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Gamma-Ray Production Cross Sections for 5- to 8-MeV Neutron Interactions with ^{235}U

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ABSTRACT

Neutron-induced gamma-ray production cross sections for neutrons with energies of 5 to 8 MeV have been measured for ^{235}U. The results are compared with estimates based on evaluated cross sections.

I. INTRODUCTION

The neutron-induced fission cross section for ^{235}U is rather constant and featureless from 0.5 to 6 MeV, and then increases by about 50% as the incident neutron energy is changed from 6 to 8 MeV. This rather sudden increase has long been known to be due to second-chance fission.[1]

As the incident neutron energy goes from 0.5 to 6 MeV, the number of channels available for fission increases. Similarly, the number of channels available for inelastic neutron scattering increases with the same type of energy dependence. The net result is that fission and inelastic scattering compete on fairly equal terms for the available nonelastic cross section, and neither shows any strong energy dependence.

In the 6- to 8-MeV incident neutron energy region, an inelastically scattered neutron may leave the residual nucleus with an excitation energy large enough to permit fission. Thus the fission process has a second chance to compete with other decay modes and, as a result, the fission cross section rises. The purpose of this experiment was to measure gamma-ray production cross sections in the neutron energy region (5 to 8 MeV) where the second-chance fission becomes important. It is possible to predict the total amount of energy emitted as gamma rays and also the spectral shape[2] if the appropriate cross sections are known, but the absence of experimental data creates some uncertainties in these predictions.

The experiments reported here were done using the pulsed neutron beam available at the Los Alamos Scientific Laboratory's vertical Van de Graaff accelerator, with the $d(d,n)^3He$ reaction as the source of the 5- to 8-MeV neutrons. The variation of the total amount of gamma-ray energy emitted as a function of neutron energy is discussed and results are compared with some earlier measurements.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement was the same as that described in LA-5048 (Ref. 3), except for the source of neutrons. The 5- to 8-MeV neutron bursts were produced by a pulsed beam of deuterons passing through a gas cell filled with about 2 atm of deuterium. The neutrons came from the $d(d,n)^3He$ reaction and had an energy spread of 0.23 to 0.45 MeV (Table I), including 0.05 MeV caused by straggling. The ^{235}U, ^{238}U, and iron samples used in this experiment were the same ones described in LA-5048 (Ref. 3).

TABLE I

ENERGETICS OF THE NEUTRON-PRODUCING DEUTERON BEAM

Neutron Energy (MeV)	Accelerated Deuteron Energy (MeV)	Energy Lost in the Foil (MeV)	Energy Lost in the Gas Cell (Mev)	Neutron Energy Spread (MeV)
5	2.509	0.54	0.39	0.45
5.5	2.894	0.48	0.33	0.39
6	3.31	0.43	0.28	0.33
6.5	3.750	0.40	0.25	0.30
7	4.207	0.36	0.22	0.27
7.5	4.677	0.34	0.20	0.25
8	5.156	0.31	0.18	0.23

III. DATA COLLECTION AND DATA ANALYSIS

Not all three samples (^{235}U, ^{238}U, and iron) were used for each neutron energy or for each running period, but over several months enough data were collected on ^{238}U to make a reasonable subtraction of 5% ^{238}U contamination from the ^{235}U sample. Also, we could check the internal consistency of the runs by using the prominent 0.846-MeV gamma ray from ^{56}Fe. Over the course of the experiment the number of counts in this peak agreed to within 3% for the same incident neutron energy.

The techniques used in data collection and analysis are essentially those described in Ref. 3, with the exception of the neutron flux measurement. For these higher energies the neutron flux was measured only with a proton recoil counter which consisted of 3 mg/cm^2 polyethylene foil mounted 7.6 cm in front of two silicon detectors. A coincidence was required between both detectors before pulse heights from both were stored on magnetic tape. The coincidence requirement nearly eliminates pulses that are made by fast neutron interactions with silicon, such as (n,α) and (n,p), which, at the higher neutron energies, are in the same energy region as the proton recoil pulses and are an order of magnitude more frequent.

