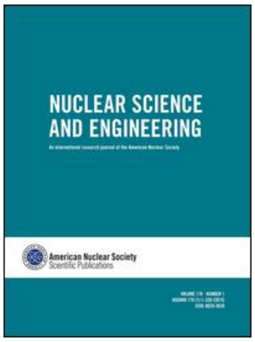

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Cross Sections for the $^{25}Mg(\alpha,n)^{28}Si$ Reaction for $E_\alpha < 4.8$ MeV

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The four neutron groups populating the ground state and the lower three excited states of ^{28}Si were studied with a stilbene neutron spectrometer. Total neutron cross sections were obtained from measurements at detection angles of 0, 45, 90, and 135 deg. A large number of resonances were seen, indicating many levels in ^{29}Si. By using the reciprocity theorem, the cross sections for $^{28}Si(n,\alpha_0)^{25}Mg$ reaction were obtained and compared with those given in the literature.

INTRODUCTION

Natural magnesium consists of ~79% ^{24}Mg, 10% ^{25}Mg, and 11% ^{26}Mg. Neutron production from natural magnesium by alpha particles of <8.4 MeV is confined to ^{25}Mg and ^{26}Mg because of the high negative Q value for the $^{24}Mg(\alpha,n)$ reaction of 7.2 MeV. Excitation curves with alpha particles from ^{210}Po on natural magnesium were studied by Nagy[1] and Halpern[2] with rather poor resolution. Thick-target neutron yield curves on natural magnesium were measured by Bair and del Campo[3] and by West and Sherwood[4] with 4π neutron detectors. Such measurements are of importance for environmental considerations in the spent reactor fuel technology, where actinide alpha-particle emitters come in contact with light elements in the fuel and its encapsulation.

Measurements on ^{26}Mg were carried out by Bair and Willard,[5] who studied the neutron production cross section on a thin target using the Oak Ridge graphite sphere as a 4π neutron detector. Similarly, Russell et al.[6] measured the excitation curve with a long counter at 0 deg. A large number of resonances corresponding to compound states in ^{30}Si were seen.

No differential cross-section measurements on ^{25}Mg or ^{26}Mg have been published. In both cases, several neutron groups, populating the ground state and excited states of the silicon product nucleus, are formed. The knowledge of the relative intensities of these groups would allow the making of efficiency corrections of 4π neutron detectors to improve the direct measurements of total cross sections and also permits the calculation of neutron spectra from radioactive $Mg(\alpha,n)$ sources.

With the total cross section for the $^{26}Mg(\alpha,n)$ reaction already available, we decided to measure differential cross sections for the $^{25}Mg(\alpha,n)^{28}Si$ reaction (Q = 2.653 MeV) and to derive total cross sections for the individual groups by solid angle integration. As the neutron detector, we used the stilbene spectrometer, which we have developed over the past ten years to study neutron-producing reactions (e.g., Ref. 7). Its detection efficiency, calculated from the number of hydrogen atoms in the stilbene,

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with corrections for multiple scattering and edge effects, had been compared by Huynh[8] at E_n = 2.5 MeV with the response found by other laboratories. We believe that the systematic error in our neutron fluence measurements does not exceed ±5% within the energy range of from 1 to 10 MeV.

EXPERIMENTAL METHOD

The irradiations were carried out on the nominally 4-MV Van de Graaff accelerator at the National Research Council of Canada laboratory. Targets were prepared either by vacuum evaporation of metallic magnesium (99.7% ^{25}Mg) or by reduction of MgO (98.3% ^{25}Mg) with zirconium at 1500°C and subsequent evaporation of the metal. Target backings of silver, tantalum, and gold were used; for good adhesion of the target material, the backing had to be heated to 125°C. The thickness of the heaviest target (95 μg/cm^2) was determined by weighing. This measurement was confirmed by the proton energy loss seen in the target at the ^{25}Mg(p,γ) resonances at proton energies of 390 and 435 keV. The stopping power tabulated by Andersen and Ziegler[9] was used to convert from energy loss to weight. The thicknesses of thinner targets were obtained by comparing their gamma-ray yields with the yield of the 95 μg/cm^2 target for the same ^{25}Mg(p,γ) resonances.

