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Progress Report
University of Michigan Cyclotron

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ABSTRACT

This report describes the experimental and theoretical research effort of the Michigan 42" cyclotron group during the period from August 1958 to July 1959. Five problems received major attention: the level structure in the Mg isotopes; levels of Ti^{47}, Ti^{49}; levels of B^{11}; states of low excitation in O^{19}; and proton polarization in the (d,p) reaction.

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* Two-thirds time cyclotron, one-third time scanner.

I. Introduction

During the period covered by this report the principal effort of the cyclotron group has been devoted to work on five problems: The structure of the ld-shell with emphasis on the level structure of the Mg isotopes; the structure of the lf-shell as displayed by Ti^{47} and Ti^{49}; the character of the levels in B^{11}; states of low excitation in O^{19}; and polarization of the outgoing proton in the (d,p) reaction. In addition the theoretical investigation of direct reactions was continued, and further improvements were made in the instrumentation associated with the cyclotron.

The cyclotron continued to operate in a satisfactory manner, the shut-down time due to machine repairs amounting to only eleven days. An additional three weeks of running time were lost however, due to the installation of the radiation shielding described in the 1958 report.

II. The Experimental Program

A. Structure of the ld-Shell; Levels of Magnesium

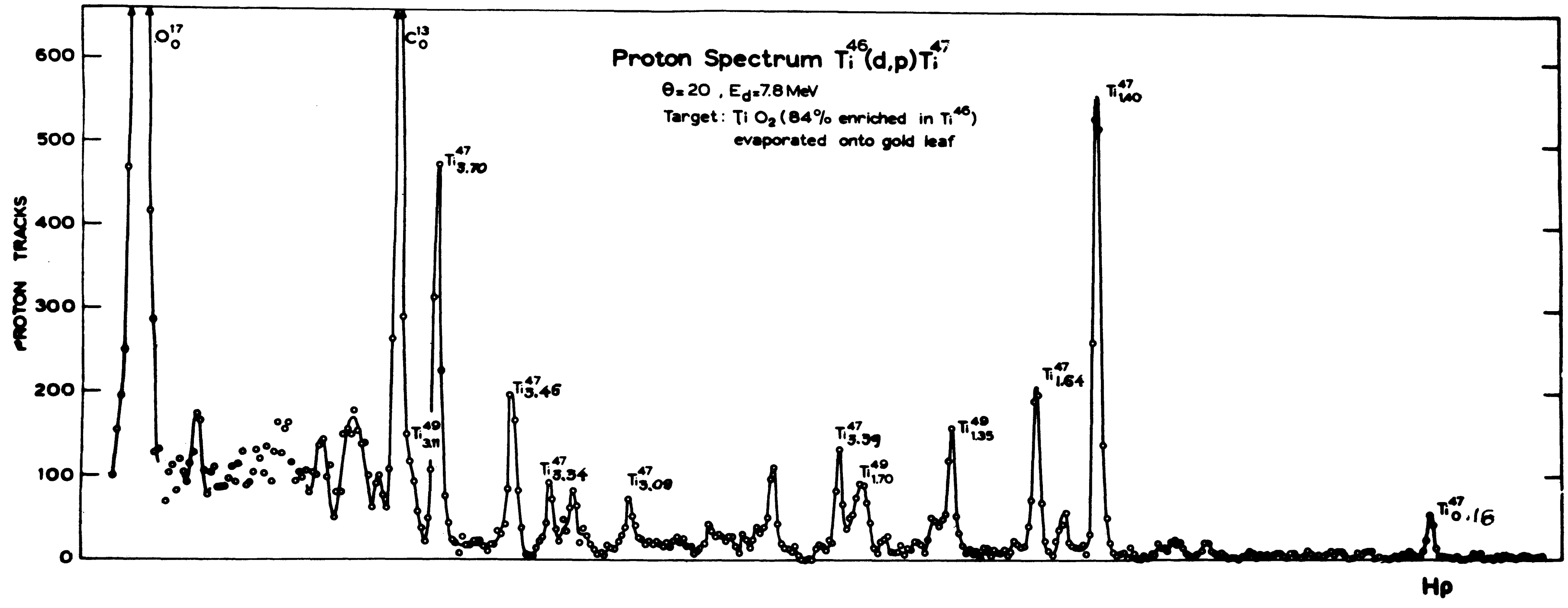
The study of the level structure of the magnesium isotopes, discussed at some length in the 1958 report, was continued, and occupied the full-time of about half of the staff. Essentially all of the previously reported levels have been identified, and most of the effort has gone into the identification of new levels and into obtaining final differential cross-sections. The identification of each new level requires a careful analysis of the reaction kinematics and of the relative intensities with natural and enriched targets. For example, we believe the "missing" 9/2+ level belonging to the K = 5/2+ rotational band in Mg^{25} has been located, yet some uncertainty remains in its identification because not one but three new levels have been found in the narrow energy region in which it should occur. Angular distributions with thin, natural and enriched targets should make possible its unambigious identification.

The nuclear emulsion scanner continues to play an important role in the extraction of data from the photographic plates. While the efficiency is not as yet constant to within ± 20% and therefore all peaks must be hand scanned to obtain the absolute intensities necessary for angular distributions, nevertheless, a method of operation has been developed that makes full use of its present capabilities. The scanner, as a matter of routine, reads out the data from essentially all plates. The results are directly useful in establishing level identification via energy-angle relations and in locating on each plate the levels to be hand-scanned. Details of the method of operation and productivity will be given in the annual progress report of the scanner project.

The problems that have arisen in the level identification have prompted further refinements in the instrumentation for reaction products analysis. These are discussed in Section F.

