# Neutron Transmission Cross Sections in the Kilovolt Region

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(Received November 12, 1951)

Neutron transmission cross sections have been measured with about 2 kev resolution in the energy range from 2 kev to 25 kev, and to higher energies in some case. The neutrons, produced by the $Li^7(p,n)Be^7$ reaction with a van de Graaff generator, were detected by a highly efficient (~15 percent) bank of boron trifluoride filled proportional counters placed to detect neutrons emitted at an angle of 120° from the proton beam direction. Measurements at the lower energies were made possible by a collimator and shield around the counters, which reduced background, and by the high efficiency obtained by many counters embedded in an array in a paraffin moderator. Resonances were observed in Na, Ti, V, Mn, Fe, Co, and Ni.

## INTRODUCTION

HITHERTO, a gap has existed in the data on neutron cross sections between the lowest energies that could be satisfactorily measured with the electrostatic generator (about 15 kev) and the highest energies for which velocity spectrometers have adequate resolution (about 3 kev). Several groups[1–4] have been developing methods of increasing the upper energy limit of time of flight spectrometers and undoubtedly in the near future improved resolution will be obtained.

The lower energy limit to the electrostatic generator technique as developed by Barschall *et al.*[5] has been determined by the rapid fall in neutron yield of very low energy neutrons and the large background counting rate (for the $Li^7(p,n)Be^7$ reaction; no other reaction has been used so successfully, as yet, for this low energy neutron work). In this work to be reported, a new detection scheme has been employed in which a massive shield reduces the background counting rate and the large group of boron trifluoride proportional counters embedded in paraffin increases the counting efficiency to overcome the decline in yield of low energy neutrons. This equipment has been briefly described[6] and will be more fully described in a later publication elsewhere. Figure 1 shows the essence of the device.

## PROCEDURE

The collimator and shield, Fig. 1, was set up with its axis at 119.6° to the proton beam direction, as determined by triangulation with a transit. Transmission samples were placed immediately in front of the collimator hole entrance. No corrections for scattering-in by the transmission sample are necessary in this arrangement. Monitoring of the neutron flux was achieved by a standard boron trifluoride "long counter"[7] placed in the neutron flux along a line extended from the proton beam direction. Presence or absence of a transmission sample does not appreciably disturb this monitor since scattering by the face of the shield is already complete and the sample scarcely perturbs the scattering equilibrium. Measurements were made with and without the transmission samples and with and without a paraffin plug 2 inches in diameter by $5\frac{1}{2}$ inches long placed at the scattering sample position inside the counter assembly in the collimated beam. Measurements without the paraffin plug are the background measurements. This technique of background measurement differs from the prior method involving use of a paraffin cone[5,8] and is probably more reliable and less likely to be disturbed by systematic errors. The paraffin plug when in position was located at a point at which the counting rate was a maximum (except in some of the earlier exploratory data.)

The lithium targets were evaporated onto the tantalum end cap of the rotating target, and the thickness was controlled by observing the neutron yield during evaporation and then measured by the rise curve, as described by Taschek.[9] A typical rise curve is shown at the left side of Fig. 2. The rise curve was usually re-run before and after each day's work and a new target prepared if the old one was found to be too thick. Proton energies were measured relative to the $Li(p,n)$ threshold

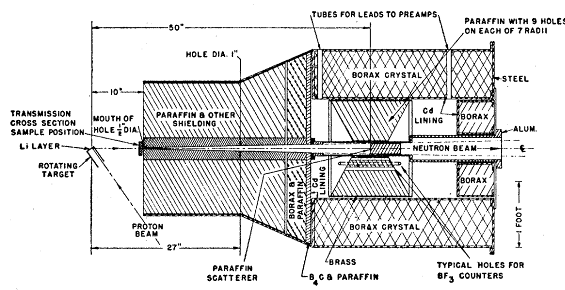


FIG. 1. Collimator and shield with neutron counter assembly inside the shield. In this work the collimator was placed at 119.6° to the proton beam direction. The solid angle subtended by the collimator at the neutron source is 0.001 steradian.

