difference is accidental and that no true net yield is indicated. It is not fruitful to examine the angular distribution of tracks in this region since the large background contribution cannot be separated from the gross yield. For the sake of quantifying the yield in this region, a cross section may be computed on the assumptions that the net yield observed does represent (n,p) yield and that the angular distribution is isotropic between 10° and 45°. On the basis of these assumptions the differential cross section for this low-energy portion of the spectrum is 6.6 mb/steradian.

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Study of $Al^{27}(n,p)Mg^{27}$ at 14 Mev*

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Protons emerging from aluminum foil bombarded by D+T neutrons have been studied with 400 μ emulsions recording over a continuous range of angles from 15° to 165°. Groups in the composite energy spectrum correspond to known Mg^{27} levels at 1.0 and 3.5 Mev and suggest additional ones at 1.6, 5.7, and 7.0 Mev. The nuclear "temperature" for the continuous portion of the spectrum is 1.2 Mev. The following cross sections are tabulated: for each energy group, isotropic and anisotropic total cross sections and maximum differential cross section; for all protons over 2 Mev, differential cross sections at 30° intervals. The isotropic component greatly exceeds the forward-peaked one for each group. Total cross section for the reaction is estimated to be 79±15 millibarns.

INTRODUCTION

EXCITED levels of the Mg^{27} nucleus have been identified[1–3] from the reaction $Mg^{26}(d,p)Mg^{27}$ and spins assigned by reference to stripping theory,[3] as follows: ground state ($\frac{1}{2}+$), 1.0 Mev ($\frac{3}{2}+$, $\frac{5}{2}+$), and 3.5 Mev ($\frac{1}{2}+$). Studies of proton emission from the same compound nucleus in the (n,p) reaction on Al^{27} have been limited to determinations (for neutrons of 14 Mev) of the total cross section [79 mb[4] and 52.4 mb[5]] and the differential cross sections [10 mb[6] over the range 0° to 50° and 16 mb[7] at 0°]. In the experiment to be reported, nuclear emulsions have been employed to study the reaction $Al^{27}(n,p)Mg^{27}$ in detail.

EXPERIMENTAL DETAILS

Neutrons were produced by the D+T reaction initiated by 150-kev deuterons in an rf Cockcroft-Walton.[8] The source provides a neutron group of 14.1-Mev maximum energy and approximately 1-Mev width at half-maximum, at the laboratory angle (90° to the incident deuterons) employed in the experiment.

Protons were recorded in Ilford C2 emulsions 400 μ thick, placed at mean angles of 30°, 60°, 90°, 120°, and 150° to the neutron beam, and a sixth plate directly in the neutron beam was exposed simultaneously to determine neutron flux and check its energy spectrum. The emulsion planes were vertical and inclined at 15° to the direction of proton incidence from the center of the aluminum target. The target was a sheet of commercial aluminum foil mounted at 45° to the neutron beam. Nominal purity of the foil is 99.5%, the principal contaminants being iron (0.4%) and silicon (0.1%); its thickness, 4.5 mg/cm², is equivalent for protons to 200 kev at 10 Mev and 500 kev at 2 Mev.

Plates and aluminum target were enclosed in an evacuated cylindrical steel chamber 16 inches in diameter and 6 inches high. This chamber was lined with lead to reduce proton background from reactions in the walls. External shielding amounted to approximately 18 inches of iron and reduced the neutron intensity at the plates by a factor of 2000 (observed) over the unshielded value. A channel in the iron shield permitted the passage of an unobstructed neutron beam 2 inches in diameter at the aluminum target.