B. $Ti^{46}(d,p)Ti^{47}$ and $Ti^{48}(d,p)$ Ti^{49} and the 1f-Shell

The investigation of the 1f-shell through the study of the level structure in Ti^{47} and Ti^{49} has been continued. The proton spectrum for the reaction $Ti^{46}(d,p)Ti^{47}$ is shown in Fig. 1 and includes all the previously known levels of Ti^{47},



Proton Spectrum $Ti^{46}(d,p)Ti^{47}$
θ=20 , E_d=7.8 MeV
Target: Ti O_2 (84% enriched in Ti^{46})
evaporated onto gold leaf
PROTON TRACKS
0
100
200
300
400
500
600
O^{17}_0
C^{13}_0
$Ti^{47}_{3.70}$
$Ti^{49}_{3.11}$
$Ti^{47}_{3.46}$
$Ti^{47}_{3.34}$
$Ti^{47}_{3.09}$
$Ti^{47}_{3.39}$
$Ti^{49}_{1.70}$
$Ti^{49}_{1.35}$
$Ti^{47}_{1.64}$
$Ti^{47}_{1.40}$
$Ti^{47}_{0.16}$
Hρ

Fig. 1

up to 4 Mev excitation, and two new levels at 3.34 Mev and at 3.45 Mev. The ground state is so weak that it does not appear in Fig. 1. A series of long exposures, however, have permitted this group to be distinguished from the background, and from impurity groups, by its consistent appearence at 160 Kev above the first strong $Ti^{46}(d,p)Ti^{47}$ group. These new results reconcile the findings reported last year with the spin assignment of J = 5/2 by Jeffries.[1] The relative intensities of Ti^{47} ground state and 0.160 Mev group imply that the configuration of Ti^{47}_{0} is predominantly $(f_{7/2})^{5}_{5/2}$ while the 160 Kev state has the single particle configuration of $\left[(f_{7/2})^{4}_{0} f_{7/2}\right]$. The angular distribution of Fig. 2 further corroborates this interpretation.

Data on the angular distributions for levels in Ti^{47} at 1.64, 2.39, 3.09, 3.34, 3.45, and 3.70 Mev excitation have been recorded in nuclear emulsions and are in the process of being evaluated. In addition, angular distributions for levels in Ti^{49} at 0, 1.35, 1.70, and 3.11 Mev have been measured and the results, now shown here, are in agreement with previous low resolution findings.[2]

A preliminary report on this work was given at the 1959 spring meeting of the American Physical Society.[3]

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(1) C. D. Jeffries, Phys. Rev. 92, 1262 (1953).
(2) M. M. Bretscher, et al, Phys. Rev. 96, 103 (1954).
(3) L. H. Th. Rietjens and O. M. Bilaniuk, Bull. Am. Phys. Soc. 11-4, 233, (1959).

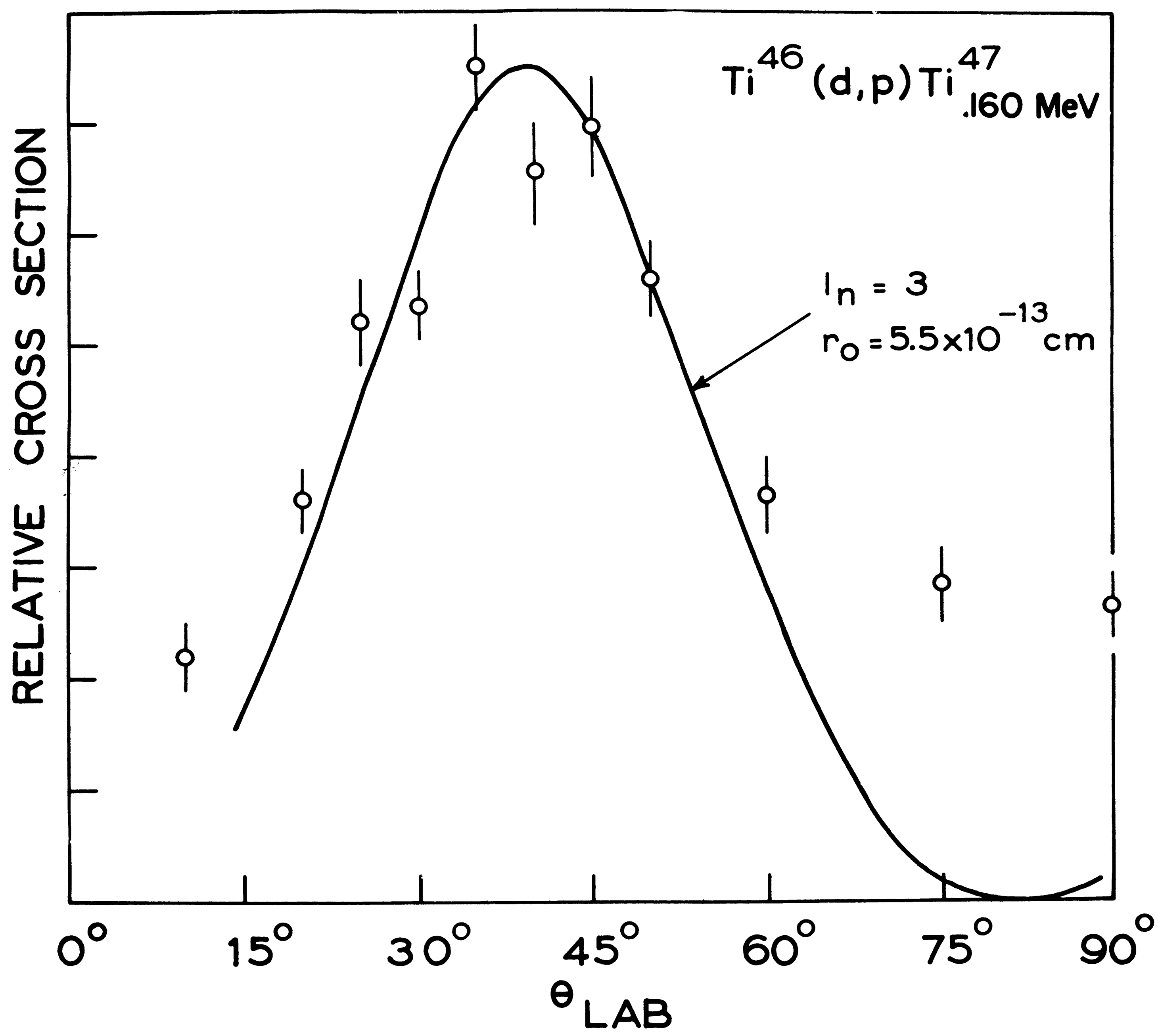
Ti46(d,p)Ti47 .160 MeV
ln = 3
ro = 5.5x10−13 cm
RELATIVE CROSS SECTION
0°
15°
30°
45°
60°
75°
90°
θLAB