The energy calibration of the beam-deflecting magnet was carried out on the ^{24}Mg(α,γ)^{28}Si reaction, using the well-known resonance[10] at E_α = 3199.8 ± 1.0 keV. Beam energies were known to ±4 keV; the energy spread within the beam was ±1.5 keV.

Neutron yields and the resulting differential cross sections were measured with a proton recoil detector consisting of a stilbene crystal 0.5 cm long X 2.54 cm in diameter. The center of the crystal was 10.65 cm from the target. Pulse-shape discrimination[11] eliminated the gamma-ray component. The required corrections for geometric effects, anisotropy of light response, and double scattering in the crystal are discussed in detail in Refs. 7 and 12.

An example of a neutron spectrum is given in Fig. 1. The peak at the highest neutron energy, marked n_0, represents the neutron group populating

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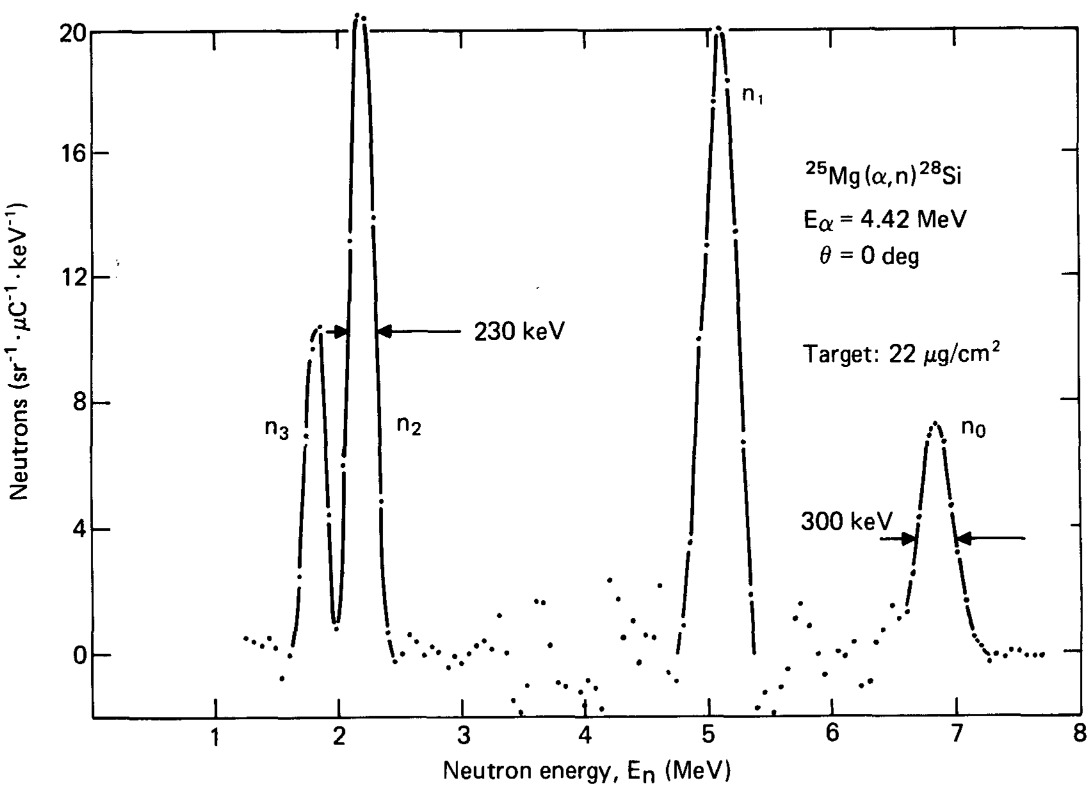

Fig. 1. Neutron spectrum from a ^{25}Mg target obtained with a stilbene scintillator.

the ground state of ^{28}Si. The spectrometer resolution was sufficient to separate the neutron groups n_1, n_2, and n_3 that feed the excited states in ^{28}Si at 1.78, 4.62, and 4.98 MeV (see inset of Fig. 2). The differential cross sections for the production of the individual groups could then be extracted from the area under the peaks, except at neutron energies below 500 keV, the low-energy limit of the spectrometer.