Total neutron flux at the aluminum was 1.5×10^9 neutrons/cm² as determined from recoil track density

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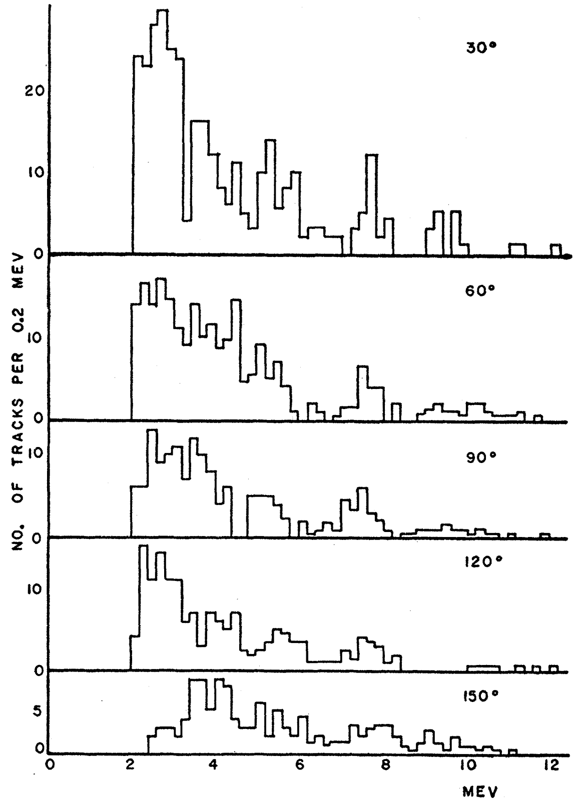

FIG. 1. Energy distribution of protons observed at the various laboratory angles, after subtraction of observed background. Proton energy (abscissa) is in center-of-mass system.

in the monitor plate, roughly confirmed by a long counter determination. A second exposure of 0.5×10^9 neutrons/cm^2 was made to evaluate background effects, under conditions identical with the primary exposure except for the absence of the aluminum foil.

Plates were developed by a two-solution temperature-controlled method[9] and searched with a Zeiss Model W binocular microscope. A dry objective (over-all magnification 250×) was used in searching and rough discrimination and in length measurements for long tracks; for all other measurements and precise discrimination an oil objective (1000×) was employed. Accepted tracks were required to originate at the emulsion surface, to terminate within emulsion, and to travel in directions assuring points of origin within a 2-inch diameter circle at the center of the aluminum target, i.e., in the region irradiated by the unobstructed neutron beam. For each acceptable track measurements were made of range and angle components in the planes parallel and normal to the emulsion surface. From these data the energy of each accepted proton was determined, using the range-energy calibration of Rotblat.[10]

TABLE I. Groups in energy spectrum.

Proton energy (Mev)	Mg^{27} excitation (Mev)	Previous observations (references)
11.3	0.0	a, b, c
10.3	1.0	a, b, c
9.7	1.6	not reported
7.9	3.5	c
5.7	5.7 (+*d*)	not reported
4.5	7.0 (+*d*)	not reported

[a] See reference 1.
[b] See reference 2.
[c] See reference 3.

ENERGY SPECTRUM

The histograms of Fig. 1 show separately the energy distributions obtained, after subtraction of the observed background yield, in each of the plates. The common abscissa is proton energy in the center-of-mass system and all ordinates have the same absolute significance, *viz.*, net number of tracks per 200 kev in the area scanned (one-quarter plate). These spectra can be integrated over laboratory angle to give the "total" energy spectrum of Fig. 2. Vertical arrows show the expected extrapolated energy (high-energy extremity of the group) corresponding, from right to left, to the ground state transition group, 1.0-Mev and 3.5-Mev transitions, and deuterons from the ground state transition of the Al(n,d) reaction.[11]

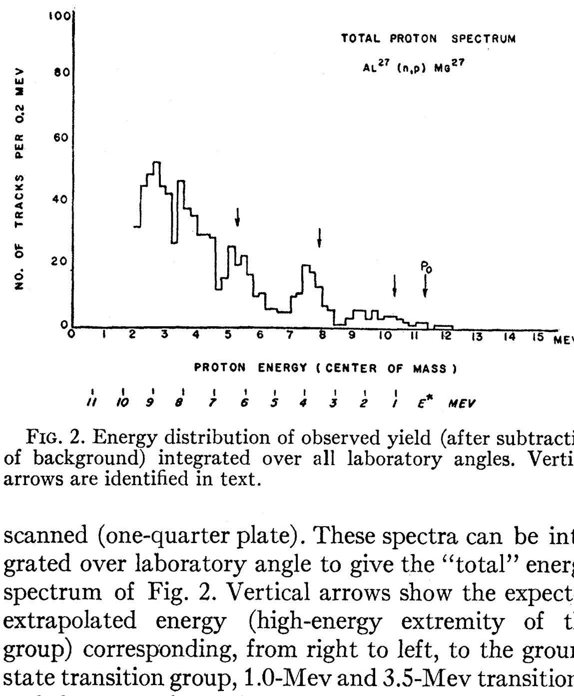

FIG. 2. Energy distribution of observed yield (after subtraction of background) integrated over all laboratory angles. Vertical arrows are identified in text.

