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Neutron Physics Division

MEASUREMENTS OF THE AVERAGE NUMBER OF PROMPT NEUTRONS EMITTED PER FISSION OF ^{239}Pu AND ^{235}U

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ABSTRACT

Measurements of the average number of prompt neutrons $\bar{\nu}_p(E)$ emitted in neutron induced fission of ^{235}U and ^{239}Pu relative to $\bar{\nu}_p$ for spontaneous fission of ^{252}Cf have been made over an incident neutron energy range from 0.005 eV to 10 MeV. The incident neutrons were generated in pulses at the Oak Ridge Electron Linear Accelerator and their energies defined by time-of-flight methods. The samples were contained in fission chambers located in a large liquid scintillator. Fissions in the samples were identified by the simultaneous detection of prompt fission gamma rays in the scintillator and a pulse from the fission chamber. Fission neutrons were identified by the detection of the prompt gamma-ray cascade resulting from neutron absorption in gadolinium loaded in the liquid scintillator. The value of $\bar{\nu}_p(E)$ for ^{239}Pu at 0.0253 eV agrees with the value given in ENDF/B-IV, whereas the corresponding value for ^{235}U is about 0.7% larger than that given in ENDF/B-IV.

I. INTRODUCTION

Measurements have been made of the neutron energy dependence of $\bar{\nu}_p(E)$, the average number of prompt neutrons emitted per fission, for ^{239}Pu and ^{235}U. These experiments covered the neutron energy range from 0.005 eV to ~10 MeV. The normalization of $\bar{\nu}_p(E)$ was made relative to $\bar{\nu}_p$ for ^{252}Cf; therefore, the results of this work are ratios R(E) of $\bar{\nu}_p(E)$ for the fissile isotope relative to $\bar{\nu}_p$ for ^{252}Cf.

The prime notivation for the measurement was to obtain $\bar{\nu}_p(E)$ for ^{239}Pu over the neutron energy region of the Fast Breeder Reactor. Both the criticality constant k_{eff} and the breeding ratio are related to $\bar{\nu}(E)$. The present work was extended into the thermal energy region both to contribute to the existing differential data and to test the present data with the available integral (and differential) data in that region.

Lemmel[1] noted a 2% difference between the results of evaluations of $\bar{\nu}$ at 2200 m/s for ^{233}U and ^{235}U which included integral measurements and those which used only differential data obtained at 2200 m/s. Weinstein et al.[2] observed a change in $\bar{\nu}(E)$ for ^{239}Pu and ^{235}U of about 1% and 0.6% respectively as the energy increased from 0.012 to 0.3 eV. Variations in $\bar{\nu}(E)$ of this magnitude should be included in reactor calculations and in evaluations of nuclear data.

II. EXPERIMENTAL METHOD

The present experiments of $\bar{\nu}_p(E)$ utilized a gadolinium-loaded liquid scintillator to detect fission neutrons (with an efficiency of about 83%) and a fission chamber (efficiency ~95%) to define fission events. A description of the experimental techniques and some corrections made on the data are given by Hopkins and Diven[3] and by Mather et al.[4] The present experiments were performed at neutron flight paths of 21.6 m and 83.4 m with most of the present experiments being performed at a neutron flight path of 21.6 m. The liquid scintillator used at 21.6 m had a volume of about 710 ℓ and the diameter of the through tube was about 17.8 cm. One set of experiments covering the neutron energy range above 500 eV on ^{239}Pu was performed at a neutron flight path of 83.4 m using a similar neutron detector and a through tube 13.3 cm in diameter.

The fission chamber was located at the center of the liquid scintillator in a through tube which traverses the scintillation tank. Neutrons from a pulsed source were collimated to impinge on the fission chamber. A fission event was identified by the simultaneous detection of the prompt fission gamma rays by the large liquid scintillator and a pulse from the fission detector system. Approximately 0.5 μsec after fission a counting system was enabled to record pulses from the large liquid scintillator for a fixed time interval. In the present work counting gates (intervals) of 32 μsec and 50 μsec were used. Fission neutrons are moderated in the scintillator, diffuse, and are absorbed in the gadolinium with the neutron absorption rate increasing after fission, reaching a peak at about 8 μsec, and then decreasing exponentially such that about 90% of the neutrons are absorbed in 32 μsec.

Several fission chambers were used in the course of the present experiments. The fissile isotopes were deposited on aluminum discs to a surface density of ~100 μg/cm . These plates were than assembled to make a parallel plate pulse ionization chamber. For the experiments covering the thermal energy region a chamber was assembled which comprised four separate sections; one ^{235}U, two ^{239}Pu, and one ^{252}Cf used as the primary normalization standard. The ^{252}Cf was deposited in a pie-shaped section on the aluminum disc; the object being to have the physical geometry of the ^{252}Cf section of the fission chamber similar to the sections containing the fissile isotopes. Fission chambers containing a single fissile isotope (80 mg fissile isotope, active length 6.6 cm) were assembled for measurements at neutron energies above a few eV. A separate ^{252}Cf fission chamber (secondary standard), small enough to be placed outside the neutron beam was used as a monitor for these latter experiments.

Neutrons for the present work were generated by the Oak Ridge Electron Linear Accelerator (ORELA). Other measurements of $\overline{\nu}_p(E)$, those of Weinstein et al.[2] and Frehaut and Shackleton,[5] for example, have been made using a "white" source of neutrons produced by a linear accelerator. The energy of the neutron producing the fission event was established using the time-of-flight method.

