Thresholds Observed in the $C^{12}(\alpha,n)O^{15}$, $Si^{28}(\alpha,n)S^{31}$, $S^{32}(\alpha,n)Ar^{35}$, $S^{34}(\alpha,n)Ar^{37}$, and $Cl^{35}(p,n)Ar^{35}$ Reactions*

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The following thresholds have been measured in the (α,n) reaction: C^{12} 11.341±0.015; Si^{28} 9.30±0.05, 10.55±0.05, 11.83±0.05, 12.78±0.05; S^{32} 9.846±0.020, 10.69±0.05, 11.97±0.08; S^{34} 5.17±0.10, 5.96±0.05, 6.90±0.05, 8.04±0.05, 9.09±0.05, 10.09±0.05, 10.31±0.05 MeV. These results are in agreement with previously published results except for the $S^{32}(\alpha,n)Ar^{35}$ ground threshold which is 140 keV higher than expected. To confirm the value of the mass of Ar^{35}, the $Cl^{35}(p,n)Ar^{35}$ threshold energy was measured and is 6.942±0.020 MeV. Since this result agrees with the accepted value of the Ar^{35} mass, the 140-keV discrepancy was not resolved. In the $C^{12}(\alpha,n)O^{15}$ excitation curve a prominent resonance of half-width 220±60 keV was found corresponding to a level in O^{16} of excitation 18.10±0.06 MeV. The cross section rises to about 22 mb at the peak of this resonance. Half-life determinations yielded the values: O^{15} 122.6±1.0, S^{31} 2.56±0.10, and Ar^{35} 1.76±0.03 sec.

INTRODUCTION

THE (α,n) reaction involves a proton enrichment, and unstable product nuclei tend to decay by positron emission. Detection of the radioactivity alleviates the difficulty of measuring the low neutron yield in the vicinity of the threshold; this is especially advantageous in the presence of a neutron background. The information obtained may be compared with the energetics determined from mass values and decay data. The results also provided information about the level schemes. In some cases the reactions are convenient energy calibration experiments. Only two (α,n) thresholds out of the total of 37 reaction thresholds appear in the 1959 Nuclear Data Tables[1] tabulation of ground-state neutron threshold energies (measured to better than 1%).

In this paper, the results of threshold measurements to both the ground and excited states of the residual nuclei are presented. The values quoted supersede those of the preliminary reports.[2,3] A discrepancy of 140 keV in the $S^{32}(\alpha,n)Ar^{35}$ ground-state threshold is discussed but not resolved. In this connection the results of an accurate determination of the $Cl^{35}(p,n)Ar^{35}$ threshold are presented. The data otherwise agree within experimental error with previously reported results.

EXPERIMENTAL PROCEDURE

Threshold measurements with C^{12}, Si^{28}, and S^{32} targets were carried out by counting the residual nuclear activity. Positrons were observed using a 2-in.×2-in. Ne 102 plastic scintillator or annihilation γ rays were counted in a 3-in.×3-in. NaI crystal. For excitation curves a "leaky" integrator[4] was used. Half-lives were measured with a Technical Measurements Corporation 256 channel analyzer and multiscaler logic unit. Counting time per channel was determined by the sweep of a Tektronix Oscilloscope and measured using the standard frequency output of a Hewlett-Packard Electronic Counter Model 524-C. A least-squares fit to the half-life data was programmed[5] for the IBM 709 computer.

Alpha-particle beams of 3–10 mμA from Florida State University Tandem Van de Graaff Accelerator were analyzed by a 90° magnet of radius 86 cm. Calibration of the analyzing magnet was based on the $C^{13}(p,n)N^{13}$ ground-state threshold, 3237.2±1.6 keV.[6] With this calibration both the Li^7 and $Li^6(\alpha,n)$ threshold[7] values agree within 20 keV with previous measurements.[8] Linearity of the magnet was established earlier by measuring the $Li^7(\alpha,n)B^{10}$ threshold with both He^+ and He^{++} ion beams.

