SECONDARY GAMMA-RAY-PRODUCTION CROSS SECTIONS OF SEVERAL MATERIALS*

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Abstract

Absolute gamma-ray-production cross sections have been measured as a function of both incident neutron and emitted gamma-ray energy for tantalum, iron, silicon, and carbon. The data include gamma-ray energies between 0.7 and 10.6 MeV for incident neutron energies up to 20 MeV. Measurements were made at angles of 90° and 125° for tantalum and carbon and at 125° for iron and silicon. Detailed tables of cross sections have been transmitted to the National Neutron Cross Section Center.

I. Introduction

Gamma rays produced by the interaction of neutrons with nuclei constitute an important fraction of the radiation produced when fast neutrons are transported through various materials. As a result, many requests for such cross sections have been tabulated.¹ This paper reports measurements of the production cross sections for gamma radiation resulting from neutron interactions with tantalum, carbon, iron, and silicon for incident neutron energies up to 20 MeV.

The results reported here constitute rather complete cross-section sets suitable for use in transport calculations. Gamma-ray energies from 0.7 to 10.6 MeV were measured. For tantalum the incident neutron energy range varied from 0.007 to 20.0 MeV; data were taken at 125° and 90°. For carbon, iron, and silicon neutron energies range from the threshold for exciting the first excited state up to 20.0 MeV. Carbon was studied at 125° and 90°, while measurements on iron and silicon were made only at 125°. Detailed tables of cross sections have been transmitted to the National Neutron Cross Section Center.

II. ² Experimental Procedure

The experimental technique employed for the measurements reported here has been described in detail elsewhere^{2,3} and will only be discussed briefly.

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The Oak Ridge Electron Linear Accelerator (ORELA) was used as the neutron source. Neutrons produced at the linac target traversed a 47-m flight path and were incident on a thin slab of the material under investigation. Gamma rays produced in the sample were observed by a 12.7 by 12.7 cm NaI crystal located inside a lead and lithiated paraffin shield 1.4 meters from the sample. A 25-cm-thick slab of lithium hydride was used to shield the NaI detector from neutrons scattered by the sample.

For each gamma ray detected, the pulse height of the event in the detector and the elapsed time from the linac neutron burst were recorded in a two-parameter array (≈ 512 by 512 channels). Background was due mainly to neutron interactions in the NaI crystal. Background corrections for the pulse-height distributions were obtained by studies made using a lead shadow bar between the detector and sample as well as by tests made with a beryllium sample (which produces no gamma rays under fast-neutron bombardment).

Gamma-ray energy distributions and thus cross sections were determined by unfolding the background-corrected pulse-height distributions for each of a number of incident neutron energy intervals. Absolute normalization for incident neutron energies above 0.7 MeV was determined using the sample thickness and neutron flux as measured using a 5 cm by 5 cm calibrated NE213 scintillation counter.

In the case of tantalum at the lower neutron energies only capture gamma rays can be observed and the gamma-ray distributions were normalized to absolute cross sections using the neutron binding energy and previously measured values of the $Ta(n,\gamma)$ cross section (see ref. 4).

III. Data Reduction and Results

As mentioned above, gamma-ray distributions were obtained by unfolding the pulse-height distributions using the unfolding code FERD⁵⁻⁷ and measured response functions^{2,3} for the NaI detector. The incident neutron energy intervals were chosen so as to provide the best energy resolution consistent with adequate statistics in the pulse-height spectrum. The exception to this procedure was the carbon data. Since there is only one gamma ray ($E_\gamma = 4.43$ MeV) produced by neutron inelastic scattering from carbon, these data were not unfolded. Instead, the pulse-height spectra were summed over channels from 3.0 to 4.75 MeV and the detector efficiency was obtained by integrating the response function between these limits.

The results for carbon at 90° are shown in Fig. 1. Also shown are data⁸ obtained using a Van de Graaff accelerator and Ge(Li) detector. Agreement is quite good. The data for 125° also show satisfactory agreement (see ref. 2).

