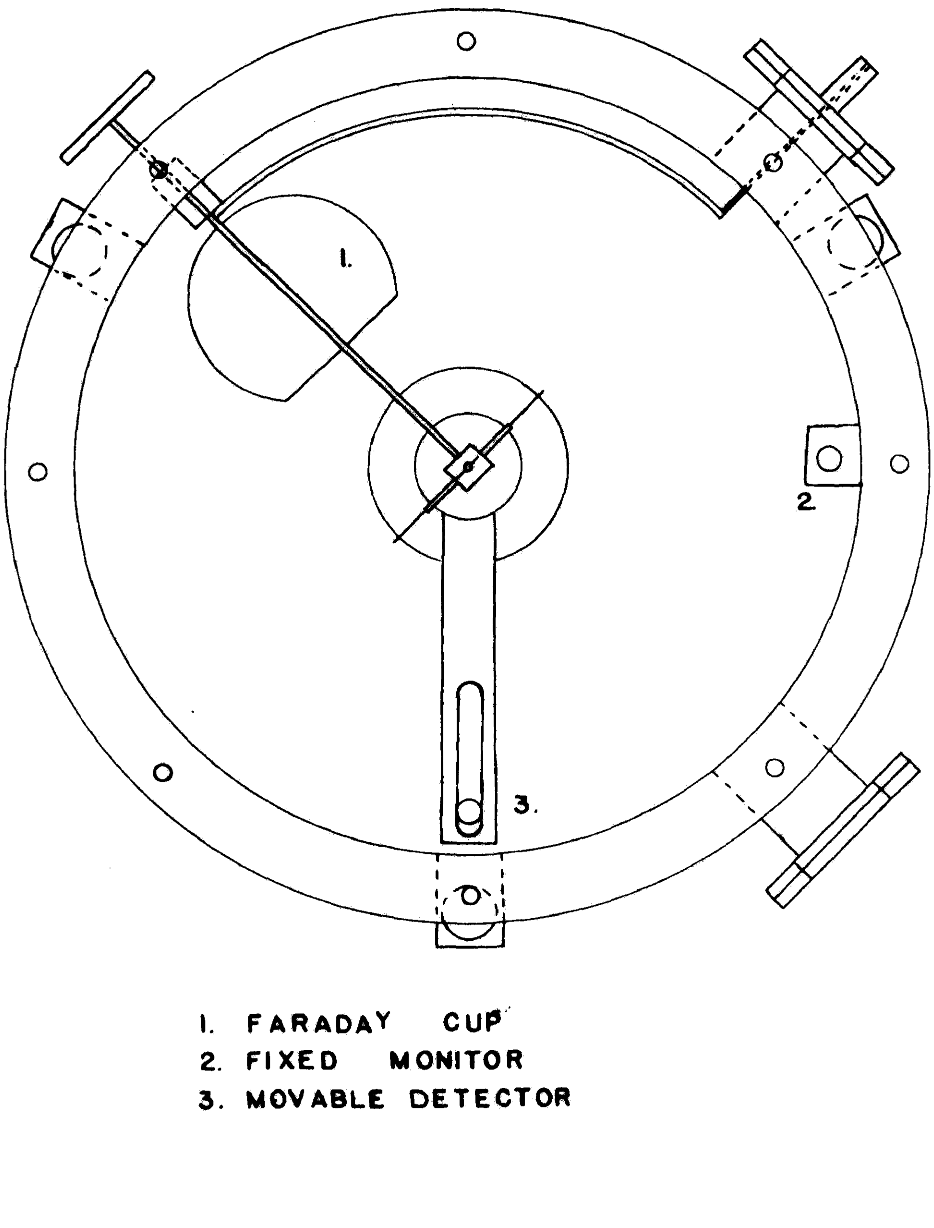
SCHEMATIC



BLOCK DIAGRAM

TARGET CHAMBER

TOP VIEW



1. FARADAY CUP
2. FIXED MONITOR
3. MOVABLE DETECTOR

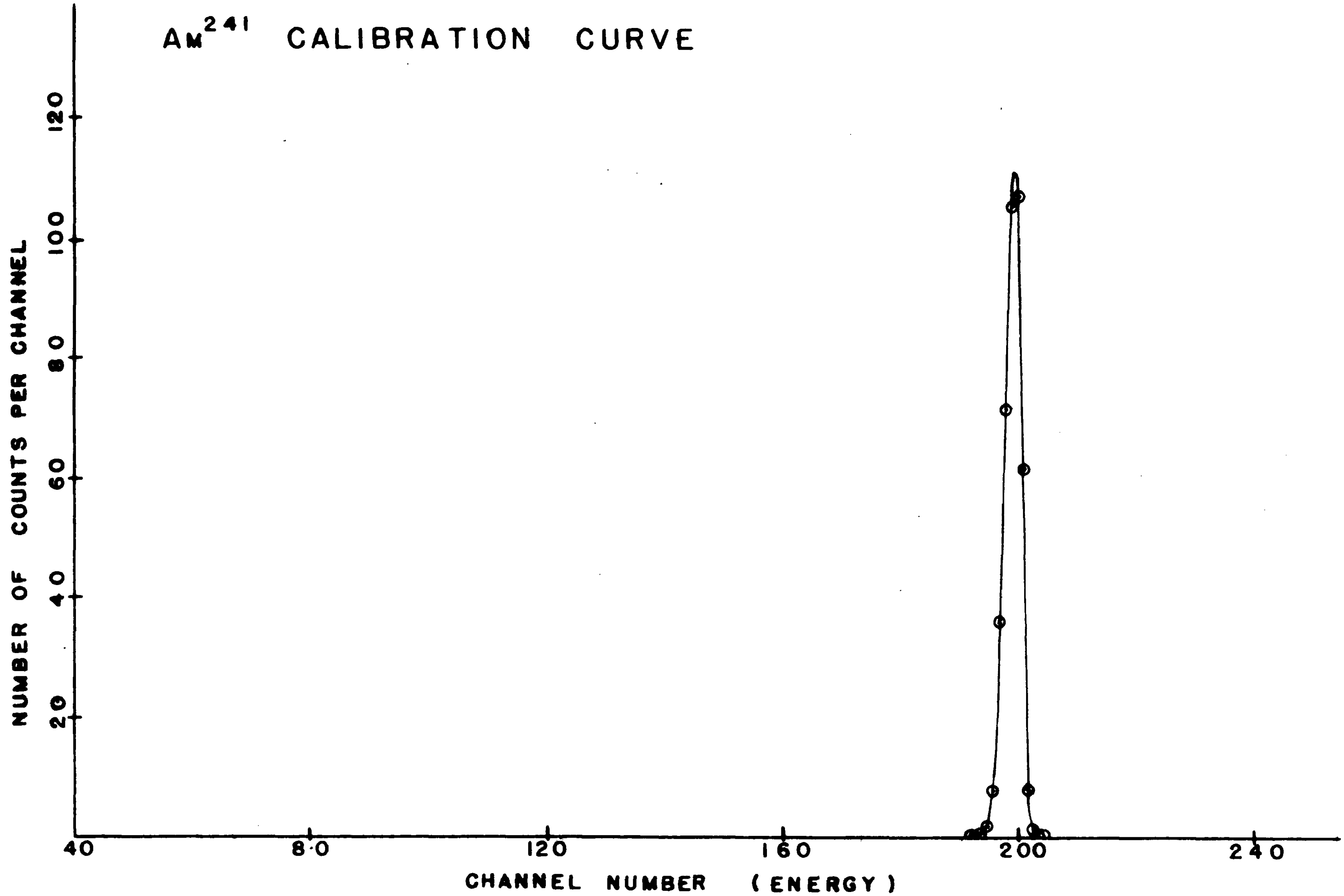
APPARATUS AND EXPERIMENTAL TECHNIQUE

(a) Apparatus

A schematic diagram on page 9 shows the Van de Graaff generator with the target chamber and vacuum system.

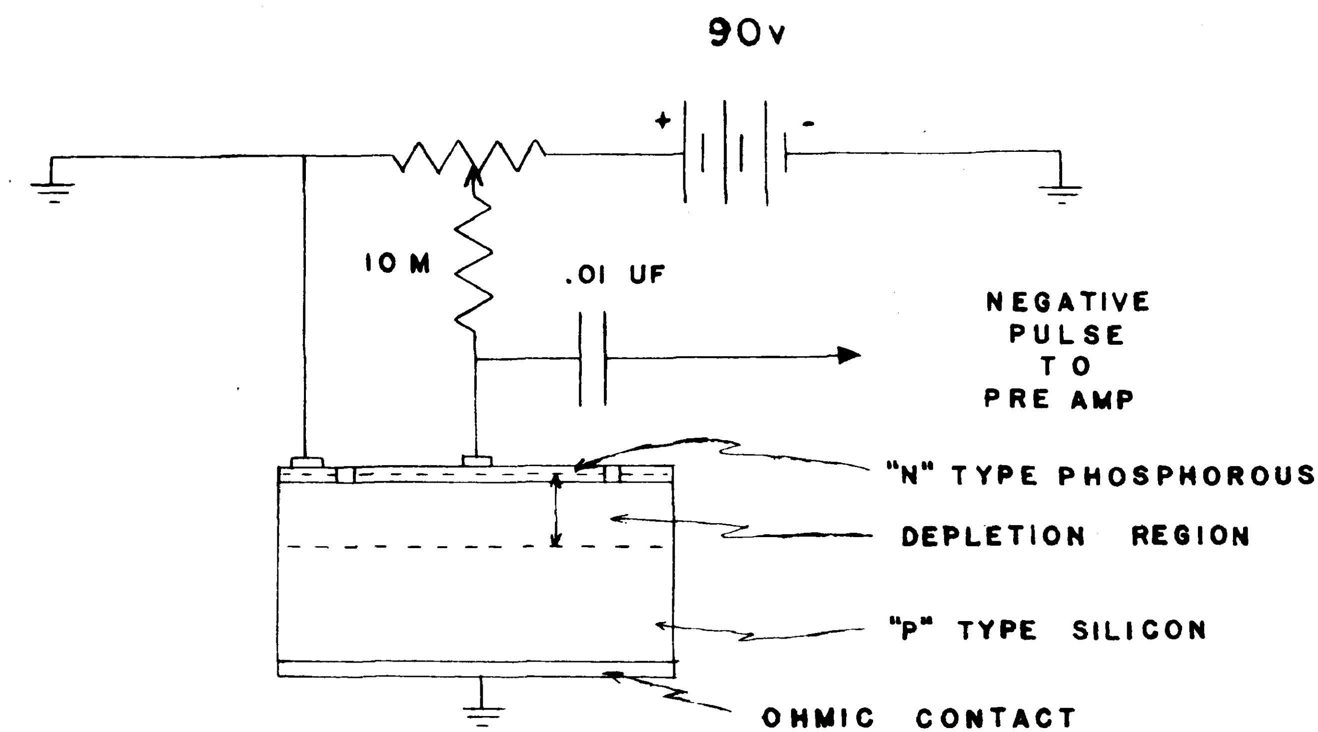
In this measurement, two systems were used, one for the movable detector and the other for the monitoring detector. A block diagram of the electronics is given on page 10. The output of the movable detector, after passing through a Tennelec charge sensitive pre-amplifier and a linear amplifier (ARL model # 101) was fed into the 512 channel Nuclear Data pulse height analyser. From the analyser one could put the data on a model 2DR-2 Moseley X-Y plotter and an IBM typewriter. The electronic system for the monitor was similar except that the output, after suitable discrimination, was fed into a scaler. An Americium 241 alpha source was used to provide a calibration point (E = 5.48 Mev). The calibration spectrum, obtained under conditions identical with those under which normal measurements were made, is shown on page 13. The Wright-Patterson Air Force Base 2 Mev Van de Graaff generator was used to provide a 0.1 micro ampere deuteron beam at 1350 kev energy.

