Cross section of ^{27}Al(n,2n)^{26}Al$_{g.s.}$ near 14 MeV

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The total cross sections for the ^{27}Al(n,2n)^{26}Al$_{g.s.}$ ($T^{1/2}=7.2\times10^5$ yr) reaction have been measured near the threshold energy. The data show a steep energy dependence. The cross sections in the d-t neutron energy range are several times smaller than those of the theoretical prediction by the Blatt and Weisskopf formula and that in the data file, which is commonly used to calculate activation in fusion materials. The calculation in the partial statistical model, in which the intermediate spin states are limited, reproduces the experimental results well.

Aluminum has been thought to be not suitable as a fusion reactor material because of the long-life activity from the (n,2n) reaction, in spite of its rapid decay of the activation level and other attractive features as a structural material. The threshold energy of the ^{27}A(n,2n) ^{26}Al$_{g.s}$ reaction is 13.56 MeV (E_{th}), slightly below the d-t neutron energy, and the cross section is supposed to be a steep function of the neutron energy. The ground state of ^{26}Al decays into ^{26}Mg with a half-life of 7.2×10^5 yr, emitting a 1.809 MeV γ ray. On the other hand, this reaction can be used as a measure of the energy spectrum of neutrons from a d-t reacting plasma, if the total neutron number is obtained from other dosimetry reactions such as ^{27}Al(n,p) ^{27}Mg.[1] In both cases the activation rate, which is proportional to the product of the cross section and the decay rate of ^{26}Al$_{g.s.}$, is essential. Recently Smither and Greenwood obtained the cross sections around 14 MeV through the measurement of the production rate of ^{26}Al by accelerator mass spectrometery.[1] Their cross sections are smaller than the theoretical prediction of the Blatt and Weisskopf formula, especially at the neutron energy less than 14.5 MeV.

In the present work, the activation rates, the rates of formation of particular radioactivity per unit neutron flux, have been directly measured as a function of the neutron energy, by detecting the 1.809 MeV γ rays following the β decay of ^{26}Al, which is produced through the ^{27}Al(n,2n) ^{26}Al$_{g.s}$ reaction. Calculations using the partial spin-dependent statistical model have been performed and the results are compared with the experimental data.

We measured the cross sections by using the Intense 14 MeV Neutron Source Facility at Osaka University (OKTAVIAN). Pure aluminum targets (99.99%), fabricated into a disk shape (thickness, 5—10 mm; diameter, 15—30 mm), were fixed at the average angles of 13°—106° to the beam line, and were irradiated with the integrated flux of $(0.5-3)\times10^{14}$ neutrons/cm^2. The angular dependence of the neutron energy has been measured through the activation of ^{90}Zr and ^{93}Nb, by using the steep energy dependence of the ratio of the ^{90}Zr(n,2n)^{89}Zr cross section to the ^{93}Nb(n,2n)^{92} Nb^m near 14 MeV.[2] The results agree with the kinematical calculation within the statistical errors of measurement ($\sim\pm100$ keV). The average neutron energy

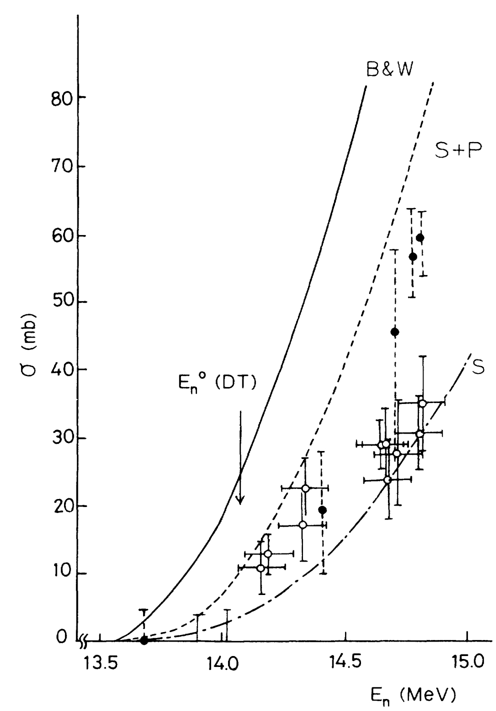

FIG. 1. Cross sections of ^{27}Al(n,2n)^{26}Al$_{g.s.}$. The open circles (this work) and closed circles [Smither (Ref. 1)] are the experimental data. The solid line, dashed line, and dot-dashed line indicate the calculated results with the BW formula, those in the partial statistical model including the s-wave contribution only, and those including s- and p-wave contributions, respectively.

at each aluminum target position is kinematically calculated to lie between 14.8 and 13.9 MeV. The neutron energy width (FWHM$\simeq$0.2 MeV) is determined mainly by the tritium target thickness, as measured by time of flight (TOF) on the pulsed beam line. The integrated neutron flux is obtained from the average activation levels of Ni foils attached on the front and back surfaces of each target. The difference between that of the front surface and that of the back surface is about 5%. The energy degradation of the incident neutrons can be estimated from the differential elastic scattering cross section,[3] and the fraction with the energy degradation of $\Delta E \geq 0.2$ MeV is found to be less than 4%. The effect of the target thickness on the accuracy of the cross sections has been checked by comparing the results of different thicknesses.

