As to previous range measurements, it appears that our triton range, 60.0±0.6 mm, is in agreement with that found by Livingston and Hoffman,[10] *viz.* 59.0±0.6 mm, and also with that found by Rumbaugh, Roberts, and Hafstad,[11] *viz.*, 61 mm (which is, however, not claimed to be very accurate). The latter authors have determined the alpha-range, too, but their value, 11.8 mm, exceeds ours by more than 10 percent and leads to $Q=4.97$ Mev, which is in serious disagreement with the data given above.

In conclusion, the authors wish to express their gratitude to Professor Niels Bohr, who placed at their disposal the facilities of the institute, for his kind interest and valuable advice regarding this investigation. Our thanks are also due Mr. O. B. Nielsen, civil engineer, and Mr. S. Holm for valuable assistance during the experiments.

[10] M. S. Livingston and J. G. Hoffman, Phys. Rev. **53**, 227 (1938).

[11] L. R. Rumbaugh, R. B. Roberts, and L. H. Hafstad, Phys. Rev. **54**, 657 (1938).

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Thresholds for Fast Neutron Fission in Thorium and Uranium*

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The threshold energy for fast neutron fission of thorium and uranium has been measured by using the neutrons from thin lithium films through the $Li^7(p,n)$ reaction. Neutron energy fission thresholds were found to be 1.0±0.1 Mev for U^{238} and 1.10±0.05 Mev for Th^{232}.

INTRODUCTION

The reaction $Li^7(p,n)Be^7$ provides a convenient source of fast neutrons, the maximum energy of which is determined by the energy of the bombarding protons. These neutrons may be used to investigate the threshold of any fast neutron reaction which occurs with an observable cross section within the range of neutron energies available. Preliminary reports[1] were published for the thresholds of fast neutron fission in uranium and thorium obtained by this method. This paper gives a more complete description of these experiments, together with the results of experiments on the threshold of fast neutron fission in uranium, in which the neutrons were obtained from thin foils of lithium bombarded with protons. As a part of this problem, the yield of neutrons from thin foils of lithium was measured as a function of the energy of the bombarding protons.[2]

* This work was completed in 1941 and has been recently declassified. Even though more accurate values may have been made since then, these results are of value due to their historical importance and may serve some use until more accurate values are made available.

[1] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. **57**, 1088A (1940).

THICK TARGET EXPERIMENTS

In these experiments the uranium and thorium targets were bombarded with neutrons obtained from thick targets of lithium metal or lithium

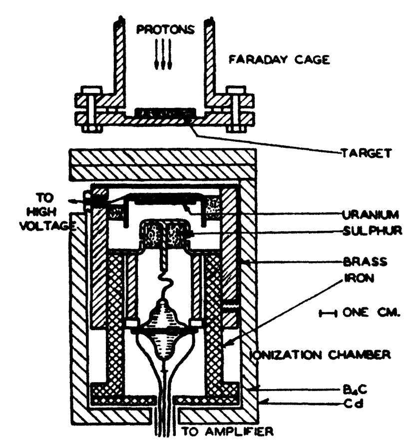

Fig. 1. Arrangement for measuring neutron fission.

[2] J. E. Hill and W. E. Shoupp, Phys. Rev. **73**, 931 (1948).

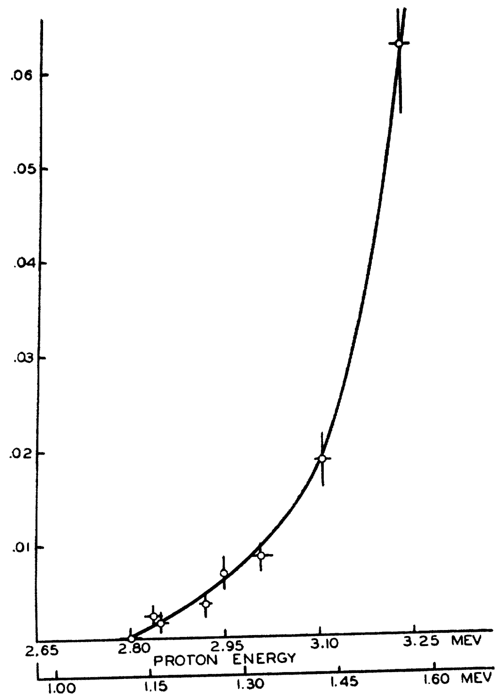

FIG. 2. Number of fissions produced in thorium per microcoulomb of protons incident on lithium as a function of the maximum energy of the neutrons.