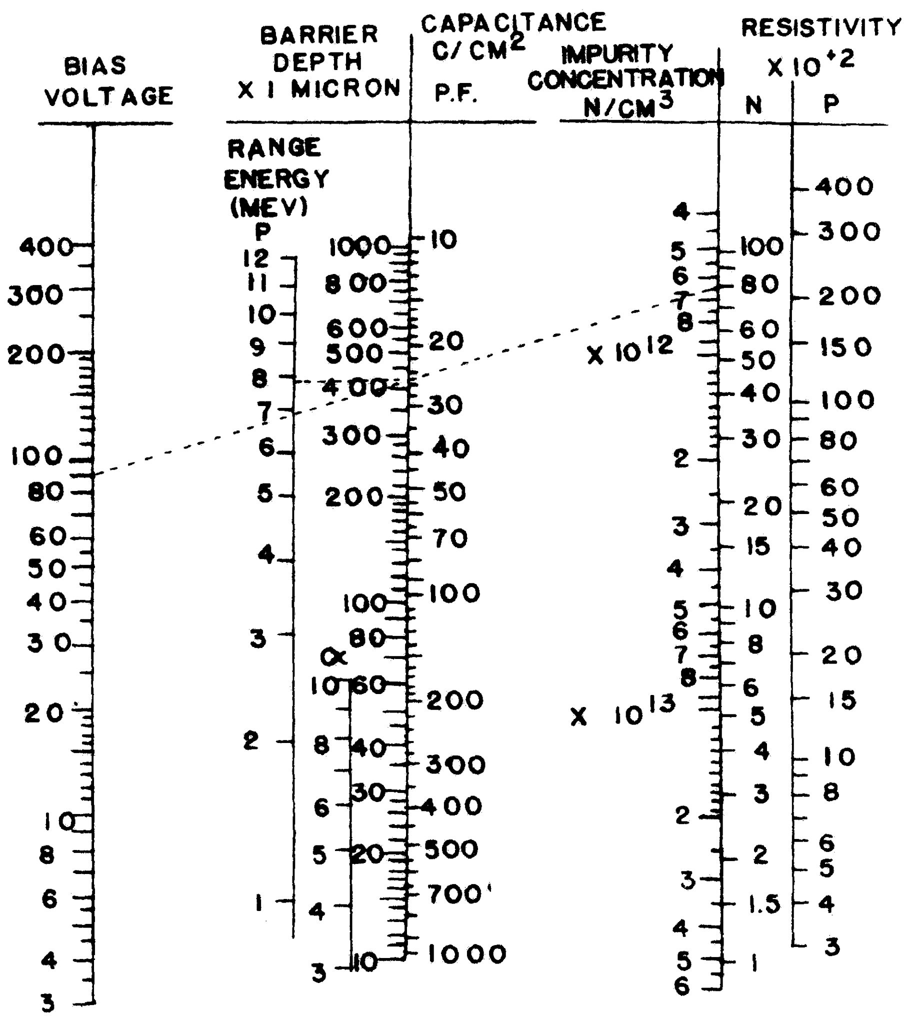
The target chamber, seen on page 11, is a 30 cm. diameter iron cylinder with vacuum port and beam port. Electrical


AM^{241} CALIBRATION CURVE
120
100
80
60
40
20
NUMBER OF COUNTS PER CHANNEL
40
80
120
160
200
240
CHANNEL NUMBER (ENERGY)

covar seal outlets were available for the two detectors and the Faraday cup. Four targets could be placed in the chamber and rotated into the path of the deuteron beam. The monitor detector was located at 160 degrees with respect to the deuteron beam. The position of the movable detector was adjustable from the outside and the angle read directly from the scale marked on the base of the chamber. The top of the chamber was made of a half inch thick glass plate with an O-ring seal. The chamber was evacuated to a pressure of the order of .01 micron by a system of diffusion pumps with dry ice/liquid nitrogen cold traps. The detectors used were Solid State Radiation detectors, NSPG-25. These detectors are sensitive to charged particles ranging from betas to fission fragments. A charged particle, say a proton, incident on the surface of the detector, penetrates the thin n-type layer and produces electron - hole pairs in the depletion layer, coming to rest in the depletion layer if its width is large enough to stop it. The depletion layer is the region on either side of the n - p junction which has neither excess electrons nor holes and is the sensitive region of the detector. The width of the depletion region, within limits, is determined by the bias voltage and the resistivity of the detector. The intense electric field in the depletion region sweeps apart the charge carriers produced by the incident radiation and the electrons are collected at the positive plate producing a negative voltage pulse, whose magnitude is proportional

