MEASUREMENT OF THE $^{27}$Al($n,2n)^{26}$Al REACTION CROSS SECTION FOR FUSION-REACTOR APPLICATIONS

Robert K. Smither and Larry R. Greenwood

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
The $^{27}$Al($n$,2$n$)$^{26}$Al reaction is of considerable interest to the fusion reactor program. Aluminum is an attractive material for many structural applications, and the ($n$,2$n$) reaction is the major source of long-lived activity ($^{26}$Al, g.s. $T_{1/2} = 7.34 \times 10^3$ g).$^{1,2}$ The threshold for this reaction falls within the spread of neutron energies generated by a D-T plasma. Its cross section is therefore a steeply rising function of energy for the primary fusion neutrons. This special feature makes it possible to use this reaction to measure plasma ion temperatures as well as neutron yields and neutron spectral shapes. The $^{27}$Al($n$,2$n$)$^{26}$Al reaction is one of the major sources of displacement damage in Al-metal alloys and other aluminum containing fusion materials, thus the cross section near threshold will strongly affect the amount of displacement damage in these materials as well as the long-lived radioactivity.

All of the above applications require accurate measurements of the $^{27}$Al($n$,2$n$)$^{26}$Al cross section near threshold, but no data was available in the 14-15 MeV energy range of interest so a series of activation experiments$^3,4$ were performed at the neutron sources at LLL (RTNS-II),$^5,6$ U.S. at Davis (cyclotron),$^7$ and at PPL (electrostatic generator).$^4$ In some experiments the new technique of accelerator mass spectrometry$^3,8$ was used to measure the production rate of $^{26}$Al. The new measurements$^3$ suggest that most of the ($n$,2$n$) yield near threshold is associated with the direct production of the $3^+$ state of 416.9 keV rather than the $5^+$ ground state. This raises the Q-value and neutron threshold energy for this reaction by a similar amount and greatly reduces the effective cross section of the ($n$,2$n$) reaction for D-T fusion neutrons. The effective cross section for a 9 keV D-T plasma is reduced by a factor of 5 by this shift.
in Q-value. Similar reductions occur for the displacement damage and the long-lived radioactivity.

1. Introduction

The $^{27}$Al($n$,2$n$)$^{26}$Al reaction has several interesting applications and special consequences for fusion reactors and fusion research. Aluminum is an attractive material for many structural applications because of its high strength-to-weight ratio and relatively low activation rate. The extremely long half life of the $^{26}$Al ground state ($T_{1/2} = 7.3 \times 10^5$ g)$^1,2$ is of some concern as an activation product since this activity will increase steadily during the lifetime of an operating reactor and may complicate the disposal of the aluminum components. The threshold of the $^{27}$Al($n$,2$n$)$^{26}$Al reaction falls within the spread of neutron energies produced by a D-T plasma. The production rate of the above mentioned long-lived radioactivity is therefore a sensitive function of the ($n$,2$n$) cross section near threshold. The ($n$,2$n$) reaction is a major source of displacement damage so the neutron damage rates in aluminum alloys and aluminum containing fusion materials will also be a sensitive function of the ($n$,2$n$) cross section near threshold.

Once the cross section near threshold is measured the $^{27}$Al($n$,2$n$)$^{26}$Al can be used to measure the ion temperature of the D-T plasma. The sensitivity to ion temperature is a result of the strongly non-linear nature of the cross section in the region of interest. This non-linearity makes the reaction sensitive to the width of the neutron energy distribution which is a sensitive function of the plasma ion temperature. If the threshold of the dosimetry reaction falls outside the neutron distribution from the D-T plasma by a few hundred keV or more, then the cross section tends to be linear with energy over the range of interest and the increased yield of the high energy portion of the
spectrum is balanced by the loss of yield from the low energy portion of the neutron distribution. In this case, which corresponds to the situation for most of the foil dosimetry reaction presently being used, the yield is sensitive only to the change in centroid energy. These centroid energy shifts are quite small as can be seen in Table 1. The change in the plasma temperature from 1 keV to 9 keV causes the centroid energy to change only about 26 keV which changes the yield of even a strongly varying reaction like $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$ by only 1.3%. This is too small to be useful and most dosimetry foils give a much smaller shift. A dosimetry foil with a threshold that falls within 100 keV of the centroid will show increases in yield of 3 to 20 times as one increases the ion temperature from 1 keV to 9 keV, the larger changes occurring for the cases with thresholds that are above the centroid energy.