Fig. 2

C. The $B^{10}(d,p)B^{11}$ Reaction and Configurations of B^{11}

The investigation of the reaction $B^{10}(d,p)B^{11}$ discussed in the 1958 report was limited to states of high excitation. Measurements have now been extended to include most of the states of B^{11} lying below 9 Mev and the results are in process of publication.[4]

The low lying states of B^{11} are believed to arise mainly from excitation within the 1p-shell and on this assumption the intermediate coupling model[5,6] predicts the ordering to be 3/2-, 1/2-, 7/2-, 5/2-, and 3/2- with some freedom in ordering the last three depending upong a particular choice of intermediate coupling parameter a/K and exchange parameter L/K. Earlier measurements[7,8,9] of the angular distribution of the proton groups from $B^{10}(d,p)B^{11}$ indicated that the neutrons were captured with $\ell_n=1$ for the ground state and for each of the first four excited states at 2.14, 4.46, 5.03, (6.76-6.81) Mev excitation respectively. The anomalous angular distribution for the level at 2.14 Mev placed some doubt on the $\ell_n=1$ interpretation although it was not inconsistent with the proposed spin-flip mechanism.[10]

(4) J. C. Hensel and O. M. Bilaniuk, Phys. Rev. (to be published)
(5) D. R. Inglis, Rev. Mod. Phys. <u>25</u>, 390 (1953).
(6) D. Kurath, Phys. Rev. <u>101</u>, 216 (1956).
(7) N.T.S. Evans and W. C. Parkinson, Proc. Phys. Soc. (London) <u>A67</u>, 684 (1954).
(8) S. A. Cox and R. M. Williamson, Phys. Rev. <u>105</u>, 1799 (1957).
(9) B. Zeidman and J. M. Fowler, Phys. Rev. <u>112</u>, 2020 (1958).
(10) J. C. Hensel and W. C. Parkinson, Phys. Rev. <u>110</u>, 128 (1958), and references therein.

A careful examination of this energy region has now been made to exclude the possibility of an unresolved doublet or that contributions from target impurities influenced the angular distribution. The angular distributions obtained for the ground and 2.14 Mev states with an overall resolution of 35 Kev are in agreement with earlier work,(7,9) except for the abrupt rise in intensity at forward angles (below $\theta cm=15^{\circ}$) for the 2.14 Mev level shown in Fig. 3. Measurements at the forward angles with the beam energy increased from E_d = 7.78 Mev to E_d = 7.92 Mev gave the same angular distribution. This does not lend weight to the suggestion that the rapid variation in angular distribution with energy might be due to resonance in the excitation function.

The previously unresolved doublet (6.76-6.81) was effectively separated by using thin targets which permitted 20 Kev resolution. The 6.76 Mev proton group is approximately 50 times more intense at $\theta=20^{\circ}$ than the 6.81 Mev group. Because of the difference in intensity and the close spacing of the groups the angular distribution of the 6.81 Mev level could not be obtained. The angular distribution for the 6.76 level (Fig. 4) indicates neutron capture with ℓ_n=1 and the unusually good fit of the Butler curve together with the high relative intensity of the group suggest a single particle configuration.

To assist in making spin assignments for the first five states of B^{11} the experimental reduced widths were compared with those calculated using the B^{10} and B^{11} intermediate-

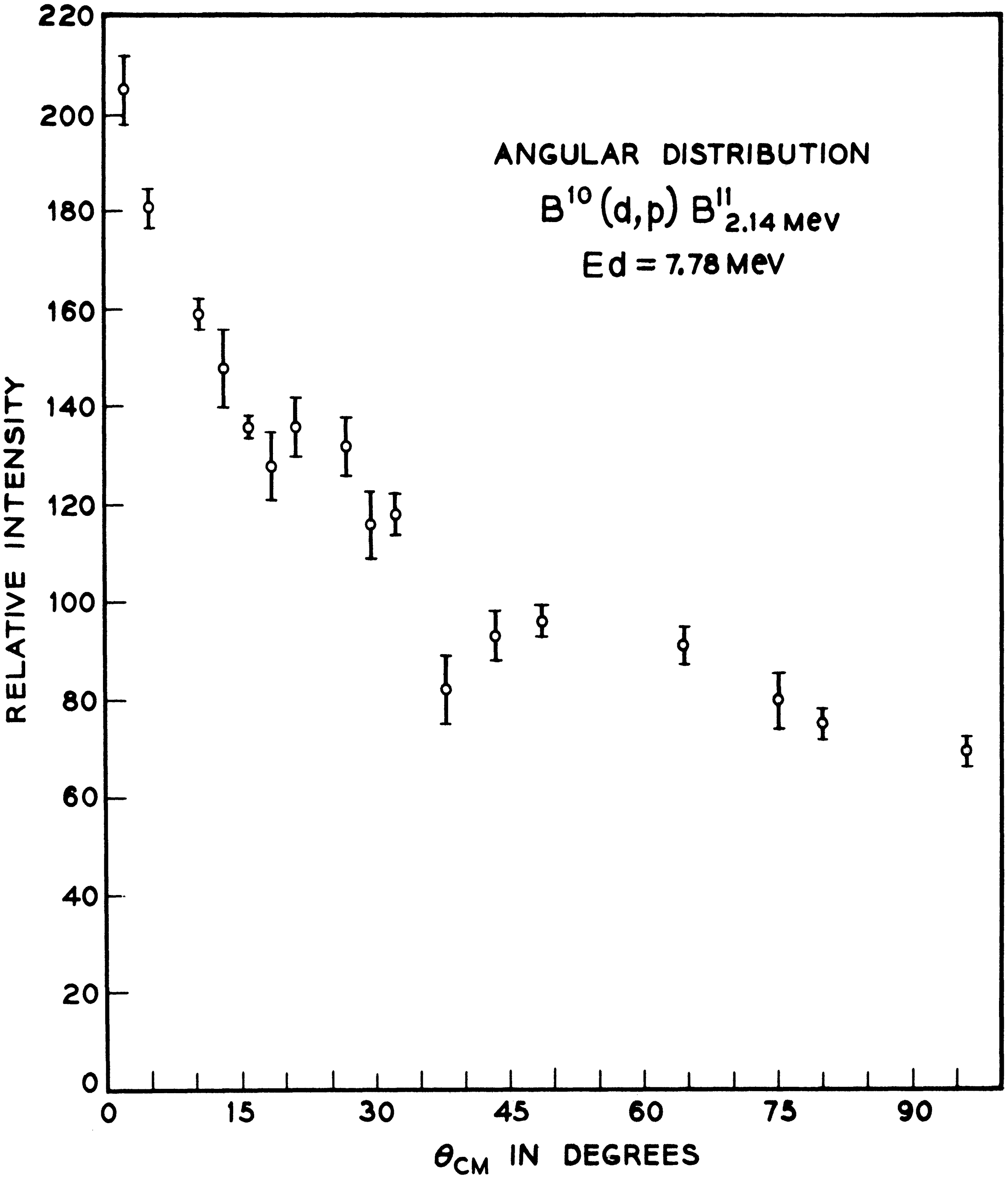
ANGULAR DISTRIBUTION
$B^{10}(d,p)\,B^{11}_{2.14\,\text{Mev}}$
Ed = 7.78 Mev
RELATIVE INTENSITY
0
20
40
60
80
100
120
140
160
180
200
220
0
15
30
45
60
75
90
θ_{CM} IN DEGREES