SOLID STATE DETECTOR





NOMOGRAM FOR

SILICON JUNCTION DETECTORS

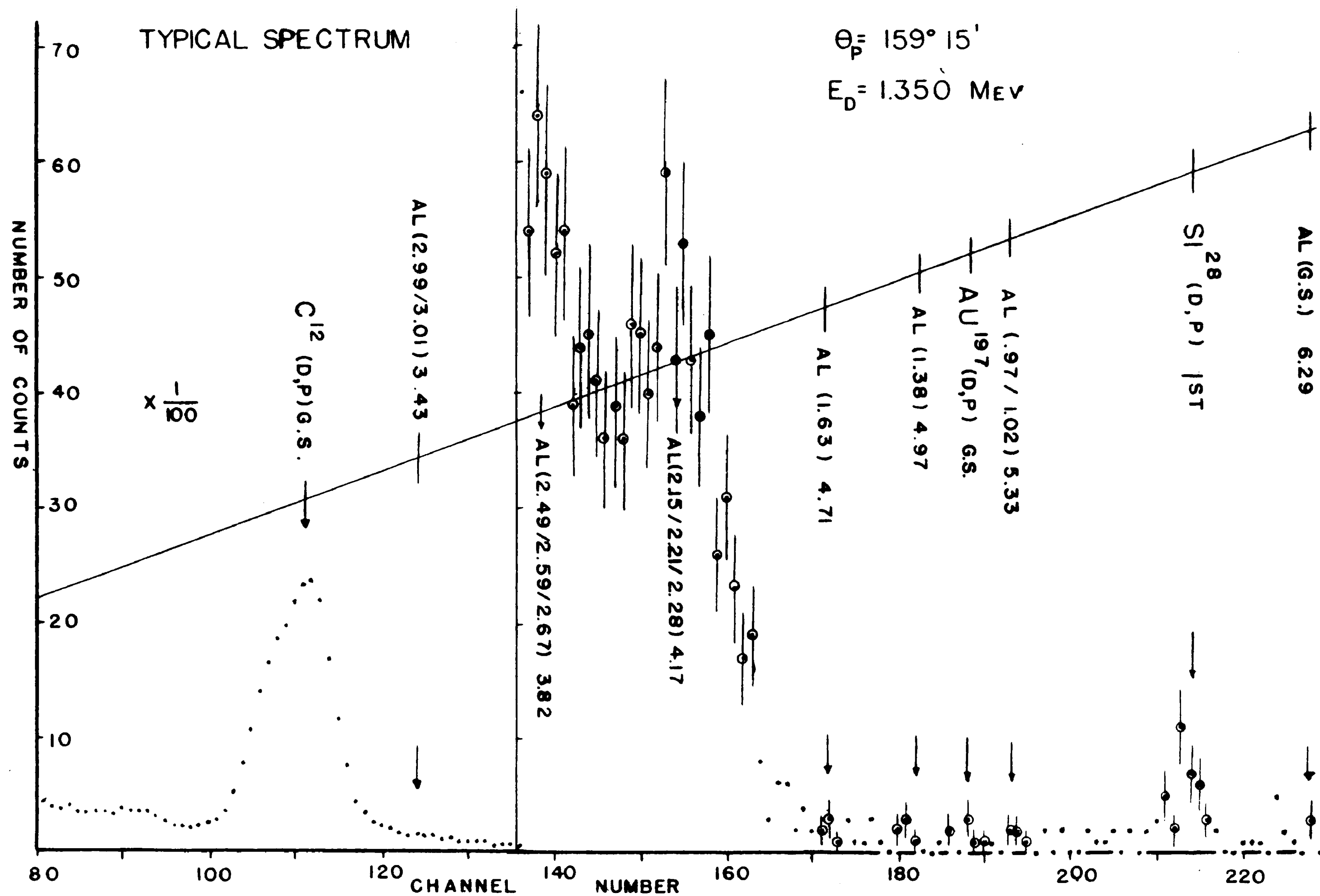
to the number of electrons crossing the junction. The rise time for a typical detector pulse is of the order of 3×10^{-9} seconds. This is to be compared with 10^{-7} seconds for a scintillation counter. In addition, the resolution using solid state detectors is considerably better than the most precise ion chambers.[10]

A Nomogram for silicon junction solid state detectors is shown on page 16. This allows one to determine capacitance per unit area of the detector surface and what energy protons and alphas, the detector will stop by knowing the bias voltage and the resitivity of the detector.

In the particular detector used, shown on page 15, a circular groove 50 micros wide and 10 microns deep is etched in the diffused n-type layer. Thus it extends through the junction into the p - region. This isolates the inner portion, which is the sensitive region, from the outer portion, which allows the noise generated by surface current at the edge of the wafer to be removed through the battery circuit. The reliability of the detector is seen to be greatly improved by the use of this "ring-guard".

---

[10] Editor, Nucleonics, 18, Number 5, 98, (May 1960).



TYPICAL SPECTRUM
Θ_P = 159° 15'
E_D = 1.350 MEV
x 1/100
C^{12} (D,P) G.S.
AL (2.99/3.01) 3.43
AL (2.49/2.59/2.67) 3.82
AL (2.15/2.21/2.28) 4.17
AL (1.63) 4.71
AL (1.38) 4.97
AU^{197} (D,P) G.S.
AL (.97/1.02) 5.33
SI^{28} (D,P) 1ST
AL (G.S.) 6.29
NUMBER OF COUNTS
CHANNEL NUMBER
70
60
50
40
30
20
10
80
100
120
140
160
180
200
220

(b) Experimental Procedure

The targets were prepared by mounting gold foils onto tantalum frames (90% tantalum, 10% tungsten) carefully cutting the foils and floating them on water. The frames were dipped in the water and drawn out so that the foils were flat on the frames and allowed to dry. Finally the aluminum was evaporated onto the gold. Several aluminum targets of different thicknesses were made in order to experimentally determine the most efficient thickness. The aluminum, kindly supplied by Alcoa, was of 99.99% chemical purity.

The thickness of the aluminum was determined in the following manner. First the thickness of the gold foil was found by measuring the weight of a large foil of known area. Deuterons, elastically scattered from gold and transmitted through the foil were detected with S.S.R. detectors. Next, the same deuterons, i.e. deuterons scattered through the same angle were observed from gold foils with aluminum evaporated on them. The difference in the energy corresponds to the energy lost by the deuterons in passing through the aluminum deposit. Using Kahn's tables[11] to obtain dE/dx for 674 kev protons in aluminum, dE/dx for 1350 kev deuterons in

---

[11] David Kahn, *Phys. Rev.*, 90, 503, (1953).

aluminum was obtained, since one may assume dE/dx for these two cases to be equal. The thickness was found to be

1.9×10^{-2} mg/cm^2.

When aluminum is bombarded with deuterons, a number of reactions occur. These can be broken down into the four main groups;

$_ZX^A(d,\alpha)_{Z-1}Y^{A-2}$, $_ZX^A(d,n)_{Z+1}Y^{A+1}$, $_ZX^A(d,p)_ZX^{A+1}$, and $_ZX^A(d,d)_ZX^{A*}$. The second group was no problem since the detectors used are not sensitive to neutrons. The first group was accounted for by the fact that the stopping power for alpha particles in any material is much larger than it is for protons in that material. Thus by placing an absorber foil over the detector, alpha particles can be stopped while the protons, although reduced in energy, will pass through and be detected. This was done and then the absorber was removed and another run was made. No new peaks were found in the second run, so that the (d,α) reaction could be considered negligible and the actual runs were made with no absorber on the detector.