EXCITATION FUNCTIONS

Because a large number of resonances were found in the excitation curves, we had to confine ourselves to measurements at 0, 45, 90, and 135 deg to obtain the total neutron production cross sections. The target was water cooled; therefore, the absorption for neutrons when passing through the target and its backings obliquely was substantial. By appropriate orientation of the target, such absorption was minimized. The neutron absorption was calculated and further verified by measuring the neutron fluence at a constant detector angle but changing the angle of the target. The absorption was largest for the measurement at the 45-deg detection angle—up to 8%, depending on neutron energy.

The angular distributions so obtained were fitted in terms of Legendre polynomials using coefficients from A_0 to A_2. This produced a fit nearly always consistent with the experimental errors of the measurements. The A_0 coefficients in most cases were relatively insensitive to the degree of fit used. Near threshold for the n_2 and n_3 neutron groups, where the measurements at 90 and 135 deg resulted in neutron energies below the detection capabilities of the spectrometer, isotropic distributions were assumed. We believe this was justified since the angular distributions did approach isotropy in the low-energy region.

Figures 2 and 3 show the total cross sections for the individual neutron groups as well as their sum, which is the total neutron production cross section for the reaction. A target of thickness 22 μg/cm^2 was used above E_α = 3.64 MeV, corresponding to a loss of from 14- to 17-keV alpha-particle energy within the target. At the lower alpha-particle energies,