Fig. 3

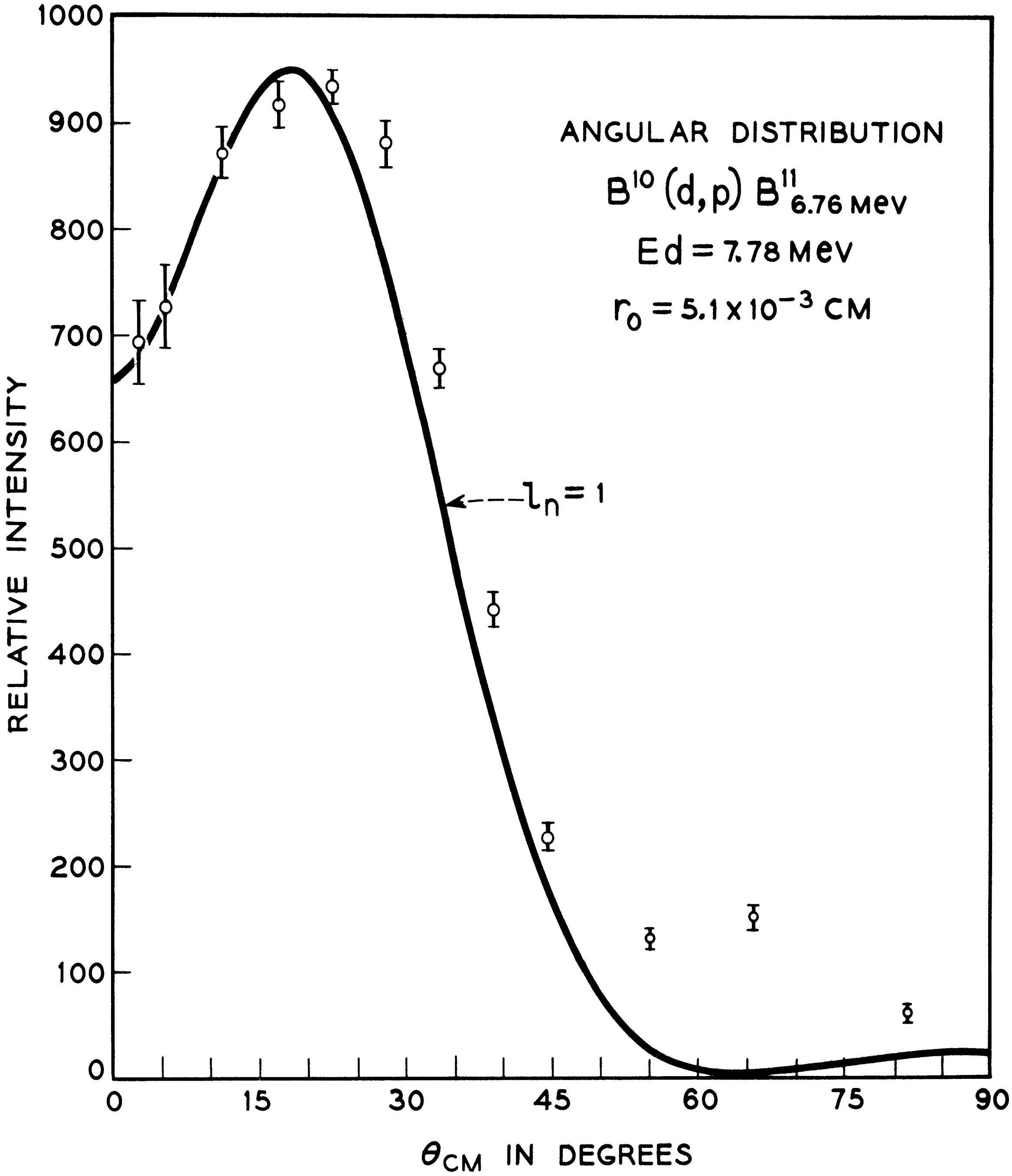
ANGULAR DISTRIBUTION
$B^{10}(d,p)B^{11}_{6.76\ MeV}$
$E_d = 7.78$ MeV
$r_0 = 5.1 \times 10^{-3}$ CM
$l_n = 1$
RELATIVE INTENSITY
0
100
200
300
400
500
600
700
800
900
1000
0
15
30
45
60
75
90
θ_{CM} IN DEGREES

Fig. 4

coupling wavefunctions of Kurath.[6,11] The reduced widths calculated as a function of a/K(L/K=6.8) for the lowest p-shell states are shown in Fig. 5. The second J=5/2 state is expected to lie very high ($\sim$10-11 Mev) and should not be relevant to the present work. The J=1/2 state does not appear because its reduced width for simple stripping is zero.