The third group contained the reaction to be investigated plus various impurity reactions such as reactions with oxygen, carbon and nitrogen which remained in the target chamber. The change in the Q value with angle is a characteristic of a reaction and the various (d,p) reactions could be distinquished by use of the following equation, see diagram on page 5.

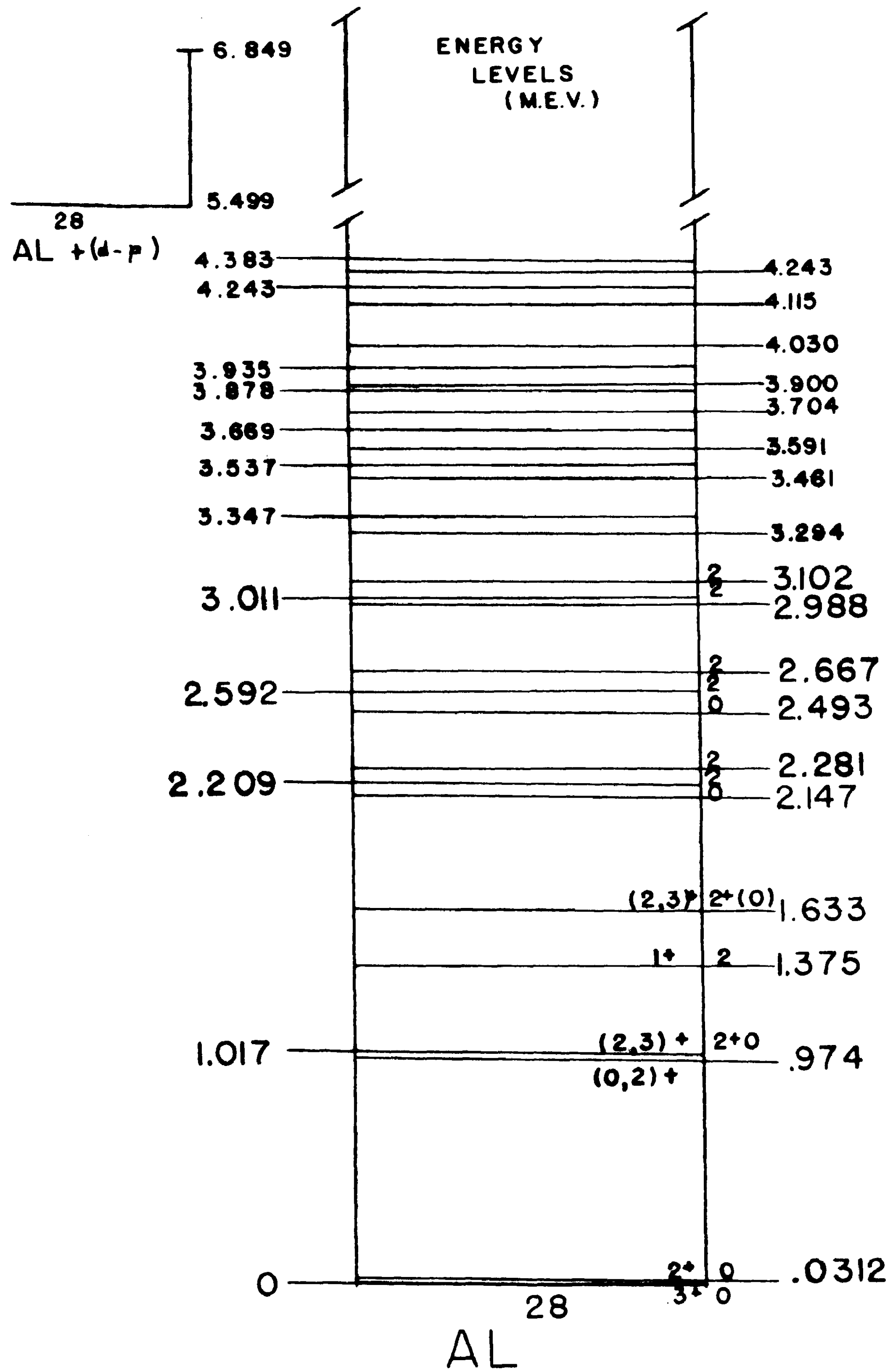
$$(E_3)^{\frac{1}{2}} = \frac{(M_1 M_3 E_1)^{\frac{1}{2}}}{M_3+M_4} \cos\theta_p \left(1 \pm \left\{1 + \frac{1+M_4/M_3}{\cos\theta_p}\left[\frac{M_4}{M_1}\left(1+\frac{Q}{E_1}\right)-1\right]\right\}^{\frac{1}{2}}\right) \quad (3)$$

Where 1 refers to the incident particle, 2 to the target particle, 3 to the remainder of the incident particle, 4 to the residual nucleus and the angle θ_p to the angle that the remainder of the incident particle makes with the incident deuteron beam. Obviously one can determine any of these reactions this way, so that even without the absorber one can account for the (d,α) reactions.

The fourth group is the elastic and the inelastic scattering of deuterons. These can produce deuterons with, at most, energies equal to the incident deuteron energy which is only 1.350 Mev. Thus these appear well below the first fifteen energy levels and do not create any ambiguities.

In order to realize the full potentialities of the detectors, the deuteron beam had to be kept at the relatively low value of .1 micro amp. This naturally caused the runs to be somewhat long in order to obtain reasonable statistical accuracy. For this reason, the number of angles, at which usable intensities of the proton groups were measured, had to be kept low. (d,p) reactions with nitrogen, oxygen and carbon complicated the spectrum in the lower energy region and few peaks were resolved at those energies.

By running the experiment with just the gold backing on the frame one can subtract out the contribution due to the various impurities. This was done.