III. CORRECTIONS TO THE DATA AND UNCERTAINTIES IN THE RESULTS

1. Uncertainties in $\overline{\nu}_p$ for the ^{252}Cf Fission Chambers

The average number of events (neutrons) detected by the scintillator system was 0.25% larger when the secondary standard ^{252}Cf sample initiated the fission event than when the fission event was indicated by the primary standard. No satisfactory reason for this discrepancy has been definitely established although geometric differences in the chambers may be partially responsible. The ^{252}Cf used as the primary standard was certified material and that used in the monitor was considered as acceptable. An uncertainty of ±0.25% has been applied to the experimental ratios because of the discrepant results obtained using the two ^{252}Cf fission chambers.

2. Correction for Displacement of the Fission Samples from the Center of the Liquid Scintillator

Measurements of the neutron detection efficiency of the large liquid scintillator were made for various displacements of the ^{252}Cf standard sample from the center of the through tube. The results of these measurements were used to correct the ratio measurements for the displacement of the fissile isotope or the ^{252}Cf monitor from the center of the scintillator. The maximum correction required (^{239}Pu experiments at the 85 meter station) was 0.15% with an estimated uncertainty of 0.03%.

3. Correction for False Fissions

The random coincidence of a pulse from the fission chamber caused by the known alpha particle activity or noise with a pulse from the neutron detector initiates a counting gate which is called a false fission. The false fissions rate was estimated by generating a random signal (mock alpha) and treating it in the electronic system as a fission chamber pulse. A coincidence of this mock alpha pulse and a scintillator pulse permitted a measure of the false fission rate as a function of time after the neutron burst. The required correction increases rapidly as the neutron intensity decreases below 0.01 eV.

4. Corrections for Backgrounds in the Neutron Detector

Backgrounds from the large liquid scintillator during the fission counting gate are due to local radioactivity, counts introduced by operation of the ORELA, scattered neutrons for example, to delayed gamma rays, and to delayed neutrons. The effect of delayed neutrons on the present work is negligible because of the low yield of delayed neutrons (<2%) and the long half lives (>10 ^{3}sec) of the delayed neutron precursors.

Delayed gamma rays are not measured in the methods of estimating the background used in the present work. Data on the half lives and cascade energies of delayed gamma rays from fission suggested by Boldeman[6] were folded with the measured response of the liquid scintillator to gamma rays to obtain correction factors for the present work. Correction factors of -0.4% and -0.2% were calculated for R(E) for ^{239}Pu and ^{235}U, respectively. An uncertainty of ±50% of the correction has been assumed.

Counting gates for estimation of the backgrounds other than from delayed gamma rays were generated by a random (random background) signal and by a signal from a neutron flux monitor (BF_3 pulse ionization chamber) in the neutron beam (beam-weighted background). It has been assumed that the background measured using randomly generated counting gates is appropriate for analyzing the ^{252}Cf data. Since for the fissile isotopes the probability of fission and the probability of neutron scattering are proportional to the neutron flux, the background measured using a randomly generated gate would not be appropriate if the neutron intensity of the source varies from pulse to pulse. It was observed that the beam weighted background was larger than the random background as will be discussed later.

5. Correction for Pulse Pile Up

The recovery time of the detector system for the large liquid scintillator following a pulse was about 0.075 μsec. A fixed dead time of 0.1 μsec was imposed upon the neutron detector system. Correction of the data for pulse pile up (dead time) was made in the manner given by Ribrag et al.[7] The correction factor obtained for the ratios R(E) for ^{239}Pu and ^{235}U were -0.24% and -0.35%, respectively, (for the thermal energy region). Boldeman and Dalton[8] obtained a correction of -0.3% for their work on R(E) for ^{235}U. An uncertainty of 30% has been assumed for the dead time correction factors.

6. Correction for Fission Spectrum Differences

A calculation of the relative efficiency of the liquid scintillator for capturing fission neutrons from ^{252}Cf, ^{239}Pu, and ^{235}U was made by John J. Ullo.[9] These calculations yield correction factors for R(E) of -0.13 ± 0.04% and -0.03 ± 0.03% for ^{235}U and ^{239}Pu, respectively.

7. Correction for Cross Talk in the Multi-Isotope Chamber

Experiments were performed using the multi-isotope fission chamber to investigate "cross talk" between sections of the fission chamber and to measure the probability that fission neutrons from the ^{252}Cf fission would cause detectable fissions in the other sections of the chamber. No measurable cross talk nor correlation between fissions in the chamber sections were observed.

IV PRESENTATION OF THE RESULTS

1. Experimental Results for ^{239}Pu and ^{235}U 0.005 to 60 eV

Table 1 shows the results obtained for $R_p(E)$ for ^{239}Pu and ^{235}U from 0.005 to 60 eV. The uncertainties given include the statistical error, and that due to false fissions. To obtain the estimated total uncertainty for the experimental values of R(E) an additional fully correlated error of 0.33% and 0.29% must be folded with the errors given in Table 1 for ^{239}Pu and ^{235}U, respectively. These latter correlated uncertainties were compounded from the errors discussed in previous sections of this paper. The statistical errors were calculated using the method given by Mather et al.[4] and consisted of the errors in the foregound and background determination for both the fissile isotope and ^{252}Cf.

Values of R(E) obtained in the present work and given for specified energy intervals are weighted in the experimental process with the neutron flux and the neutron cross section.

Figure 1 shows a plot of R(E) for ^{239}Pu (from Table 1) as a function of neutron energy over the range 0.001 to 1 eV. A pronounced dip in the value of R(E) was observed for neutrons in the energy region of the 0.3 eV resonance of ^{239}Pu. A similar behavior has been measured by Weinstein et al.[2] A fit of the data shown in Fig. 1 was made to a linear function of the log of the neutron energy up to 0.1 eV. This fitting procedure yields R(E) = 0.765 ± 0.003 for the energy interval 0.02 to 0.03 eV which agrees within errors with the 0.7647 ± 0.0018 suggested for ^{239}Pu by Boldeman,[6] the 0.764 ± 0.002 recommended by Lemmel,[1] and the 0.7632 given in ENDF/B-IV.