Table 1. D-T Plasma Neutron Energy Spectrum Line Widths and Centroid Shifts as a Function of Plasma Ion Temperature. All Energy Values are in keV.

<table>
<thead>
<tr>
<th>Ion Temperature (keV)</th>
<th>FWHM (keV)</th>
<th>Centroid Shift (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>198.</td>
<td>6.6</td>
</tr>
<tr>
<td>4.0</td>
<td>369.</td>
<td>10.9</td>
</tr>
<tr>
<td>9.0</td>
<td>594.</td>
<td>33.0</td>
</tr>
<tr>
<td>16.0</td>
<td>792.</td>
<td>46.0</td>
</tr>
<tr>
<td>25.0</td>
<td>990.</td>
<td>58.0</td>
</tr>
</tbody>
</table>

2. Cross Section Measurements for $^{27}\text{Al}(n,2n)^{26}\text{Al}$ for Near Threshold Neutron Energies

The Q-value of the $(n,2n)$ reaction in aluminum is such that the threshold neutron energy falls within the energy range of neutrons produced in fusion reactors. The reaction is therefore a potentially useful dosimetry
reaction for monitoring the plasma ion temperatures. This cross section separates naturally into two partial cross sections. One part produces the 5+ ground state of 26Al, while the second part produces the 0+ isomeric state at 228 keV (see Fig. 1). These two levels decay in quite different ways allowing their separation through dosimetry measurements. The 5+ ground state decays (99%) through the 2+, 1808.6 keV state of 26Mg and can be monitored by observing the 1808.6 keV gamma ray. The 0+ isomeric state decays directly to the 0+ ground state of 26Mg (see Fig. 1) and is monitored by observing the 511 keV annihilation radiation associated with the positron production. The 5+ ground state decay also produces positrons, but the lifetimes of the two states is so different that no real interference occurs. Basically this means that the (n,2n) reaction produces two reaction channels whose cross sections vary rapidly with neutron energy in the energy range appropriate for fusion reactors.

When these reaction rates are compared with the observed reaction rates for the 27Al(n,p)27Mg and 27Al(n,α)24Na reactions or other dosimetry reactions where the neutron cross section is varying quite slowly in this neutron energy region, then considerable information about the energy spectrum of the fusion-produced neutrons is obtained. This procedure is illustrated in Fig. 2 where the theoretical near threshold cross sections of these two (n,2n) reactions are compared to typical fusion neutron energy spectra. The two neutron cross section curves are calculated assuming a simple evaporation model9,10 that leads directly to either the 5+ ground state or the 0+ isomeric state. The relatively slowly varying cross section for the (n,p) and (n,α) reactions is also shown in Fig. 2. The comparison of either (n,2n) reaction rate to one of the slowly varying reactions will give a plasma ion temperature. Figure 3 is a plot of the normalized ratio of the production of the 5+ ground
Fig. 1. $^{27}\text{Al}(n,2n)$ population of states in $^{26}\text{Al}$ followed by decay to $^{26}\text{Mg}$. 
Fig. 2. Comparison of \((n,2n)\) cross section (theoretical) for the production of the \(5^+\) ground state and the \(0^+\) isomeric state at 228 keV with neutron energy distributions associated with 1 keV and 16 keV, D-T plasmas.
Fig. 3. Normalized ratio of the theoretical \( (n,2n) \) cross section (Ref. 9) to the \( (n,p) \) cross section for the production of the \( 5^+ \) ground state and the \( 0^+ \) isomeric state (solid lines) and the normalize ratio of \( (n,2n)/(n,p) \) for \( ^{58}\text{Ni} \).
state through the \((n,2n)\) reaction (theoretical, Ref. 9) to the production of 
\(^{24}\text{Na}\) through the \((n,p)\) reaction. The even more rapidly rising ratio of the 
production of the \(0^+\) isomeric state (theoretical, Ref. 9) to the \((n,p)\) is also 
shown. The dashed curve is normalized production ratio for: \(^{58}\text{Ni}(n,2n)/^{58}\text{Ni-}\) 
\((n,p)\) which is typical for most other dosimetry materials where the threshold 
energy for the \((n,2n)\) reaction falls close to but not in the fusion energy 
region. The ratios are normalized to one for ion temperatures approaching 
zero.