Analysis of the observed proton yield into significant cross sections requires that the spectrum be separated into meaningful energy groups. The best division permitted by statistical limitations is given in Table I. The ground state transition is scarcely observed but is included in the table for reference. As noted in the Introduction, the levels at 1.0 and 3.5 Mev are known from previous work. A level in the neighborhood of

[9] J. C Allred and A. H. Armstrong, Laboratory Handbook of Nuclear Microscopy, LA-1510 (Los Alamos Scientific Laboratory, 1951).

[10] J. Rotblat, Nature **167**, 550 (1951).
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1.6 Mev (the exact location can only be a guess) is presumed because of the otherwise extraordinary width of the group lying between 8.8 and 10.8 Mev. No such level was reported by Holt and Marsham,[3] but their $Mg^{26}(d,p)Mg^{27}$ spectrum was obscured in the region in question by protons attributed to O^{16} and C^{12} contaminants. The group assigned by them to C^{12}, if attributed instead to the $Mg^{26}(d,p)$ reaction, would reflect a Mg^{27} level at 1.5 Mev. In the (n,p) reaction the carbon and oxygen contributions fall outside the energy range studied.

The group at 5.7-Mev proton energy clearly may be expected to contain some deuterons from the $Al^{27}(n,d)$ reaction. However a substantial number of the tracks in this group have emulsion ranges greater than the expected deuteron range, so that some proton yield is

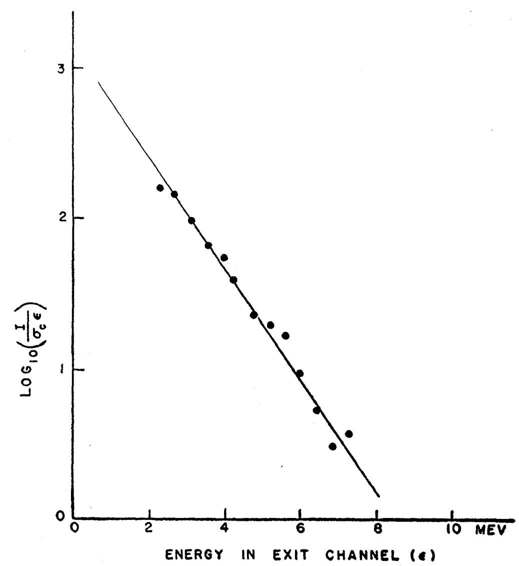

FIG. 3. Semilogarithmic plot of continuous portion of energy spectrum. Abscissa is total kinetic energy in the center-of-mass system. Ordinate, on logarithmic scale, is observed yield divided by energy and cross section for compound nucleus formation. Straight line corresponds to temperature parameter 1.16 Mev.

indicated and hence a corresponding level in Mg^{27}. The group at 4.5-Mev "proton" energy may represent deuterons, protons, or a combination, and the corresponding level listed in Table I is consequently uncertain, although the equivalent deuteron energy does not correspond to a known level[12] in Mg^{26}. It is clear that most or all of the yield below 6 Mev may belong to the continuum. Colli and Facchini,[6] using proportional and scintillation detectors, have reported faintly resolved groups corresponding to levels at approximately 3 and 6 Mev. Alpha particles are assumed not to affect interpretation of the spectrum, since the most energetic alphas to be anticipated correspond to 2 Mev on the abscissa of Fig. 2.

[12] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

TABLE II. Cross sections for proton groups.

