Total Neutron Yield from the (α, n) Reaction on ^{21,22}Ne†

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Compound states of high excitation in ^{25,26}Mg have been observed, with good resolution, in the total neutron yield from α-particle bombardment of ^{21,22}Ne. Bombarding energies were from 1 to 5 MeV. Analysis of the areas under the yield curves gives α-particle strength functions of $\bar{S}_\alpha = 0.031 \pm 0.021$ for ^{21}Ne + α and $\bar{S}_\alpha = 0.026 \pm 0.012$ for ^{22}Ne + α. For astrophysical purposes these strength functions are used to extrapolate the averaged cross sections to lower energies.

I. INTRODUCTION

Very little is known about the level structure of ^{25,26}Mg at excitation energies above 11 or 12 MeV even though this region is accessible via the α-particle bombardment of ^{21,22}Ne. Ashery[1] has measured the ^{22}Ne$(\alpha, n)^{25}$Mg reaction from about 12.2 to 14.6 MeV excitation using a gas target; Deuchars and Dandy[2] measured this reaction from 12.5 to 13.2 MeV with a "drive-in" target of unknown thickness. Tanner[3] has observed the ^{21}Ne-$(\alpha, n)^{24}$Mg reaction from about 11.3 to 12.3 MeV using a drive-in target about 60 keV thick for 4-MeV α particles. Of these three papers, only that of Ashery reports absolute cross-section measurements. These reactions, in addition to their usual nuclear physics interest, have been recognized for many years to be of considerable astrophysical importance; see for example the recent Refs. 1, 4, and 5.

II. EXPERIMENTAL TECHNIQUES

Using procedures previously described,[6] we have measured the total neutron yield from the reactions ^{21,22}Ne$(\alpha, n)^{24,25}$Mg for bombarding energies from below 1 to 5 MeV. The targets were "drive-in" types (we would like to thank Gerald Alton of the Oak Ridge National Laboratory Isotopes Division for producing all of the "drive-in" targets used in this work) made by bombarding tantalum blanks with 25-keV Ne ions. Selin, Arnell, and Almen[7] have made a careful study of just such ^{22}Ne targets using the ^{22}Ne$(p, \gamma)^{23}$Na reaction. Their proton values can be converted to give a target thickness of 16.4 ± 1.2 keV for 5.2-MeV α particles and to an inactive tantalum surface layer of ≤ 1.2 keV. In our work with drive-in targets made by bombarding tantalum blanks with ^{17}O ions accelerated by 24 kV, we were able to measure the target thickness and to determine that the thickness of any inert surface layer was <1 keV. These ^{17}O values are consistent with the data of Selin, Arnell, and Almen. In correcting the energy scale of the cross-section curves for target thickness we have assumed that any inactive surface layer is of zero thickness and have subtracted half of the above target thickness in the usual way.

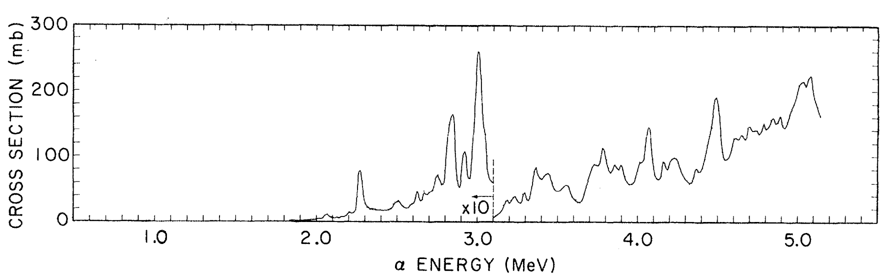

FIG. 1. These data were obtained by means of a "drive-in" target made by bombarding a tantalum blank with 25-keV ^{21}Ne ions in a magnetic separator. The target thickness is ~24 keV at 2 MeV. The cross-section scale has been obtained by normalizing to the gas target data.