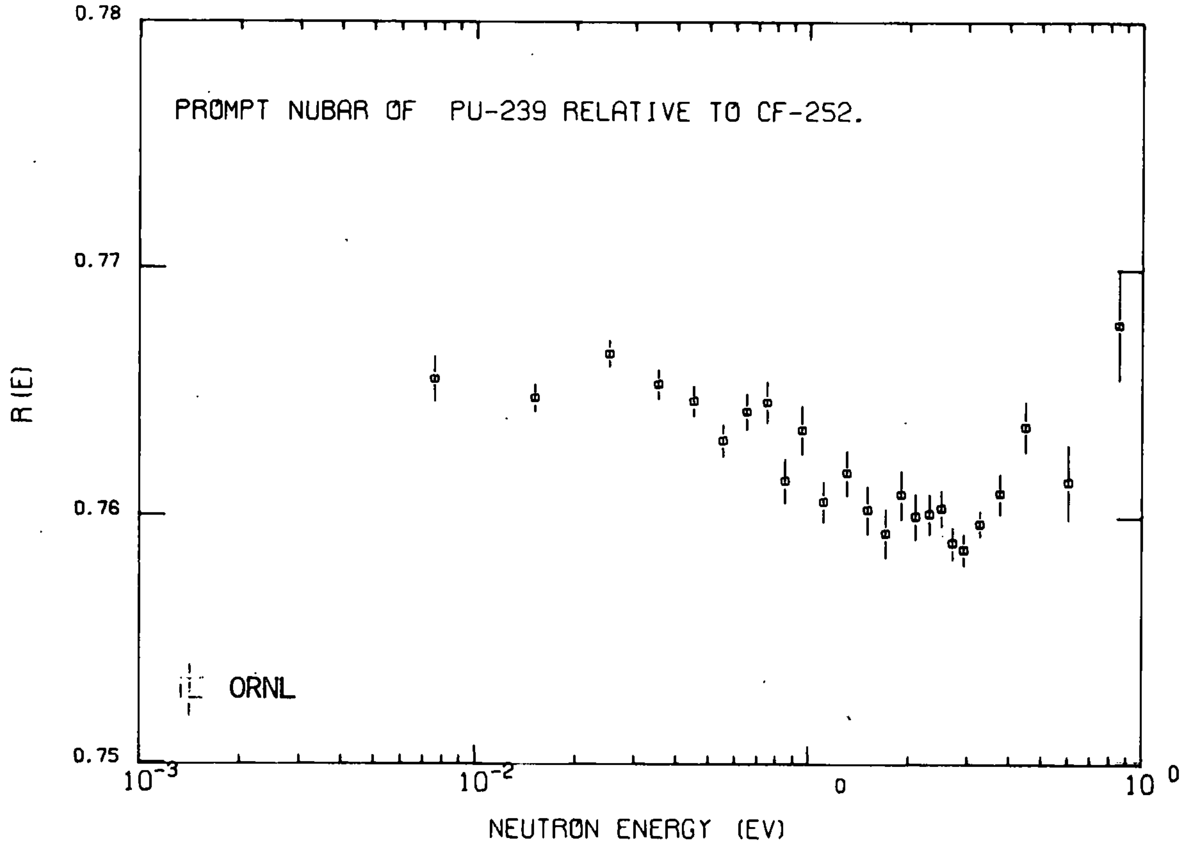

Fig. 1. Neutron energy dependence of $\overline{\nu}_p$ for ^{239}Pu over the neutron energy region 0.001 to 1.0 eV.

TABLE I. Experimental Values of $\overline{\nu}_p(E)$ for ^{235}U and ^{239}Pu Relative to $\overline{\nu}_p$ for ^{252}Cf, 0.005 to 60.0 eV

		^{239}Pu		^{235}U	
E1(eV)	E2(eV)	$R_p(E)$	$\Delta R_p(E)$[a]	$R_p(E)$	$\Delta R_p(E)$[a]
0.005	0.01	0.7653	0.0009	0.6470	0.0014
0.01	0.02	0.7646	0.0006	0.6431	0.0009
0.02	0.03	0.7664	0.0006	0.6426	0.0009
0.03	0.04	0.7651	0.0006	0.6444	0.0009
0.04	0.05	0.7644	0.0006	0.6455	0.0010
0.05	0.06	0.7628	0.0007	0.6423	0.0011
0.06	0.07	0.7640	0.0008	0.6464	0.0013
0.07	0.08	0.7644	0.0009	0.6467	0.0015
0.08	0.09	0.7612	0.0009	0.6454	0.0016
0.09	0.1	0.7633	0.0010	0.6395	0.0018
0.1	0.12	0.7604	0.0008	0.6419	0.0016
0.12	0.14	0.7615	0.0009	0.6447	0.0019
0.14	0.16	0.7600	0.0010	0.6383	0.0023
0.16	0.18	0.7591	0.0010	0.6429	0.0025
0.18	0.20	0.7606	0.0010	0.6481	0.0027
0.20	0.22	0.7598	0.0008	0.6450	0.0029
0.22	0.24	0.7599	0.0008	0.6460	0.0030
0.24	0.26	0.7601	0.0008	0.6453	0.0030
0.26	0.28	0.7587	0.0006	0.6431	0.0030
0.28	0.30	0.7584	0.0006	0.6418	0.0031
0.30	0.35	0.7595	0.0005	0.6455	0.0024
0.35	0.4	0.7607	0.0008	0.6410	0.0029
0.40	0.5	0.7634	0.0011	0.6420	0.0027
0.5	0.7	0.7611	0.0015	0.6466	0.0027
0.7	1.0	0.7676	0.0023	0.6516	0.0028
1.0	1.8	0.7685	0.0025	0.6414	0.0026
1.8	7.4	0.7641	0.0024	0.6452	0.0024
7.4	10.	0.7571	0.0019	0.6431	0.0024
10	15	0.7610	0.0012	0.6333	0.0028
15	20.5	0.7598	0.0024	0.6365	0.0027
20.5	33	0.7609	0.0023	0.6446	0.0027
33	41	0.7604	0.0065	0.6437	0.0034
41	60	0.7632	0.0021	0.6434	0.0030