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[1] Nuclear Sci. Abst. **5**, 636 (1951) (refers to CUD-65, Sec. 1; DR-1578).
[2] W. Selove, Phys. Rev. **76**, 187 (1949).
[3] Hibdon, Muehlhause, Selove, and Woolf, Phys. Rev. **77**, 730 (1950).
[4] A. W. Merrison and E. R. Wiblin, Nature **167**, 346 (1951).
[5] Barschall, Bockelman, and Seagondollar, Phys. Rev. **73**, 659 (1948).
[6] A. Langsdorf, Jr., Phys. Rev. **80**, 132 (1950).
[7] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[8] J. M. Blair and J. R. Wallace, Phys. Rev. **79**, 28 (1950).
[9] R. F. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

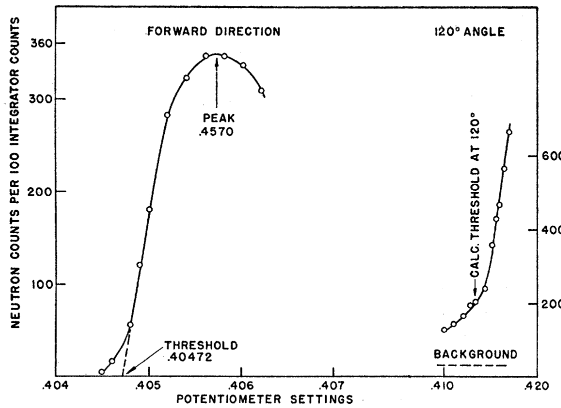


FIG. 2. At left: typical target thickness and threshold determination data. At right: neutron counting rate at 120° to proton beam using collimator-detector, in the region from just below to just above the threshold for appearance of neutrons at this angle. The point marked "threshold at 120°" is calculated from the threshold point determined by the graph at the left. The tail of the counting rate curve below threshold at 120° was higher here than it should have been because a small air blower accidentally was in the flux of neutrons at 60° to the proton beam and in the line of sight of the collimator so neutrons were back-scattered into the detector.

at 1.882-Mev and neutron energies calculated as described by Hanson *et al.*[10] Neutron counting rates near the 120° threshold are shown at the right side of Fig. 2. A typical measurement and calculation is shown in Table I.

## ENERGY RESOLUTION

The best measure of the over-all energy resolution is attained by observation of the measured widths of the sharpest observed resonances, which are about 1.5 to 2-kev full width at half-maximum. Part of the energy spread is due to the finite angular spread of neutrons accepted by the detector, namely, $\pm 1°$ from the mean angle of 119.6°. This introduces[10] a spread of about $\pm 500$ ev which is a small error compared to the over-all resolution observed.

Three remaining sources of energy spread are those which relate to the actual energy of a proton at the instant when it reacts with a Li nucleus. In the energy region of interest in this work, the spread in energy of protons at the instant of reaction is about double the spread in energy of neutrons emitted near 120°; the exact relation depends upon the energy itself.[10] The three sources of energy spread referred to are: target thickness, spread in proton energy within the ion beam, and fluctuations in this energy due to imperfect constancy of the generator voltage. Since the Li targets have a known thickness of about 2-kev stopping power, one may conclude that the latter two sources of fluctuation correspond to not over 2.5 to 3.5 kev, which is the best available measure of the true energy resolution of the proton beam in this electrostatic generator.

## SOURCES OF ERROR

In addition to the usual random statistical errors, two known sources of systematic error should be mentioned. One of these is a defect in the energy control system of this electrostatic generator, which is observable as a shift in the electrostatic analyzer voltage setting for the Li($p$,$n$) reaction threshold when the focus of the proton beam is modified. It is believed that the shift, which has a maximum observed value of about 2 kev at the Li($p$,$n$) threshold of 1.882 Mev, is a result of the design of the electrostatic analyzer. This analyzer focuses a parallel incident beam at the pick-up electrodes for the emergent beam. Hence, if the direction of the incident beam is changed, the position of the focused emergent beam is changed for constant analyzer deflection voltage. Presumably changes in beam focusing change the effective direction of the incident beam. Knowing of this effect, an effort was made to keep the focusing conditions constant during each series of measurements. It is believed that the actual errors in resonance positions observed in the data were much less than 2 kev.

