the ground state of the Re^{188} appears to be more probable.

The 155-kev level is indicated[7] as a rotational level. If it be so, the subsequent levels should be at 516.6, 1085, 1860 kev with spins 4, 6, and 8 and with even parity. The 1086-kev level found experimentally tallies rather closely with the one expected as a rotational level. However, if the spin assignments suggested are indeed the case, the presence of the 931-kev gamma ray with its observed intensity is difficult to explain.

[7] A. Bohr and B. R. Mottelson, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 489.

ACKNOWLEDGMENT

The writer wishes to express his appreciation to Dr. C. E. Mandeville for his guidance, to Mrs. Mary Elizabeth Brandt, Mrs. Marian Patterson, and Mrs. Erma Rodgers for their kind assistance in preparation of the manuscript. The help of Mr. W. B. Todd in making the beta-ray spectrometer measurements is appreciated. Finally, the writer is grateful to Dr. W. F. G. Swann for his kind interest.

PHYSICAL REVIEW VOLUME 104, NUMBER 3 NOVEMBER 1, 1956

Energy Levels of Si^{28}†

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(Received July 30, 1956)

The neutron spectrum from the $Al^{27}(d,n)Si^{28}$ reaction has been investigated at eight angles by means of nuclear emulsions. The energy of the incident deuterons was 2.167±0.015 Mev. The data indicate energy levels of Si^{28} at 1.78±0.10, 4.54±0.2, 4.95±0.2, 6.24±0.06, 6.88±0.06, 7.39±0.06, 7.89±0.06, 8.31±0.10, 8.57±0.08, 9.37±0.04, 10.00±0.10, and 10.25±0.06 Mev.

INTRODUCTION

IT is of interest to study alpha-particle nuclei because of the partial success of the alpha-particle model in correlating theory with experiment in light alpha-particle nuclei, for instance[1] in O^{16}. We have used the nuclear emulsion technique to study the reaction $Al^{27}(d,n)Si^{28}$ in order to obtain more accurate values for the energies of the excited states of $_{14}Si^{28}$. In a future paper it is hoped to present evidence on the parities of many of these states.

The position of the first excited state has been extensively investigated,[2–8] and its spin and parity have been found. The region of excitation above 11.8 Mev in Si^{28} shows many levels, found by studying resonances in the yield of reactions involving Si^{28} as the compound nucleus. These are listed in the compilation of Endt and Kluyver.[9] The intermediate region, between 1.8 and 11.8 Mev, has been investigated by Rutherglen,[8] Casson,[10] Hattori,[11] Peck,[12] and Calvert.[13] In these experiments possible ambiguousness in the interpretation of the results or lack of accuracy in energy measurements precluded the precise determination of level energies. Bent *et al.*[14] used a magnetic lens pair spectrometer to find the energies of the γ rays from the reaction $Al^{27}(d,n)Si^{28}$. The interpretation of the origin of these γ rays is sometimes obscure, since they may come either from direct transitions to the ground state or by cascades through excited states. The accuracy of their energy measurements, however, is comparable to or better than those of the present experiment, as can be seen in Table I.

EXPERIMENTAL PROCEDURE

A thin aluminum target having a thickness corresponding to an energy loss, for deuterons, of 15 kev

† This research was supported by the United States Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command.

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TABLE I. Energy levels in Si^{28}.[a]