[a] These uncertainties ΔR are combined from statistical errors and uncertainties in corrections which are energy dependent. (The latter uncertainties are negligible below ∿ 0.02 eV.

Figure 2 shows R(E) for ^{235}U (from Table 1) over the neutron energy range from 0.001 eV to 1.0 eV. The uncertainties shown include only those due to statistics and those which depend upon the neutron energy (in the present work). Weinstein et al.[2] reported a variation of R(E) for ^{235}U of a few tenths of a percent over the energy region of Figure 2. Treating the present data shown in Figure 2 as a constant yields a value for (χ^2/DF) chi-square divided by degrees of freedom of 2. Inclusion of a linear term in energy to describe the data does not improve the fit. A similar analysis of the denominator of R(E), that is the average number of neutrons observed following fission of the ^{252}Cf standard, for the individual experiments performed in the thermal energy range yields values of χ^2/DF which range from 0.9 to 1.3.

The value of R(E) for ^{235}U in the thermal energy region derived from the present work is

$$R(E) = 0.6441 \pm 0.0019$$

which agrees with the value of 0.642 ± 0.002 recommended by Lemmel[1] but is 0.8% larger than the result 0.6386 ± 0.0010 suggested by Boldeman,[6] and 0.7% larger than the ENDF/B-IV value.

The background in the experiments covering the thermal energy region ranged from the ambient background of ∿ 0.04 cts/gate at about 0.01/eV to ∿ 1 cts/gate at 60 eV. Only the random method was used to generate background gates in the experiment covering the thermal energy range. For the cases measured in the present work (see next section) the beam weighting technique yields a 5 to 10% larger background than the random method. A 5% change in the estimated background for a background of 0.5

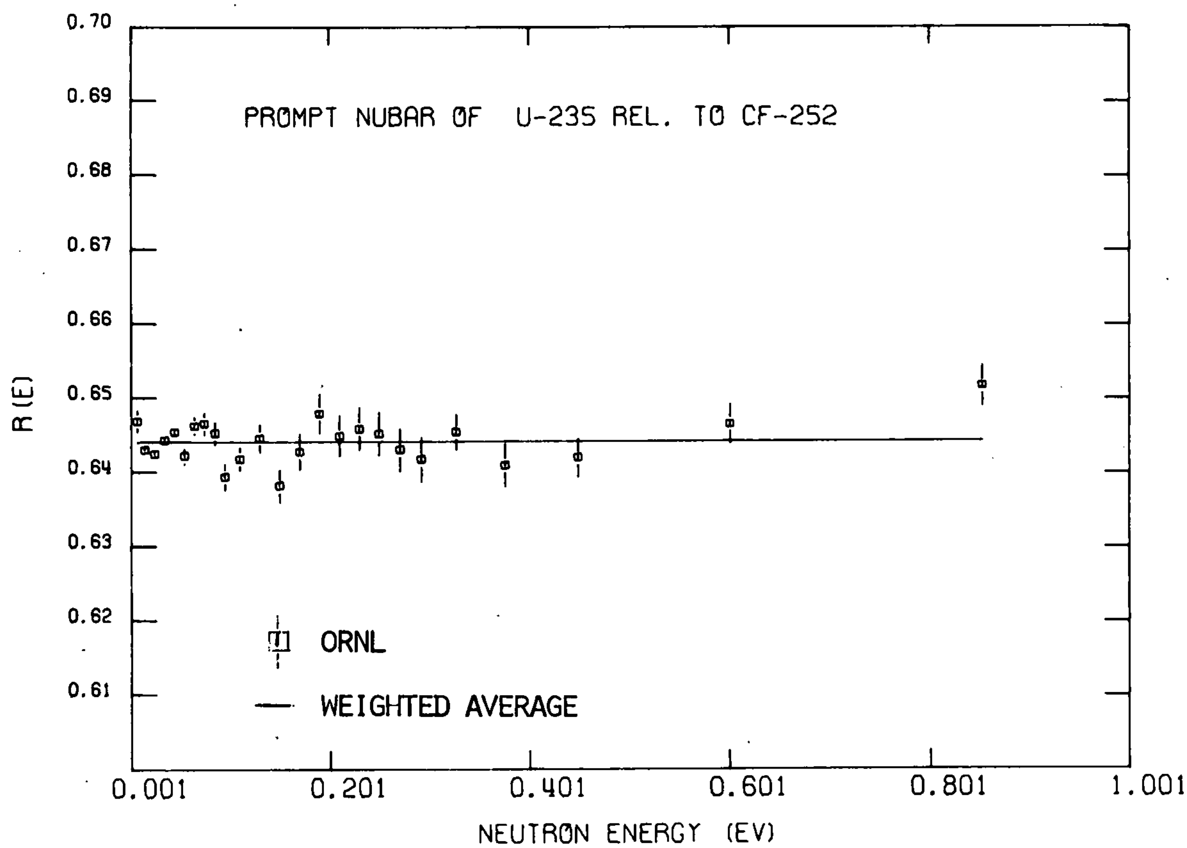

Fig. 2. Neutron energy dependence $\bar{\nu}_p$ for ^{235}U over the neutron energy region 0.001 to 1.0 eV.

