Title

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Publication Date

1956-03-08

UCRL 3337

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

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BERKELEY, CALIFORNIA

UCRL-3337

UNIVERSITY OF CALIFORNIA
Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

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Printed for the U. S. Atomic Energy Commission

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ABSTRACT

The differential cross section for the production of neutrons from 190-Mev proton bombardment of uranium has been measured at 135° and 45° to the beam direction in the neutron energy interval 0.5 to 12 Mev. The neutrons were detected by the observation of proton recoils in nuclear emulsions. The internal cyclotron beam was monitored by comparing the activity of polyethylene foils placed over the target to the activity of polyethylene foils exposed to the external cyclotron beam. The differential cross section at 135° appears identical with the differential cross section at 45°. The observed spectral shape is in good agreement with evaporation theory as amended by LeCouteur. Assuming spherical symmetry in the laboratory system, we have 17.8 ± 3.6 barns as the total cross section for the production of neutrons in the energy interval 0 to 12 Mev by 190-Mev proton bombardment of uranium. It is concluded that 9.4 ± 1.9 neutrons are evaporated per inelastic collision of 190-Mev protons with uranium, and that the average excitation energy delivered to the struck nucleus is 88 ± 18 Mev.

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I. METHOD

The differential cross section for the production of neutrons in the energy interval 0.5 to 12 Mev was measured from a natural uranium target at 45° and 135° to the 190-Mev proton direction. The method of observing proton recoils in nuclear emulsions[1,2] was used to detect the emitted neutrons. The experimental arrangement, the method of monitoring the beam, and the treatment of the data have been described in a previous report.[3] The uranium target was 1.63 g/cm^2 thick in the beam direction.

II. RESULTS AND DISCUSSION

The corrected neutron spectra are presented in Fig. 1. Each spectrum contains about 800 events. The errors indicated are statistical errors only. The absolute cross section scale has a further uncertainty of about ± 20%.

The 45° and 135° data are consistent with an isotropic angular distribution. This is in agreement with previous data[3] on the yield of neutrons from 190-Mev proton bombardment of Au and Ag.

Weisskopf[4] has derived an expression for the energy spectrum of neutrons emitted from a nucleus, assuming that the process is described by the statistical model.[5] The resulting neutron energy spectrum is given by

$$\frac{d\sigma}{d\Omega dE}(E) \sim \sigma_c(E)\, E\, e^{-\frac{E}{\tau}}, \qquad (1)$$

where $\sigma_c(E)$ is the neutron capture cross section for the inverse reaction and T is the temperature of the residual nucleus. The plot of $\ln\left(\frac{d\sigma}{d\Omega dE}/E\,\sigma_c\right)$ versus E should then be a straight line with the slope $-1/T$. The average of the 135° and 45° data is plotted as a "temperature" plot in Fig. 2. For comparison, the neutron spectrum[6] resulting from slow neutron fission of U^{235} is also presented in Fig. 2. The data are in fair agreement with Eq. (1) and would lead to a temperature of about 1.3 Mev. The agreement of the observed neutron spectra resulting from 190-Mev proton bombardment with Eq. (1) becomes worse as the atomic weight of the target is reduced.[3] However, because of the distribution of excitation energies that result from 190-Mev proton bombardment[7] and because of the changes in temperature that result from the successive evaporation of particles, disagreement with the simple expression