The other known source of systematic error chiefly perturbs transmission measurements and hence causes errors in transmission cross sections so determined, without, however, causing a large systematic shift in the energy at which a resonance is found. This source of error was observed during some work just subsequent

TABLE I. Typical data. Neutron threshold observed at potentiometer setting 0.40420 v. Potentiometer setting for these data 0.41574 v. Lithium target thickness by rise curve, 1.4 kev. Peak neutron energy at 119.6° calculated 2 kev; mean energy 1.7 kev. Time for each 40,000 monitor counts about 320 seconds. Beam current approximately 10$\mu$a.

| Transmission sample | Detector scatterer | Monitor counts | Detector counts | Reduced[a] detector counts | Net counts, $I$ | $I_0/I$ | Atoms/cm² $\times 10^{-24}$ | $\sigma_t$ calc. barns |
|---|---|---|---|---|---|---|---|---|
| None | In | 40,003 | 2897 | 2897 | 2595($I_0$) | | | |
| | Out | 40,360 | 305 | 302 | | ... | ... | ... |
| Na | In | 39,670 | 2483 | 2504 | 2212 | 1.173 | 0.0165 | 9.5±2 |
| | Out | 39,968 | 292 | 292 | | | | |
| Mn | In | 40,984 | 1301 | 1270 | 978 | 2.65 | 0.0510 | 19±1 |
| | Out | ... | ... | 292[b] | | | | |

[a] Corrected to 40,000 monitor counts.
[b] Background assumed same as measured for Na, error in this assumption is negligible.

[10] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).

to the work reported in this article. It has been noticed that the yield of neutrons for a given amount of integrated beam current varies systematically as a function of slight shifts in the position and shape of the proton beam spot on the lithium target. Furthermore, the variation is not the same at different angles of neutron emission, relative to the proton beam direction. Hence, flux monitoring by the long counter at 0° is inaccurate, and monitoring by a beam integrator is also inaccurate. Deviations of yield at 120° might occasionally be as large as 10 percent, by extrapolation from similar data at higher proton energy. No direct information is available to evaluate this source of error properly, in the data reported here. It is clear that, in the future, such errors in this type of measurement can be minimized most surely by using a neutron flux monitor which consists of an auxiliary collimator and counter, oriented at the same angle to the proton-beam direction as the main apparatus. The reasons for this type of error are known to reside in non-uniformity in thickness of the lithium-layer and in variations in the thickness of the layers of oxide and carbon which build up upon the lithium layer during operation. It seems to be very difficult to hold errors, because of these effects, to as low as one percent, even when great care is taken to keep them minimized.

## RESULTS

### Iron

The iron sample used was "Puron" brand of specially pure iron made by Westinghouse Electric Company.

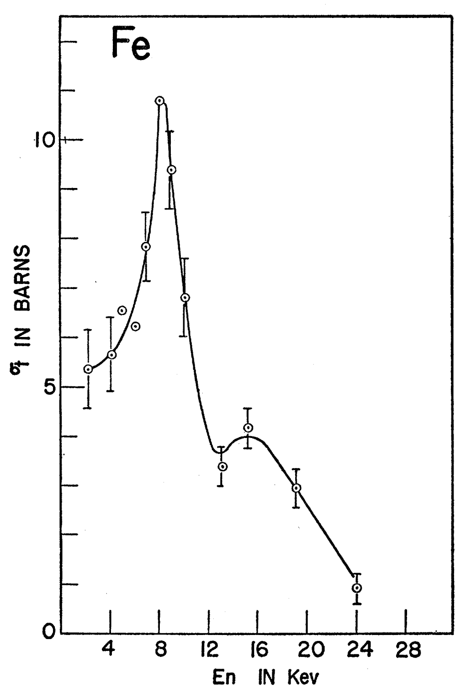


FIG. 3. Transmission cross section of iron. Thickness $0.1613\times10^{24}$ atoms/cm². Li target thickness 2.9 kev.

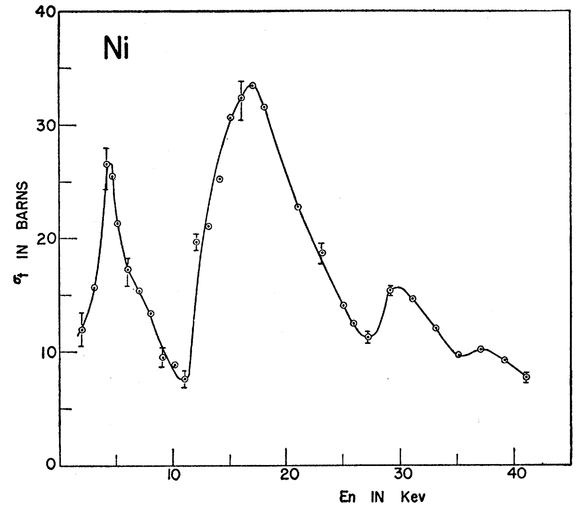


FIG. 4. Transmission cross section of nickel. Thickness 0.0698 $\times10^{24}$ atoms/cm². Li target thickness: 3.0 kev to 6 kev neutron energy; 3.5 kev, 7 to 24 kev neutron energy; 2.4 kev, 26 to 41 kev neutron energy. Probable errors of all points similar to those of nearby points for which it is shown.