ENERGY
LEVELS
(M.E.V.)
6.849
5.499
28
AL +(d-p)
4.383
4.243
3.935
3.878
3.669
3.537
3.347
3.011
2.592
2.209
1.017
0
4.243
4.115
4.030
3.900
3.704
3.591
3.461
3.294
3.102
2.988
2.667
2.493
2.281
2.147
(2,3)+ 2+(0) 1.633
1+ 2 1.375
(2,3)+ 2+0 .974
(0,2)+
2+ 0 .0312
3+ 0
28
AL

(c) Calculations

The differential cross sections have been calculated for the transitions to excited levels of Al^{28} listed in Table 1. The ground state and .0312 Mev states could not be resolved and were very weak as was also the case for .974 and 1.017 Mev states and the 2.988 and 3.011 Mev states. The resolution for the 2.147, 2.209 and 2.281 Mev levels and the 2.493, 2.592 and 2.667 Mev levels also was not very good. The diagram on page 18 shows a typical spectrum over the energy range resolved. The diagram on page 23 gives the excited energy levels in Al^{28}.

TABLE 1

Al^{28} Groups	Excitation Energy Mev	$Q(\theta_p)$ Mev, θ in c.m. units				
		27°25'	55°55'	117°10'	140°	159°15'
1	0	6.816	6.717	6.421	6.334	6.287
2	1.0	5.797	5.706	5.434	5.354	5.311
3	1.375	5.421	5.334	5.071	4.993	4.951
4	1.633	5.172	5.086	4.829	4.754	4.712
5	2.147	4.685	4.604	4.359	4.287	4.249
6	2.209	4.602	4.522	4.280	4.209	4.170
7	2.281	4.531	4.451	4.211	4.140	4.102
8	2.493	4.321	4.243	4.008	3.940	3.907
9	2.592	4.223	4.149	3.914	3.846	3.810
10	2.667	4.149	4.072	3.843	3.775	3.739
11	3.0	3.820	3.746	4.516	3.461	3.427

From the charge incident on the target, one can calculate the number of deuterons incident on the target. This charge was found by use of the Faraday cup. This is used in the expression for total cross section[12] for the i$\underline{th}$ process:

$$\sigma = \frac{n_i}{IN_s} \tag{4}$$

where n_i is the number of incident particles which cause the i$\underline{th}$ process or the number of protons in the i$\underline{th}$ group, I is the number of incident particles (deuterons) per unit time and N_s is defined by:

$$N_s = \frac{N_A\ (\rho S \Delta x)}{M} \tag{5}$$

where N_A is Avagadro's number, ρ is the density of the target, S is the area that the beam covers on the target, Δx is the thickness of the target and M is the gramatomic weight of the target. n_i is found by obtaining the integrated number of protons in the peak and Δx is found as previously described. The area of the beam was determined to be $\sim .12\ cm^2$.

The differential cross section per unit solid angle is given by:

$$\sigma_i (\theta_i, \phi_i) = \frac{\Delta n}{IN_S} \tag{9}$$

---

12 Alex E.S. Green, Nuclear Physics, McGraw-Hill, (1955).

where $\Delta\Omega_1 = 2\pi \sin\theta_1 d\theta_1$

is an element of solid angle and Δn is the number of reaction particles which go into $\Delta\Omega_1$ and is dependent on θ.

The effective differential cross sections given in Table II on page 30 are not evaluated at a particular angle, but is the value $d\sigma/d\Omega$ would have if the protons emerged with spherical symmetry.

The cross sections for pure Butler theory and Butler plus Coulomb effect for values l ± 0,1,2,3; L ± 0,2; λ = 2; and Ex ± 0, 1.633, 2.147, and 2.592 Mev were calculated by hand where

L = orbital angular momentum of the captured neutron

l = orbital angular momentum of the emerging proton

λ = orbital angular momentum of the incident deuteron

It was assumed that the contribution due to the separate levels in close lying groups was equal. Also the assumption was made in the cross section calculations that $K_N r$ was large compared to L, where $K_N r$ is given by

$$|K_N|^2 r^2 = 2|E_N| M_N \hbar^{-2}(1+M_N/M_I)^{-1} r^2$$

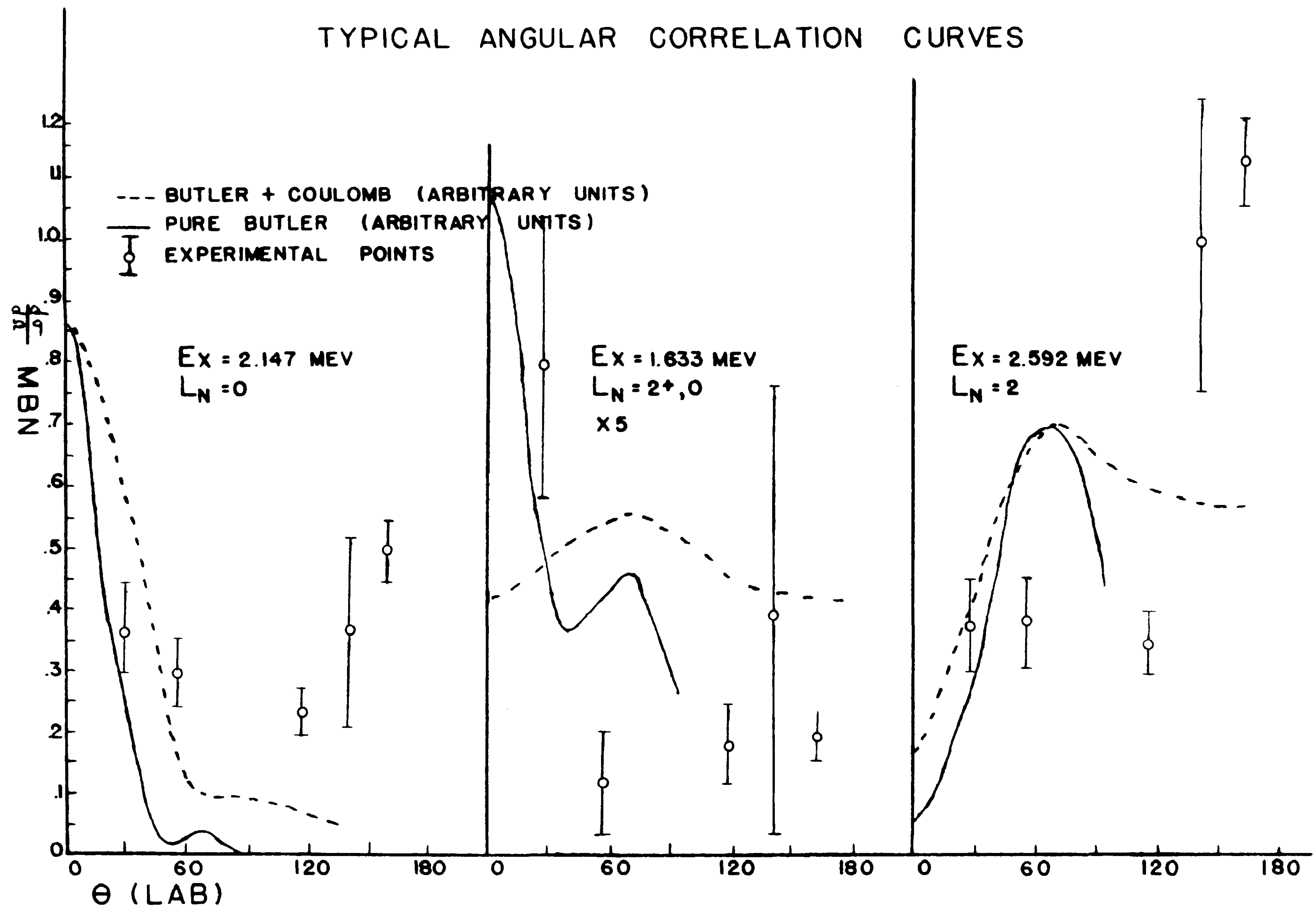
This introduces some error, but simplifies the calculations considerably.

