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Prompt neutrons from neutron-induced fission of ^{237}Np†

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The average number of prompt neutrons per fission has been measured for ^{237}Np using a scintillator tank that has a neutron detection efficiency of about 70%. The measurements at six energies between 1.0 and 14.7 MeV have an accuracy of $\pm 2\%$. A least squares fit to the results gives $\bar{\nu}_p = 2.605 + 0.153 E_n$ (MeV).

[NUCLEAR REACTIONS, FISSION ^{237}Np(n,f), $E=1.0$–14.7 MeV; measured $\bar{\nu}_p(E)$.]

We have measured $\bar{\nu}_p$, the average number of prompt neutrons emitted per event, for neutron-induced fission of ^{237}Np. The measurements were made with an accuracy of about ± 2% at six neutron energies from 1.0 to 14.7 MeV. A 75-cm-diam liquid scintillator tank detected neutrons from a fission chamber, and scalers recorded the neutron multiplicity of each event.

The fission chamber is a 2.5-cm-diam by 2.5-cm-long spirally wound cylinder of the type described by Rossi and Staub.[1] It contains a 300-cm^2 aluminum foil that has about 0.3 g of ^{237}NpO$_2$ deposited uniformly on each side. The neptunium contaminants are 5.3% ^{238}U and 0.4% ^{239}Pu. The chamber was placed at the center of the scintillator tank with its axis rotated about 15° from that of the neutron beam.

The scintillator tank has been previously used to measure $(n,2n)$ and $(n,3n)$ cross sections.[2] It is a sphere with a 15-cm-diam hole through the center for the neutron beam, and it contained about 200 l of NE-323 liquid scintillator loaded with 0.5-wt% gadolinium.[3] The neutrons from a fission event entered the tank and scattered in the liquid where most of them were thermalized and either escaped or were captured. The amount of gadolinium used made the half-life for capture of a thermal neutron about 8 μs. Consequently, neutrons that entered the tank simultaneously were captured at different times and could be detected individually by observing the γ rays from their captures. Eight 13-cm-diam photomultiplier tubes counted the number of neutrons captured in the tank during the 40 μs following a fission event. A large amount of shielding surrounded both the detector and the neutron source to minimize the effects of backgrounds from the accelerator, but shielding could not be used to reduce backgrounds originating from the fission chamber itself.

The efficiency of the tank was measured by replacing the neptunium fission chamber with one containing ^{252}Cf and counting neutrons from the spontaneous fission events. The efficiency, relative to $\bar{\nu}_p = 3.733$ for ^{252}Cf (Ref. 4), was 0.690 ± 0.007 for the first running period and 0.659 ± 0.007 during the second, several weeks later. The efficiency was below the maximum possible value of slightly over 80% because the photomultiplier discriminator thresholds were raised to reduce the background counts from low-energy γ rays from the neptunium fission chamber.

The neutrons were produced by accelerating protons or deuterons in the Los Alamos Scientific Laboratory vertical Van de Graaff accelerator and letting them strike a gas target about 2.5 m in front of the tank. Measurements at 3 MeV and below used neutrons from the ^{3}H(p,n) reaction, those at 6.0 and 7.5 MeV used ^{2}H(d,n) neutrons, and those at 14.7 MeV used ^{3}H(d,n) neutrons. The neutron beam was pulsed periodically by deflecting the charged particle beam in the accelerator ion source, so that the beam was on for 1.0 μs and off for about 43 μs. For the fission chamber runs, the 40-μs scintillator tank counting gate started 1.0 μs after a fission event, but the event was excluded if a second fission occurred before the end of the gate. For the background runs the gate started 0.5 μs after the end of each neutron burst. Pulsing the beam off during the counting gate greatly reduced the backgrounds from neutron-induced events in the fission chamber walls, and the 1.0-μs delay excluded counts from prompt fission γ rays and from recoil protons associated with neutrons scattering in the scintillator. Background rates were about 0.25 counts/gate for the three low-energy runs and somewhat smaller for those at higher energies.

The measured multiplicity distributions were corrected for dead time in the detector, and the backgrounds were subtracted as described in Ref. 5. The dead time correction was about 0.4% for the neptunium measurements as well as for the efficiency determination. The corrected multiplicities were summed and divided by the efficien-

TABLE I. Average number of prompt neutrons per event from neutron-induced fission of ^{237}Np and the uncertainties in the measurements. A least squares fit to the results gives $\bar{\nu}_p = 2.605 + 0.153 E_n$ (MeV).