2.1 Production of the \(5^+\) Ground State

The near threshold cross section measurements of Smither and 
Greenwood\(^2\) of the \(5^+\) ground state are shown in Fig. 4. These measurements\(^3\) 
used the new technique of accelerator mass spectrometry (AMS), which has been 
pioneered at Argonne to measure the amount of \(^{26}\text{Al}\) produced in the dosimetry 
foils. This method has a sensitivity of \(10^{-12}\) to \(10^{-14}\) atoms of \(^{26}\text{Al}\) to those 
of \(^{27}\text{Al}\) and makes it possible to use relatively small samples or dosimetry 
foils weighing a few hundred mg's. The extremely long half-life of the \(^{26}\text{Al}\) 
g.s. (\(T_{1/2}\) = \(7.3 \times 10^5\) g) makes the use of the more standard technique of gamma 
ray counting with Ge-detector impractical for these relatively small samples. 
The long-dashed curve is the theoretical calculation\(^9,10\) that assumes all of 
the near threshold cross section forms the \(5^+\) ground state directly. The only 
adjustable parameter is the nuclear temperature. The value of this parameter 
is taken as the same as found to be appropriate for similar nuclei. The fit to 
the data is very poor. The solid curve is a similar calculation where one 
assumes that all of the threshold yield proceeds through the direct production 
of the \(3^+\) ground state at \(416.9\) keV. In this case the theoretical curve fits 
the data very nicely. The short-dashed curve is a second calculation of the 
cross section based on the direct production of the \(5^+\) ground state using a
Fig. 4. Comparison of theoretical $(n,2n)$ cross sections with the data of Smither and Greenwood (Ref. 2).
less likely value for the nuclear temperature. It does not fit the data very well, but is not completely ruled out by the data. New experiments are planned using neutron energies in the 13.8 to 14.4 MeV range to clear up this uncertainty. These new experiments will make use of the RTNS-II neutron generator at LLL as did the earlier experiments.

2.2 Production of the $0^+$ Isomeric State at 228 keV

The cross section measurements of G. S. Harj, et al.\textsuperscript{10} for the production of the $0^+$ isomeric state are plotted in Fig. 5 as squares. The lowest energy neutron used in these experiments was 16.2 MeV, but already at these energies the yield was well below the expected yield\textsuperscript{10} as indicated by the long-dashed curve. The two short-dashed curves are attempts to fit the data by varying the nuclear temperature. Neither of these attempts fit the data in an acceptable manner. The solid curve assumes that all the cross section near threshold for this reaction channel is associated with the direct production of the $1^+$ state at 1057.8 keV. This curve fits the data very well. Although strongly suggestive, the data does not completely rule out a small component of the near threshold cross section being associated with the direct production of the $0^+$ isomeric state. In order to determine whether or not there is any appreciable cross section related to the direct production of the $0^+$ state, a new set of experiments\textsuperscript{4} was performed at the Princeton Plasma Physics Laboratory in March 1983, using their small D-T neutron generator. The neutron energies used in this experiment were in the range of 14.6 to 14.9 MeV which nicely brackets the threshold neutron energy, $E_n(\text{lab}) = 14.636$ MeV, for the production of the $1^+$ state. The very low cross section (less than 1 mb) measured in this region confirms the lack of any $(n,2n)$ cross section associated with the direct production of the $0^+$ state. This effectively raises the Q-value for this reaction channel by 730 keV.
The experimentally determined cross section curves are plotted in Fig. 6 for the direct production of the $3^+$ state at 416.9 keV and the $1^+$ state at 1057.8 keV. These curves are compared to the neutron energy spectra associated with ion plasma temperatures of 1 keV, 16 keV, and 25 keV. The $3^+$ cross section samples the central part of these distributions while the $1^+$ is sensitive to the high energy tails of the distributions.