Thus one obtains the following average integrated value for (d,p) cross section for the excited level at 2.209 Mev

$\sigma_{(d,p)} = .577 \pm 70\%$ micro bns.

The uncertainty is determined by using the statistical error and then doubling it to account for approximations.

The comparison of the Butler theory and the Butler theory modified to include Coulomb effects is shown along with the experimental points on page 28.


TYPICAL ANGULAR CORRELATION CURVES
--- BUTLER + COULOMB (ARBITRARY UNITS)
PURE BUTLER (ARBITRARY UNITS)
EXPERIMENTAL POINTS
Ex = 2.147 MEV
L_N = 0
Ex = 1.633 MEV
L_N = 2+,0
X 5
Ex = 2.592 MEV
L_N = 2
$\frac{d\sigma}{d\Omega}$ MBN
Θ (LAB)
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
0
60
120
180

CONCLUSIONS

The extremely poor fit of the experimental points with the pure Butler Theory indicates that the plane wave assumption is no longer valid in this energy region. Even with the addition of the Coulomb correction the fit is very poor.

The back angle intensity seems to indicate that heavy particle stripping is playing a part. However, there is nothing to discourage normal stripping in this reaction: the neutrons could go into the 2 $s_{1/2}$, $1d_{3/2}$ or 2 $p_{3/2}$ sub shells. Perhaps D.W.B.A. might fit the data better. Further measurements are in progress. It is hoped that the new extensive measurements will present an answer to the correct theoretical approach.

SUMMARY

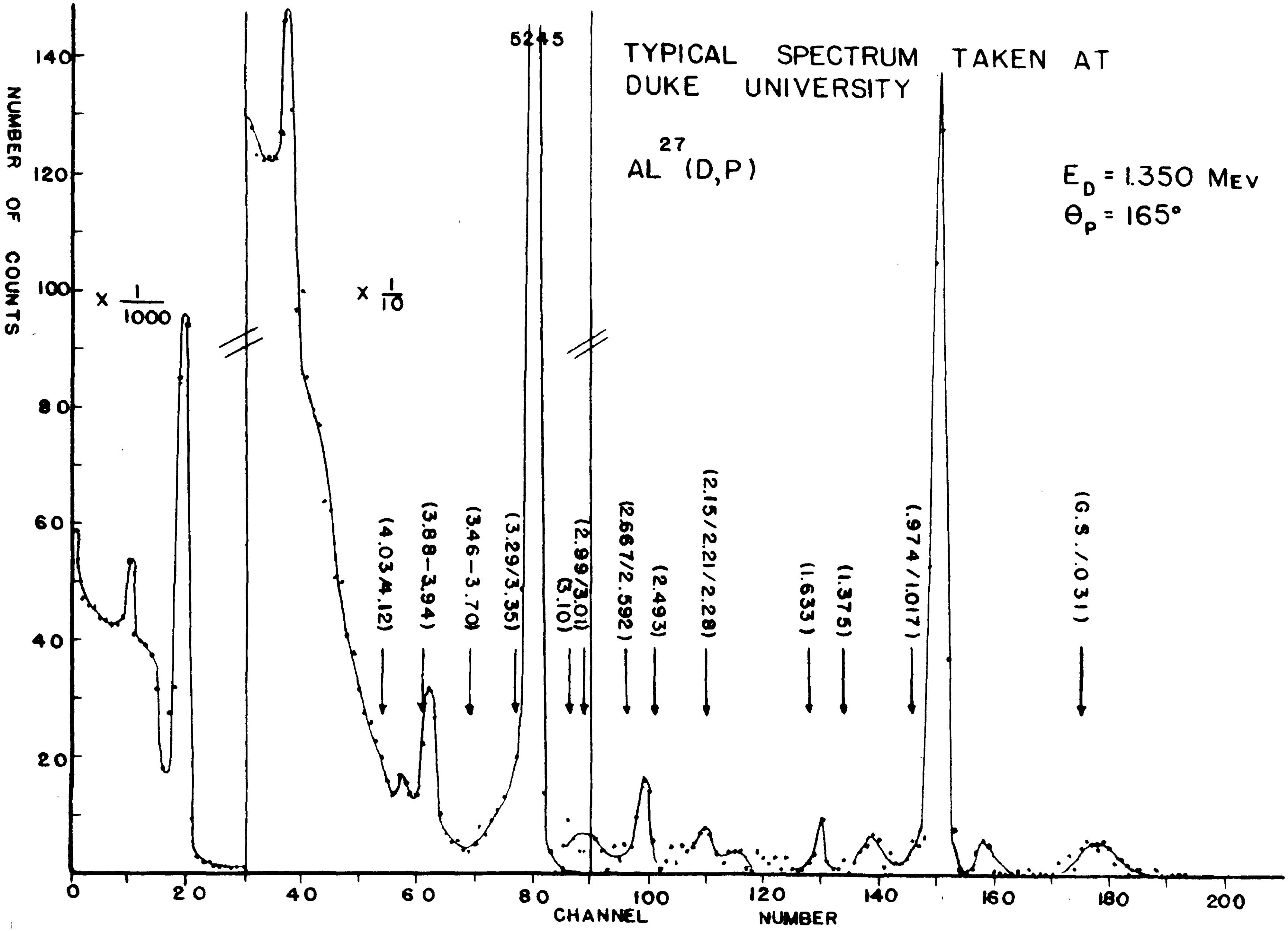
The effective partial differential cross section and the peak back angle differential cross section to the various energy levels are given in Table II. The effective differential cross sections were obtained by use of the differential cross sections given by equation (9). $d\sigma/d\Omega$ was plotted against θ and the area under the curve was found. This integrated value was then used to determine what constant value of $d\sigma/d\Omega$ would give the same integrated value under the experimental points. This is equivalent to assuming the pattern of protons after stripping to be spherically symmetrical. As was noted earlier, several