$C^{12}(\alpha,n)O^{15}$

The excitation curve for this reaction was measured by counting the 1.7-MeV positrons from the decay of O^{15}. Since this positron activity has a half-life of about two minutes, three Mylar [$C_{10}(H_2O)_4$] targets were employed in taking the excitation curve. Use of three targets allowed the major portion of the activity of one target to decay while data were being taken using the other two targets. The target thickness was 0.93 mg per square centimeter and the targets were placed with the target plane at 45° with respect to the beam. The beam energy loss in the target was then 400 keV at

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[1] *Nuclear Data Tables*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C., 1959).
[2] J. W. Nelson, E. B. Carter, G. E. Mitchell, and R. H. Davis, Bull. Am. Phys. Soc. **6**, 235 (1961).
[3] J. W. Nelson, E. B. Carter, G. E. Mitchell, and R. H. Davis, Bull. Am. Phys. Soc. **7**, 286 (1962).
[4] S. C. Snowden, Phys. Rev. **78**, 299 (1950).
[5] J. D. Oberholtzer, Ph.D. dissertation (to be published).
[6] R. O. Bondelid and C. A. Kennedy, Phys. Rev. **115**, 1601 (1959). National Research Council Reports NRC-59-6-59, Ar^{35}−1 and NRC-49-6-55 (unpublished).
[7] M. K. Mehta, W. E. Hunt, H. S. Plendl, and R. H. Davis, Bull. Am. Phys. Soc. **6**, 226 (1961).
[8] R. Day and M. Walt, Phys. Rev. **117**, 1331 (1960).

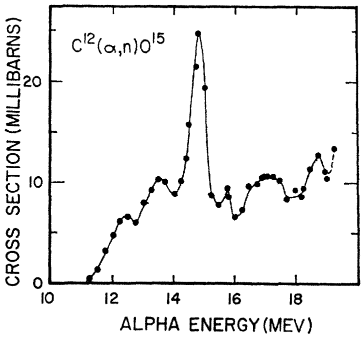

FIG. 1. Excitation curve for the $C^{12}(\alpha,n)O^{15}$ reaction. The estimated error in the cross section is 50%.

14.75 MeV. In addition to the run using Mylar targets, several measurements of the threshold were made with thick graphite targets.

Figure 1 is the excitation curve. The threshold was observed (Fig. 2) at 11.341±0.015 MeV. Within the experimental errors this value is in agreement with the value calculated from the Q value listed in reference 1 (11.343±0.002 MeV). This threshold should be most useful for calibration of accelerators since the masses of C^{12} and O^{15} are accurately known. In addition the experiment can be performed with 5 mμA of alpha particles on a natural carbon target using only a simple "leaky integrator."

The half-life of the O^{15} activity was measured after bombardment of a thick graphite target with 13.6-MeV alpha particles. The value obtained from a least-squares fit of the data is 122.6 sec with an estimated error of ±1.0 sec. This agrees well with the mean value 123.6 ±0.45 sec of several previous determinations.[9]

The outstanding feature of the excitation curve, Fig. 1, is the resonance for alpha-particle bombarding energy of 14.3 MeV. This corresponds to an energy level in the compound nucleus O^{16} at 18.10±0.06 MeV with a half-width of 220±60 keV (c.m.). (See Fig. 3.)

This level probably appears as a resonance in the elastic scattering excitation curves and has a spin and parity of 1^-, 3^-, or 5^-.[10] Levels of similar energy and width are also seen in the reactions $C^{12}(\alpha,\alpha_1)C^{12*}$,[11] $C^{12}(\alpha,p)N^{15}$, and $N^{15}(p,\alpha)C^{12}$.[12] The appearance of this level in several reactions suggests compound nucleus formation.

A comparison with the $C^{12}(\alpha,n)$ excitation curve from 15 to 19 MeV taken at Purdue[13] shows fairly good agreement. In the Purdue work, two peaks appear in place of the broad peak at 16.9 MeV. The peaks at 14.7- and 18.7-MeV bombarding energy are 0.2 MeV higher than in the Purdue work. The fact that the Purdue targets were 350 keV thick as compared with 400 keV thick only partially explains these differences. The absolute cross sections agrees with the Purdue values considering the large experimental error of about 50%.

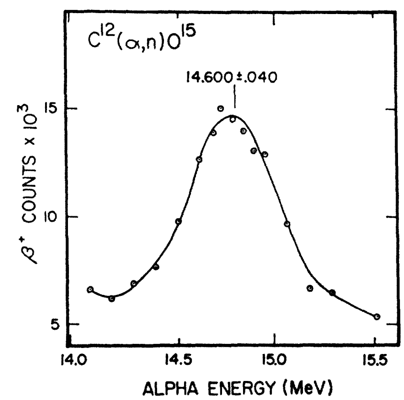

FIG. 3. The prominent resonance at bombarding energy 14.6 MeV. The corresponding excitation energy in O^{16} is 18.10 MeV and the width is 220±60 keV.