Level	Angle 0°	10°	20°	30°	45°	60°	90°	120°	Weighted[b] Q	E_x from present work	Best previous values
1	7.50 (2)			7.80 (1)	7.58 (2)	7.53 (2)	7.59 (2)	7.59 (1)	7.58±0.10	1.78±0.10	1.782±0.01[c]
2	5.08 (1)		4.73 (1)	4.79 (1)	4.79 (3)	4.73 (3)	5.05 (1)		4.82±0.2	4.54±0.2	4.47±0.10,[d] 4.6,[e] 4.65±0.10[f,g]
3	4.57 (2)			4.37 (1)	4.33 (3)	4.25 (1)	4.56 (1)		4.41±0.2	4.95±0.2	4.91±0.21,[d] 5.2,[e] 5.04±0.10[f,g]
4	3.09 (2)	3.14 (2)	3.17 (2)		3.08 (2)	3.17 (1)	3.09 (2)	3.11 (2)	3.12±0.06	6.24±0.06	6.11±0.10,[d] 6.13±0.15[f,g]
5	2.49 (2)	2.42 (3)	2.47 (4)		2.48 (4)	2.46 (4)	2.51 (4)	2.52 (4)	2.48±0.06	6.88±0.06	6.9±0.1[g,h]
6		2.00 (1)	1.90 (1)			1.95 (3)	2.02 (3)	1.96 (4)	1.97±0.06	7.39±0.06	7.38±0.06[g,h]
7		1.44 (1)			1.54 (1)	1.45 (3)	1.44 (3)	1.49 (3)	1.47±0.06	7.89±0.06	7.91±0.04[g,h]
8			0.98 (1)	1.11 (1)				1.06 (1)	1.05±0.10	8.31±0.10	8.28±0.04[g,h]
9	0.81 (4)	0.78 (4)	0.77 (3)	0.78 (2)	0.82 (2)	0.79 (3)	0.78 (2)	0.82 (3)	0.79±0.08	8.57±0.08	
10	−0.02 (2)	−0.01 (2)	−0.01 (2)	−0.03 (1)	−0.02 (1)	−0.01 (1)	−0.03 (1)	+0.01 (1)	−0.01±0.04	9.37±0.04	9.45±0.08[g,h]
11								−0.64	−0.64±0.10	10.00±0.10	9.87±0.08[g,h]
12			−0.87 (2)	−0.96 (2)	−0.90 (3)	−0.90 (3)	−0.89 (2)	−0.84 (2)	−0.89±0.06	10.25±0.06	

[a] All energies are given in Mev.
[b] The weighting factor at each angle is indicated in parentheses under the Q-value at the angle. It was taken to be roughly proportional to the relative number of tracks in the group.
[c] See reference 2.
[d] See reference 12.
[e] See reference 8.
[f] See reference 10.
[g] The energies listed are γ-ray energies and are not directly determined to be ground-state transitions in Si^{28}.
[h] See reference 14.

was bombarded with 2.167±0.015 Mev deuterons from the Rockefeller Van de Graaff generator at the Massachusetts Institute of Technology. The target was an aluminum foil, which was caused to adhere to a tantalum backing with a drop of water. Neutrons from the reaction $Al^{27}(d,n)Si^{28}$ were detected by means of Ilford C-2 emulsions, 1×3 inches, and 400 microns thick. The plates were wrapped in several thicknesses of aluminum foil and mounted[15] at nine angles to the incident beam, with the one-inch edge of the plates vertical, and pointing toward the target. The distance from the target to the front edge of the plates was 10 centimeters. The exposure was 10 000 microcoulombs, and gave a density of tracks satisfying acceptance criteria[16] of about 1000 tracks per cm² scanned. The plates were subsequently developed by using a modification[17] of the Los Alamos method.[18]

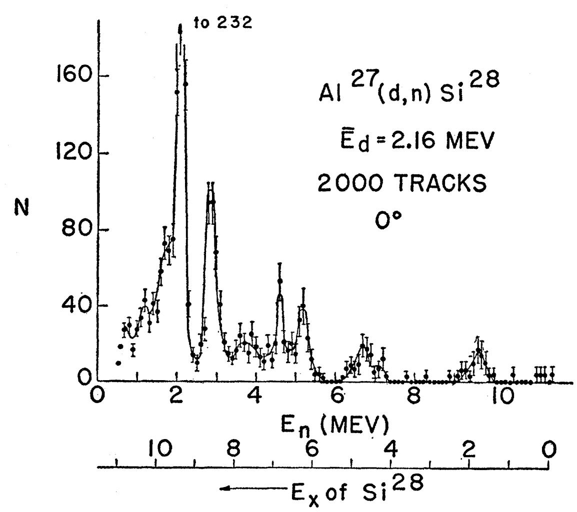

FIG. 1. Data at 0° (in the laboratory system). N is the corrected number of neutrons per 100-kev interval. E_n is the neutron energy. E_x is the excitation energy in Si^{28}.