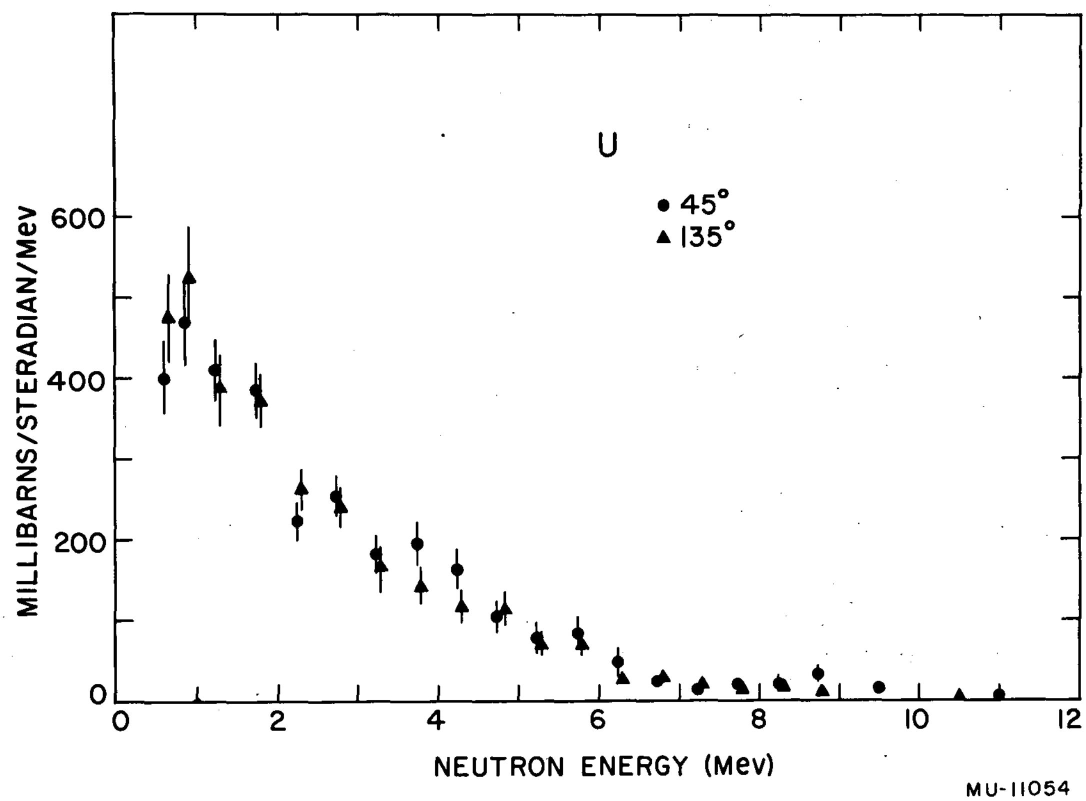

Fig. 1. Differential cross section for the production of neutrons from 190-Mev proton bombardment of uranium. The errors are statistical errors only.