hydride bombarded with protons, accelerated in the Westinghouse pressure electrostatic generator,[3] and analyzed magnetically. The proton current was measured by means of a current integrator and the energy of the incident protons was measured by means of a generating voltmeter. The voltmeter was calibrated before and after each run by checking the threshold for the lithium (p,n) reaction. The fission fragments were detected by means of a 1-cm deep air ionization chamber. A potential of 2000 volts was impressed on the collector plate of the chamber. The pulses produced by the fission particles were amplified by means of a linear amplifier and were either counted visually by observing the kicks on an oscilloscope screen, or—when necessary—were sent to a scale of eight circuit and a mechanical recorder. The scaling circuit was biased to respond only to fission fragments. This was easily accomplished since the fission pulses were, in general, several times the size of the pulses from natural alpha-particles. In the case of uranium fission the ion chamber was surrounded by about one cm of boron carbide and two mm of sheet cadmium, to reduce the slow neutron fission in U^{235} as much as possible. Figure 1 shows the geometrical arrangement of the apparatus as used in these experiments.

Equation (1) enables us to calculate the *maximum* energy of the neutrons, E_n, produced in the forward direction by the reaction for each value of the energy of the bombarding protons, E_p, from the relation

$$(E_n)^{\frac{1}{2}} = \tfrac{7}{8}(E_p - E_{p0})^{\frac{1}{2}} + \tfrac{1}{8}(E_n)^{\frac{1}{2}}. \qquad (1)$$

The quantity E_{p0} is the threshold proton energy which will just cause neutrons to be emitted from the lithium target and was taken as 1.85 Mev for the reaction $Li^7(p,n)Be^7$. More recent works carried out at Westinghouse Research Laboratories[4] and the University of Wisconsin,[5, 6]

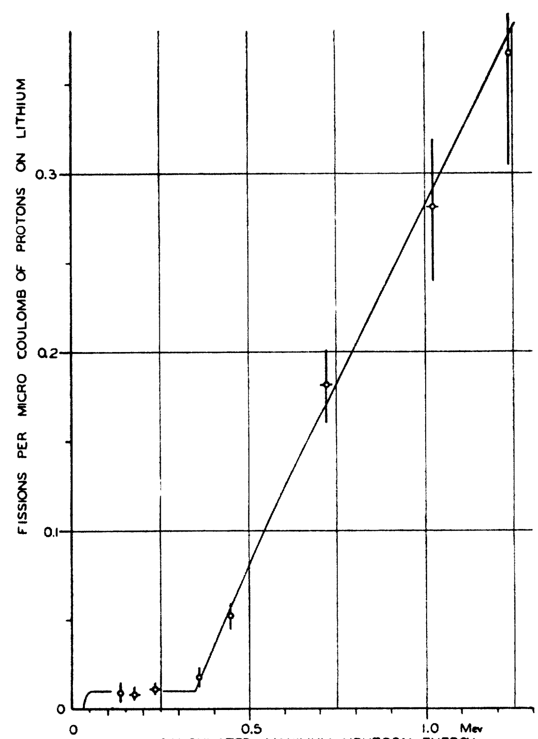

FIG. 3. Number of fissions produced in uranium per microcoulomb of protons incident on lithium as a function of the maximum energy of the neutrons.

[3] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. 58, 162 (1940).

[4] W. E. Shoupp, B. Jennings, W. Jones, and M. Garbuny, to be published.

[5] A. O. Hanson and D. L. Benedict, Phys. Rev. 65, 33 (1944).