cts/gate leads to a 1% change in R(E) for ^{235}U. An examination of Table I shows no evidence within errors of an increase in R(E) for ^{235}U as the neutron energy increases toward 60 eV. Below 0.6 eV the contribution of the neutron beam to the background is about 0.02 cts/gate and a 5% uncertainty on this quantity introduces a 0.04% error in R(E) for ^{235}U. For data from the present experiments in the energy region above 1 eV an uncertainty of 1 to 2% should be included as a systematic error since the beam weighting method of measuring the background was not used.

2. Experimental Results for ^{239}Pu and ^{235}U, 50 eV to 10 MeV

Measurements of $R_p(E)$ were made for both ^{239}Pu and ^{235}U at a flight path of 21.6 m and covered the neutron energy region from about 50 eV to 7 MeV. The background was measured using the random method of generating the counting gate. Experiments for ^{239}Pu were also performed at a flight path of 83.4 m and covered the neutron energy range from about 50 eV to 10 MeV. In these experiments (83.4 m) the background was measured using both the random and the beam weighted techniques.

Table II gives $R_p(E)$ for ^{239}Pu and ^{235}U derived from the experiment at 21.6 m and Table III lists $R_p(E)$ for ^{239}Pu from the experiments at 83.4 m. In Table III the uncertainties shown were calculated using the background data obtained by beam weighting. The uncertainties on the background are statistical and are the same within 5×10^{-4} for both methods of measuring the background. A systematic uncertainty of 0.37 and 0.26% must be folded with those given in Tables II and III for the ^{239}Pu data obtained at the 21.6 and 83.4 m flight path respectively. A systematic uncertainty of 0.33% should be applied to the ^{235}U values of

TABLE II. Experimental Values of $\overline{\nu}_p(E)$ for ^{239}Pu and ^{235}U Relative to $\overline{\nu}_p$ for ^{252}Cf Obtained at a 20 M Neutron Flight Path, 0.05 keV to 7.0 MeV.

E1 (keV)	E2 (keV)	^{239}Pu $R_p(E)$	^{239}Pu $\Delta R_p(E)^a$	^{235}U $R_p(E)$	^{235}U $\Delta R_p(E)^a$
0.050	0.100	0.7701	0.0021	0.6339	0.0037
0.10	0.20	0.7750	0.0038	0.6310	0.0067
0.20	0.30	0.7716	0.0040	0.6341	0.0073
0.30	0.40	0.7650	0.0050	0.6345	0.0058
0.40	0.50	0.7668	0.0044	0.6410	0.0048
0.51	0.61	0.7631	0.0039	0.6435	0.0053
0.61	0.71	0.7585	0.0098	0.6458	0.0072
0.71	0.80	0.7841	0.0086	0.6346	0.0069
0.80	0.90	0.7734	0.0078	0.6314	0.0073
0.90	1.00	0.7662	0.0071	0.6295	0.0070
1.0	2.0	0.7690	0.0035	0.6440	0.0043
2.0	3.0	0.7848	0.0110	0.6439	0.0055
3.0	4.0	0.7676	0.0080	0.6442	0.0137
4.0	5.0	0.7661	0.0109	0.6220	0.0143
5.0	6.0	0.7577	0.0131	0.6400	0.0128
6.0	7.0	0.7490	0.0108	0.6380	0.0109
7.0	8.0	0.7669	0.0055	0.6262	0.0191
8.0	9.0	0.7582	0.0159	0.6537	0.0165
9.0	10.0	0.7593	0.0167	0.6465	0.0125
10.0	20.0	0.7711	0.0063	0.6406	0.0139
20.0	30.0	0.7715	0.0082	0.6367	0.0189
30.0	40.0	0.7598	0.0138	0.6443	0.0127
40	50	0.7609	0.0081	0.6471	0.0099
50	60	0.7675	0.0069	0.6529	0.0097
60	74	0.7665	0.0070	0.6488	0.0117
74	85	0.7522	0.0092	0.6518	0.0181
85	94	0.7565	0.0191	0.6735	0.0165
94	100	0.7654	0.0189	0.6635	0.0128
100	200	0.7793	0.0045	0.6632	0.0072
200	300	0.7746	0.0043	0.6684	0.0060
300	400	0.7764	0.0042	0.6738	0.0094
400	500	0.7870	0.0043	0.6753	0.0094
500	600	0.7892	0.0046	0.6752	0.0083
600	710	0.7903	0.0047	0.6731	0.0085
710	800	0.7936	0.0048	0.6717	0.0121

TABLE II. -continued-

800	920	0.7944	0.0049	0.6933	0.0148
920	1000	0.8012	0.0051	0.6863	0.0097
1000	2100	0.8179	0.0024	0.6973	0.0175
2100	3100	0.8575	0.0041	0.7373	0.0225
3100	4100	0.8994	0.0054	0.7845	0.0115
4100	5100	0.9376	0.0070	0.7961	0.0376
5100	6400	0.9812	0.0077	0.8775	0.0230
6400	7200	1.0226	0.0080	0.9195	0.0266

[a] These uncertainties reflect the statistical errors and the known errors which affect the neutron energy dependence of $R_p(E)$. The uncertainties are the standard deviation from the mean.