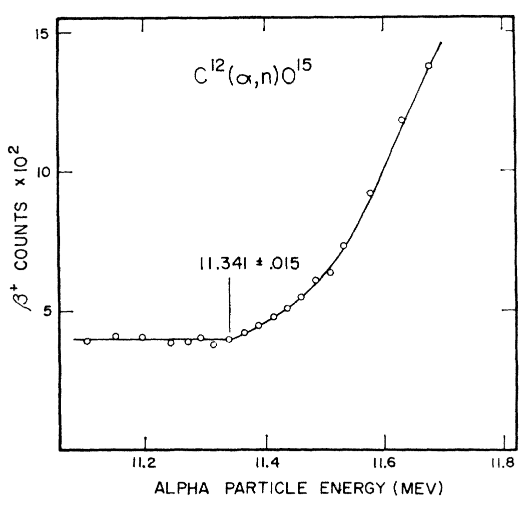

FIG. 2. Ground-state threshold curve for the $C^{12}(\alpha,n)O^{15}$ reaction.

$Si^{28}(\alpha,n)S^{31}$

Threshold for this reaction was observed by counting the annihilation gamma rays resulting from the positron decay of S^{31}. A thick Vycor (96% SiO_2) target was used. The half-life of the activity was measured to be 2.56 seconds with an estimated error of ±0.10 sec. For the half-life measurement, the bombarding energy was 13.500 MeV.

The thick target excitation curves (Figs. 4 and 5) show ground threshold to be 9.30±0.05 MeV. This agrees within experimental error with the value (9.297 ±0.019 MeV) calculated from the 1960 Nuclear Data Tables Part I.[1] Sharp increases in the slope of the excitation curve above the ground-state threshold were interpreted as thresholds due to excited states of the

[9] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1 (1959).

[10] E. B. Carter, G. E. Mitchell, and R. H. Davis (to be published).

[11] G. E. Mitchell, E. B. Carter, and R. H. Davis (to be published).

[12] G. Roy and G. M. Temmer (private communication).

[13] A. G. Rubin, G. D. Johnson, and J. B. Reynolds, Phys. Rev. 10, 1444 (1956).

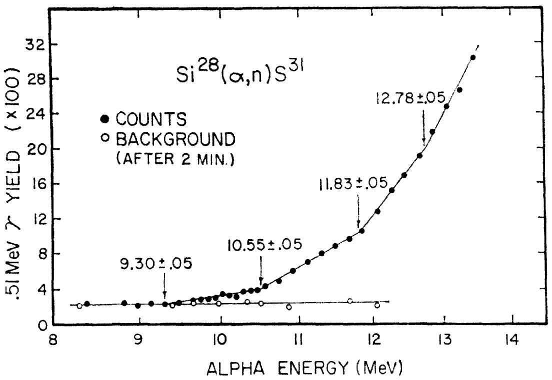

FIG. 4. Thick target excitation curve for the reaction $Si^{28}(\alpha,n)S^{31}$. The threshold energy due to neutrons populating the ground state of S^{31} is 9.30 ± 0.05 MeV. Thresholds due to excited levels of S^{31} are also indicated in the figure.

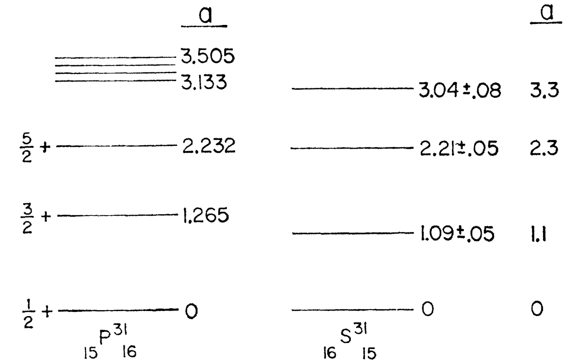

FIG. 6. Energy level diagram showing the levels of S^{31} as determined in this work. Columns labeled *a* are taken from reference 14 for comparison.

residual nucleus although one cannot rule out the possibility that they are due to compound system effects. In Fig. 4, three such excited state thresholds are labeled. A more detailed study of the first excited threshold (Fig. 5) confirms the break at 10.55 MeV in Fig. 4.