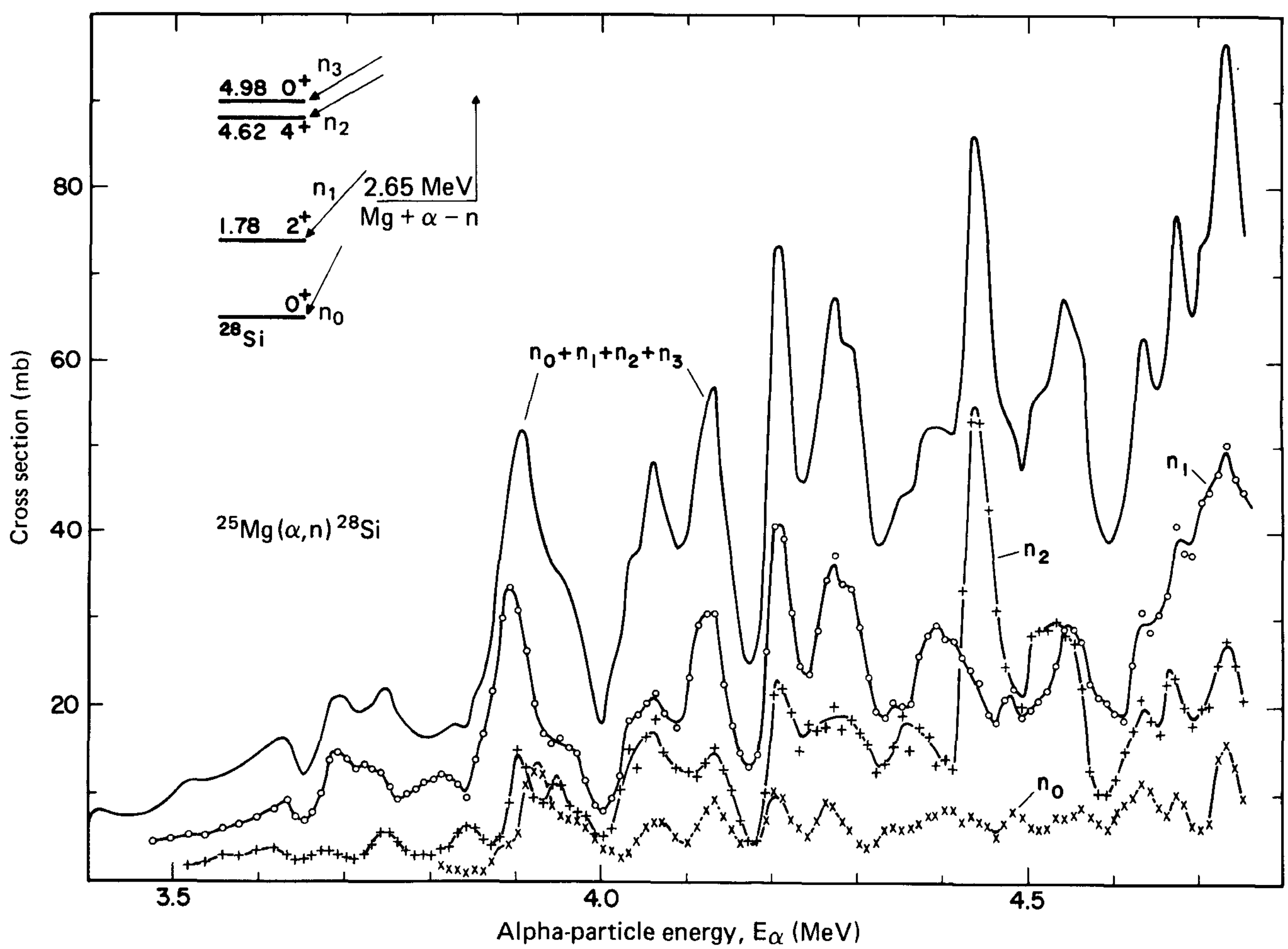

Fig. 2. Total neutron production cross sections for the upper energy range. Statistical errors are ±10%. In addition, there is a systematic error of ±10%. The inset shows the energy levels of ^{28}Si, which are populated by the neutron groups n_0 to n_3.

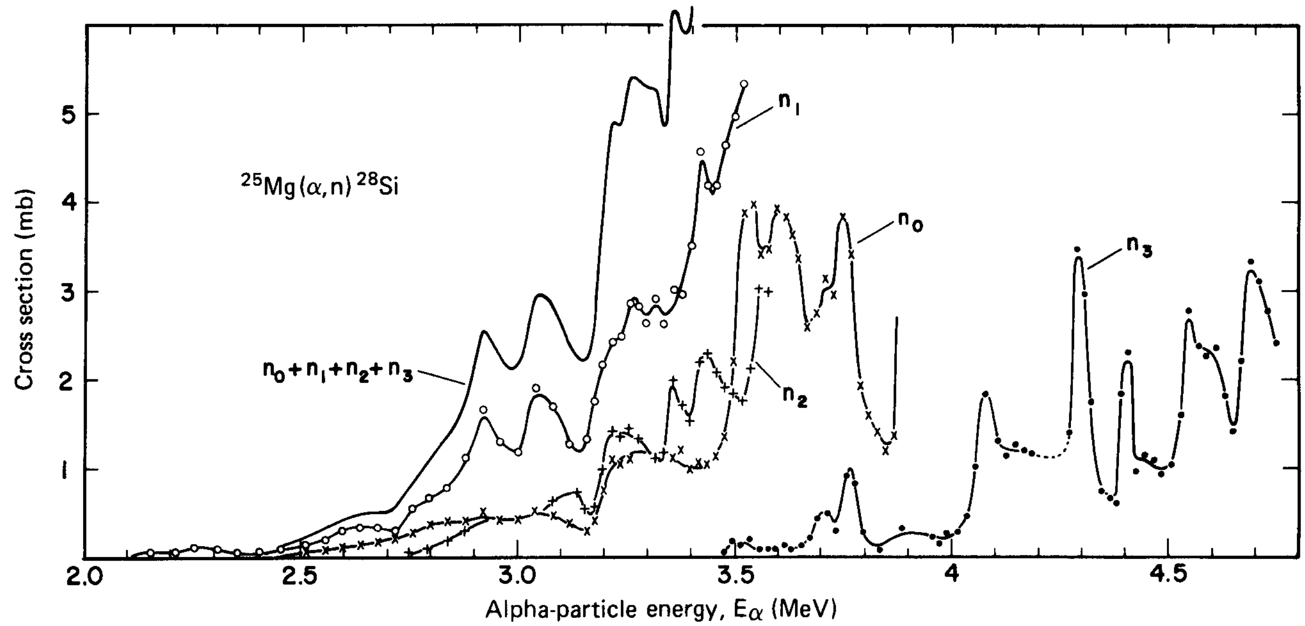

Fig. 3. Total neutron production cross sections for the lower energy range and n_3 neutron group. This group has a statistical error of ±15%; for other errors, see Fig. 2.

heavier targets of 57 and 95 μg/cm^2 were needed so as to have an adequate neutron intensity. The alpha-particle energies given in the figures are those found in the middle of the target layer.