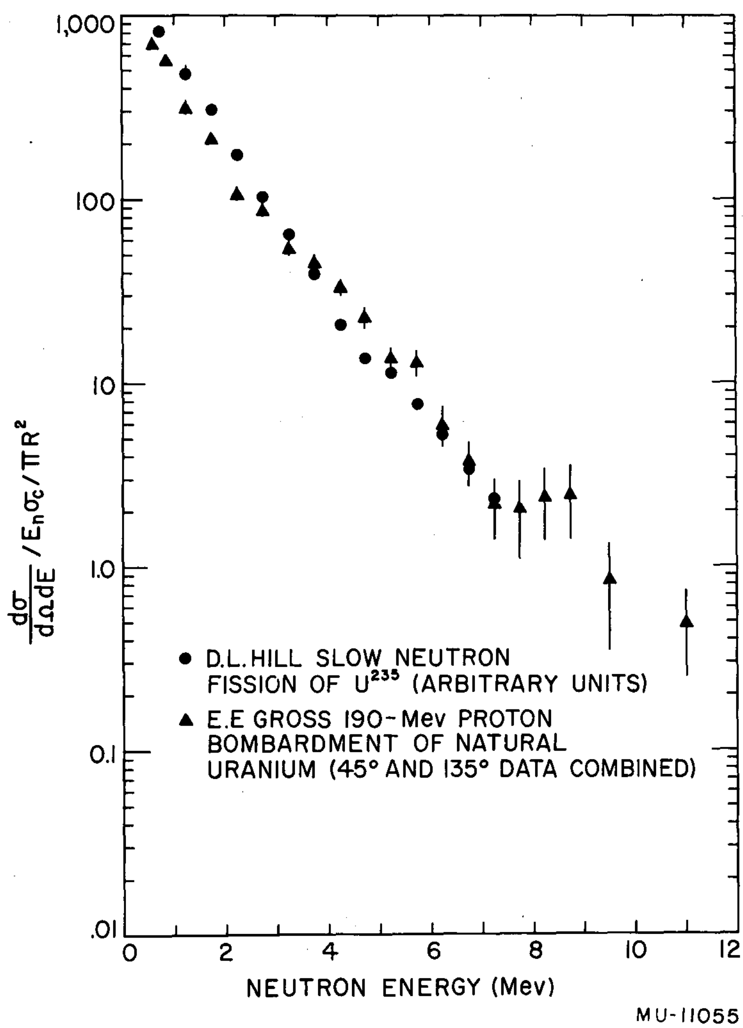

Fig. 2. A plot of $\ln \frac{d\sigma}{d\Omega dE} / \frac{\sigma_c}{\pi R^2}$ as a function of neutron energy for the neutrons resulting from 190-Mev proton bombardment of natural uranium. The quantity σ_c is the inverse neutron capture cross section and R is the radius of the target nucleus. The values of $\sigma_c / \pi R^2$ were taken from Blatt and Weisskopf.[12] The triangles represent the average of the 45° and 135° data. The circles are based on data[6] from slow neutron fission of U^{235}.

given by Eq. (1) is to be expected. LeCouteur[8] has modified Eq. (1) to take into account the effect of cooling following particle emission. Assuming the nucleus to be described by the Fermi gas model, we have the energy spectrum of evaporated neutrons, taking into account cooling, given by[2]

$$P(E)\, dE \sim E^{5/11}\, e^{-\frac{12\, E}{11\, T_0}}\, dE\,, \qquad (2)$$

where T_0 is the initial nuclear temperature. Then $\ln\left(\frac{d\sigma}{d\Omega dE}/E^{5/11}\right)$ plotted against E should result in a straight line with the slope $-(11/12)T_0$. Figure 3 presents the average of the 45° and 135° data plotted in this way. The agreement with Eq. (2) is seen to be very good. The resulting "temperature" is $T_0 = 1.9 \pm 0.1$ Mev. However, when Eq. (2) is compared with the neutron spectra observed[3] from 190-Mev proton bombardment of Au, Ag, Ni, Al, and C, the agreement becomes worse as the atomic weight of the target is reduced.

Assuming the differential cross section to be isotropic in the laboratory system, and assuming the "temperature" observed above 0.5 Mev to hold down to zero neutron energy, we find that the total cross section for the production of neutrons from 190-Mev proton bombardment of uranium in the neutron energy interval 0 to 12 Mev is then 17.8 ± 3.6 barns. Hicks and Kirschbaum[9] measured the attenuation cross section for 185-Mev protons in uranium as 1.9 barns. This results in an average of 9.4 ± 1.9 neutrons evaporated per inelastic collision of 190-Mev protons on uranium. The total cross section is plotted in Fig. 4 together with the total neutron cross sections observed[3] from 190-Mev proton bombardment of Au, Ag, Ni, Al, and C.

The yield[10] of evaporation protons and α-particles from 190-Mev proton bombardment of Au, compared with the yield of evaporation neutrons under the same bombarding conditions, indicates that practically all the excitation energy appears in the evaporation of neutrons. The method of calculating the average excitation energy from the observed yield of emitted particles has been described in the previous report.[3] Assuming all the excitation energy to appear as evaporation neutrons, we find that this method yields an average excitation energy of 88 ± 18 Mev for the 190-Mev proton bombardment of uranium. This result is plotted in Fig. 5 together with the average excitation energies obtained from 190-Mev proton bombardment of Au, Ag, Ni, Al, and C. Also presented in Fig. 5 is the theoretical average excitation energy obtained by Monte Carlo calculations.[7] The experimentally determined excitation energies are seen to be somewhat higher than the predicted values. The Monte Carlo calculations were made by using a Fermi momentum distribution for the nucleons within the nucleus. A Gaussian momentum distribution with higher momentum components than the Fermi distribution would be more in agreement with experimental results[11] and would also result in higher excitation energies.