Figure 6 is the mirror level diagram for the pair P^{31} and S^{31}. Levels in S^{31} observed in this work are compared with the levels for both P^{31} and S^{31} given in the tabulation by Endt and Van der Leun.[14] Within the experimental errors, the energies of the first two excited levels agree with those reported by Rubin, Johnson, and Reynolds,[13] who measured neutron energies in the reaction $P^{31}(p,n)S^{31}$. The present experiment fixes the position of these levels with a smaller experimental error. The accuracy is sufficient to establish a downward shift of the first excited state relative to ground state in S^{31} as compared to P^{31}.

$S^{32}(\alpha,n)Ar^{35}$ and $Cl^{35}(p,n)Ar^{35}$

Thick sulfur targets of natural isotopic abundance were used in taking data on this reaction. Half-life determinations were made after bombardment with 12.20-MeV alpha particles. Least-squares fits to five runs yield an average value for the half-life of 1.76 sec with an estimated error of ±0.03 sec. This value is slightly lower than the mean of five previous determinations[14] (1.804 ± 0.12) but is in agreement within experimental errors with the most recent of these measurements.[15,16]

Three thresholds are indicated in the excitation curve (Fig. 7). The ground-state threshold was found to occur at 9.846 ± 0.020 MeV which is 140 keV higher than expected from the Q value listed in reference 1. Figure 8 is a more detailed observation of the ground-state threshold which agrees with the data of Fig. 7. One possible explanation for the 140-keV discrepancy in the location of this threshold is that the measurement of the mass of Ar^{35} was incorrect. This mass is based on two independent observations[15,17] of the Ar^{35} positron endpoint which are in agreement within experimental errors (4.93 ± 0.05 and 4.96 ± 0.04 MeV). To confirm these values, the $C^{35}(p,n)Ar^{35}$ threshold was measured

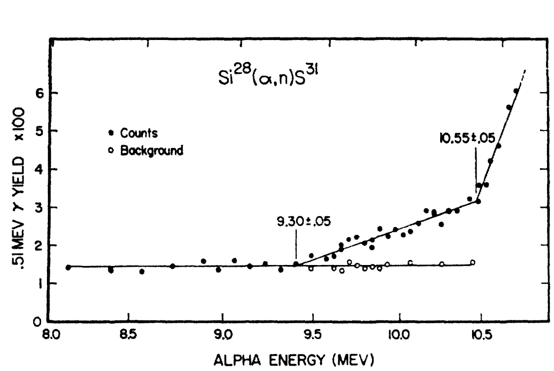

FIG. 5. Thick target excitation curves for $Si^{28}(\alpha,n)S^{31}$. This figure shows more clearly (than Fig. 4) the threshold due to the first excited state of S^{31}.

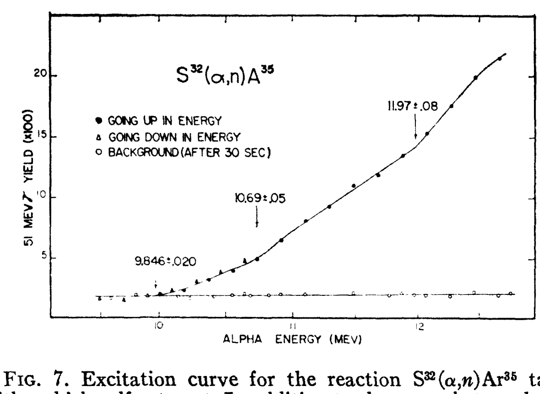

FIG. 7. Excitation curve for the reaction $S^{32}(\alpha,n)Ar^{35}$ taken with a thick sulfur target. In addition to the ground-state threshold, two excited state thresholds are labeled with arrows.

[14] P. M. Endt and C. Van der Leun, Nucl. Phys. 34, 1 (1962).

[15] R. Wallace and J. A. Welch, Jr., Phys. Rev. **117**, 1297 (1960).

[16] J. Janecke, Z. Naturforsch **15a**, 593 (1960).

[17] O. C. Kistner, A. Schwarzschild, and B. M. Rustad, Phys. Rev. **104**, 154 (1956).