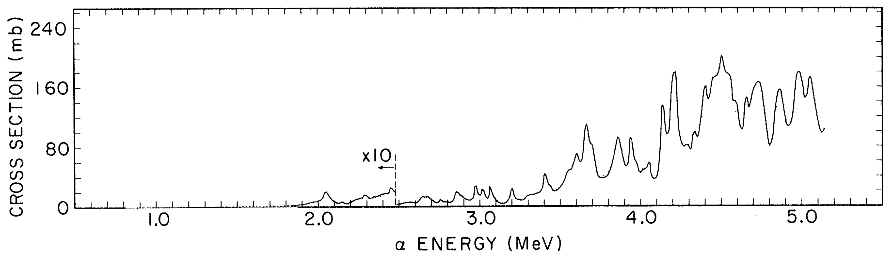

FIG. 2. These data were obtained by means of a "drive-in" target made by bombarding a tantalum blank with 25-keV ^{22}Ne ions in a magnetic separator. The target thickness is ~24 keV for 2-MeV α particles. The cross-section scale has been obtained by normalizing to the gas target data.

III. RESULTS

Figures 1 and 2 show the yield curves for the ^{21}Ne$(\alpha,n)^{24}$Mg and ^{22}Ne$(\alpha,n)^{25}$Mg reactions, respectively. The cross-section scale was obtained by measurements made from 3 to 4 MeV using a gas target (resolution ~40 keV) and highly isotopically enriched gases. The comparison was made by comparing the energy-integrated yields. No correction has been made for the variation of detector efficiency with neutron energy. In the case of ^{22}Ne we can use Ashery's[1] data to estimate that the detector efficiency correction, averaged over individual levels, is less than $+\frac{1}{2}\%$ for 2-MeV α particles and less than $+2\frac{1}{2}\%$ for 4-MeV α particles. For ^{21}Ne we can only state that at the highest bombarding energy if all neutron emission is to the ground state of ^{24}Mg (the worst possible case) a maximum correction of +9% would be necessary. Exclusive of the detector efficiency correction, we believe the error in the cross section is ±12% for energies above about 1.7 MeV and for structure wider than the target resolution.

Ashery's[1] ^{22}Ne$(\alpha,n)^{25}$Mg data, taken with a gas target and unstated energy resolution, is in general agreement with ours although we see many more maxima than he does. In particular, Ashery's total cross section is essentially constant at 100 mb from about 3.58 to 3.95 MeV (lab),

TABLE I. Estimates of the energy of the maxima in the ^{21}Ne$(\alpha,n)^{24}$Mg yield curve, the corresponding excitation energy in the ^{25}Mg compound system, and estimates of the experimental laboratory width.

Level	E_{lab} (MeV)	E_{ex} (MeV)	Γ (keV)	Level	E_{lab} (MeV)	E_{ex} (MeV)	Γ (keV)
1	1.86	11.45	<30	21	3.78	13.06	35
2	2.06	11.62	<25	22	3.86	13.13	25
3	2.21	11.74	<20	23	3.90	13.16	25
4	2.27	11.79	35	24	4.02	13.26	40
5	2.50	11.98	50	25	4.07	13.30	50
6	2.59	12.06	20	26	4.16	13.38	25
7	2.63	12.09	20	27	4.23	13.44	80
8	2.67	12.13	20	28	4.37	13.56	30
9	2.75	12.19	30	29	4.43	13.61	~35
10	2.84	12.27	55	30	4.49	13.66	50
11	2.92	12.34	30	31	4.61	13.76	~35
12	3.01	12.41	50	32	4.65	13.79	~35
13	3.05	12.45	25	33	4.70	13.83	~35
14	3.18	12.56	25	34	4.74	13.87	~50
15	3.23	12.60	35	35	4.79	13.91	~25
16	3.29	12.65	25	36	4.84	13.95	~35
17	3.37	12.72	40	37	4.89	13.99	~25
18	3.44	12.77	80	38	5.03	14.11	90
19	3.56	12.87	65	39	5.08	14.15	35
20	3.73	13.02	85				

whereas our drive-in target data vary by a factor of about 3. Thus while our peak cross sections are not in disagreement, our average cross sections are considerably different. Our results on $^{21}Ne(\alpha,n)^{24}Mg$ are not in agreement with those of Tanner.[3] In the region where the two experiments overlap, Tanner sees two maxima at 2.10 and 2.58 MeV which we do not seem to see, and we see a strong maximum at 2.27 MeV which he does not see. Although Tanner's data are the 30° yields and our data are the angle-integrated yields, it would seem unlikely that the discrepancy is due to angular distribution effects.

Tables I and II list the bombarding α-particle energies of the maxima in the yield curves, the corresponding excitation energies in the compound nucleus, and estimates of the experimental widths.