Spectrographic analysis showed no impurity sufficient to interfere in these measurements. Figure 3 presents the results. The resonance observed at 8.5 kev was expected to be present, as prior unpublished resonance overlap data obtained by the annular chamber technique using a pile beam and a vanadium detector had shown overlapping resonances. The resonance overlap method has been described by Hibdon and Muehlhause.[11] The results on V presented in Fig. 6 confirm the overlap of resonances at about 8 kev. There may be a weak resonance in Fe at 16 kev but the data are insufficient to establish it. The 8.5-kev resonance is certainly in one of the iron isotopes of minor abundance.

### Nickel

The nickel sample contained somewhat under one percent cobalt impurity, and less of other known impurities. Resonance peaks are evident in the data (Fig. 4) at 4.5 and 17 kev and possibly a weaker resonance at 30 kev. The 17-kev resonance is undoubtedly the one reported by Barschall *et al.*[5] at 15 kev. The lower resonance may be the one observed in the 4-kev region by the Columbia University group.[12] At this laboratory, strong resonance overlapping has been observed between nickel and sodium and also nickel and vanadium (not published). One may conclude that the nickel 4.5-kev resonance shows some overlapping with the 2.8-kev resonance in Na and the 7-kev resonance in V.

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[11] C. T. Hibdon and C. O. Muelhause, Phys. Rev. **76**, 100 (1949); C. T. Hibdon, Phys. Rev. **79**, 747 (1950).
[12] W. W. Havens, Jr., and L. J. Rainwater, Phys. Rev. **75**, 1296 (1949).

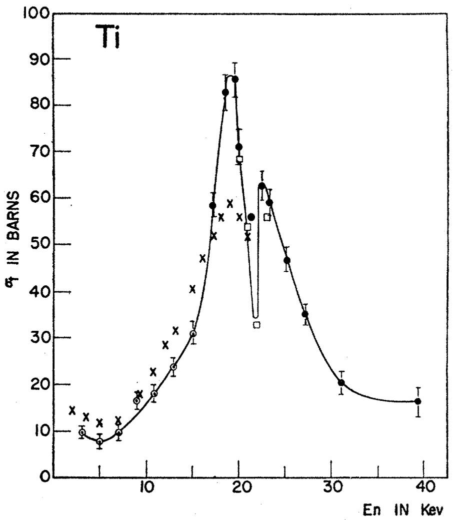


FIG. 5. Transmission cross section of titanium. Open circles: titanium thickness $0.1037\times10^{24}$ atoms/cm$^2$, lithium target 3.7 kev. Solid circles titanium thickness $0.011\times10^{24}$ atoms/cm$^2$, lithium target thickness 3.7 kev. Crosses: titanium sample $0.0343\times10^{24}$ atoms/cm$^2$, lithium target thickness 3.1 kev. Squares: titanium sample $0.011\times10^{24}$ atoms/cm$^2$, lithium thickness 3.1 kev. Probable errors of all points about the same as for those indicated.