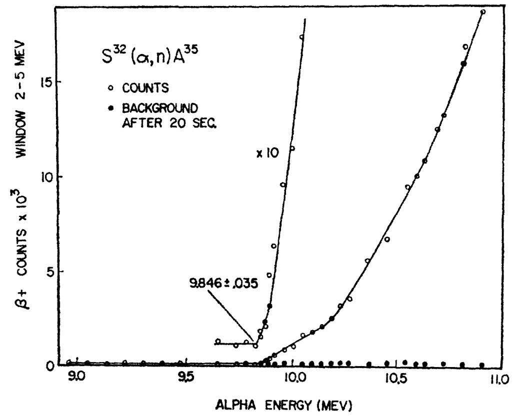

FIG. 8. Ground-state threshold for the reaction $S^{32}(\alpha,n)Ar^{35}$. This threshold occurs 140 keV higher in energy than would be expected from the 1960 Nuclear Data Tables Part I (reference 1).

using a thick AgCl target. Figure 9 shows this threshold to be 6.942±0.020 MeV (corresponding to a positron end point of 4.944±0.020 MeV) which agrees with the end-point measurements.

Another possible explanation of the 140-keV discrepancy is that there is little or no yield at the $S^{32}(\alpha,n)Ar^{35}$ threshold. This implies that the partial width of the neutron or the alpha particle is small (or both) in the energy interval 140 keV above the threshold. From the $Cl^{35}(p,n)Ar^{35}$ excitation curve in Fig. 9, it appears that the neutron channel is open. This excitation curve was extended well above the threshold (Fig. 10) and the curve does turn upward at about 140 keV above the threshold (7.094-MeV bombarding energy). This may indicate an increase in compound system level density which is related to the discrepancy. The argument is made less attractive by the very steep rise of yield (see Fig. 8) in the $S^{32}(\alpha,n)Ar^{35}$ excitation curve. One would expect that well-separated compound system resonances in the vicinity of threshold would yield plateaus in the excitation curve and this is not the case.

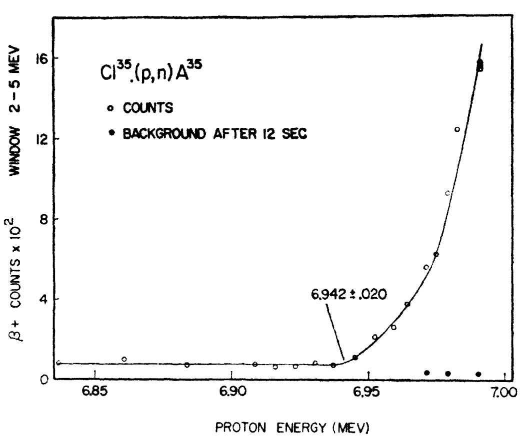

FIG. 9. Ground-state threshold for the reaction $Cl^{35}(p,n)Ar^{35}$. The threshold energy agrees within experimental errors to the value calculated from reference 1.

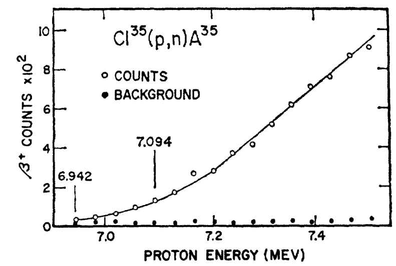

FIG. 10. Excitation curve for the reaction $Cl^{35}(p,n)Ar^{35}$. The slope of the curve increases above 7.094-MeV bombarding energy, and this may indicate a rapid increase in the density of intermediate compound nucleus states for the reaction $S^{32}(\alpha,n)Ar^{35}$ at about 140 keV above the threshold.

Still another possibility is the presence of a contaminant film on the target face of 140-keV thickness for α particles. This seems unlikely since the curve of Fig. 7 was made using a melted sulfur target while for the curve of Fig. 8, a pressed target was used. The chance that either one of the stable masses (S^{32} and Cl^{35}) are incorrect by 140 keV seems even more unlikely.

Changes in slope of the excitation curve are interpreted as excited-state thresholds due to excited levels in the product nucleus, and the energy assignments for levels in Ar^{35} are shown in Fig. 11. The location of the levels was calculated using the mass of Ar^{35} as given in reference 1. For comparison the first two known levels in Cl^{35} are displayed (from reference 14). The distinct change in slope at alpha energy 10.69 MeV in Fig. 7 was not interpreted as a threshold since no corresponding level is known in the mirror nucleus. It represents either a level in Ar^{35} at 0.332 MeV or a level in the compound nucleus Ar^{36} at 15.7 MeV.