Figures 2 and 3 show the measured gamma-ray-production cross sections for tantalum at 125°. The error bars shown do not include the uncertainty in normalization (10% above 1-MeV neutron energy, about 25% below this energy). It should be noted that some points are plotted even where the cross section must be zero; for example, at gamma-ray energies above the binding energy for neutron energies where only capture can occur. These points are shown only to indicate the quality of the data in this region with respect to background subtraction. As is clearly indicated by the error bars, the uncertainties are large, due mainly to counting statistics. The effect of the high-energy region on the unfolded spectrum at the lower energies is negligible. Note also that the unfolded spectra still contain

the effects of the finite intrinsic energy resolution of the NaI detector. This resolution varies from about 10% at 1 MeV to 5% at 6 MeV. There are approximately 2000 data points shown in these figures. Data were also acquired at 90° for neutron energies between 0.4 and 20.0 MeV. Comparison of the data obtained at the two angles indicate that the gamma radiation from Ta is isotropic.

Figure 4 shows the data at 90° for the neutron energy interval from 7 to 8 MeV. Shown also are some representative points taken from the data of Perkin and Starfelt.⁹ These authors derived their absolute cross sections by comparison to the $C(n,n'\gamma)$ (4.43 MeV) cross section for which their quoted values are somewhat different from the present results shown in Fig. 1. Therefore for purposes of comparison, the data of ref. 9 as shown in Fig. 4 have been renormalized to the same $C(n,n'\gamma)$ cross section presented in Fig. 1. Agreement between the two sets of data is satisfactory.

The $Fe(n,x\gamma)$ data were obtained over 0.5-MeV neutron energy intervals for incident neutron energies between 1.0 and 10.0 MeV, 1.0-MeV intervals from 10.0 and 16.0 MeV, and 2.0-MeV intervals from 16.0 to 20.0 MeV. The complete data set for the one angle (125°) includes about 3500 data points. For purposes of comparison to existing data the gamma-ray distributions were integrated over 240-keV gamma-ray energy intervals to produce group cross sections. An example of such a comparison is shown in Fig. 5 for the interval $0.71 \leq E_\gamma \leq 0.95$ MeV. This interval is dominated by the 846-keV gamma ray from the de-excitation of the first excited state in ⁵⁶Fe. Shown also are the data of references 10, 11, and 12, as well as the ENDF/B evaluation for material 1180. Agreement is generally within the quoted uncertainties.

Several representative gamma-ray spectra for natural silicon are shown in Fig. 6. Evaluation of the data is not complete at the present time, but preliminary comparison to existing data (refs. 10, 13, 14, and 15) show quite satisfactory agreement.

IV. Summary

Data have been accumulated and reduced for carbon, silicon, iron, and tantalum. The data include many points and are essentially complete descriptions of gamma-ray production by neutrons in the MeV region. Comparison with existing data have shown our system, using the ORELA and the NaI spectrometer, to be a fast, economical, and accurate method for producing extensive cross-section sets. The program under way at this time includes measurements on N, O, Mg, Al, Ca, Cu, Ni, and W at one or more angles.

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Figure Captions

Fig. 1. Cross section for the $C(n,n'\gamma)$ (4.43 MeV) reaction at 90° compared to the results in Ref. 8. Below 10 MeV the plotted points represent averages over 50-keV intervals, above 10 MeV the intervals are 500 keV. Error flags for the present results do not include uncertainty in normalization ($\approx 10\%$).

Fig. 2. Results of the present measurement for the $Ta(n,x\gamma)$ reaction at 125° . Error bars with arrows indicate uncertainties greater than one decade.

Fig. 3. Present results for the $Ta(n,x\gamma)$ reaction at 125° .

Fig. 4. Comparison of the present results for $Ta(n,x\gamma)$ with the data of Ref. 9 at $E_n = 7.5$ MeV and $\theta = 90^\circ$.

Fig. 5. Elemental differential cross sections for gamma rays due to the $Fe(n,x\gamma)$ reactions for the gamma-ray energies between 0.703 and 0.946 MeV. Results are compared to the data of Refs. 10, 11, and 12 and the current ENDF/B evaluation.

Fig. 6. Several typical gamma-ray spectra for the $Si(n,x\gamma)$ reaction. The angle is 125° , incident neutron energy intervals are as given by the labels.