The relative intensities of the first nine proton groups at $\theta=20^{\circ}$ are given in column 2 of Table I. Column 3 gives the measured relative intensities with kinematic factors removed. The large ratio $\overline{S}/\overline{S}_{gnd}=1.72$ for the 6.76 Mev group is consistent only with the J=7/2 state shown in Fig. 5. Assuming this assignment the intermediate coupling parameter is fixed at (a/K)=4.0 for a best fit. The calculated ratios for the J=5/2 and J=3/2 excited states are therefore 0.12 and 0 respectively which best fit the 4.46 and 5.03 Mev levels respectively. The proposed assignments, summarized in Table I, are 3/2-, 1/2-, 5/2-, 3/2- and 7/2- for the first 5 states respectively of B^{11} and are in complete agreement with the assignments[12,13] given by the Chalk River group based on γ-ray decay scheme.

Angular distributions have also been taken for proton groups leading to 7.99 and 8.57 Mev levels of B^{11}. The final results, (not shown) corroborate the preliminary data and

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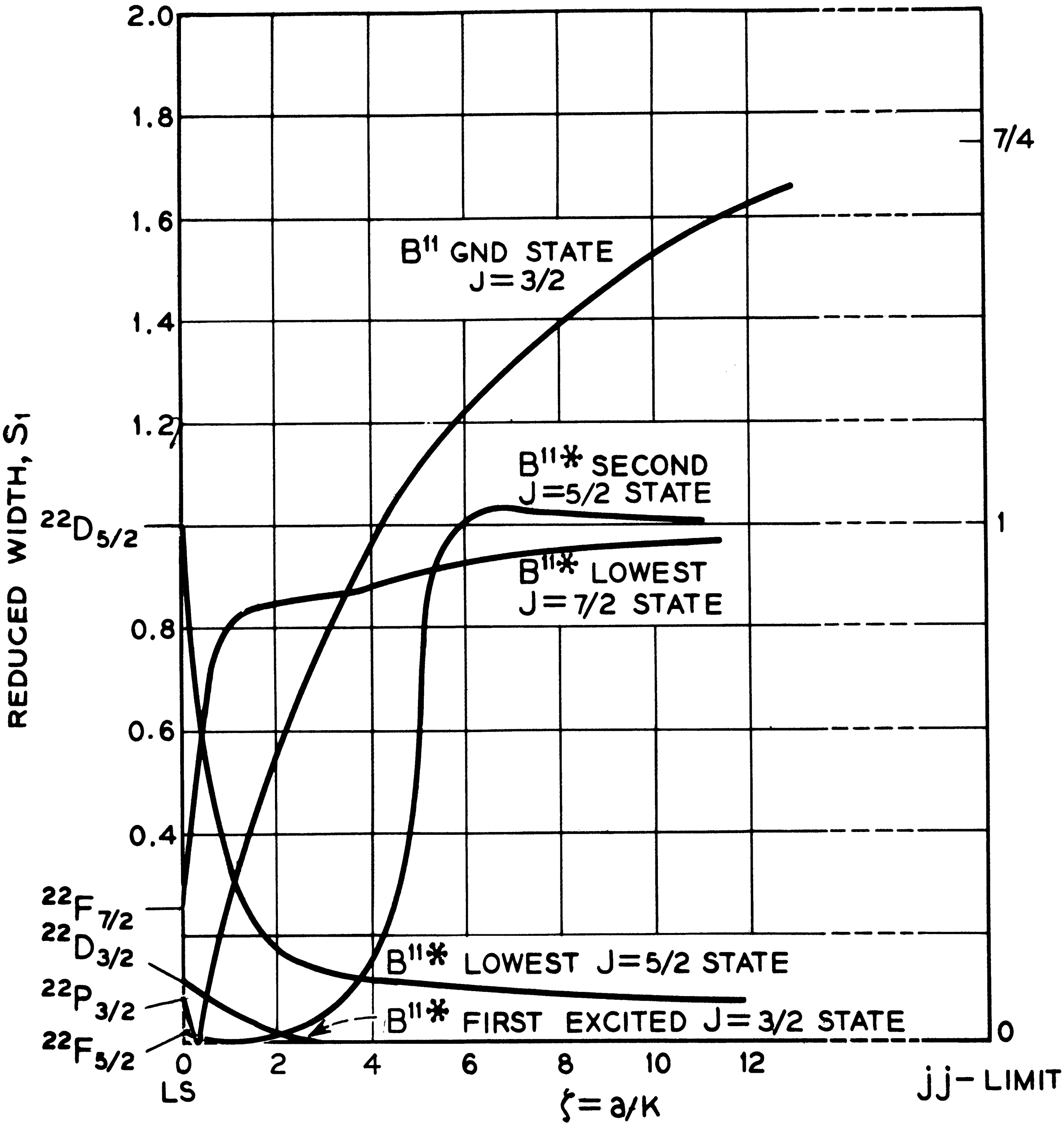
(11) D. Kurath, private communication.

(12) A. J. Ferguson, H. E. Gove, J. A. Kuehner, A. E. Litherland, E. Almquist, and D. A. Bromley, Phys. Rev. Let. 1, 414 (1958).

(13) A. J. Ferguson, private communication.