The neutron flux was measured at 5.0 and 7.5 MeV, and values for the flux at the other energies were interpolated from the d(d,n)^{3}He differential cross section at 0°.[4]

Figure 1 shows the pulse height spectrum of both the E and ΔE crystal for 7.5-MeV incident neutrons. The flux measurement was made such that the standard deviation of the net counts at 7.5 and 5 MeV was less than 1%, and the error is therefore dominated by other uncertainties in the experiment.

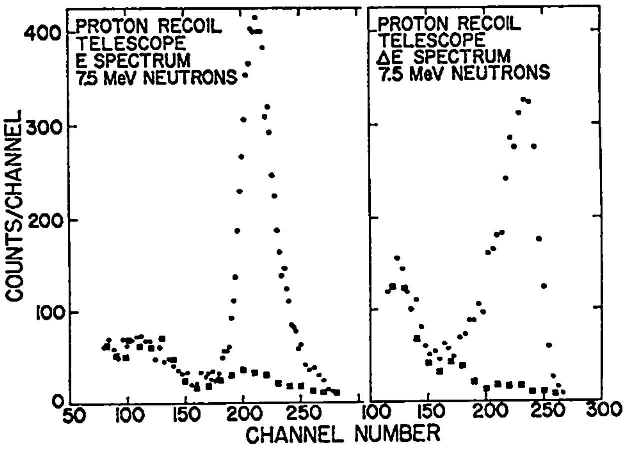

Fig. 1. Pulse height spectra for the proton recoil telescope for incident neutrons of 7.5 MeV. Dots represent the recoil spectrum with polyethylene foil in place, squares represent a similar run with the foil removed.

Figure 2 shows a gamma-ray pulse height spectrum for incident neutrons of 5 MeV. The pulse height spectra for other neutron energies are quite similar.

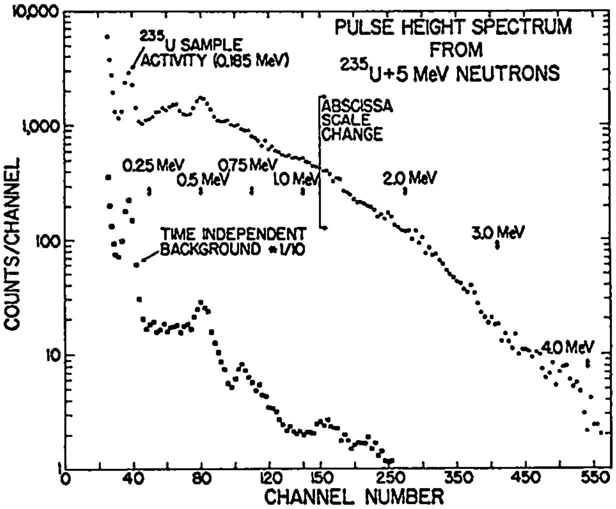

Fig. 2. Gamma-ray pulse height spectrum for incident neutrons of 5 MeV, along with time-independent background.

IV. DISCUSSION OF RESULTS

Differential cross sections as a function of gamma-ray energy are listed in Table II. These results show a rather slow increase in gamma-ray production cross sections as a function of neutron energy with no noticeable effect due to second-chance fission. The cross sections for neutrons of 6 MeV agree with previously reported results.[5] The 7.5-MeV cross sections, however, are 20 to 30% higher than those reported in Ref. 5. Stewart[2] pointed out the probability that the early 7.5-MeV results were anomalously low.