TABLE III. Experimental Values of $\overline{\nu}_p(E)$ for ^{239}Pu Relative to $\overline{\nu}_p$ for ^{252}Cf Obtained at a Neutron Flight Path of 85M, 0.005 to 10 MeV.

E1 (MeV)	E2 (MeV)	^{239}Pu $R_p(E)$[a]	$\Delta R_p(E)$[b]	$R_p(E)$[c]
0.0005	0.001	0.774	0.010	0.774
0.001	0.003	0.767	0.007	0.767
0.003	0.005	0.761	0.009	0.761
0.005	0.007	0.768	0.010	0.769
0.007	0.010	0.756	0.009	0.757
0.01	0.02	0.762	0.006	0.763
0.02	0.03	0.782	0.008	0.784
0.03	0.04	0.769	0.009	0.772
0.04	0.05	0.779	0.010	0.783
0.05	0.06	0.761	0.010	0.766
0.06	0.07	0.772	0.011	0.776
0.07	0.08	0.771	0.012	0.773
0.08	0.09	0.761	0.013	0.764
0.09	0.10	0.755	0.013	0.758
0.1	0.2	0.764	0.004	0.767
0.2	0.3	0.772	0.006	0.777
0.3	0.4	0.776	0.006	0.778
0.4	0.5	0.786	0.007	0.790
0.5	0.6	0.782	0.007	0.783
0.6	0.7	0.787	0.007	0.790
0.7	0.8	0.806	0.008	0.807
0.8	0.9	0.796	0.009	0.802
0.9	1.0	0.796	0.009	0.806
1.0	2.0	0.812	0.005	0.818
2.0	3.0	0.856	0.008	0.866
3.0	4.1	0.887	0.012	0.897
4.1	5.2	0.922	0.016	0.935
5.2	6.1	0.968	0.020	0.988
6.1	7.2	1.011	0.021	1.032
7.2	8.2	1.060	0.023	1.071
8.2	9.2	1.112	0.027	1.121
9.2	10.0	1.154	0.026	1.165

[a]Derived using beam weighted background.

[b]$\Delta R_p(E)$ applies to both techniques of measuring the background and reflects the statistical uncertainties and the uncertainty in the corrections to the data which affect the energy dependence of $R_p(E)$.

[c]Derived using random background.

R(E) shown in Table II. The above systematic uncertainties were compounded from those given in prior sections of this paper.

Figure 3 shows a plot of $R_p(E)$ from 1 keV to 10 MeV for ^{239}Pu derived from the present experiments. The data shown for the experiments at the 83.4 m flight path were analyzed using the beam weighted background. Also shown in Figure 3 are the values of $R_p(E)$ from ENDF/B-IV. The data shown in Figure 3 suggest a linear relation between $R_p(E)$ and E, however, the data do not preclude structure. An analysis of the present experimental data on ^{239}Pu was made using the assumption that a linear relation

$$R_p(E) = A + B \times E$$

does describe the data shown in Figure 3. Table IV lists the parameters A and B and their uncertainties derived in the analysis. Parameters A and B were derived using the energy region up to 0.7 MeV, the region above 0.7 MeV, and using the entire energy region covered by the experiments. Note that for the energy region up to 0.7 MeV corresponding values of A and B derived with the data obtained at both flight paths using the random background method agree within their uncertainties. The difference in the slope B derived using the data obtained at the larger flight path for the two background cases is statistically significant. Interpretation of the intercept A as the value of $\bar{\nu}_p(0)$ is not straightforward, however, the values of A given in Table IV do agree with the value $R_p(0.025\ eV)$ obtained from the measurements at thermal energy within the given uncertainties. The present data for $R_p(E)$ for ^{239}Pu agree with the ENDF/B-IV values to about 2 MeV within experimental error and for the case using the beam weighted background fall about 1% less (about the total known uncertainty of the present data) than the ENDF/B-IV value at 4 MeV.

