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High-Resolution Neutron-Induced γ-Ray Production Cross Sections for Oxygen and Beryllium for Neutron Energies from 4 to 200 MeV

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Measurements of discrete gamma-ray spectra from neutron-induced reactions on a BeO sample have been performed using the broad-spectrum neutron spallation source of the WNR facility at LANSCE. Incident neutron energies were determined by the time-of-flight technique. Two high-purity Ge detectors were used to detect gamma rays in the energy range from 0.150 to 9.0 MeV. Spectra were measured at seven angles. Absolute gamma-ray production cross sections were determined from the measured neutron fluence and detector efficiencies. A new evaluation of the reaction cross sections has been performed based on this data. GNASH model calculations were performed for $20 < E_n < 150$ MeV, and are compared with the data.

KEYWORDS: ***neutron-induced reactions, gamma-ray cross section, measurement, evaluation, oxygen, beryllium, germanium detector***

I. Introduction

Neutron-induced reactions on oxygen are of practical importance in a wide range of applications. From radiotherapy with high-energy neutrons[1,2] to detection of explosives using nuclear techniques[3], to neutron transport in water, air, or concrete, knowledge of the reaction cross sections and photon production is required to predict performance. Despite the need for accurate data there are large differences in the measured cross sections between experiments and hence large uncertainties in the data evaluations.

In this work we have addressed the data problems by performing an absolute measurement of the neutron-induced photon production cross sections for oxygen over a very wide energy range with continuous coverage using the spallation neutron source of the WNR facility at the Los Alamos Neutron Science Center (LANSCE). Problems in the ENDF evaluations have been addressed by a new evaluation of all of the data including a detailed extraction of the (n,n') cross sections made possible by the photon angular distribution measurements reported here. The extracted (n,n') cross sections are in good agreement with the available measurements.[4]

Beryllium is a very attractive neutron multiplier through the low-threshold ^{9}Be(*n,2n*) reaction for some fast-neutron systems, such as those used in the production of fusion energy. Tritium is also produced when beryllium is irradiated with 14-MeV neutrons emitted from fusion of deuterium and tritium ions. Of the two exit channels of the ^{9}Be(*n,t*)^{7}Li reaction around 14-MeV incident-neutron energy, the ^{9}Be($n,t_1\gamma$)^{7}Li channel emits a 0.478-MeV gamma ray. In the study of O(n,xγ) reactions with a BeO sample, data were obtained for the ^{9}Be($n,t_1\gamma$)^{7}Li reaction and the inclusive ^{9}Be($n,x\gamma$)^{7}Li reaction for incident-neutron energies from the 12-MeV threshold to 200 MeV. Because there is essentially no feeding from higher-lying levels of ^{7}Li, the study of this reaction directly gives access to the cross section for the formation of ^{7}Li in its 0.478-MeV excited state. The few previous data for this reaction are centered near 14 MeV and show large discrepancies from one another. The data obtained are presented and compared with previous data on the ^{9}Be($n,t_1\gamma$)^{7}Li* and the ^{9}Be(*n,t*)^{7}Li reactions. A new evaluation of the ^{9}Be(n,t$_1$γ)^{7}Li* cross section was also performed.

II. Experiment

The measurements were performed on the 30L 40-meter flight path of the WNR facility of LANSCE. An 800-MeV pulsed proton beam incident on a small tungsten cylinder produced neutron by spallation reactions. The WNR facility is described in more detail in Ref.[5]. The data span an incident-neutron energy range from 4 to 200 MeV. The well-collimated neutrons were used with the time-of-flight technique to measure neutron-induced reaction cross sections by measuring gamma rays with two high-purity Ge detectors on a 40-meter flight path. The measured gamma-ray energy range was from 0.15 to 9 MeV. The two detectors were positioned in separate runs to obtain 7-point angular distributions. The sample was a 0.6426-cm thick by 15.24

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by 15.24-cm plate of BeO oriented at 45 degrees with respect to the incident beam. The incident neutron fluence was measured during the experiments with a ^{238}U fission ionization chamber[6], and absolute efficiencies of the Ge detectors were measured using a variety of calibrated gamma-ray sources up to 6.129 MeV. The experiment and analysis are described in more detail in Ref.[4].

III. Results

Excitation functions were extracted for 27 gamma rays from a total of 7 product nuclei ($^{16,15}O$, $^{16,15,14}N$, and $^{13,12}C$), and total photon-production cross sections were deduced from the data. Generally good agreement with previous measurements is observed.

The gamma rays analyzed are listed in **Table 1** with the associated reactions and the level properties. The 6.129-MeV gamma ray is one of the stronger gamma rays observed. Because this is an octupole transition it is possible to have large deviations from angular isotropy and indeed these are observed. While the a_4 coefficient is limited to small values, the a_2 and a_6 coefficients of the usual angular distribution expansion in terms of Legendre polynomials can be rather large.

