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Measurement of $^{27}Al(n,p)^{27}Mg$ Activation Cross Section

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Abstract: The cross section of the $^{27}Al(n,p)^{27}Mg$ was measured by the foil activation technique at several energies of 5 MeV and between 14.6 and 19.9 MeV. The cross section at 5 MeV was determined absolutely, while the cross section for the higher energies between 14.0 and 19.9 MeV was determined relatively by referring to the $^{27}Al(n,\alpha)^{24}Na$ cross section measured in our previous work. The present results are rather consistent with Ryves' measurements, but are lower than those of ENDF/B-V evaluation.

($^{27}Al(n,p)^{27}Mg$ reaction, reaction cross section, foil activation, $4\pi\beta$-γ coincidence method, associated α-particle counting, ENDF/B-V)

Intrduction

The threshold reaction of the $^{27}Al(n,p)^{27}Mg$ gives advantageous features as one of activation reactions for reactor dosimetry as well as such $^{27}Al(n,\alpha)^{24}Na$ and $^{56}Fe(n,p)^{56}Mn$ reactions which have been included among the standard reference data by IAEA/1/. One of the most authoritative assessment of cross section data on the reaction is commonly accepted to be that represented by the evaluated data given in ENDF/B-V/2/. These data, however, have been evaluated on the basis of measurements/3-8/ reported before 1972.

The Electrotechnical Laboratory(ETL) provided the $^{27}Al(n,\alpha)^{24}Na$ and the $^{56}Fe(n,p)^{56}Mn$ cross sections for the energies between 14.0 and 19.9 MeV/9/, and has been extending the measurements to other important reactions. The present study covers precise measurements of the cross sections presented for the $^{27}Al(n,p)^{27}Mg$ reaction in the energy range between 14.6 and 19.9 MeV and in the energy point of 5.0 MeV. The measurements were made in standard neutron fields at ETL, whose consistency with those of other standardizing laboratories was confirmed by a series of international intercomparisons held under the auspicies of the Bureau International des Poids et Measures/10-12/.

The results of the present cross section measurements are compared with the recent evaluations/2,13,14/ and measurements/15/.

Experimental

Neutron Irradiations and Fluence Monitoring

A 4 MV van de Graaff type accelerator (Pelletron from Nuclear Electrostatic Co., USA) was used for producing neutrons of energies in the range of 5 MeV - 19.9 MeV, excepting the neutrons at 14.6 MeV, which were produced by a Cockcroft type accelerator (conventional machine from World Engineering Co., Japan). With both types of accelerator, the accelerated deuteron beam was transported to a tritium-titanium(Ti-T) target or tritium-deuterium(Ti-D) target positioned at the center of an experimental room measuring 11.5m x 11.5m x 11.5m. The $T(d,n)^4He$ reaction at 0.22, 0.241, 0.527, 1.139, 1.839 and 3.228 MeV deuteron energy and the $D(d,n)^3He$ reaction at 1.767 MeV deuteron energy were used as sources of monoenergetic neutrons.

The Ti-T target was occluded in 0.4 mg/cm^2 thick Ti layer evaporated on a 0.25 mm thick Cu backing, and the Ti-D target had the same dimensions and specifications as well as the Ti-T target. The target was cooled by air jet in the case of the Cockcroft type accelerator and by freon gas circulation with the van de Graaff.

Scatter-back of neutrons from the floor was reduced by setting the target assemblies and measuring instruments on an elavated aluminum grating supported at mid-height of the room. The contribution of the secondary neutrons to the ^{27}Mg radioactivity was estimated by the neutron transport calculation, PALLAS/16/ as described further on.

The aluminum foils used in all irradiation runs were of purity exceeding 99.99 %, and the thickness ranged from 0.05 mm to 0.5 mm with the diameter of 25.4 mm. The foil was irradiated with a deuteron beam current ranging 3 - 10 μA, which ensured a fairly stable neutron yield. Variation in time of the neutron flux was monitored by α-particle counters or else by long counters/9/. The irradiation time was about 30 min.