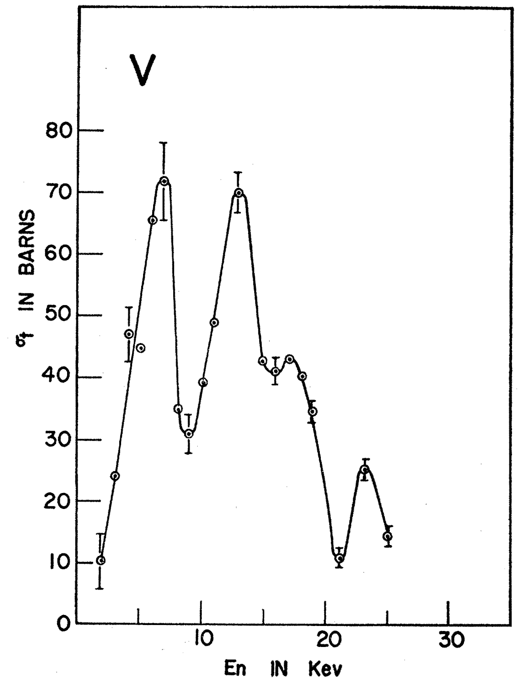


FIG. 6. Transmission cross section of vanadium. Thickness $0.0228\times10^{24}$ atoms/cm$^2$, lithium target thickness 1.6 kev to 11-kev neutron energy, 2.6 kev above.

### Titanium

Figure 5 presents the results for several separate runs on this element. Resonances are indicated at 19 and 23 kev with a narrow minimum near 22 kev which was best resolved with a thin sample. The largest known impurity in the titanium is 0.1 percent of manganese. The fall in cross section from 2 to 6 kev suggests there may be a resonance below 2 kev. Results from annular chamber measurements, using a vanadium detector, indicated resonance overlapping with titanium, which, comparing Fig. 5 and 6, may be due to overlap of the 17-kev resonance in V with the 19-kev resonance in Ti.

### Cobalt

In Fig. 7 results of three runs on cobalt are presented. Resonances are indicted at 5.5 and 29.5 kev and a poorly resolved resonance at 8 kev is probably present. Insufficient data were obtained to determine higher energy resonances which may lie in the vicinity of 53, 78, and 88 kev. The cobalt samples contained major impurities of Cr 0.5 percent, Fe 1 percent, Ni 0.5 percent. Prior unpublished resonance overlap observations with Na and V detectors are explained by the overlap of the 5.5-kev Co resonance with the 2.8-kev Na resonance (Fig. 8) and the 7-kev V resonance (Fig. 6). Data obtained with time of flight spectrometers at Columbia University[1] and Argonne National Laboratory (unpublished) had indicated a resonance in the 3 to 10 kev region which is undoubtedly the doublet observed here at 5.5 and 8 kev.

### Vanadium

The resonance overlapping of vanadium and cobalt which had been observed previously led us to measure both V and Co by this new technique. The results for V are shown in Fig. 6. Strong resonances are apparent at 7 kev and 13 kev, and a partially resolved resonance at 17 kev. There is probably a smaller resonance near 23 kev. The major impurity in the vanadium sample is 0.5 percent carbon. Data obtained with a time-of-flight spectrometer had indicated a resonance at 3300 ev[13] which has been recalculated to lie at about 6 kev. This is undoubtedly the resonance observed here at 7 kev.

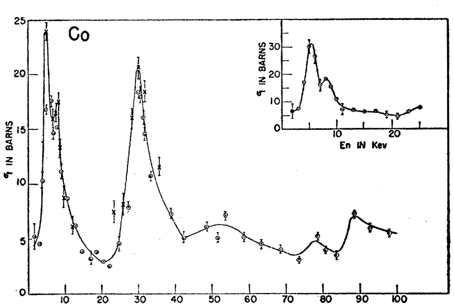


FIG. 7. Transmission cross section of cobalt. Large graph, open circles: cobalt thickness $0.0822\times10^{24}$ atoms/cm$^2$, lithium thickness 4.4 kev. Crosses: cobalt thickness $0.0419\times10^{24}$ atoms/cm$^2$; lithium thickness 1.4 kev to 17.5 kev neutron energy and 4.6 above kev. Inset graph at upper right: cobalt thickness $\sim0.02097\times10^{24}$ atoms/cm$^2$; lithium thickness 1.6 kev to 11 kev neutron energy, 2.6 kev above. Probable error of all points about the same as for nearby points for which it is shown.

[13] S. P. Harris, Phys. Rev. **83**, 235 (1951).

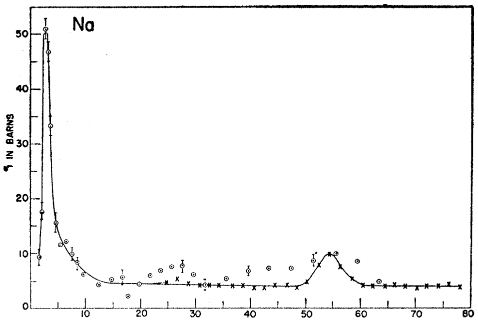


FIG. 8. Transmission cross section of sodium. Circles: sodium thickness $0.0165\times10^{24}$ atoms/cm², lithium target thickness 1.4 kev to 17.5 kev neutron energy, 4.6 kev above. Crosses: sodium thickness $0.0666\times10^{24}$ atoms/cm², lithium thickness 7.1 kev. Probable error of all circled points similar to those for which indicated, for crosses about the size of the cross.