Scanning was performed with a Leitz binocular microscope on which was mounted a Heine stage equipped with dial gauges. Track lengths were measured by means of an eyepiece scale if shorter than several fields of view, and with the moving stage if longer. The angle of dip of the proton recoil track into the

[15] See illustration in F. Ajzenberg and W. W. Buechner, Phys. Rev. 91, 674 (1953).

[16] The dip angle must be less than 9° in the unprocessed emulsion and the angle which the proton recoil track makes with the long edge of the plate must be less than ten degrees, for a track with a dip, and less than 15° for a track with no dip. For terminology, see reference 18.

[17] The plates are presoaked in distilled water for 45 minutes at 19°C, placed in solution A for 80 minutes at 4°C, in solution B for 80 minutes at 4°C, dry developed for 35 minutes (being warmed to 19°C in the process) and then placed in 1½% acetic acid for 40 minutes at 19°C. The surface silver is removed, and the plates are first placed in 1:3 hypo solution for approximately 7 hours at 19°C, and then in fresh 1:6 hypo solution overnight at 19°C (no agitation). The plates are washed for 6 hours and dried for about two days at 50% relative humidity. For further details of the development procedure and formulas for solutions A and B, see reference 18.

[18] L. Rosen, Nucleonics 11, 33 (July, 1953).

emulsion was measured with the fine-focus adjustment of the microscope, which is calibrated in microns. The angle made by the track with the long edge of the plate was measured by means of an eyepiece goniometer to an accuracy of one degree. An oil

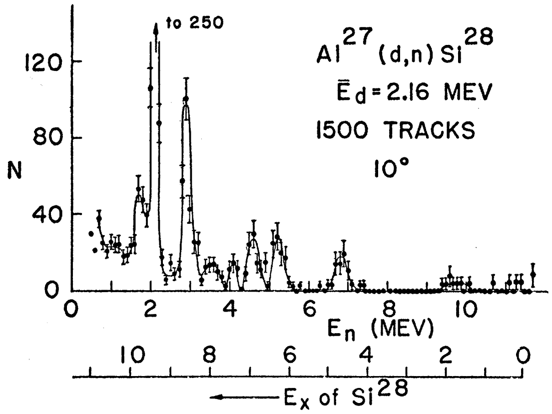

Fig. 2. The 10° data (see also caption of Fig. 1).

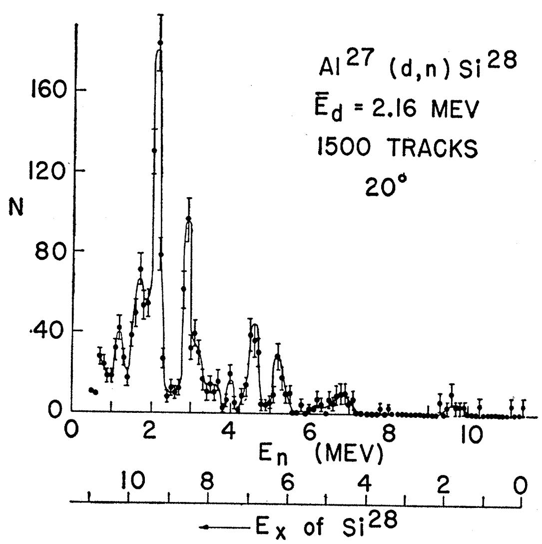

FIG. 3. The 20° data (see also caption of Fig. 1).