Runs using the Cockcroft type accelerator were performed with the Ti-T target set at 45° inclination to the incident deuteron beam of 220 keV. The foil was irradiated at an angle of 45° to the deuteron beam. The mean neutron energy corresponding to the angle was determined as 14.6 MeV by using an associated α-particle counting technique/9/. The distance from the target was varied in the range from 50 to 100 mm.

Runs using the van de Graaff accelerator, were made with an activation foil placed along the beam axis behind the Ti-T or Ti-D target at distances from 50 to 100 mm. The neutron flux at 5.0 MeV was determined absolutely by using a Si surface barrier detector with a 1 mm thick polyethylene radiator. The pulse height spectrum from the experiment was shown in Fig.1 with the fitted spectrum calculated by the Monte Carlo code/17/.

Radioactivity measurement

The ^{27}Mg activity from the $^{27}Al(n,p)^{27}Mg$ reaction was measured by the γ counting method with a calibrated pure Ge detector or by the 4πβ-γ counting technique. In the latter method, the disintegration rate N_0 of the source is given by

$$N_\beta N_\gamma / N_c = N_0 (1 + K),$$

where N_β, N_γ and N_c are respectively the β, γ and coincidence count rates, corrected for background, dead-time and chance coincidence. The value K represents an efficiency-dependent correction factor to cover the complex decay mode of ^{27}Mg and differences in γ-sensitivity of the β counter. The aluminum foils of different thickness were irradiated at the same time and the K value was measured as 0.003±0.004 for the 0.1 mm thick foils mainly used for the measurements. The finally determined β-efficiencies for different foil thickness were shown in Fig.2 together with the Ryves' value/15/.

For the half-life of ^{27}Mg and the γ-ray intensity for 844 keV, 9.462 min./18/ and 71.8 % /19/ were adopted respectively. The recent evaluation/14/ adopted 71.8 % instead of 73.0 % /18/ as the γ-ray intensity. Our measurements also suggested the value of 71.8 % to be more preferable rather than 73.0 % by comparing the results between the γ counting and β counting method.

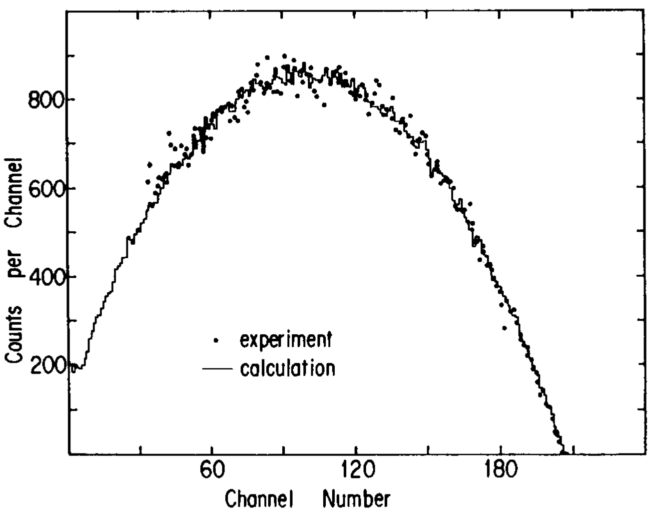

Fig.1 Pulse height spectra by a Si surface barrier detector with a 1 mm thick polyethylene radiator