The cross section data have been used to obtain the left-hand side of the energy conservation equation of Stewart:[2]

$$\int_0^\infty E_\gamma \, \sigma_{prod} \, (E_\gamma) \, dE_\gamma = E_{\gamma f}\sigma_{n,f} + (E_o-\bar{E}_n) \, \sigma_{n,n'} + (E_o+E_b) \, \sigma_{n,\gamma} + (E_o+Q_{2n}-2\bar{E}_n) \, \sigma_{n,2n} \quad ,$$

where E_γ is the gamma-ray energy, $\sigma_{prod}(E_\gamma)$ is the angle integrated gamma-ray production cross section as a function of gamma-ray energy, $E_{\gamma f}$ is the energy emitted as gamma rays from the fission fragments, $\sigma_{n,f}$ is the fission cross section, E_o is the incident neutron energy, $\bar{E}_n$ is the average kinetic energy of the inelastically scattered neutron, $\sigma_{n,n'}$ is the inelastic scattering cross section, E_b is the binding energy of a neutron in ^{236}U, $\sigma_{n,\gamma}$ is the capture cross section, Q_{2n} is the binding energy of a neutron in ^{235}U, and $\sigma_{n,2n}$ is the cross section for emission of two neutrons.

TABLE II

DIFFERENTIAL CROSS SECTIONS AS A FUNCTION OF GAMMA-RAY ENERGY

$\sigma(45°, E_\gamma)$ in mb/MeV-sr

(Errors shown are statistical; errors omitted are statistically less than 10%.)

Gamma-Ray Energy Interval (MeV)	Neutron Energy (MeV)						
	5.0	5.5	6.0	6.5	7.0	7.5	8.0
0.25-0.35	880	930	960	960	1130	1160	1210
0.35-0.50	970	980	1010	1120	1290	1290	1365
0.50-0.75	970	1040	1070	1130	1200	1240	1350
0.75-1.0	570	580	590	640	720	750	820
1.0-1.5	380	390	394	400	433	450	480
1.5-2.0	240	270	280	250	250	230	230
2.0-2.5	170	170	170	150	150	140	140
2.5-3.0	77	85	87	84	83	68	74
3.0-3.5	31	38	38	37	39	40	42
3.5-4.0	13	19	19	19	21	26	28
4.0-4.5	4.9 ±1.3	4.8 ±0.7	4.8 ±0.5	9.6 ±1.2	13 ±1.5	13 ±1.3	13 ±1.1
4.5-5.0	3.6 ±1.0	3.2 ±0.4	3.3 ±0.5	4.5 ±0.7	5.8 ±2.0	6.4 ±0.8	6.7 ±0.8
5.0-5.5	0.5 ±0.4	2.1 ±0.3	2.1 ±0.5	2.8 ±1.2	3.2 ±1.5	3.6 ±0.4	4.5 ±1.2
5.5-6.0		1.6 ±0.3	1.5 ±0.4	1.3 ±0.4	1.6 ±0.7	1.4 ±0.2	1.3 ±0.4

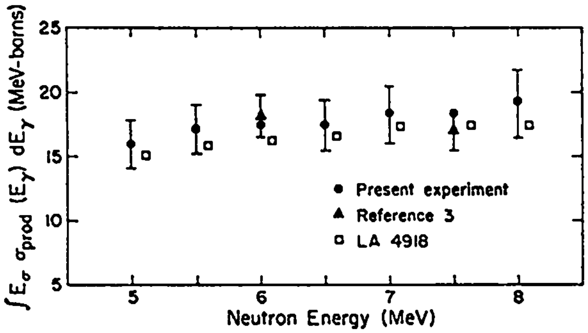

Fig. 3. Energy-weighted gamma-ray production cross section. The dots are the results of this experiment. The squares are calculated from Eq. (1) of Ref. 2 using ENDF/B cross sections and are offset to 0.1-MeV higher energy for clarity. Error bars are ± 12%. Error bars for 6 and 7.5 MeV are for data of Ref. 3.

These results are shown in Fig. 3 along with calculations of the right-hand side of the equation using ENDF/B[6] cross sections. The agreement with the previous measurement and with the evaluation calculations is good. The moderate increase of 20% in the energy-weighted production cross section with neutron energy from 5 to 8 MeV is in good agreement with the calculated increase of 15%, using the energy conservation equation.

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