## Sodium

The existence of a resonance in sodium was first discovered[3,11] by the unexpected resonance overlap effect found with a manganese detector using the annular scattering chamber. The fact that this overlap was related to resonances near 3 kev was determined by measurements made with a neutron time-of-flight spectrometer. The present work confirms this earlier work, and has better resolution, especially on the high energy side of the resonances. The sodium data are shown in Fig. 8. The first sodium sample used to obtain clearer results near 2.8 kev was too thin at higher energies. Better data above 25 kev were later obtained using a thicker sample. Another resonance occurs at 55 kev; it is undoubtedly the same one observed by Adair *et al.*[14] at 60 kev.

The sodium used was ordinary commercial metal sealed in a cylinder with one-mil thick steel diaphragm covers on the ends. It was not analyzed chemically.

## Manganese

The results for manganese are shown in Fig. 9. In addition to the resonance mentioned above, at 2.8 kev, others are clearly shown at 8, 23, and 38 kev. Less pronounced ones probably occur in the vicinity of 60, 67, and 78 kev.

The manganese contained about 1 percent iron; all other impurities were less than 0.01 percent by spectrographic analysis.

## CORRELATION OF THE RESULTS

Some of the data discussed above were obtained by grouped measurements on several elements in sequence while holding the energy setting of the electrostatic generator fixed. Also, several elements were measured on more than one run. Thus a check upon consistency of the data is obtained which indicates that the sources

[14] Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949).

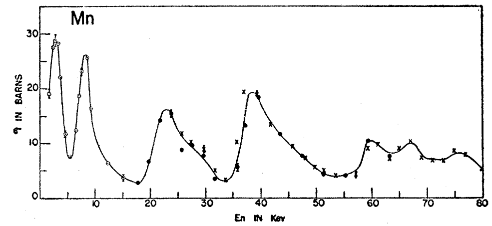


FIG. 9. Transmission cross section of manganese. Manganese thickness $0.051\times10^{24}$ atoms/cm². Open circles: lithium target thickness 1.4 kev; solid circles: lithium thickness 4.6 kev; crosses: lithium thickness 7.1 kev. Probable errors of all points about the same as for those indicated.

of systematic error previously discussed did not in fact cause errors as large as they might have. The following are the groups of data obtained simultaneously:

Group I. Na data, all points shown as circles; Mn data, all points shown as open and solid circles; Co data, all points shown as crosses.

Group II. All data on V; all Co data in inset graph at upper right of Fig. 6.

Group III. Na data, points shown as crosses; Mn data, points shown as crosses.

## DISCUSSION

The most important feature of the work reported is the presentation of a method for extending the electrostatic generator techniques downward to neutron energies of 2 kev or even lower. The new method of detecting neutrons with a highly efficient shielded detector is responsible for this extension in range. It is a fortunate feature of the technique of measurement at "back-angles" (e.g., at 120° to the proton beam direction as here employed) that the neutron energy resolution is about twice the resolution in energy of the proton beam and lithium target thickness. This circumstance leads us to believe that with the use of a new 40-inch radius electrostatic analyzer, now under construction, similar to the one at the University of Wisconsin,[15] sufficient resolution will be attained to permit measurements with about 1-kev resolution down to as low as 1-kev neutron energy before difficulties become insuperable.

It will also be possible to apply resonance self-detection and resonance overlap techniques to neutron cross section measurements with this equipment. If a scattering sample made of some element under investigation is placed inside the paraffin and counter tube assembly instead of the paraffin plug used in the measurements reported here, additional data concerning resonance widths and peak cross sections can be obtained by transmission measurements. This technique will permit determination of resonance properties with resolution better than that allowed by the actual spread of energies in the neutron beam.