REDUCED WIDTH, S_1
2.0
1.8
1.6
1.4
1.2
0.8
0.6
0.4
$^{22}D_{5/2}$
$^{22}F_{7/2}$
$^{22}D_{3/2}$
$^{22}P_{3/2}$
$^{22}F_{5/2}$
7/4
1
0
B^{11} GND STATE
J=3/2
B^{11*} SECOND
J=5/2 STATE
B^{11*} LOWEST
J=7/2 STATE
B^{11*} LOWEST J=5/2 STATE
B^{11*} FIRST EXCITED J=3/2 STATE
0 2 4 6 8 10 12
LS
$\zeta = a/K$
jj- LIMIT

Fig. 5

Table I

excitation energy	Rel. Intensity $\theta_{lab} = 20^{\circ}$	$\overline{S}/\overline{S}_{(gnd)}$	J	Exp't $S/S_{(gnd)}$	Calc. $S/S_{(gnd)}$ a/K=4.0
0	1.00	1.00	3/2	1.00	1.00
2.14	.12±.01	.09	1/2	.18	0
4.46	.88±.04	.46	5/2	.31	.12
5.03	.22±.02	.11	3/2	.11	.00
6.76	4.86±.20	1.72	7/2	.86	.86
6.81	.11±.03				
7.30	.24±.04				
7.99	.09±.01				
8.57	.17±.02				

discussion in the 1958 report. The distribution from the 7.99 Mev state is isotropic while the distribution for the 8.57 Mev state indicates $\ell_n=2$ capture without $\ell_n=0$ admixture. The most probable assignment for the 8.57 Mev state is 1/2+ or 3/2+ in agreement with the relative γ-ray intensity measurements.[8,9]

D. States of Low Excitation in O^{19}

The investigation of O^{19} by the reaction $O^{18}(d,p)O^{19}$, mentioned in the 1958 report, has been extended. New states in O^{19} have been discovered at excitation energies of 3.14 Mev and 3.94 Mev. Final (d,p) angular distributions have been measured for the previously known ground and second excited states and also for the two new states. The results for the two new states are shown in Figs. 6 and 7.

The loss of O^{18} from the target under bombardment has so far prevented the measurement of the proton angular distribution for the very weak first excited state.

The relative intensities of the five transitions are now being determined.[14] The experimental results make no further contact with the published theoretical work of Elliot and Flowers[15] and of Redlich.[16] Instead, one of the new states appears to arise from breakup of the O^{16} core and the other from a moderately excited O^{19} configuration for which inter-

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(14) The measurements on O^{19} will constitute the experimental part of the thesis of W. Williams.

(15) J. P. Elliot and B. H. Flowers, Proc. Roy. Soc. (London) A229, 536 (1955).

(16) M. G. Redlich, Phys. Rev. 99, 1427 (1955).