$S^{34}(\alpha,n)Ar^{37}$

Thresholds for this reaction were observed by counting the neutrons at zero degrees with a BF_3 counter. A thick target of normal isotopic abundance was used.

In Fig. 12 thresholds are indicated by arrows. The inset shows the ground-state threshold in more detail. Due to inability to focus the beam at energies as low as 5 MeV, the error quoted in the ground threshold energy is larger than that in the excited-state thresholds. Within experimental errors the ground-state threshold energy agrees with the value corresponding to the Q

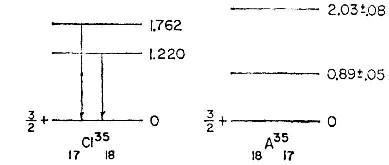

FIG. 11. Energy level diagram showing the first two excited levels of Ar^{35} as determined in this work. For comparison the first two excited states of Cl^{35} are also shown (from reference 14).

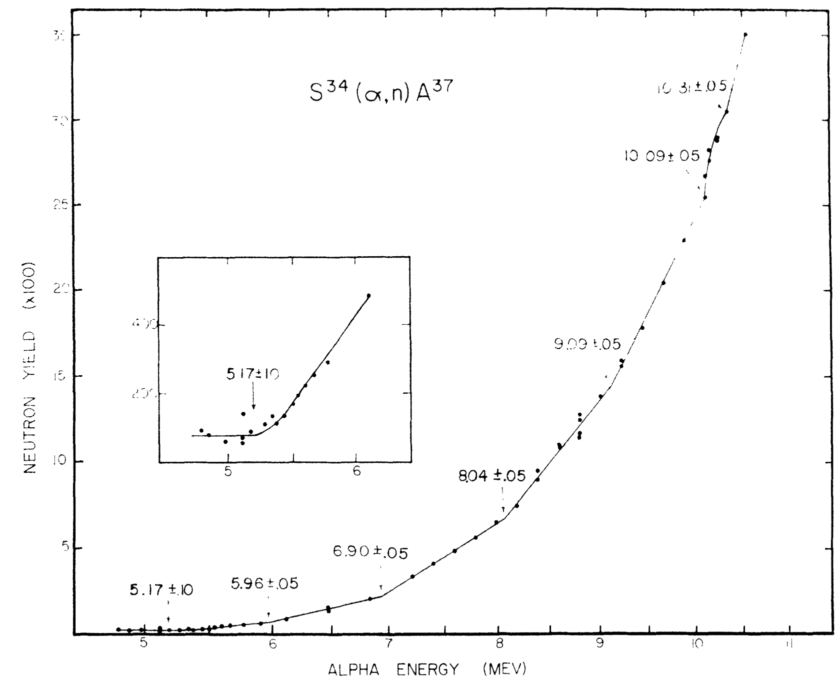

FIG. 12. Thick-target excitation curve for the reaction $S^{34}(\alpha,n)Ar^{37}$. Threshold energies are indicated by arrows. A detailed measurement of the ground-state threshold is shown in the inset.

TABLE I. Energy levels (in MeV) in Ar^{37} observed in the reaction $S^{34}(\alpha,n)Ar^{37}$. The results of the present experiment are tabulated and compared with previously published results.[a]

$S^{34}(\alpha,n)Ar^{37}$	$Ar^{36}(d,p)Ar^{37}$	$Cl^{37}(p,n)Ar^{37}$
(0.70±0.05)	none	none
1.54±0.05	1.44, 1.53, 1.67	1.42, 1.61
none	2.27	2.25
2.56±0.05	2.54, 2.56	2.41
3.50±0.05	3.46, 3.54, 3.55	
4.40±0.05	4.40	
4 63±0.05	4.63	

[a] See reference 14.

value listed in the Nuclear Data Tables Part 1.[1] The latter value was used in computing the energies of excited levels in Ar^{37} contained in Table I. For comparison, Table I contains levels of Ar^{37} as observed in the $Ar^{36}(d,p)Ar^{37}$ and $Cl^{37}(p,n)Ar^{37}$ reactions.[14] The level in Ar^{37} at 0.70±0.05 MeV is listed in parenthesis to indicate tentative assignment since the increase in yield may be due to a resonance in the compound system. If it is a level in the residual nucleus Ar^{37}, high angular momentum may suppress its effects in the lower energy (d,p) and (p,n) experiments.