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ORELA Measurements of the $^{235}\text{U}(\text{n},\text{f})$ Cross Section to 100 keV*

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The purpose of this paper is to elucidate briefly two measurements of the $^{235}\text{U}(\text{n},\text{f})$ cross section in the 0.1- to 100-keV range. Both measurements were made at the Oak Ridge Electron Linear Accelerator using apparatus chosen primarily to allow simultaneous measurements of fission and capture cross sections, but these measurements have weight and need to be considered. Most of these results are believed to be essentially final and for each experiment the respective authors are now preparing more complete documentation.^{1,2}

In each case fission was detected by coincidence between pulses from a multiplate fission chamber utilizing 99.7% pure ^{235}U and a large two-segment boron-loaded scintillator tank,³ each segment biased at a fast pulse height corresponding to an electron energy release of about 0.2 MeV. A total deposited energy of ≥ 3 MeV was required in the scintillator for an event to be recorded. The fission chamber has 20 plates 7.5 cm in diameter spaced by ~ 1.5 mm, with electroplated ^{235}U deposits of about 1.7 mg/cm^2 on both positive and negative plates. As operated the fission chamber efficiency for detecting a fission event was about 0.6, and the tank efficiency for a fission was about 0.85 or 0.6 depending on whether or not a fast coincidence was required between the two segments of the tank.

Background, including that from off-energy neutrons, was determined by the "notch filter" technique to be $< 1\%$. By studying tagged events from a ^{252}Cf -loaded fission chamber present during the measurements, it was possible to exclude any effects of efficiency variations as a function of neutron energy.

Neutron flux was measured using a Be-walled parallel-plate pulse ion chamber containing $\sim 9 \text{ mg/cm}^2$ of $^{10}\text{BF}_3$. This chamber was used in the transmission mode and recorded the spectrum during the fission measurements. A stable fraction of the spectrum was selected for use and it was then assumed that the efficiency of the chamber was proportional to the $^{10}\text{B}(\text{n},\alpha)$ cross section.

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Beyond the similarities of equipment listed above, the experiments and analysis of Perez *et al.* and of Gwin *et al.* were quite independent. Both, however, assumed the shape of the $^{10}\text{B}(n,\alpha)$ cross section given by Sowerby.⁴

Gwin, Silver, Ingle, and Weaver performed their main experiments at a flight distance of 40 meters and in some cases used a sufficiently low burst repetition rate that the measurements included the thermal neutron energy range. These measurements were normalized to the value of 83.74 barn-eV over the energy interval 0.02 to 0.4 eV, implying a normalization about 2.5% below the values given by Deruytter in 1971 for the 7.4- to 10-eV interval.⁵ (Different thermal cross sections were assumed.)

Perez, de Saussure, Silver, Ingle, and Weaver utilized measurements at both 40 meters and 150 meters; the results at the shorter distance are now prepared for publication, while those at the longer flight path are considered more preliminary. The present results are to be used in preference to the preliminary results released in 1971 based on part of the same experimental data.⁶ For the 40-meter measurements a boron filter was used to cut off the neutrons of lowest energy to enable use of a higher repetition rate. The results were normalized in the 100- to 200-eV range to a value consistent with the ORNL-RPI experiment,⁷ the Saclay work of Blons,⁸ and the LASL work of Lemley.⁹ (In turn, the ORNL-RPI values are normalized to 127.9 barn for the resonance integral from 0.45 to 10 eV. For the fission integral from 5.0 to 10.0 eV, the ORNL-RPI normalization is ~1% below that proposed by Deruytter⁵ and by inference somewhat above that now adopted by Gwin *et al.*) The results of Perez *et al.* at the 150-meter flight-path length were in turn normalized to the integral of the 40-meter data over the 2- to 10-keV range. The measurements at 150 meters have the advantage of a smooth incident flux because ORELA replaced aluminum with beryllium in the container for the water moderator surrounding the tantalum electron target.

Figure 1 illustrates the unit-weight average cross-section results of both experiments on a segmented scale, along with some results of other well-known experiments. Table I contains the corresponding experimental results. It is seen that the two sets of ORELA results are

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almost parallel in the energy region shown, so that the main difference between them is a matter of normalization which is to some extent subject to review by data evaluators. Since the results of Gwin *et al.* nearly agree with the ORNL-RPI data below 10 eV, one correctly concludes that the shape of the Gwin data between 20 and 100 eV does not quite agree with that given in the ORNL-RPI work. No explanation for this difference has been located after considerable effort, and indeed the corresponding data sets for $^{239}\text{Pu}(n,f)$ are in better agreement.

To check the question of low-energy shape for $^{235}\text{U}(n,f)$, Gwin and Weston prepared an independent test with a 20 meter flight path using the fission chamber without the presence of the scintillator tank. The shape of the recent Gwin data appeared to be confirmed.