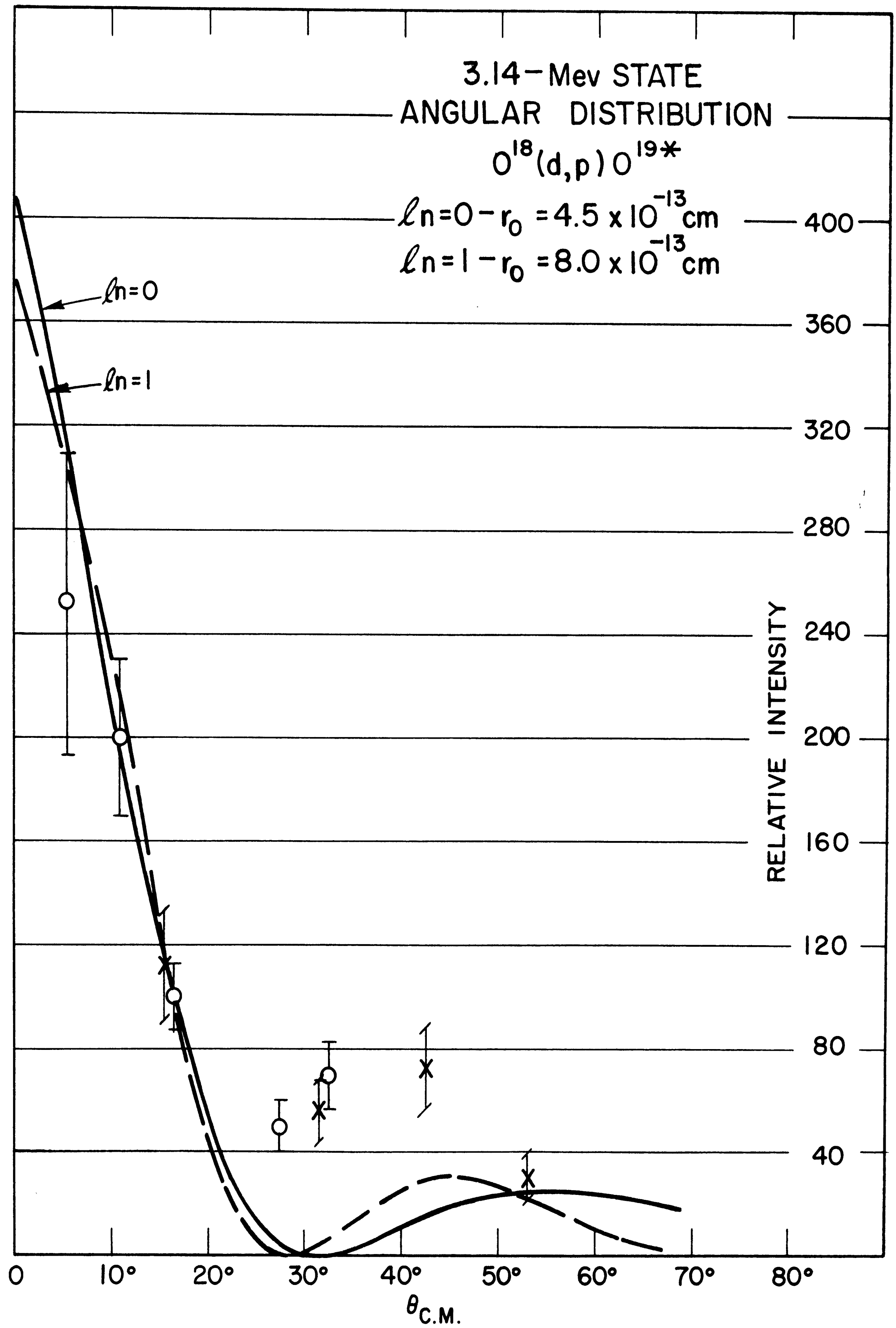
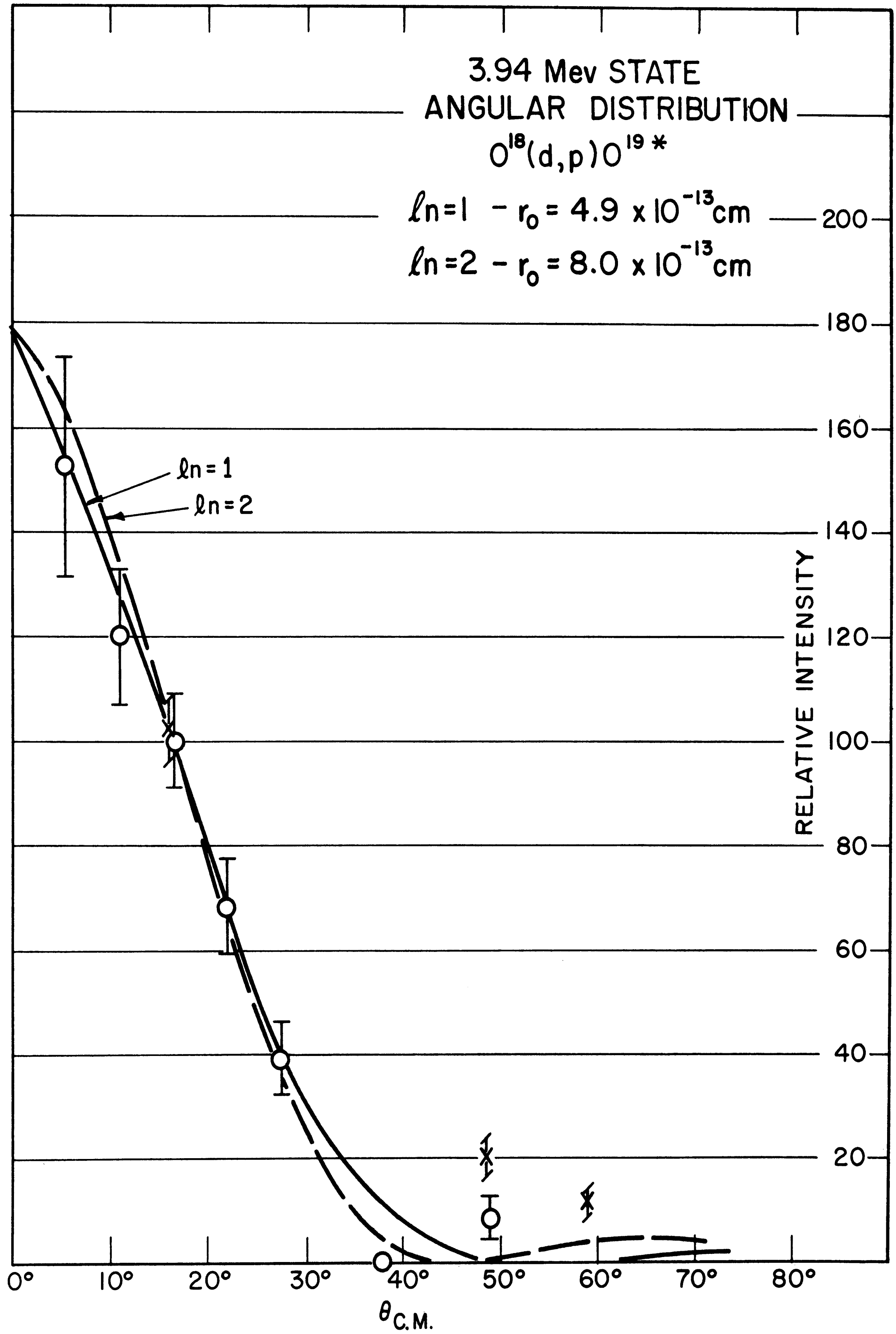

3.14-Mev STATE
ANGULAR DISTRIBUTION
O18(d,p)O19*
ℓn=0 - r0 = 4.5 x 10-13 cm
ℓn=1 - r0 = 8.0 x 10-13 cm
ℓn=0
ℓn=1
RELATIVE INTENSITY
400
360
320
280
240
200
160
120
80
40
0
10°
20°
30°
40°
50°
60°
70°
80°
θC.M.

Fig. 6



3.94 Mev STATE
ANGULAR DISTRIBUTION
$O^{18}(d,p)O^{19*}$
$\ell n=1 - r_0 = 4.9 \times 10^{-13}$ cm
$\ell n=2 - r_0 = 8.0 \times 10^{-13}$ cm
$\ell n=1$
$\ell n=2$
RELATIVE INTENSITY
200
180
160
140
120
100
80
60
40
20
0°
10°
20°
30°
40°
50°
60°
70°
80°
$\theta_{C.M.}$

Fig. 7

mediate-coupling calculations are not now available.

E. Polarization of Protons in Stripping

The polarization measurements described at some length in the 1957 report(17) are being extended to include the polarization as a function of scattering angle for the reaction $Be^{9}(d,p)Be^{10*}$. The interest here is not only in the determining the spin of the state as in the previous measurements, but also to add experimental data to fix an additional parameter in the current models of stripping. The particular reaction is of interest because of the angular correlation data alreay available(18) from $Be^{9}(d,p\gamma)Be^{10}$.