We have made extensive comparisons with almost all of the available data[4]. In **Fig. 1** we show our results for the cross section at 125 degrees in comparison with other measurements. In this case several of the measurements exhibit considerably lower cross sections than the present work, but there is satisfactory agreement with the data of

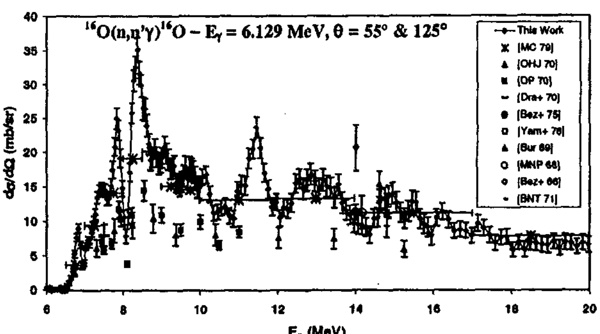

Fig. 1 Comparison of data at 125 degrees for the 6.129-MeV γ ray.

Morgan et al.[7] In general we have a good average agreement with the results of other measurements although in most cases there is a wide range of values observed.

In **Fig. 2** we show the angular distributions for the 6.129-MeV gamma ray at 7.5 MeV incident neutron energy. The data are plotted versus $\cos^2(\theta)$ so that a term in P_2 is linear, P_4 is quadratic and P_6 will show a cubic dependence in the plot. The cubic nature of the curve arises from the large a_6 coefficient. In **Fig. 3** we show the 298-keV transition from the $^{16}O(n,p)^{16}N$ reaction near the peak of the cross section at E_n=11.4 MeV. Here a large anisotropy is observed for the 3^- to 2^- transition.

The new angle integrated cross section data for the 6.129 MeV gamma ray in ^{16}O are shown with evaluations in **Fig. 4**.

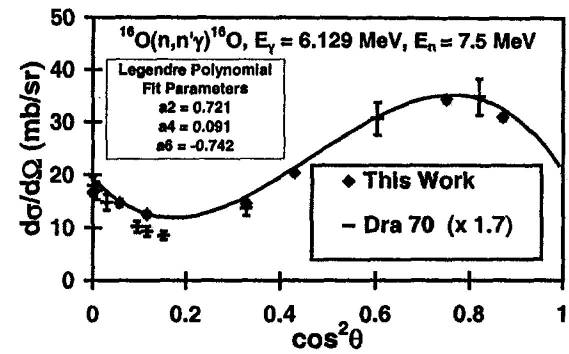

Fig. 2 Cross section angular distribution for the 6.129-MeV γ ray compared with the data of Drake[8].

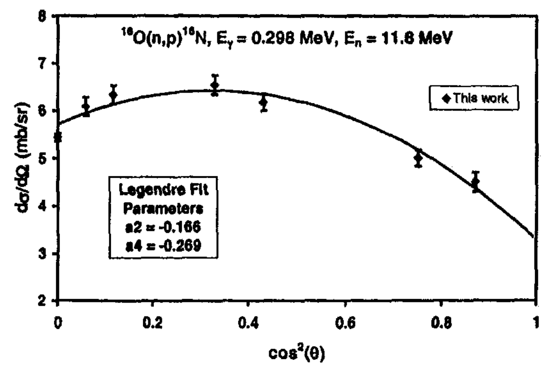

Fig. 3 Cross section angular distribution for the 0.298-MeV γ ray from ^{16}N.

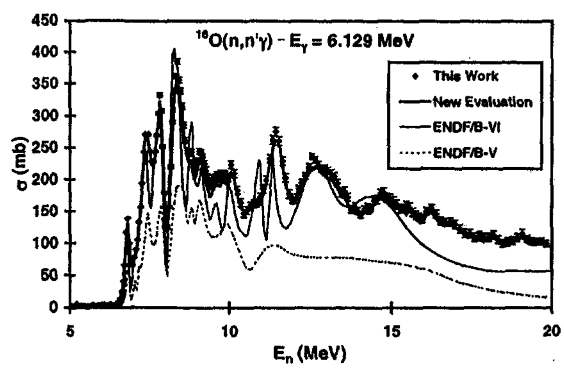

Fig. 4 Angle-integrated cross section for the 6.129-MeV γ ray compared with the ENDF/B-V and VI evaluations and with our new evaluation.

Note the poor agreement of the ENDF/B-V and VI evaluations with the new results. The new evaluation follows the present data closely.

From the angle-integrated gamma-ray data we inferred neutron scattering cross sections that are in good agreement with neutron measurements.[4]

At incident-neutron energies greater than 20 MeV, we have performed nuclear reaction model calculations using the preequilibrium plus Hauser-Feshbach code GNASH.[9]

Table 1 Observed reactions, γ rays, and their properties (data from Ref[10]).