[6] R. G. Herb, M.I.T. Conference on Electrostatic and High Energy Accelerators, June 8, 1948.

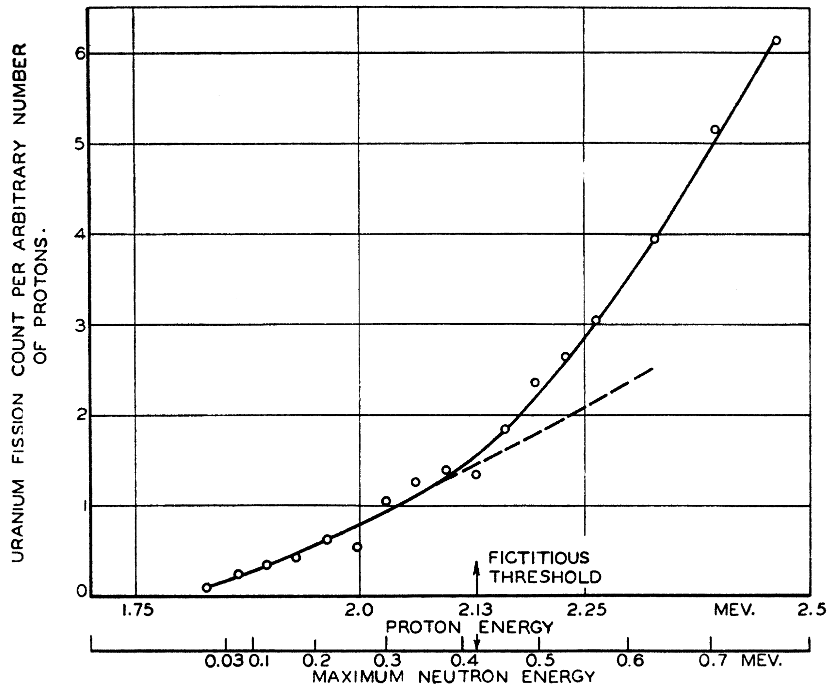

FIG. 4. Uranium fission count as a function of proton energy.

using independent methods, indicates that this threshold is in the neighborhood of 1.881 Mev.

In Fig. 2 the number of fissions produced in thorium per microcoulomb of protons incident on the lithium is plotted as a function of the maximum energy of the neutrons. This gives an upper limit for the fast neutron fission threshold for thorium of $Q_n = 1.10$ Mev± 0.05.

Figure 3 gives a similar curve for uranium. It will be noted that in this case there are always some fission pulses for all neutron energies, but that there is a sharp increase at about $Q_n = 0.35$ Mev. This break was previously interpreted as the threshold energy for the fast neutron fission in U^{238}. The fission counts obtained below this energy were observed as soon as neutrons were obtained and were attributed to slow neutron fission in U^{235}. The above data were obtained by visual observation of the pulses on an oscilloscope screen. The average counting rate for visual observation was kept less than one per second in order to avoid missing counts. Consequently, it was impractical to obtain large numbers of counts by this method. Therefore, the statistical uncertainty in the points in Figs. 2 and 3 is rather large. In the case of uranium the presence of the slow neutron fission in U^{235} makes the determination of the fast neutron fission threshold, by visual counting methods, very uncertain.

The uranium experiment was repeated using an amplifier and scale of eight biased so that only fission pulses were recorded. The resulting data thus taken are shown in Fig. 4. Again the slow neutron fission in U^{235} makes it difficult to

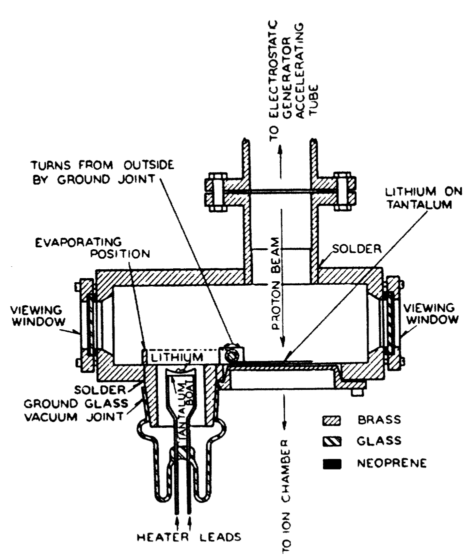

FIG. 5. Construction of lithium evaporator.