E_n (MeV)	$\bar{\nu}_p$	Statistical uncertainty	Total uncertainty
1.0 ± 0.11	2.718	0.057	0.063
2.0 ± 0.08	2.934	0.057	0.064
3.0 ± 0.06	3.037	0.056	0.064
6.0 ± 0.13	3.495	0.052	0.063
7.5 ± 0.09	3.856	0.055	0.067
14.7 ± 0.15	4.785	0.071	0.085

cy to get $\bar{\nu}_p$, the average number of neutrons emitted per fission. A small (<0.2%) correction was made for fission neutrons from the contaminants in the neptunium, and a correction of up to 0.9% was made to account for the differences in energy spectra between ^{237}Np(n,f) and ^{252}Cf spontaneous fission neutrons. To make the efficiency correction we used a Monte Carlo calculation of the energy dependence of the detector efficiency[2] and estimated the average neutron energies using the equations of Terrell.[6,7] Delayed γ rays emitted during the counting gates would affect the results if there were a significant difference between the ^{237}Np and ^{252}Cf rates, but because of the lack of information about the effect no correction was made. Charged-particle energies were kept low to minimize the number of fissions induced by low-energy neutrons in the beam, but the neutron spectra were not measured because the accelerator could not be pulsed fast enough to do time-of-flight work. Deuteron energies were below the threshold for breakup in the molybdenum entrance foil of the gas cell, the fission chamber was shielded from the apertures in the beam line, and a gold beam stop was used. For 14.7 MeV the number of neutrons from d-d reactions was estimated to be less then 10^{-3} of the number from d-t reactions, and for deuterium in the cell the number of low-energy neutrons from d-d breakup was similarly small. Thermal neutrons in the beam did not cause a significant number of fissions because the neptunium fission cross section is very small below 400 keV.

To check the experimental method we measured $\bar{\nu}_p$ for ^{238}U(n,f) at 14.7 MeV by substituting a ^{238}U fission chamber for the neptunium chamber. The measurement gave $\bar{\nu}_p = 4.51 \pm 0.05$, in good agreement with the evaluation of Davey[8] ($\bar{\nu}_p = 4.494$) and the measurements by Frehaut, Mosinski, and Soleilhac[9] ($\bar{\nu}_p = 4.514 \pm 0.025$ at 14.79 MeV).

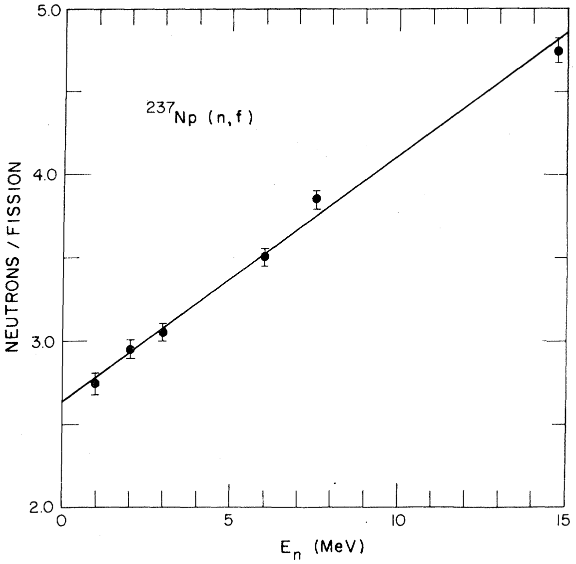

FIG. 1. Average number of prompt neutrons per event from neutron-induced fission of ^{237}Np. The points are the measured results and the total uncertainties; the line is a least squares fit to the measurements that is given by $\bar{\nu}_p = 2.605 + 0.153 E_n$ (MeV).

The results of the neptunium measurements are given in Table I and Fig. 1. The statistical uncertainties in the table are the rms standard deviations in the results. Total uncertainties include the uncertainty in measuring the efficiency of the detector. Uncertainties resulting from the width of the beam burst and any anisotropy in the fragments are smaller and have been disregarded. Likewise the effects of delayed γ rays and fissions caused by low-energy neutrons have not been included. The uncertainties in the neutron energies are caused by the variation of charged-particle energies in the gas cell. A least squares fit to the results gives $\bar{\nu}_p = (2.605 \pm 0.043) + (0.153 \pm 0.007)\, E_n$ (MeV).

Evaluations of $\bar{\nu}_p$ for ^{237}Np(n,f) have been based on calculations and measurements made using neutrons with continuum spectra.[10-12] No measurements using monoenergetic incident neutrons have been published. Our results are several percent higher than recommended in the ENDL evaluation[13] but agree more closely with the ENDF/B-IV file.[14]

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