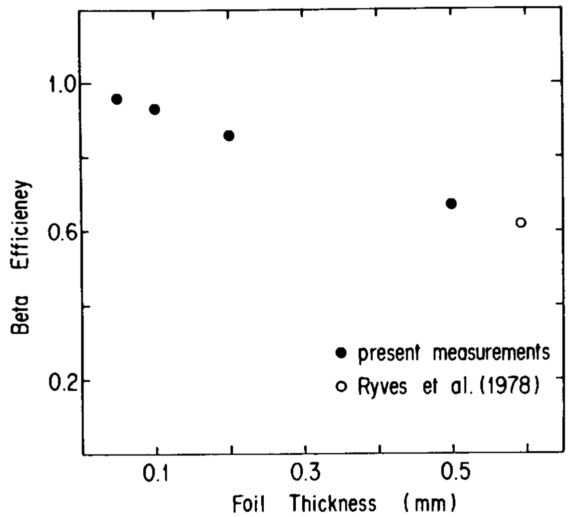

Fig.2 β efficiencies of the 4πβ counter for different aluminum foil thickness

Additional Corrections

Effect of d+D Neutrons in d+T Neutron Field

The d+D neutrons deriving from deuteron implantation in a Ti-T target will increase rapidly with augmentation of incident deuteron energy, to produce additional ^{27}Mg radioactivity. In the present study, the neutron yield from the $D(d,n)^{3}He$ reaction was measured by means of a calibrated ^{3}He proportional detector of cylindrical type filled with ^{3}He 400 kPa and Kr 200 kPa/20/. The correction required to the final ^{27}Mg activity measurement amounted to about 20 % at 19.9 MeV and about 5 % at 18.04 MeV.

Effect of Secondary Neutrons from Surroundings

The spectra of secondary neutrons produced from the target assembly and the construction of the experimental room were calculated by the PALLAS code/16/. The calculated spectra at 10 cm were shown in Fig.3 in the case of the incident energy of 14.6 MeV. The dominant contribution of the secondary neutrons comes from the target assembly compared to that from the room construction. The additional activity of ^{27}Mg presented by these secondary neutrons was calculated using the measured neutron spectrum and the $^{27}Al(n,p)^{27}Mg$ cross section given in ENDF/B-V. The result is presented in Fig.4 in terms of the reaction rate ratio of the secondary neutrons to total ones, plotted against the incident neutron energy up to 18 MeV. In the figure, the values above 18 MeV were extraporated up to 19.9 MeV presented as the dotted straight line. The correction factors finally applied to the cross section increased with the neutron energy and reached to about 3 % at 18 MeV after considering the energy resolution of a counter telescope which was used to determine the original neutron flux measurements/17/.

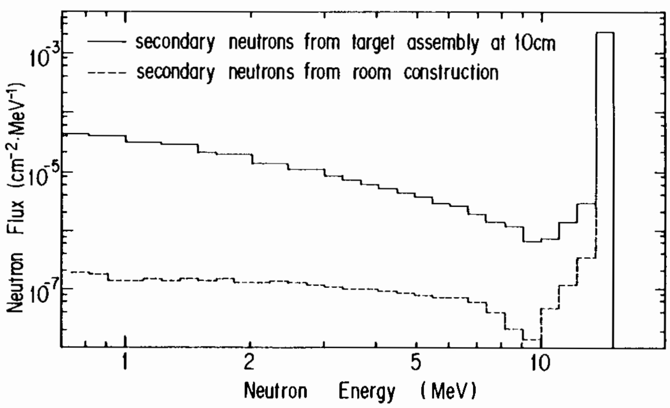

Fig.3 Neutron energy spectra in the irradiation field at 14.6 MeV calculated by PALLAS code

Results and Discussion

The results obtained from the present cross section measurements are presented in Table 1, together with the relevant overall uncertainties, derived by combining systematic and random uncertainties in quadrature. The systematic uncertainties are the quadratic sums of error estimates individually covering different factors as given in Table 2.

The results for the $^{27}Al(n,p)^{27}Mg$ reaction cross section are presented graphically in Fig.5 covering the energies of 5 MeV and between 14.6 and 19.9 MeV with Ryves' measurements/15/, together with evaluations given in ENDF/B-V, as well as those by Evain/13/ and Ryves/14/. The plots indicating the present results are seen to be in agreement with Ryves' measuremets above 14.6 MeV energy region and with the recent evaluations at 14.6 MeV, but deviate largely from the ENDF/B-V evaluation in whole energy region except 19.9 MeV.