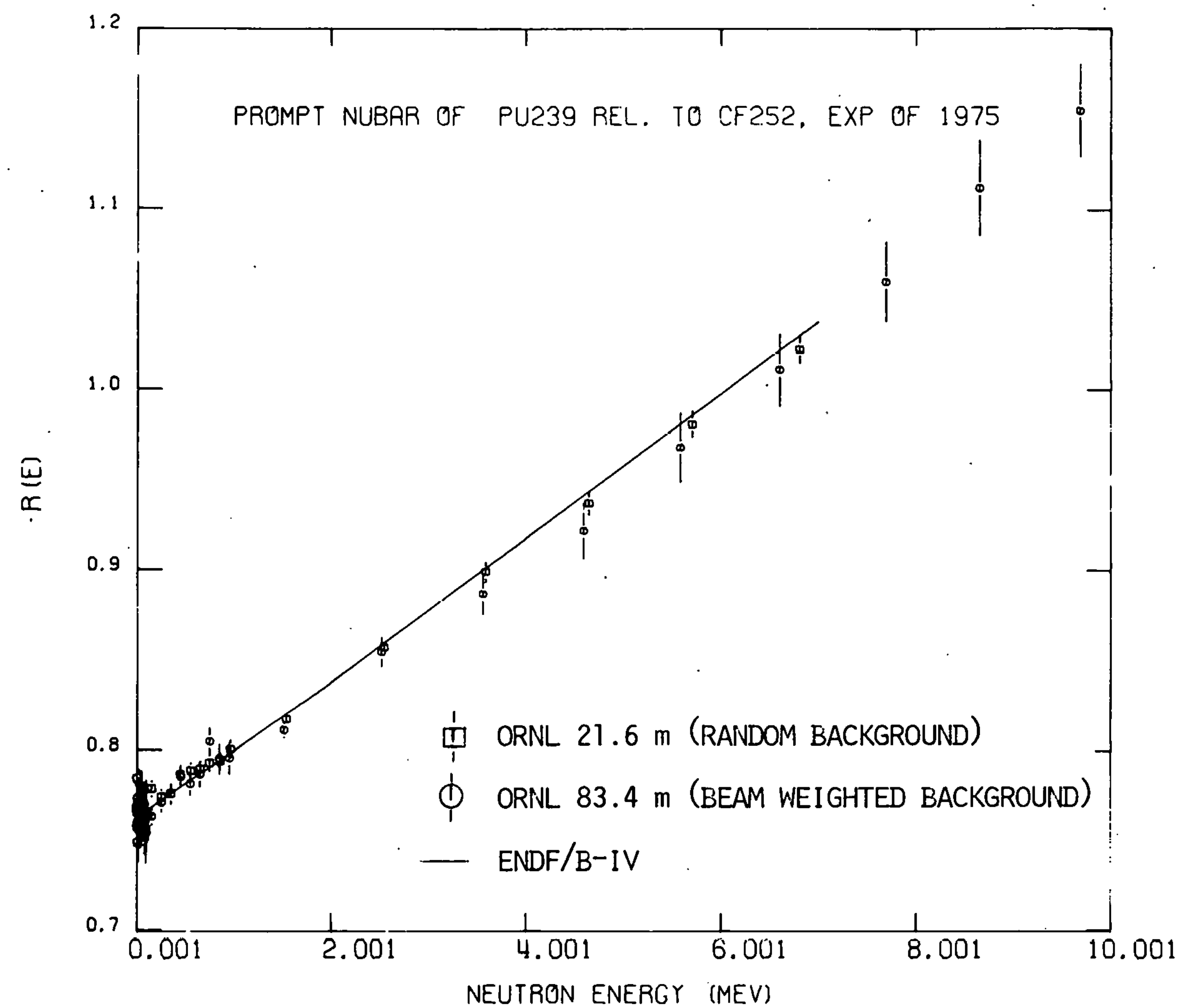

Fig. 3. Variation in $\bar{\nu}_p(E)$ for ^{239}Pu relative to $\bar{\nu}_p$ for ^{252}Cf from 0.001 to 10 MeV.

TABLE IV. Parameters of Linear Relations of $R_p(E)$ for ^{239}Pu with Neutron Energy

$$R_p(E) = A + B * E$$

E1 (MeV)	E2 (MeV)	Data[a]	A	ΔA[b]	B	ΔB[b]	DF[c]	χ^2/DF[d]
0.0	9.0	85M, BW	0.7634	0.0017	0.0365	0.0013	29	0.8
0.7	9.0	85M, BW	0.7607	0.0045	0.0373	0.0018	9	0.9
0.0	0.7	85M, BW	0.7643	0.0024	0.0335	0.0084	18	0.7
0.0	9.0	85M, R	0.7656	0.0017	0.0387	0.0013	29	0.8
0.7	9.0	85M, R	0.7645	0.0043	0.0392	0.0017	9	0.7
0.0	0.7	85M, R	0.7663	0.0024	0.0359	0.0083	18	0.8
0.0	7.0	20M, R	0.7669	0.0009	0.0364	0.0007	45	1.1
0.7	7.0	20M, R	0.7609	0.0026	0.0383	0.0010	7	0.3
0.0	0.7	20M, R	0.7676	0.0010	0.0358	0.0050	36	1.1
0.0	7.0	ENDF/B-IV	0.7613		0.0394			

[a] BW refers to Beam Weighted Background Data.
R refers to Random Background Data.

[b] Statistical uncertainties combined with those that affect the shape (slope) of the data.

[c] Degrees of freedom, for a linear fit DF = Data Points - 2.

[d] χ^2 = chi-square.

An additional uncertainty of about 1% should be folded with the results for ^{239}Pu shown in Table II since the beam weighting method was not used to obtain those results.

Figure 4 shows a plot of $R_p(E)$ for ^{235}U taken from Table II as a function of neutron energy. These data for ^{235}U (shown in Table II) were analyzed using the background estimated by the random gate method. Also shown are the ENDF/B-IV values and it is noted that the present data are 1 to 3% larger than the ENDF/B-IV values. A least squares fit of the data on $R_p(E)$ for ^{235}U to a linear relation of the neutron energy yields the result

$$R_p(E) = 0.641 \pm 0.002 + (0.040 \pm 0.003) \times E$$

where the uncertainties have been expanded by the square root of $\chi^2/DF(\chi^2/DF = 2.6)$. Only the statistical errors and those uncertainties which affect the slope of $R_p(E)$ were included in the least squares fitting procedure. A systematic uncertainty of ± 0.33% must be included to derive the total known error.

During the experiments on ^{235}U the neutron intensity was varied for individual runs such that the background counts per gate varied from about 0.4 to 1.4. A separate analysis of these individual runs indicated larger values of $R_p(E)$ for the experiments having the higher background counts. Measurements of the background using the beam weighting method were started in the set of experiments on ^{235}U at 21.6 M. Although insufficient data were obtained to correct the data, backgrounds recorded for the beam weighted case were ∿ 5 to 10% larger than those obtained when the background gate was generated by a random signal. For a background of 0.5