TABLE II

Energy Level (Mev)	Effective $d\sigma/d\Omega$ mμ bns	Peak Back Angle Value $d\sigma/d\Omega$ mμ bns
g.s./.0312	12.6 ± 11.0	18.1 ± 15.0
1.00(.974/1.017)	377 ± 196	380 ± 277
1.375	565 ± 396	364 ± 192
1.633	842 ± 387	558 ± 353
2.21(2.147/2.209/2.281)	$(16.2\pm3.2)\times10^3$	$(33.0\pm6.1)\times10^3$
2.58(2.493/2.592/2.667)	$(23.0\pm4.6)\times10^3$	$(45.7\pm7.9)\times10^3$
3.00(2.988/3.011)	$(15.7\pm1.2)\times10^3$	$(31.9\pm6.1)\times10^3$

groups were too close to be separated. In calculating the cross sections, equal contributions from each of the close lying levels in the group were assumed. In this way the partial differential cross sections for the individual levels in the group were calculated.

The results of this investigation, although not fully explained in terms of normal stripping theory, show that the direct reaction plays an important part at energies well below the Coulomb barrier. At the present time, Dr. Jag J. Singh is continuing the work with other target nuclei. Using the identical set up he obtained the spectrum shown on page 32 for the $Al^{27}(d,p)\,Al^{28}$ reaction with $E_d = 1.350$ and $\theta = 160^{o}$. The detectors used by Dr. Singh were Molechem surface barrier p-n type detectors biased to 150 volts. The depletion region width was 1 mm. Eventually, the detailed experimental results will be compared with various direct reaction theories. The use of better detectors and various incident energies should clarify the situation.


TYPICAL SPECTRUM TAKEN AT
DUKE UNIVERSITY
AL^{27} (D,P)
E_D = 1.350 MEV
Θ_P = 165°
5245
x 1/1000
x 1/10
(4.03/4.12)
(3.88–3.94)
(3.46–3.70)
(3.29/3.35)
(3.10)
(2.99/3.01)
(2.667/2.592)
(2.493)
(2.15/2.21/2.28)
(1.633)
(1.375)
(.974/1.017)
(G.S./.031)
NUMBER OF COUNTS
CHANNEL NUMBER

BIBLIOGRAPHY

Austern, N., Phys. Rev., 89, 318L (1953).

Butler, S. T., Phys. Rev., 93, 355 (1954).

Butler, S. T. and HittMair, O. H., Nuclear Stripping Reaction (John Wiley & Sons, Inc., New York, 1957).

Enge, H. A., Buechner, W. W. and Sperduto, A., Phys. Rev., 88, 963 (1952).

Evans, R. D., The Atomic Nucleus (McGraw-Hill Book Company, Inc., New York, 1955).

Francis, N. C. and Watson, K. M., Phys. Rev., 93, 313 (1954).

French, A. P., Phys. Rev., 107, 1655 (1957).

Friedland, S. S., Mayer, J. W. and Wiggins, J. S., Nucleonics, 18, #2, 54 (Feb. 1960).

Fröberg, Carl-Erick, Revs. Modern Phys., 27, 399 (1955).

Gerjuoy, E., Phys. Rev., 91 645 (1953).

Green, Alex E. S., Nuclear Physics (McGraw-Hill Book Company, Inc., New York, 1955).

Kahn, David, Phys. Rev., 90, 503 (1953).

Macfarlane, M. H. and French, J. B., Revs. Modern Phys., 32, 567 (1960).

Mandansky, L. N., Owens, George E., Phys. Rev., 99, 1608L (1955).

Shapiro, P., Phys. Rev., 93, 290 (1954).

Singh, Jag Jeet, "A Study of the S^{32}(d,p) Reaction" (unpublished).

Stokes, Richard H., Phys. Rev., 121, 613 (1961).

Tobocman, W., Phys. Rev., 94, 1655 (1954).

Tobocman, W., Phys. Rev., 115, 98 (1959).

Tobocman, W. and Kalos, M. H., *Phys. Rev.*, *97*, 132 (1955).

Wu, T. Y. and Ohmura, T., *Quantum Theory of Scattering* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1962).

Zdanis, George, Owens, E. and Mandansky, L., *Phys. Rev.*, *121*, 854 (1961).

VITA

<u>Richard Heath Parker</u>

Born in Richmond, Virginia, October 1, 1938. Graduated from Thomas Jefferson High School in that city, June 1957; B. S.; Virginia Military Institute, June 1961.

In September 1961, the author entered the College of William and Mary as a graduate assistant in the Department of Physics.