It may also be pointed out that this equipment

[15] Warren, Powell, and Herb, Rev. Sci. Instr. **18**, 559 (1947).

permits measurements of transmission cross sections with relatively small samples of rare elements or separated isotopes. Since the spot source of neutrons can be held to a region about $\frac{1}{16}$-inch diameter and the angular spread of the detector is only 2°, many materials might be measured with fair accuracy in the region of a resonance with a sample (about $\frac{5}{16}$-inch diameter) weighing about one gram.

The closing of the gap in knowledge of neutron cross sections between 2 and 15 kev will now permit more accurate calculations of interesting thermal neutron properties of many elements, including such properties as the phase of scattering and the coherent and incoherent scattering amplitudes.

We wish to thank J. R. Wallace for extensive help in operating the electrostatic generator and aid in measurements and trouble-shooting during the course of the experiments.

PHYSICAL REVIEW VOLUME 85, NUMBER 4 FEBRUARY 15, 1952

# Fission Neutron Spectrum of $U^{235}$*

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(Received November 12, 1951)

The energy distribution of neutrons (prompt and delayed) arising from thermal fission of $U^{235}$ has been studied with nuclear plates. The spectrum obtained shows a maximum in the region of 0.7–0.8 Mev and an exponential slope of 3.9±0.2 Mev per decade of intensity in the energy region above 2 Mev. The data extend over the energy range from 0.4 to 7 Mev.

## I. INTRODUCTION

A NUCLEAR plate measurement of the spectrum of neutrons from the fission of $U^{235}$ was first made by Richards[1] using Ilford half-tone plates. These measurements agreed with the original ionization chamber measurements of Staub and Nicodemus[2] above an energy of 1.8 Mev but at lower energies uncertainty existed as to the shape of the spectrum curve. The ionization chamber data showed a maximum height around 1 Mev and indicated more low energy neutrons than the plate data which gave a broad maximum centering in the vicinity of 1.8 Mev. In the light of present knowledge, this discrepancy was most likely caused by the unreliability of the half-tone emulsions for tracks corresponding to energies less than 1.5 Mev. A measurement by Hill[3] using a coincidence-anticoincidence counter arrangement (the Argonne "ranger") gave an energy distribution with a maximum around 0.8 Mev and an exponential shape in the 2–7 Mev region.

The present experiment (performed in 1948–1949) was planned to furnish additional data concerning the uncertain region of the spectrum in the vicinity of the maximum as well as to contribute more information over the energy region from 0.5 to 6 Mev. The experiment was improved over Richards' preliminary work by (1) using the newer Ilford C2 plates which are reliable down to an energy of 0.5 Mev and (2) measuring more tracks so as to improve the statistics. Other contemporary experiments on the fission spectrum have provided detailed data over certain limited energy regions of the spectrum, *viz.*, Bonner's[4] cloud-chamber work covering the low energy region from 0.075 to 0.6 Mev and Watt's[5] coincidence counter arrangement emphasizing the high energy region from 3 to 16 Mev.

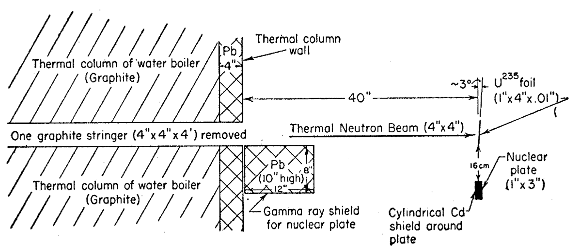


FIG. 1. Experimental arrangement.

## II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is illustrated in Fig. 1. A 10-mil thickness of $U^{235}O_3$ was coated on a $\frac{1}{32}$-inch thick aluminum strip measuring 1×4 inches. The thermal column of the Los Alamos water boiler was arranged to provide a thermal neutron beam of cross section 4×4 inches. The uranium foil was placed approximately perpendicular to this beam with the aluminum side facing the beam. Ilford type C2 nuclear plates, 100 microns thick, were placed outside of the

* This work was performed under the auspices of the AEC.
[1] H. Richards, private communications (1944–1945).
[2] H. Staub and D. Nicodemus, private communication (1944). (To be published.)
[3] D. Hill, private communication (1947).
[4] T. Bonner, private communication (1948).
[5] B. Watt, private communication (1948). Using the results of the previous two references and those of his own experiment, Watt has obtained a semi-empirical formula which fits the $U^{235}$ fission spectrum over the energy region from 0.075 to 16 Mev. (In process of publication.)