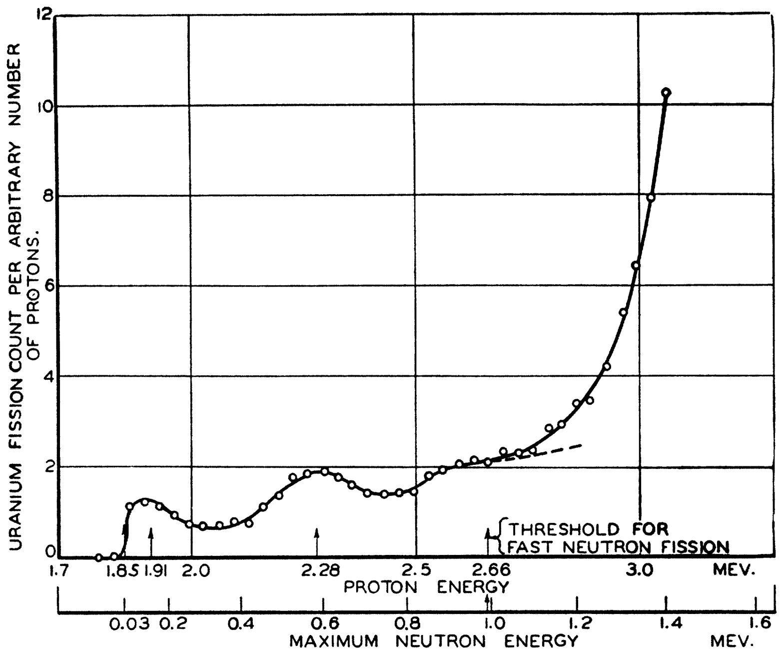

FIG. 6. Uranium fission count with neutrons from thin lithium target.

choose the threshold for fast neutron fission, but there is clearly an abrupt change of slope at $Q_n = 0.42$ Mev which is in fair agreement with the result of Fig. 3 considering the few points and poor statistics of the earlier experiment.

THIN TARGET EXPERIMENTS

Because of the uncertainty introduced into the determination of the fast neutron fission threshold for uranium by the slow neutron fission in U^{235}, it was decided to use a thin target of lithium as a neutron source. This procedure should give a much smaller yield of slow neutrons in proportion to fast neutrons for proton energies sufficiently above the threshold of the reaction $Li^7(p,n)Be^7$ and thus reduce the fission yield from U^{235}, with a corresponding improvement in the fast neutron fission threshold measurement.

The thin lithium targets were evaporated in a vacuum onto a tantalum sheet which could be turned from the evaporating position through 180° to a position under the proton beam. The construction of the evaporator is shown in Fig. 5. This design permitted easy cleaning of the tantalum sheet before evaporation of the lithium target, by bombarding the sheet with high energy protons, and also made possible an easy check to determine if any background of neutrons was being produced from lithium or other contamination in the tube, by merely turning the target out from under the beam. In no case was any neutron background observed.

With the exception of the above changes in the neutron source, the uranium experiment was repeated as outlined above. The result is shown in Fig. 6. The equivalent thickness of the lithium target was estimated in terms of kilovolts by