$^{16}O(n,x\gamma)$						
E_γ (MeV)[a]	Reaction[b]	E_{thresh}[c] (MeV)	E_{lev}[d] (MeV)	J^π Initial[e]	J^π Final[f]	Lifetime[g]
0.169	$(n,\alpha)^{13}C$	6.448	3.853807	5/2+	3/2-	8.60 ps
0.277	$(n,p)^{16}N$	10.663	0.39727	1-	0-	3.90 ps
0.298	$(n,p)^{16}N$	10.557	0.29822	3-	2-	91.3 ps
0.397	$(n,p)^{16}N$	10.663	0.39727	1-	2-	3.90 ps
0.764	$(n,\alpha)^{13}C$	6.448	3.853807	5/2+	1/2+	8.60 ps
1.755	$(n,n')^{16}O$	9.426	8.8719	2-	1-	125 fs
1.955	$(n,n')^{16}O$	9.426	8.8719	2-	2+	125 fs
2.313	$(n,t)^{14}N$	15.386	2.3128	0+	1+	58 fs
2.743	$(n,n')^{16}O$	9.426	8.8719	2-	3-	125 fs
3.089	$(n,\alpha)^{13}C$	5.636	3.089	1/2+	1/2-	1.07 fs
3.684	$(n,\alpha)^{13}C$	6.268	3.684507	3/2-	1/2-	1.10 fs
3.840	$(n,n')^{16}O$	11.642	10.957	0-	1-	5.5 fs
3.853	$(n,\alpha)^{13}C$	6.448	3.853807	5/2+	1/2-	8.60 ps
4.179	$(n,n')^{16}O$	11.791	11.097	4+	2+	0.28 keV
4.438	$(n,n\alpha)^{12}C$	12.326	4.43891	2+	0+	42 fs
4.966	$(n,n')^{16}O$	11.791	11.097	4+	3-	0.28 keV
5.240	$(n,2n)^{15}O$	22.210	5.2409	5/2+	1/2-	2.25 ps
5.269	$(n,d)^{15}N$	16.121	5.270199	5/2+	1/2-	1.79 ps
5.298	$(n,d)^{15}N$	16.152	5.298822	1/2+	1/2-	17 fs
6.129	$(n,n')^{16}O$	6.512	6.12989	3-	0+	18.4 ps
6.916	$(n,n')^{16}O$	7.348	6.9171	2+	0+	4.7 fs
7.115	$(n,n')^{16}O$	7.560	7.11685	1-	0+	8.3 fs
8.857	$(n,\alpha)^{13}C$	11.768	8.860	1/2-	1/2-	150 keV
8.869	$(n,n')^{16}O$	9.426	8.872	2-	0+	125 fs
$^{9}Be(n,x\gamma)$						
E_γ (MeV)	Reaction	E_{thresh}(MeV)	E_{lev}(MeV)	J^π Initial	J^π Final	Lifetime
0.478	$(n,t)^{7}Li$	12.138	477.612	1/2-	3/2-	73 fs

a) Energy of the emitted γ ray in the laboratory system.
b) Reaction by which the γ-ray-emitting level is excited.
c) Threshold for the production of the γ ray in the laboratory system.
d) Excitation energy of the γ-ray-emitting level in the residual nucleus.
e) Spin and parity of the γ-ray-emitting level.
f) Spin and parity of the level reached by γ-ray emission.
g) Lifetime τ of the γ-ray-emitting level expressed in units of time or alternatively in units of energy using the relationship $\Gamma \simeq \hbar/\tau$.

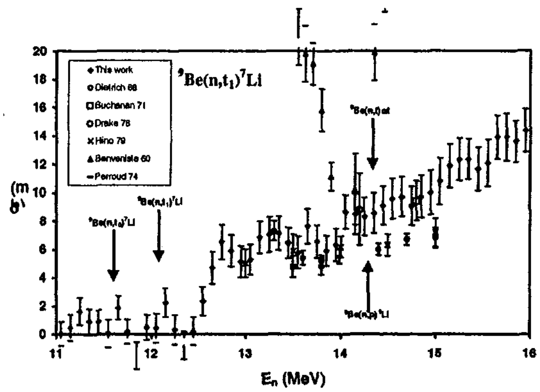

Fig. 5 Comparison of cross sections for the ^{9}Be(n,tγ)^{7}Li* reaction.

Examples of these calculations are given in Ref[4]. In general the reaction cross sections appear to be well reproduced but accurate calculation of individual gamma ray cross sections is more difficult.

The measured Be(n,tγ)^{7}Li cross section is shown in **Fig. 5** with other data for comparison. Thresholds of different reaction channels are also indicated by arrows. The data agree well with each other at lower energies, but show significant differences at higher energies.

IV. Conclusion

The data presented here are the most complete measurements made of angular distributions and cross sections for photon-induced gamma-ray production on oxygen and beryllium. Good overall agreement was obtained with previous data although large discrepancies exist. The inelastic scattering cross sections were extracted from the data and agree well where measurements are available. The new data are being incorporated into new evaluated data libraries for ENDF. These results should substantially improve the situation for a wide range of applications where neutron interactions with oxygen are important.

Acknowledgement

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