We intend to extend our measurements between 5 MeV to 10 MeV, with a view to providing more reliable cross section data.

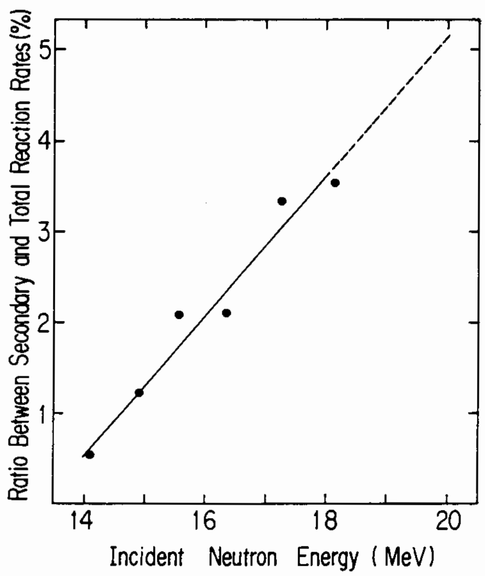

Fig.4 Ratio between secondary and total reaction rates for $^{27}Al(n,p)^{27}Mg$ reaction

Table 1 Cross sections of $^{27}Al(n,p)^{27}Mg$ reaction

Neutron energy(MeV)	Cross section(mb)
4.992 ± 0.054	21.6 ± 0.5
14.60 ± 0.04	69.8 ± 1.6
15.21 ± 0.04	64.9 ± 1.8
15.88 ± 0.05	56.5 ± 1.6
16.98 ± 0.08	47.0 ± 1.6
18.04 ± 0.08	42.7 ± 1.8
19.87 ± 0.08	33.8 ± 2.3

Table 2 Uncertainties for $^{27}Al(n,p)^{27}Mg$ cross section measurements above 14.6 MeV

Origin	Uncertainty(%)
(1) Al(n,α) reaction measurement	
Al(n,α) cross section	1.7 - 4.0
Background subtraction in γ-ray analysis	0.5
Contribution of secondary neutrons	0.2 - 3.0
Statistics	0.4
(2) Al(n,p) reaction measurement	
Relative efficiency of γ counting	0.7
γ-ray intensity	0.5
Decay factors	0.2
Contribution of secondary neutrons	0.2 - 4.0
Statistics	0.4
(3) Foil irradiation	
Target to foil distance	0.4 - 0.7
Time variation of flux	0.2

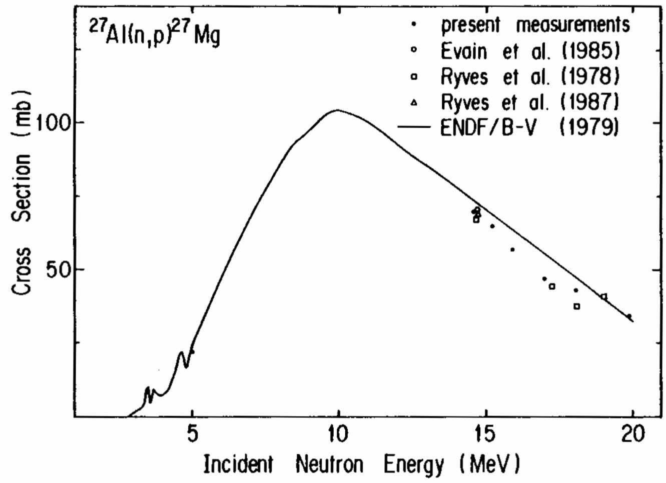

Fig.5 Cross section of $^{27}Al(n,p)^{27}Mg$ reaction for incident neutron energies

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