IV. DISCUSSION

Following the techniques used in previous work at this laboratory we have averaged the cross-section data over an energy region of 400 keV as a function of the incident energy. The resulting averages are shown as the points in Figs. 3 and 4. If we assume (1) that $\Gamma_n \gg \Gamma_\alpha$ and that all other widths are negligible and (2) that the net effect of interference terms in the total cross section is zero when averaged over the levels, we can define an α-particle strength function, $\overline{S}_\alpha$, by

$$\frac{A_{\Delta E}}{\Delta E} = \frac{2\pi^2 \lambda\!\!\!^{-2}}{2I+1} \sum_J (2J+1) \sum_{l=|J-I|}^{J+I} \frac{2kR}{A_l^{\,2}} \overline{S}_\alpha . \quad (1)$$

Here $A_{\Delta E}/\Delta E$ is the area under the averaged yield curve and the other symbols have their usual meaning [the reaction radius was taken to be $1.4\,(A^{1/3}+1.59)$ fm]. The $\overline{S}_\alpha$ defined is an average over the possible α-particle orbital angular momenta. Using Eq. (1), an $\overline{S}_\alpha$ was calculated for each energy increment: The average of these is $\overline{S}_\alpha = 0.031 \pm 0.021$ for $^{21}Ne + \alpha$ and $\overline{S}_\alpha = 0.026 \pm 0.012$ for $^{22}Ne + \alpha$ where the error is the variance for the different energy increments. The solid curves on the figures are from Eq. (1) using these values for $\overline{S}_\alpha$. The $\overline{S}_\alpha$ can be used to obtain extrapolated cross sections at low energies of interest for astrophysical purposes: We obtain 0.10 nb at 800 keV and 0.000 15 nb at 600 keV for both reactions.

A value of $\overline{S}_\alpha = 0.037 \pm 0.020$ for $^{22}Ne + \alpha$ can be obtained from Ashery's[1] data. This is somewhat higher than our value of 0.026 ± 0.012 as would be

TABLE II. Estimates of the energy of the maxima in the $^{22}Ne(\alpha,n)^{25}Mg$ yield curve, the corresponding excitation energy in the ^{26}Mg compound system, and estimates of the experimental laboratory width.

Level [a]	E_{lab} (MeV)	E_{ex} (MeV)	Γ_{lab} (keV)	Level	E_{lab} (MeV)	E_{ex} (MeV)	Γ_{lab} (keV)
1	1.98	12.29	200	22	3.70	13.74	25
2	2.05	12.35	40	23	3.86	13.88	60
3	2.15	12.43	~20	24	3.94	13.95	25
4	2.29	12.55	~25	25	3.97	13.97	20
5	2.44	12.68	~20	26	4.01	14.01	20
6	2.56	12.78	~80	27	4.05	14.04	15
7	2.64	12.85	~30	28	4.13	14.11	25
8	2.68	13.03	~30	29	4.21	14.17	45
9	2.76	12.95	~20	30	4.29	14.24	~30
10	2.86	13.02	~30	31	4.33	14.28	~25
11	2.88	13.05	40	32	4.40	14.34	~30
12	2.97	13.13	20	33	4.46	14.39	~25
13	3.02	13.17	25	34	4.50	14.42	~30
14	3.06	13.20	20	35	4.55	14.46	~25
15	3.20	13.32	25	36	4.59	14.50	~20
16	3.31	13.41	50	37	4.66	14.56	20
17	3.40	13.49	30	38	4.73	14.61	100
18	3.44	13.52	20	39	4.86	14.72	60
19	3.55	13.62	25	40	4.98	14.83	75
20	3.60	13.66	35	41	5.05	14.89	50
21	3.66	13.71	60				

[a] There exists some evidence for three very weak maxima at 1.58, 1.71, and 1.81 MeV.

expected in view of our preceding remarks concerning his peak-to-average cross-section ratio.

Figures 5 and 6 show plots of the log of the number of level spacings greater than some spacing D. If the distribution is random, such plots should give a straight line the reciprocal of whose negative slope is the average level spacing and whose intercept on the $\log N$ axis should correspond to the total number of levels. We find, for $^{21}\mathrm{Ne}(\alpha,n)^{24}\mathrm{Mg}$, that the intercept gives 65 levels, of which we actually observe 39, and that the average level spacing as given by the slope is 52 keV. For $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ the corresponding numbers are 81 levels of which we see 41 and an average level spacing of 40 keV. In their review article, Endt and Van der Leun[8] give average level spacings of about 64 keV at the somewhat lower excitation of 8 MeV for $^{25}\mathrm{Mg}$ and 52 keV at about 9 MeV for $^{26}\mathrm{Mg}$. These values are consistent with those obtained here. If we assume that the level spacing varies by $(2J+1)^{-1}$, that only the 4 lowest possible J values are observed, and that the level spacing is that obtained from the slope of Figs. 5 and 6, we predict that the spacing of $J=1/2$ levels in the $^{21}\mathrm{Ne}(\alpha,n)^{24}\mathrm{Mg}$ reaction is about 780 keV and that the spacing of $J=0$ levels in the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ reaction is about 640 keV. The corresponding spacing of $J=3/2$ and $J=1$ levels then is 390 and 210 keV, respectively.