The characteristic γ rays of 1.809 MeV have been detected with a well-shielded germanium detector after more than a month of cooling. Only γ rays from ^{26}Al were observed besides the room background. The detecting efficiency at this energy has been calculated from the efficiency curve obtained by a calibration experiment. A U-NaCl sample was fabricated into the same shape as a target, fixed at the same position on the detector, and γ rays from ^{214}Bi and ^{214}Pb were measured. The uncertainty in the neutron energy is estimated by considering the angular difference at the periphery of the target. The central neutron energy at each data point is also recalculated by taking into account the angular difference at various positions in the target and the steep energy dependence of the cross section. The correction, however, is less than 10 keV. In Fig. 1 are shown the present results (open circles) together with those of Smither *et al.*[1] Here a half-life of 7.16×10^5 yr is assumed.[4] The present results agree with the measurement by Smither *et al.*[1] within the statistical errors, and the observed cross section at the d-t neutron energy is several times smaller than that in the data file, which is commonly used to calculate activation in fusion materials.[5]

Cross sections of (n,2n) reactions are usually calculated with the Blatt and Weisskopf formula (BW) (Ref. 6) of the complete statistical calculation. In this model, neither charged particle nor photon emission is supposed to occur whenever neutron emission is energetically possible. The solid line in Fig. 1 is the BW result with the level density parameter $a=3.6$ MeV^{-1},[7] and is more than three times larger than the present experimental results.

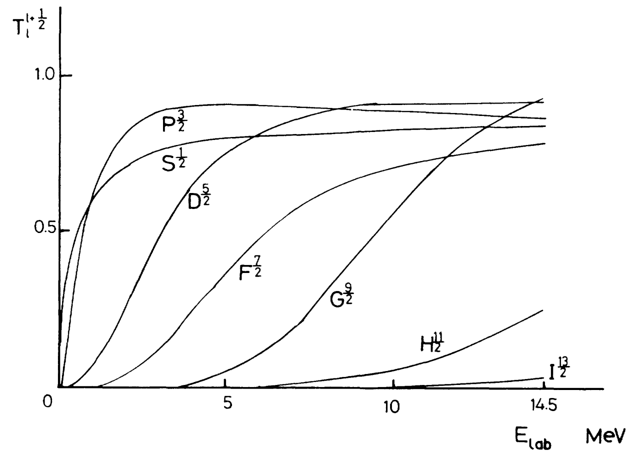

FIG. 2. Transmission coefficients of neutrons in aluminum.

One of the most probable reasons for this discrepancy is the hindrance of neutron emission through partial waves of large orbital angular momentum. The transmission coefficients $T_1^{1+(1/2)}$ are calculated with optical-model parameters of Becchetti and Greenlees,[8] and are shown in Fig. 2. As in the energy region of our interest, that is, $E_n - E_{\rm th} < 1.5$ MeV, the emitted neutron energy is less than 1.5 MeV, and it is found that mainly s and p waves contribute to the (n,2n) cross section. Then the intermediate spin states are limited.

We calculate the (n,2n) cross section in the partial statistical model[9] using the following formula:

$$\sigma(\mathrm{n,2n})(E_0)=\pi\lambda^2\sum_{Jjl}\frac{2J+1}{2(2I+1)}\frac{T^J_{jl}(E_0)\int_0^{E_0-E_{\rm th}}dE_1\sum'_{j'l'I'}T^J_{j'l'}(E_1)\rho(I',\epsilon')}{\sum_{j''l''L''}\int_0^{E_0}dE''_1T^J_{j''l''}(E''_1)\rho(I'',\epsilon'')}\,,$$

$$E_0=E_1+\epsilon'=E_{1''}+\epsilon''\,,$$

where E_0 and E_1 are the incoming and outgoing neutron energies and $E_{\rm th}$ is the threshold energy into the channel of ^{26}Al+n. I and $I'(I'')$ are spins of the target and intermediate states of ^{27}Al, and $\rho(I,\epsilon)$ is the spin-dependent level density at the excitation energy ϵ. The summation $\sum'$ was performed under the restriction of angular momentum conservation with only those intermediate spins (I') which can connect with final states of 5^+ (the ground state) and 3^+ ($E_x=0.417$ MeV) of ^{26}Al by s and p waves. The dashed line in Fig. 1 indicates the result when only the s wave contributes to the reaction, and the dot-dashed line indicates that when both s and p waves contribute. The agreement with the experimental data is improved.

The total cross section for the ^{27}Al(n,2n)^{26}Al$_{\rm g.s}$ reaction has been obtained in the energy region of 13.9–14.8 MeV by measuring the characteristic γ rays of the irradiated targets. The results show a steep energy dependence, and are smaller than that used in the activation code and that of the complete statistical model. The calculation in the partial statistical model is performed and the results reproduce the experimental data better than with the BW formula.

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