III. ACKNOWLEDGMENTS

I am indebted to Dr. Walter H. Barkas for his continued interest and guidance throughout the course of this work. I wish to thank Mr. L. Evan Bailey for his help in making the cyclotron exposures. Mrs. Toni Woodford did most of the scanning as well as most of the computations.

This work was done under the auspices of the U. S. Atomic Energy Commission.

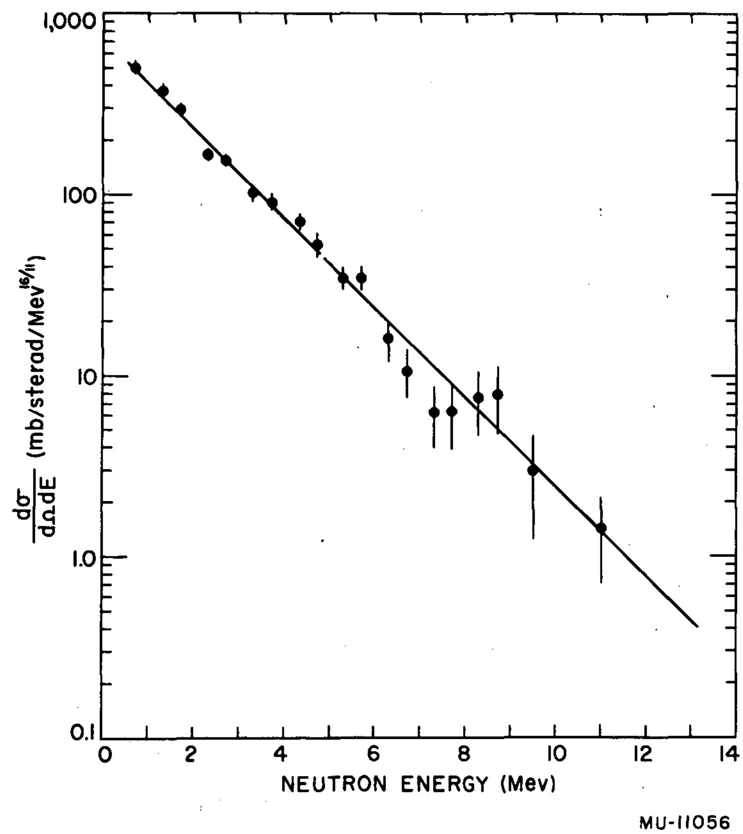

Fig. 3. A plot of $\ln \frac{d\sigma}{d\Omega dE}/E^{5/11}$ as a function of neutron energy for the neutrons resulting from 190-Mev proton bombardment of natural uranium. The points are based on the average of the 45° and 135° data. The errors indicated are statistical errors. According to LeCouteur,[8] the data should fall on a straight line with the slope $-11T_0/12$, where T_0 is the initial nuclear temperature. The straight line represents $T_0 = 1.9$ Mev.