The total cross sections of Figs. 2 and 3 are subject to a statistical error of ±10% except for the n_3 group, where the statistical error is ±15%. In addition, there is a systematic uncertainty of ±10% that takes into account the uncertainty in the neutron fluence measurement (±5%) and in the estimated uncertainty of the target thickness (±8%).

The total cross sections in Figs. 2 and 3 show a very detailed structure, indicating many levels in ^{29}Si. It is also interesting to note that the n_1 and n_2 neutron groups are nearly always more intense than the n_0 group. The n_3 group is very weak throughout the range. A list of the major resonances and of the corresponding excitation energies in ^{29}Si is given in Table I.

DISCUSSION

No other measurements on the $^{25}Mg(\alpha,n)$ reaction are available for comparison. Halpern[2] measured an excitation curve for ^{nat}Mg, which, because of poor resolution, rises rather smoothly to a neutron production cross section of 80 mb at $E_\alpha \approx 4.5$ MeV for the sum of the ^{25}Mg and $^{26}Mg(\alpha,n)$ cross sections. Bair and Willard[5] found an average cross section for the $^{26}Mg(\alpha,n)$ reaction of 80 mb (+25%, −50%) in this energy range. Our measurement for $^{25}Mg(\alpha,n)$ resulted in ~50 mb. The sum of these two individual measurements of 130 mb is larger than Halpern's cross section, but still within the errors of the measurements. In the near future, we expect to extend our investigation to the $^{26}Mg(\alpha,n)$ reaction and hope to obtain more accurate neutron production cross sections. Then we will also be in a position to calculate thick target neutron yields on natural magnesium and to compare these with the recent measurements given in Refs. 3 and 4.

The detection of charged particles from the (Si + n) reactions within a silicon solid-state detector has, in the past, been suggested for neutron

TABLE I

Prominent Resonances Seen in the $^{25}Mg(\alpha,n)$ Reaction

E_α (MeV ± keV)	E_x in ^{29}Si (MeV)	Decay
3.750 ± 15	14.359	n_0, n_2, n_3
3.893 ± 8	14.483	n_1
3.905 ± 10	14.493	n_2
3.925 ± 10	14.510	n_0
4.060 ± 10	14.626	n_0, n_1, n_2
4.130 ± 10	14.687	n_0, n_1, n_2
4.208 ± 8	14.754	n_0, n_1, n_2
4.270 ± 10	14.807	n_0, n_1
4.295 ± 10	14.829	n_3
4.435 ± 8	14.949	n_2
4.545 ± 10	15.044	n_1, n_3
4.635 ± 8	15.122	n_0, n_1, n_2
4.675 ± 8	15.156	n_0, n_1, n_2
4.733 ± 5	15.206	n_0, n_1, n_2