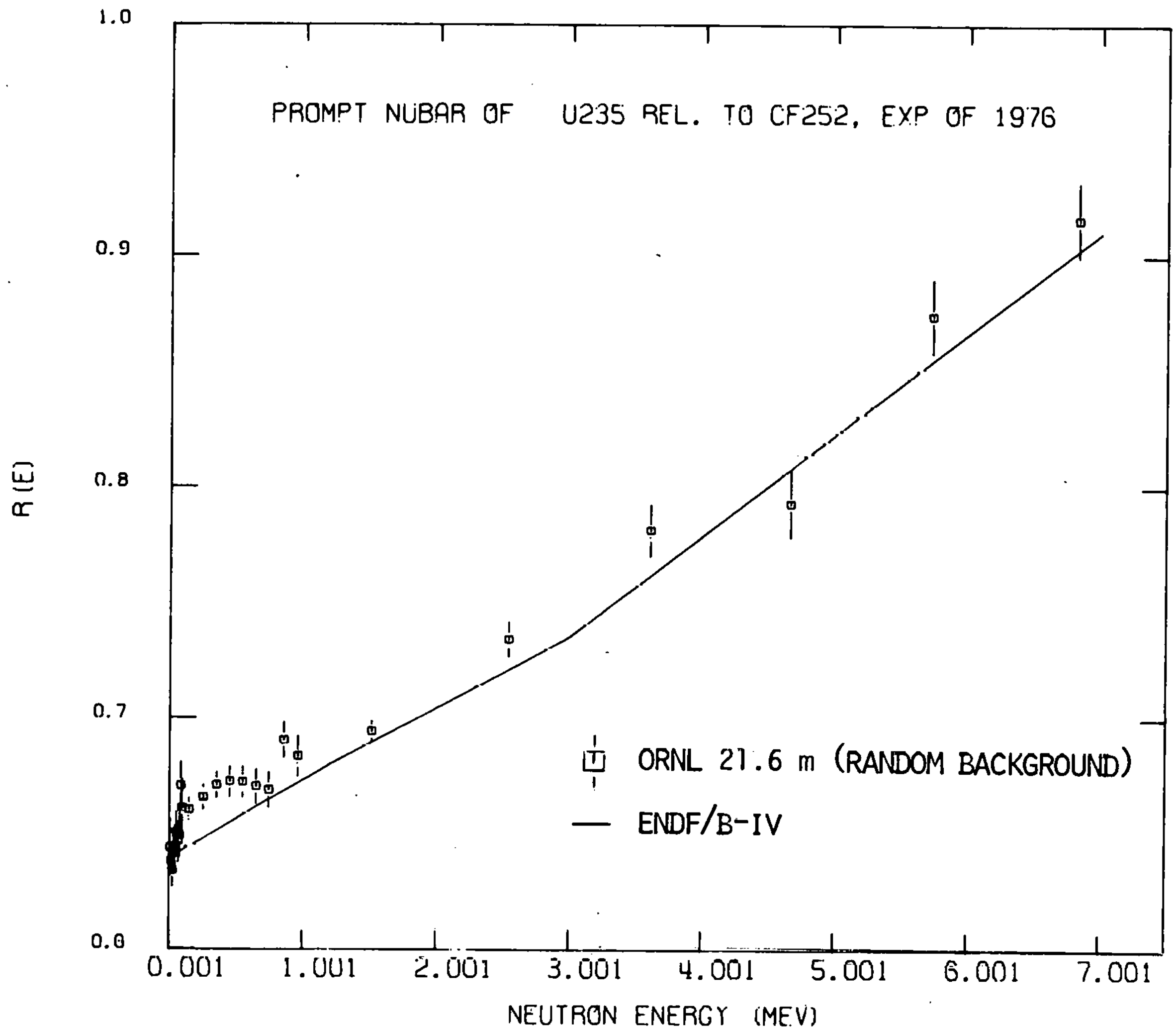

Fig. 4. Variation in $\overline{\nu}_p(E)$ for ^{235}U relative to $\overline{\nu}_p$ for ^{252}Cf from 0.001 to 7 MeV.

cts/gate a 5% uncertainty in the background generates an uncertainty of about 1% in $R_p(E)$ for ^{235}U. The present data on ^{235}U have therefore a systematic uncertainty which may be as large as 3%. For this reason it is suggested that the data on R(E) for ^{235}U not be considered in evaluations until the problems in the estimation of the background are clarified.

The intercept 0.641 ± 0.002 just overlaps the value 0.644 ± 0.001, common systematic uncertainties not included, obtained in the experiments covering the thermal energy region.

V. CONCLUSIONS

The present experimental values $R_p(E)$ for ^{239}Pu confirm the energy dependence below 1 eV observed by Weinstein et al.[2] No energy dependence of $R_p(E)$ for ^{235}U was established in the energy region below 1 eV by the present experiments. The present value of $R_p(E)$ for ^{239}Pu between 0.02 and 0.03 eV agrees with the ENDF/B-IV value within the ∿ 0.3% uncertainty of the present work. For ^{235}U, however, the present value of $R_p(E)$ (0.02 - 0.03 eV) is 0.7% larger than the ENDF/B-IV value with an estimated uncertainty of about 0.3% in the present results. Below 1.0 eV the main point to be resolved concerns the difference in the number of neutrons detected following fission in the two ^{252}Cf fission chambers used in the present work.

In the energy region above 1 keV the present measurements on ^{239}Pu agree, within errors, with the ENDF/B-IV values up to 2 MeV. Above 2 MeV the present results tend to lower values than those given in ENDF/B-IV. For ^{235}U the present results do not include an estimate of the background by the beam weighting method and have a tentative uncertainty of a few percent (∿ 3%).

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J. G. Craven wrote the computer programs used for data acquisition and assisted in formulating the data analysis procedures. Extensive use was made of a weighted least squares analysis program written by R. W. Peelle.

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L. W. Weston participated in design of the present experiments and has contributed to the continuing analysis of the experiments.

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