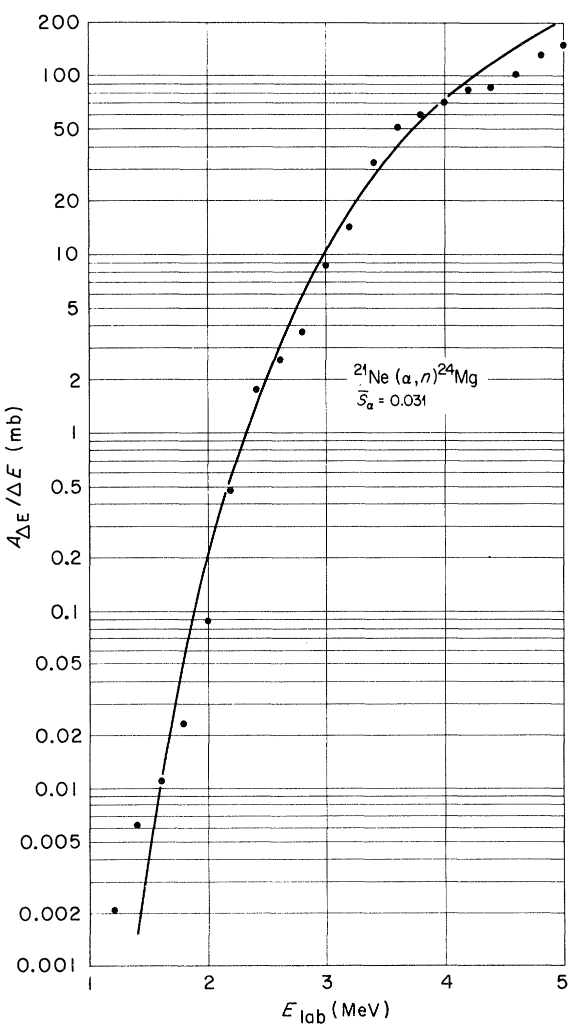

FIG. 3. Plot of $A_{\Delta E}/\Delta E$ as a function of incident α-particle energy for the reaction $^{21}\mathrm{Ne}(\alpha,n)^{24}\mathrm{Mg}$. Here $A_{\Delta E}$ is the area under the excitation curve in some energy region ΔE. The solid curve is calculated based on an α-particle strength function $\bar{S}_\alpha = 0.031$.