Group (excitation)	Isotropic (mb)	Anisotropic (mb)	Angular[a] location (degrees, lab)	Maximum differential (mb/steradian, c.m. system)
0.0	0.2	0.1	30=60	0.04
1.0	0.8	0.1	60	0.15
1.6	1.4	0.4	30	0.28
3.5	7.3	0.0	none	0.58
5.7 (+*d*)	8.3	1.4	30	1.20
7.0 (+*d*)	13.9	2.3	30=60	1.59
Residue[b]	20.8	3.6	30	3.04
All groups	52.7	7.9		

[a] Angle at which maximum differential cross section is observed; also the angle at which anisotropic yield is principally concentrated. Angular range = listed angle ±15°. "30 = 60" indicates equal yields at these two angles.
[b] Protons between 2.0 and 3.2 Mev.

The conventional "statistical theory" plot is a convenient device to characterize the gross form of an energy spectrum approximating a continuum. Figure 3 shows such a plot of the portion of Fig. 2 corresponding to proton energies below 5 Mev. The abscissa is the "channel energy" and the ordinate the logarithm of the observed yield divided by channel energy and cross section for formation of the compound nucleus. The latter cross section was taken from the table of Blatt and Weisskopf[13] for $r_0 = 1.3\times10^{-13}$ cm and $Z = 10$. The straight line in Fig. 3 corresponds to the nuclear temperature parameter 1.16 Mev at the excitation of 11.7 Mev, in close agreement with values listed by Gugelot[14] for nuclei of mass 27.

CROSS SECTIONS

Although over 2500 tracks are represented in the full set of data, the number in a given energy group at a given angle is generally small and the angular distributions for the several groups must be viewed as qualitative only. All the angular distributions show a strong isotropic contribution plus deviations therefrom which in each case are concentrated somewhere in the forward hemisphere. Total cross sections for these two components are given in Table II for the various energy groups, together with the maximum observed differential cross section for each group and the angle at which the maximum is found. It must be emphasized that each "angle" of observation represents an angular

TABLE III. Angular distribution of total yield (above 2 Mev).

Lab angle	Differential cross section (mb/steradian, c.m. system)
30°±15°	7.45
60°±15°	5.62
90°±15°	4.04
120°±15°	4.00
150°±15°	2.77

[13] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 352.
[14] P. C. Gugelot, Phys. Rev. **93**, 425 (1954).

spread of $\pm 15°$ about the listed value and that the differential cross sections are averages over this range. The predominance of isotropic over anisotropic yield for all groups is significant, but further speculation is not justified by the statistics.

Table III shows the angular variation of the differential cross section for emission of all protons observed, *viz.*, with energies above 2 Mev.

Since the emulsion observations extended over most of the energy range (above 2 Mev) and most of the angle range (15° to 165° in 30° blocks), the total cross section may be computed from them with relatively slight extrapolations. Integration over angle was accomplished by adding yields from the various plates weighted by the appropriate solid angle factors. For the unobserved ranges below 30° (0° to 15°) and above 150° (165° to 180°), the differential cross sections observed at 30° and 150°, respectively, were assumed; contributions from these regions have no appreciable effect on the final cross section. This numerical integration yields 60 mb for emission of protons with energies over 2 Mev. The yield of protons between 0 and 2 Mev may be estimated by extrapolation of the straight line of Fig. 3, which raises the total cross section to 79 mb. Combined systematic and statistical uncertainties are estimated to combine to roughly 20% in the total cross section.

It must be noted that this cross section probably contains some yield from the (n,d) reaction on Al^{27}, although alpha particles are presumably not included. The agreement with the total cross section determined by Forbes[4] (see introduction) is largely fortuitous, in view of the limited precision of the present determination. The average differential cross section for the range 0° to 50° reported by Colli and Facchini[6] is 10 mb/steradian $\pm 30\%$, while 16.0 mb is found by Allan[7] over a very small angular range about 0°. Direct comparison of these values with Table III is pointless since the values in that table do not include protons below 2 Mev. However, if the number of protons below 2 Mev has the same ratio to the number above 2 Mev at 30° as for all angles, the true differential cross section in the range $30° \pm 15°$ may be estimated as 7.45 mb/steradian (Table III) times 79 mb/60 mb, or 9.8 mb/steradian, in adequate agreement with the earlier values.