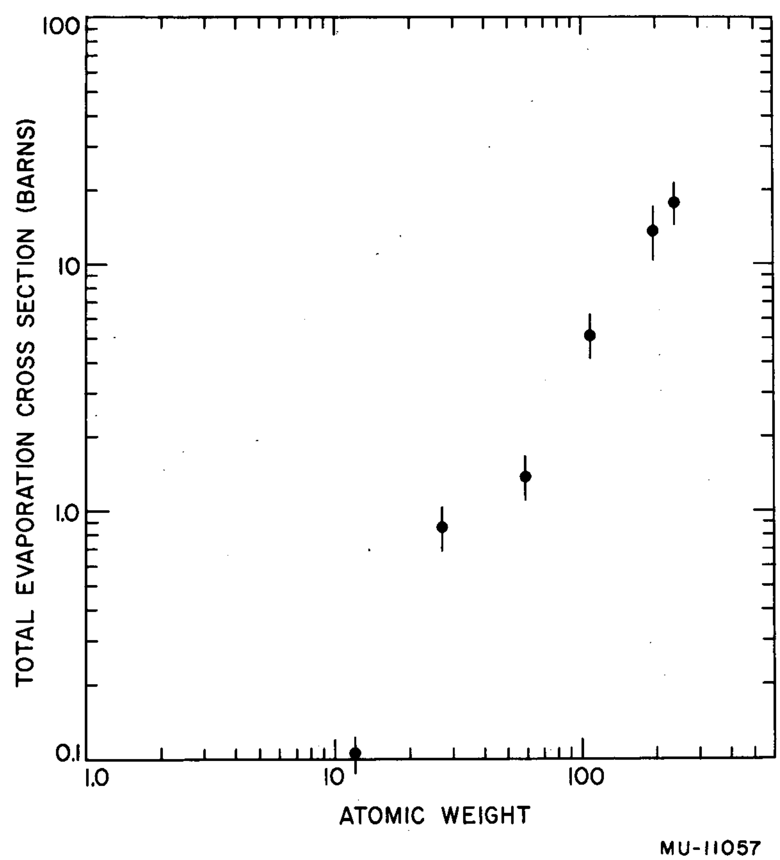

Fig. 4. Total cross section for the production of "evaporation" neutrons as a function of atomic weight of the target for 190-Mev proton bombardment.

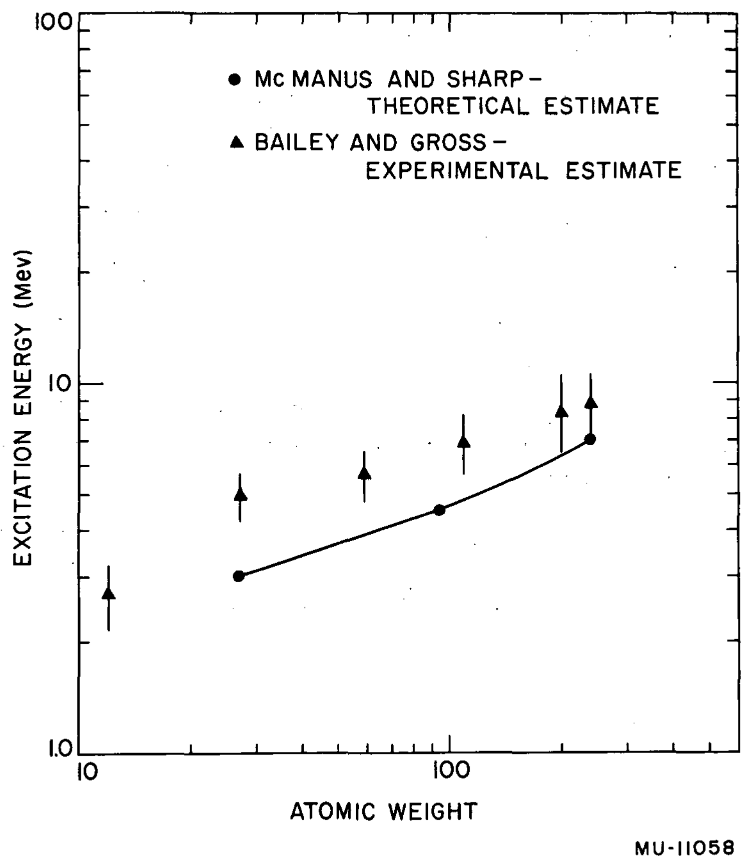

Fig. 5. The average excitation energy of the residual nucleus as a function of atomic weight of the target for 190-Mev proton bombardment.

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