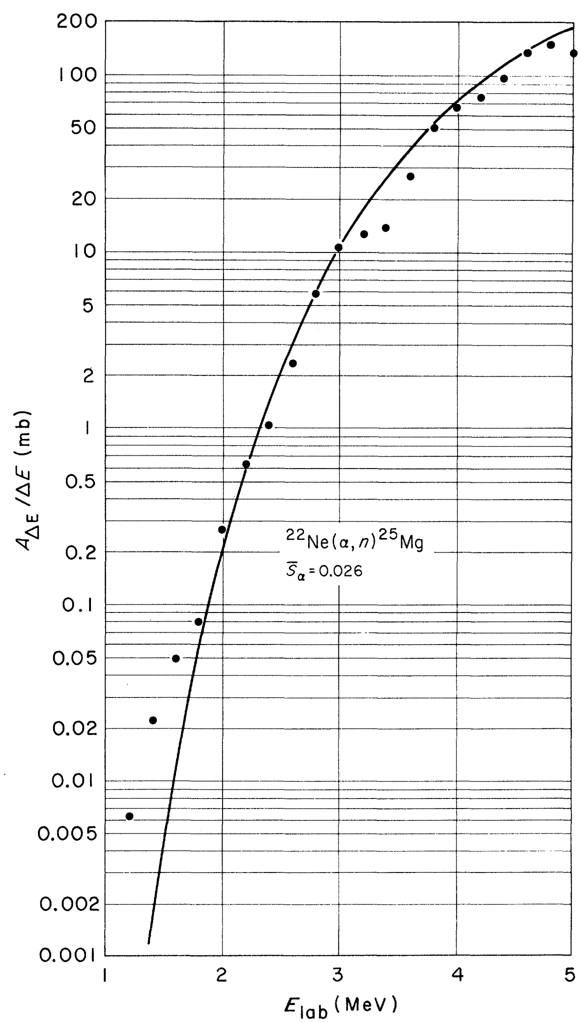

FIG. 4. Plot of $A_{\Delta E}/\Delta E$ as a function of incident α-particle energy for the reaction $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$. Here $A_{\Delta E}$ is the area under the excitation curve in some energy region ΔE. The solid curve is calculated based on an α-particle strength function $\bar{S}_\alpha = 0.026$.

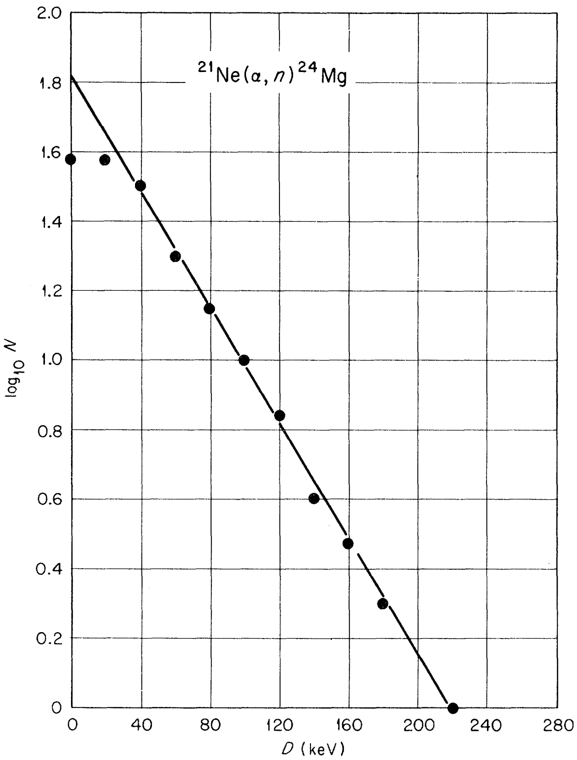

FIG. 5. Plot of the log of the number of levels in the reaction ^{21}Ne$(\alpha,n)^{24}$Mg having a spacing greater than some spacing D (in the lab system).

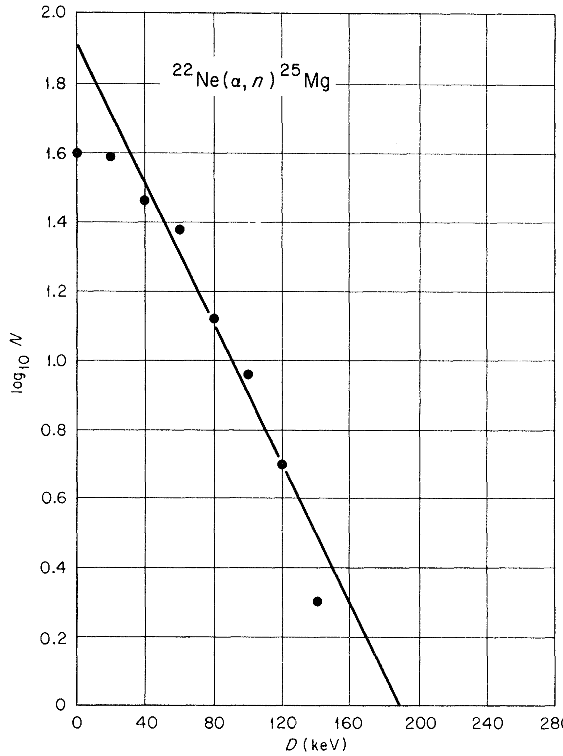

FIG. 6. Plot of the log of the number of levels in the reaction ^{22}Ne$(\alpha,n)^{25}$Mg having a spacing greater than some spacing D (in the lab system).

Since the present work is in considerable disagreement with the earlier work[3] on the ^{21}Ne(α,n)-^{24}Mg cross sections, the conclusion of Ref. 4 concerning the role of ^{21,22}Ne(α,n) reactions as sources of stellar neutrons should be reconsidered.

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