The uncertainties assigned to the average cross sections do not include any component from uncertainty in the shape of the $^{10}\text{B}(n,\alpha)$ cross section. Uncertainty in the efficiency of the boron chamber for recording a reaction is somewhat difficult to estimate, but pulse-height spectral measurements by Gwin imply an uncertainty for his data of about 4% at the highest energies. The plotted uncertainties do include observed fluctuations in results from one experimental run to the next, and uncertainties in effecting the stated normalizations. The data of Perez *et al.* above 10 keV have for the present an additional uncertainty assigned because these data will be subject to further analysis. If the two ORELA data sets were normalized together in the 7- to 11-eV region (by joining ORNL-RPI with the Perez *et al.* data), the two data sets would disagree by about 5% in the 1- to 10-keV region, not inconsistent with the estimated uncertainties.

To compare these measurements with others using continuous sources, one may inspect the results of Blons⁸ and of Lemley⁹ which both agree with the Perez *et al.* results in the 100- to 200-eV interval. The Blons work generally agrees with that of Perez *et al.*, but that of Lemley [measured against $^6\text{Li}(n,\alpha)$] drops to lower values above a few hundred eV. For orientation, all the results fall below the 40-keV value of White and the 24-keV value of Perkin,¹¹ and are nearer to the Szabo results given in 1971.¹²

Work on the $^{235}\text{U}(\text{n},\text{f})$ cross section at ORNL is expected to continue in two forms. The measurements of Perez *et al.* will be refined and extended in support of further efforts to measure the ratio of capture in ^{238}U to fission in ^{235}U . Peelle and Weston are undertaking measurements pointed directly toward the $^{235}\text{U}(\text{n},\text{f})$ cross section, but no data from this work has yet been analyzed. The emphasis so far is on use of "thin" ionization chambers in which high efficiencies can be achieved in recording the few nuclear events which take place. At first we will be satisfied with normalizations at low energy in the style of the measurements described above. Figures 2 and 3 show pulse-height distributions observed for low-energy neutrons with the counters now ready for use. The Frisch-gridded boron chamber would probably be biased just above the group of pulses corresponding to the ^7Li particles from the ground-state reaction.

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Table I. Averaged Cross Sections and Estimated Standard Errors
for Neutron Fission of $^{235}\text{U}(n,f)$

$E_1 - E_2$ (keV)	Perez <i>et al.</i> ¹		Gwin <i>et al.</i> ²		Ratio Perez/Gwin
	σ_f (barns)	$\Delta\sigma_f$ (barns)	σ_f (barns)	$\Delta\sigma_f$ (barns)	
0.10 - 0.12	18.9	0.5	18.2	0.4	1.04
0.12 - 0.15	25.0	0.8	24.4	0.5	1.02
0.15 - 0.20	19.4	0.6	19.0	0.4	1.02
0.20 - 0.25	21.9	0.7	20.7	0.4	1.06
0.25 - 0.30	19.9	0.6	18.8	0.4	1.06
0.30 - 0.40	13.3	0.4	12.8	0.3	1.04
0.40 - 0.50	14.0	0.4	13.1	0.3	1.07
0.50 - 0.60	15.6	0.5	15.5	0.4	1.01
0.60 - 0.80	11.5	0.3	10.9	0.3	1.06
0.80 - 1.00	7.98	0.24	7.6	0.3	1.05
1.0 - 1.2	9.14	0.36	8.64	0.3	1.06
1.2 - 1.5	7.72	0.31	7.22	0.2	1.07
1.5 - 2.0	6.76	0.27	6.28	0.2	1.08
2.0 - 2.5	5.65	0.23	5.14 ^a	0.2	1.07
2.5 - 3.0	5.30	0.21			
3.0 - 4.0	4.86	0.19	4.58	0.2	1.06
4.0 - 5.0	4.36	0.17	4.08	0.2	1.07
5.0 - 6.0	3.77	0.15	3.72	0.2	1.01
6.0 - 8.0	3.44	0.14	3.11	0.1	1.11
8.0 - 10.0	3.14	0.13	2.95	0.1	1.06
10 - 12	2.74	0.22	2.70	0.10	1.01
12 - 15	2.56	0.20	2.59	0.10	.99
15 - 20	2.29	0.18	2.29	0.10	1.0
20 - 25	2.19	0.17	2.18	0.09	1.0
25 - 30	2.11	0.17	2.04	0.09	1.03
30 - 40	2.02	0.16	1.94	0.08	1.04
40 - 50	1.96	0.15	1.81	0.07	1.08
50 - 60	1.92	0.15	1.82	0.07	1.05
60 - 80	1.85	0.14	1.74	0.09	1.06
80 - 100	1.73	0.13	1.57	0.09	1.10

^aFor 2.0- to 3.0-keV region.

Fig. 1. Averaged $^{235}\text{U}(n,f)$ Cross Sections of Perez *et al.* and Gwin *et al.* Compared with Some Other Representative Values from the Literature.

Fig. 2. Spectrum of Integrated Charge Pulses for ^{235}U Fission. A 0.1-mg/cm² deposit was placed on the negative electrode of the parallel plate ion chamber with ~6-mm spacing.

Fig. 3. Pulse-height Spectrum of the ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$ Reaction Observed with the Gridded Ion Chamber.