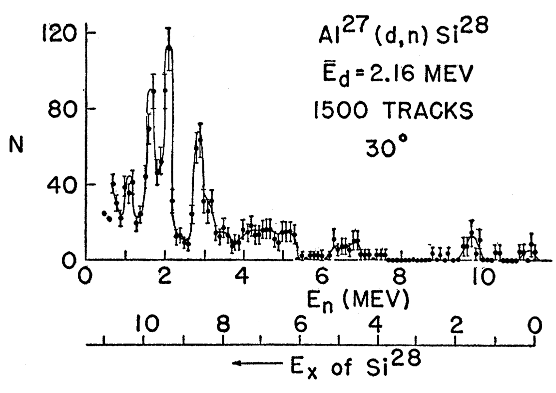

FIG. 4. The 30° data (see also caption of Fig. 1).

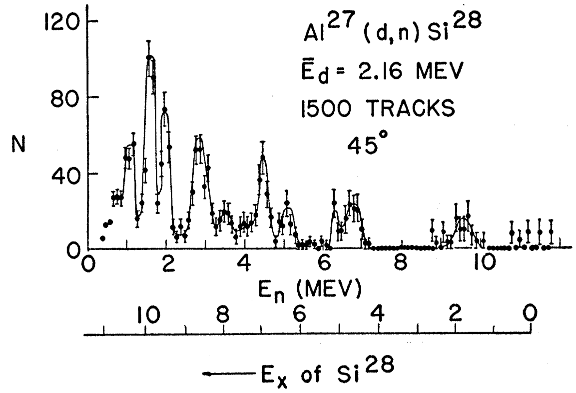

FIG. 5. The 45° data (see also caption of Fig. 1).

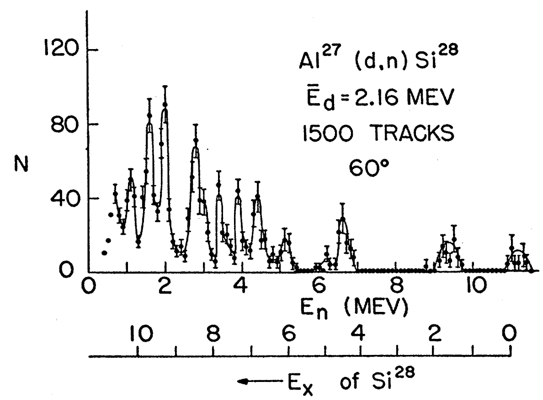

FIG. 6. The 60° data (see also caption of Fig. 1).

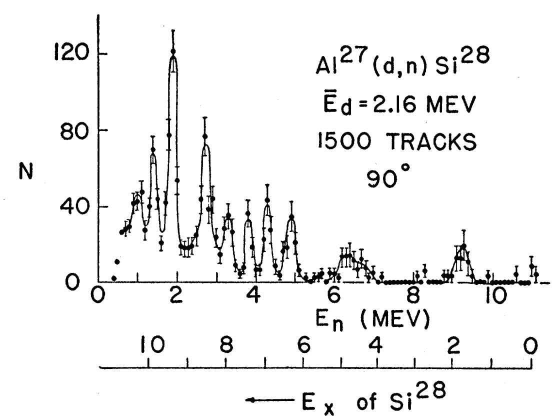

FIG. 7. The 90° data (see also caption of Fig. 1).

immersion objective (100×) was used in conjunction with a pair of 10× eyepieces. A total of 12 500 tracks were measured at eight angles to the incident beam.

The range-energy table of Gibson, Prowse, and Rotblat[19] was used to convert the lengths of proton recoil tracks to neutron energies. Neutron energies were then tabulated in 100-kev intervals, and the number of tracks in each interval was corrected for variation of

[19] Gibson, Prowse, and Rotblat, Nature **173**, 1180 (1954).