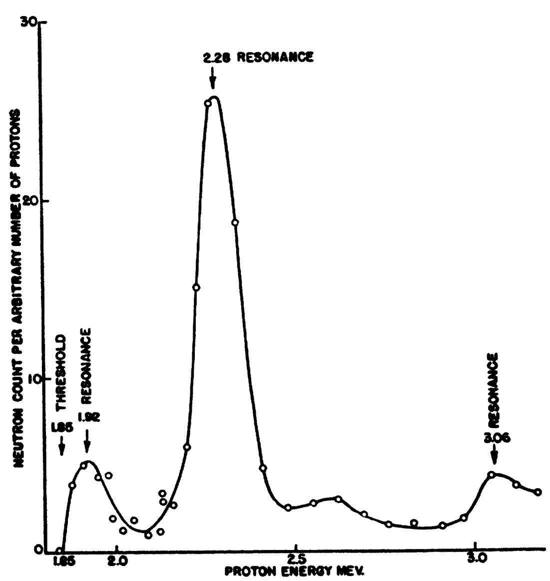

FIG. 7.

observing the half-width of the lithium gamma-ray resonance which occurs for protons of 440 kilovolts. The results of this experiment (Fig. 7) using a lithium target having an equivalent thickness of 170 kilovolts have been recently published.[2] By comparing Figs. 6 and 7, it is clear that the change of slope interpreted as the onset of fast neutron fission in the thick target experiments was in reality only the beginning of the second and the strongest neutron maximum and that the threshold for fast neutron fission is much higher. From Fig. 6, an upper limit can be set for the fast neutron fission threshold, Q_n, of about 1.0 ± 0.1 Mev. The maxima in the uranium fission yield at proton energies of 1.9 and 2.3 Mev are due to maxima in the neutron yield from the $Li^7(p,n)$ reaction.[2]

DISCUSSION

From the fast neutron fission thresholds for uranium and thorium the critical energies of fission for the nuclei U^{239} and Th^{233} may be estimated. The critical energy for fission, E_f, is the sum of the fast neutron fission threshold, Q_n, and the binding energy of the neutron, E_n. If E_n is taken equal to 5.2 Mev for U^{239} and 5.2 Mev for Th^{233}, the corresponding critical energies for fission are 6.2 Mev and 6.3 Mev. Bohr and Wheeler[7] have calculated these critical energies for fission from theoretical considerations and find the values 5.9 Mev and 6.8 Mev for U^{239} and Th^{233}, respectively. More recent and refined calculations[8] yield even higher values for these critical energies. The discrepancy, however, does not lie in the experimental determination of the thresholds, and the present results should serve as the basis for the refinement of the liquid drop theory for fission. While the experimental value of Q_n for thorium was obtained from thick target data, the value is probably very near to the true threshold since there is only one stable isotope of thorium and there is no slow neutron fission to obscure the fast neutron fission threshold as in the case of uranium. Since the experimentally determined threshold is only an upper limit to the true threshold, the fast neutron fission thresholds for thorium and possibly also U^{238} might be expected to be too high rather than too low.

[7] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).
[8] S. Frankel and N. Metropolis, Phys. Rev. **72**, 914 (1947).

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Bound Electron Creation in the Decay of Tritium

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The relative probabilities of K creation and beta-emission are calculated for both molecular and atomic tritium. This ratio is shown to be 0.0035 for the molecule and 0.0065 for the atom, assuming the maximum kinetic energy of the beta-rays to be 16.9 kev.

WHEN beta-disintegration takes place, the electron emitted usually enters one of the continuum states of the product nucleus and is called a beta-particle; we shall refer to this process as "beta-emission." There is, however, a finite probability that the emitted electron will enter one of the discrete (bound) energy levels of the product nucleus; e.g., when atomic tritium decays, the created electron may become a bound electron of He^3. This process will be called "bound electron creation." In particular, we shall speak of "K creation" when the created electron enters the K shell of the product nucleus. The general characteristics of bound electron creation have been considered by Daudel, Benoist, Jacques, Jean, and Lecoin.[1–3] It should be emphasized that the nuclear transi-

[1] R. Daudel, P. Benoist, R. Jacques, and M. Jean, Comptes Rendus Acad. Sci. (Paris) **224**, 1427 (1947).
[2] R. Daudel, M. Jean, and M. Lecoin, Comptes Rendus Acad. Sci. (Paris) **225**, 290 (1947).
[3] R. Daudel, M. Jean, and M. Lecoin, J. de phys. et rad. **8**, Series 8, 238 (1947).