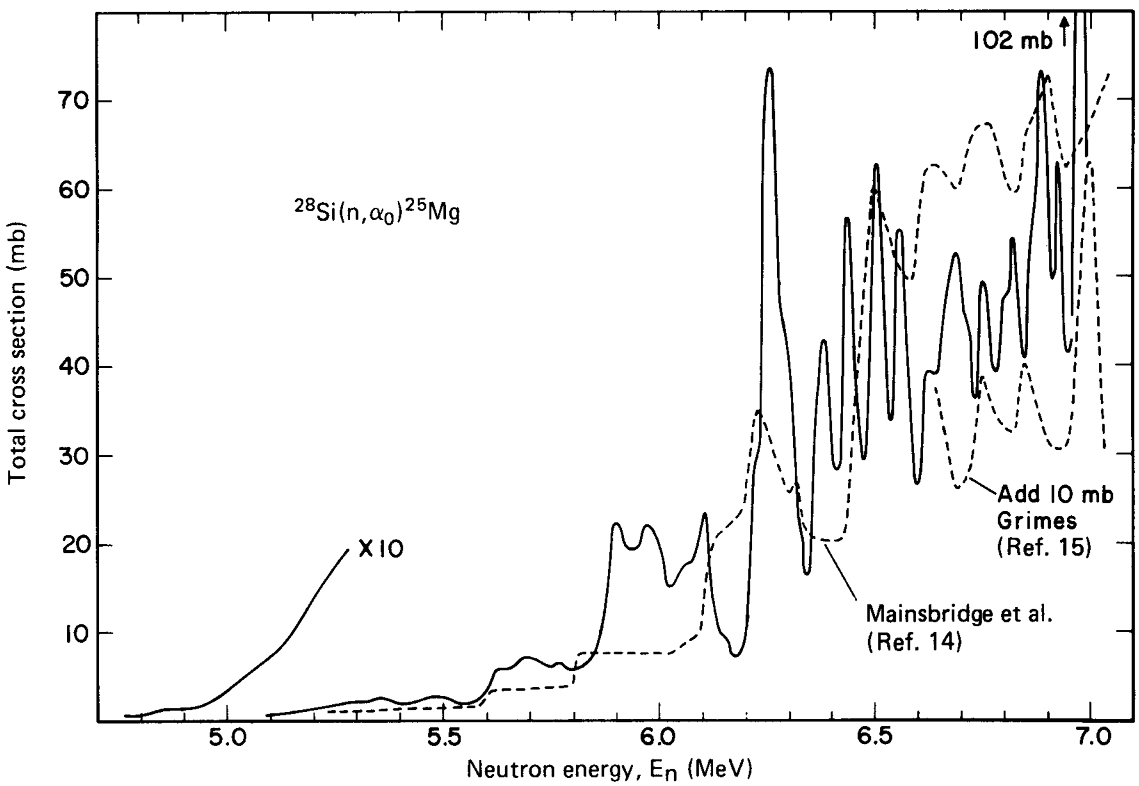

Fig. 4. The $^{28}Si(n,\alpha_0)^{25}Mg$ cross section obtained by using the reciprocity theorem. The dashed curves are direct determinations of Refs. 14 and 15. For clarity, the curve given by Grimes[15] has been lowered by 10 mb.

spectroscopy, e.g., see Refs. 13 through 16. The $^{28}Si(n,\alpha)$ and (n,p) reactions are the most predominant ones, and detailed cross sections are needed for this purpose. Invoking the reciprocity theorem, we obtained the cross sections for the $^{28}Si(n,\alpha_0)$ reaction from our $^{25}Mg(\alpha,n_0)$ data. This is shown in Fig. 4, where our calculated (n,α_0) cross section is compared with direct determinations by Mainsbridge et al.[14] and Grimes[15] using a silicon barrier detector. The much narrower resonances obtained by our measurements are evident. The difference can be explained by the rather broad neutron energy spread of their neutron beam used, namely, 33 keV in Ref. 15 and ~60 keV in Ref. 14. The location of the various peaks does not coincide very well for the three curves, but in absolute magnitude, Grimes' data are in good agreement with ours. Figure 4 shows the original data as given in Ref. 14. Rabson (unpublished, quoted in Ref. 16) pointed out that these data should be moved downward by ~200 keV. However, such shift does not significantly improve the fit with our own cross-section curve.

The very detailed cross-section structure found in our measurements does not appear to make a silicon surface barrier detector a suitable instrument for neutron spectroscopy. The widths of the resonances shown in our curve of Fig. 4 are comparable to the energy width of the alpha particles reacting in our target, and the true line widths may still be narrower. Moreover, similar narrow resonances are expected for competing (n,p) reactions and the (n,α) reactions feeding excited states in ^{25}Mg. However, Miller and Kavanagh[16] found that the best neutron resolution they could obtain from their silicon detector was 125 keV. The finer details in the variation of the neutron cross sections are therefore smoothed. The authors first calibrated their spectrometer with a set of neutron lines and subsequently obtained good results for the measurement of monoenergetic neutrons. But when irradiating with a broad neutron energy spectrum, it becomes nearly impossible to untangle the alpha and proton energy spectra in the silicon surface barrier detector.

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