3. Cross Section Ratios Versus Ion Temperature

Figure 7 shows the same normalized ratio, $\sigma(n,2n)/\sigma(n,\alpha)$ for the $5^+$ ground state (through the direct production of the $3^+$ state) as was shown in Fig. 3. The slope of this curve is much steeper than in Fig. 3 which suggests increased sensitive to the ion temperature. A similar curve can not be generated for the $0^+$ as fed through the $1^+$ because the threshold for the $1^+$ state is above the energy distribution for the low ion temperatures. The long-dashed curve in Fig. 7 is the effective cross section for the production of the $3^+$ state. This effective cross section is defined as the number of radioactive nuclei produced divided by the neutron flux through the sample (n/cm) times the number of atoms in the sample. The short-dashed curve is the effective cross section for the production of the $1^+$ state. The values of this curve are given in $\mu$b by the scale on the right. These cross sections may seem small but it should be remembered that measurements at PPPL were of the same magnitude. The measured effective cross section of $50 \mu$b ± $10 \mu$b was made with a small sample (2 gm) and a relatively low total flux of $1.5 \times 10^9$ neutrons/cm$^2$ per shot. A typical TFTR shot is expected to produce $10^{12}$ neutrons/cm$^2$ at the monitoring location so it should be possible to make measurements at the 1-3 $\mu$b level. This corresponds to ion temperatures as low as 6 keV.
Fig. 6. Comparison of the experimentally determined cross sections for the direct production of the 3+ state at 416.9 keV and the 1+ state at 1057.8 keV with the neutron energy spectra associated with ion plasma temperatures of 1 keV, 16 keV, and 26 keV, for D-T plasmas.
Fig. 7. Normalized ratio of the \((n,2n)\) cross section to the \((n,p)\) cross section for the \(3^+\) state at 416.9 keV (solid line) and the effective \((n,2n)\) cross section for the direct formation of the \(3^+\) (long dashed line) and the effective cross section for the direct formation of the \(1^+\) state (short dashed line) as a function of the plasma ion temperature.
4. Sensitivity to Neutral Beam Injection

The $^{27}\text{Al}(n,2n)^{26}\text{Al}$ cross section discussed above could be quite useful for monitoring the effects of neutral beam injection on the neutron spectrum. Figure 8 superimposes the measured cross sections for the $5^+$ ground state component and the $0^+$ isomeric state component of the $^{27}\text{Al}(n,2n)^{26}\text{Al}$ reaction on the calculated primary neutron spectrum produced by the injection of a 10 MW, 120 keV neutral deuterium beam at an angle of 48.70 in TFTR containing a 15 keV plasma. As can be seen in the Fig. 8, the yield for the $5^+$ g.s. from the production of the first $3^+$ state will be quite sensitive to the performance of the neutral beam injection system.

References


Fig. 8. The neutron energy spectrum generated by a 120 keV neutral beam of deuterium injected into a 15 keV plasma in TFTR (theory refill) is shown as a heavy solid line. This spectrum is compared with the neutron energy spectrum generated by a 1 keV and a 15 keV D-T plasma (dashed lines). Superimposed on these spectra are the measured cross sections for the production of the 3+ state at 416.9 keV (circles) and the 1+ state at 1057.8 keV (squares) in $^{26}$Al.