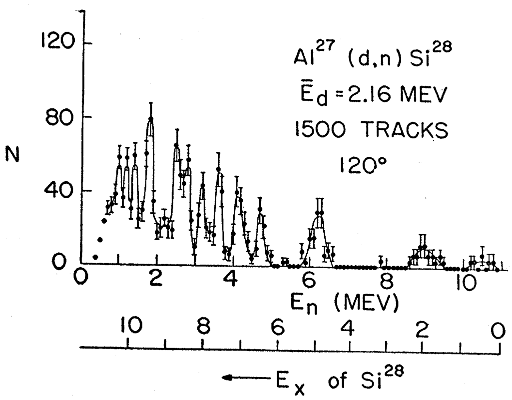

FIG. 8. The 120° data (see also caption of Fig. 1).

the n-p scattering cross section[20] and for geometry.[21] The fractional error assigned to the number of neutrons in each energy interval is the reciprocal of the square root of the number of neutrons in the interval.

DISCUSSION OF RESULTS

Figures 1 to 8 show our data. The ground state group is weak at all angles, and the statistics were too poor to obtain a Q-value for the ground state reaction. Since the energy of the first excited state is very well known, the excitation energies of the other levels were calculated from it. The second and third excited states could not be resolved because their energy separation is too small. However, nine neutron groups corresponding to higher excited states have been well enough resolved to enable us to obtain quite accurate Q-values. The Q-values obtained are shown in Table I, together with previous results of other investigators. The level scheme derived from all known data on the levels of Si^{28} below 10.5 Mev is shown in Fig. 9. We have probably not observed all the levels in this excitation region because levels whose excitation energies are separated by less than the neutron group width[22] at half-maximum cannot be resolved. In particular, above ~9.0 Mev excitation both $T=1$ and $T=0$ states can be present in Si^{28} (see the isobaric diagram[23] of $A=28$ shown as Fig. 9). From the known levels of Al^{28}, there should be six $T=1$ states in the corresponding region of $Si^{28}(9.0 \lesssim E_x \lesssim 10.5$ Mev) in addition to an undetermined number of $T=0$ states. However, we have resolved only three neutron groups in this region. The neutron groups with $E_n=1.4$ Mev (120°) to 1.8 Mev (0°) are probably due to C^{12} contamination of the target [$C^{12}(d,n)N^{13}$, $Q=-0.28$ Mev].

In a future paper we will present a stripping analysis of the angular distributions at bombarding energies

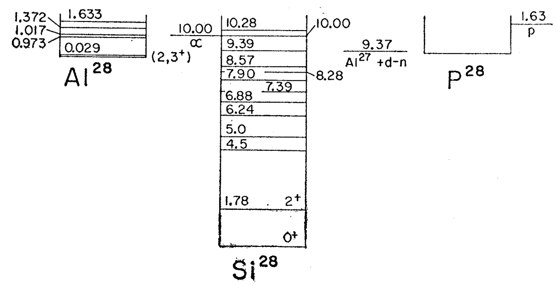

FIG. 9. The mass 28 isobaric triad. Corrections have been made for Coulomb energy differences and the n-p mass difference [see e.g., T. Lauritsen, *Annual Review of Nuclear Science* (Annual Review, Inc., Stanford, 1952), Vol. 1, p. 67].

of 2.16 and 6.00 Mev, and resulting conclusions as to the parities of states of Si^{28}. Absolute differential cross sections will also be given in the later paper.

ACKNOWLEDGMENTS

We are indebted to Matti Salomaa for his aid in carrying out the exposure and to Dr. Clark Goodman for his support. The hospitality of the Brookhaven National Laboratory where the later stages of the work were completed is gratefully acknowledged.

[20] J. Gammel (private communication).

[21] H. T. Richards, Phys. Rev. **59**, 796 (1941).

[22] The average neutron group width at half-maximum varied in this experiment from 4.5% of the neutron energy at 9 Mev to 15% at 1 Mev.

[23] The masses of Al^{28}, Si^{28}, and Pb^{28} were taken from the tables of A. H. Wapstra, Physica **21**, 367 (1955).