The experimental arrangement is similar to that previously described,(17) only minor modifications have been made to improve the energy resolution and the solid angle of the apparatus. The measurements are in progress.

F. Improvements in Instrumentation

The identification of nuclear levels in the magnesium isotopes and the measurement of their Q-value and absolute differential cross-sections have imposed more sever requirements on the beam preparation and reaction products analysis system than in the past. In particular it has been necessary to prepare a well defined deuteron beam reproduceable in

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(17) See also the attached reprint by Hensel and Parkinson, Phys. Rev. 110, 128 (1958).

(18) See the 1958 report and the attached reprint, by Taylor, Phys. Rev. 113, 1293 (1959).

energy to within ± 10 Kev from day to day, and constant in energy within ± 5 Kev in any one day. The beam energy is measured by the reaction products analyzer magnet, and once adjusted to the proper value is held constant within 5 Kev with the focusing magnet, the field of which is measured by means of a proton moment nuclear induction meter.

The reaction products analysis system has been recalibrated in terms of the relativistic momentum, the dispersion across the image plane determined more precisely than previously, and the zero degree position redetermined. It might be noted that an error in scattering angle of 1^o can shift the apparent energy of a group by the order of 20 Kev.

The determination of absolute differential cross-sections requires accurate measurements of the deuteron beam current, target thickness, and the solid angle of the analyzer system. The beam current, determined with a Faraday cup and current-integrator, is always monitored with a double proportional counter telescope looking at the target at 90^o. The telescope is then used to determine the beam for measurements at scattering angles less than 30^o, where the current integrator can not be used. The solid angle of the analyzer was determined using a Po^{210} alpha source, of the same size and shape (1 mm x 1cm) and placed in the same position as the illuminated area of the target. The alpha tracks were recorded in nuclear emulsions at the image plane of the analyzer. The source strength was calibrated using a scintillation counter of known solid angle. Target thickness is determined by standard weighing techniques, although the geometry of the evaporation, the measurement of the Newton rings which are visible with some target materials, and the width and intensity of the spectral line all serve as useful checks on the weighing procedure. The absolute differential cross-section measurements can be specified to within ± 10%, the uncertainty being due almost entirely to the target thickness determination.

III. The Theoretical Program

Extension of the Stripping Theory

The attempt described in the 1958 report to get accurate reduced widths and reasonable nuclear radii from (d,p) reactions by including proton-nuclear interactions and exchange effects did not succeed. The failure, directly traceable to the use of Born approximation, suggested an alternative approach which has been successfully carried out.

In the Born approximation the region of integration on both the captured and scattered particles coordinates includes the interior of the nucleus. In the Butler theory, the captured particle integration region is restricted to the exterior of a sphere of radius r_o. In the new method, this restriction is also applied to the scattered particle. The recent success of surface absorption models for nucleon scattering suggests that the incident wave undergoes rapid attenuation at the surface, therefore does not experience the full distorting potential at the center of the nucleus. A plane wave approximation should be valid (at least at not too large angles of scattering), because the strong forces do not have a chance to act. Since the proton wave must experience the same kind of absorption,

the integration over the proton coordinates should also be restricted to the exterior of a sphere of radius r_o. This results in the same peaked angular distributions and much smaller absolute cross-sections, but now the value of r_o needed to fit the data is $r_o \cong 1.5A^{1/3}$. Thus the principal difficulty with the results of the original Born approximation calculation is removed. The one advantage of this method over a "distorted wave" calculation is that the description of the (d,p) and (d,n) processes can be fixed (except for the characteristic spread of the wave function of the captured particle) by analysis of the elastic scattering of neutrons and protons to establish the (complex) potential wells seen by the nucleons and by analysis of the elastic scattering of deuterons which permits the cutoff distance to be re-adjusted to account for deuteron dissociation, an "absorptive" process absent in nucleon scattering.

The $C^{12}(nn)C^{12}$, $C^{12}(pp)C^{12}$, $C^{12}(d,p)C^{13}_0$ reactions have been analyzed in this way, and a radius of approximately 3.3 fermi = $1.44(12)^{1/3}$ (The Butler radius required to fit the angular distributions is 4.2 fermi.) yields a reduced width of 0.2 in good agreement with the predictions of intermediate coupling theory. The Butler theory, and its modification due to Bowcock, yield reduced widths which do not even lie in the theoretically permissible region between LS and jj coupling. Analysis of the corresponding Be^9 and $Be^9(p,d)Be^8$ reactions is almost complete at which time the results will be published.*

* C. R. Lubitz, Phys. Rev. (to be submitted for publication)

IV. Addendum - Publication Reprints

Reprints not previously submitted of six publications resulting from the research under this contract are attached. These are:

1) Spin, Parity and j-j Expansion Coefficients for States of Low Excitation in O^{18}, O. M. Bilaniuk and P.V.C. Hough, Phys. Rev. 108, 308 (1957).
2) The Study of Nuclear Collective Motion by Stripping Reactions, Anns. Phys. 3, 275-291 (1958) by G. R. Satchler.*
3) Polarization of Protons from $B^{10}(d,p)B^{11}$, $C^{12}(d,p)C^{13}$. and Spin-Flip Stripping, J. C. Hensel and W. C. Parkinson, Phys. Rev. 110, 128 (1958).
4) Ground-State Doublet of P^{32}, W. C. Parkinson, Phys. Rev. 110, 485 (1958).
5) Velocity Filter for Nuclear Spectroscopy, L. H. Th Rietjens, O. M. Bilaniuk, W. C. Parkinson, Rev. Sci. Instr. 29, 768 (1958).
6) Proton-Gamma Angular Correlation Studies of Be^9 and Ca^{40} $(d,p\gamma)$ Stripping Reactions, R. T. Taylor, Phys. Rev. 113, 1293 (1959).
7) Nuclear Potential and Symmetry Energy, G. R. Satchler, Phys. Rev. 109, 429 (1958).

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* The supply of reprints is now exhausted; a reprint is included in only one copy of the report.