Fission Neutron Spectrum of Pu^{239}†

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The energy distribution of prompt and delayed neutrons originating from thermal fission of Pu^{239} has been measured from 0.5 to 8 Mev with nuclear plates. The spectrum obtained shows a maximum intensity in the 0.6- to 0.8-Mev region and an exponential slope of 4.3±0.2 Mev per decade of intensity in the energy region above 2 Mev.

PREVIOUS measurements on the neutron spectrum from the fission of plutonium by thermal neutrons have been made by Richards[1] and by Staub and Nicodemus.[2] The cloud chamber and half-tone photoplate measurements of Richards showed a spectrum having a broad maximum between 1 and 2 Mev, while the ionization chamber data of Staub and Nicodemus indicated a maximum around 1 Mev or less. The two measurements were in agreement at energies above 2 Mev. The present spectral measurement, performed in 1949 with Ilford C2 nuclear emulsions, was intended to contribute additional information on this spectrum and was carried out mainly for providing a comparison between the unmodified fission spectrum of Pu^{239} and the degraded spectrum emerging from the Los Alamos fast reactor.

The experimental arrangement was very similar to that used in the determination of the fission neutron spectrum of U^{235}.[3] The Los Alamos Water Boiler provided a 2-in. diameter thermal neutron beam which bombarded a nickel-coated disk sample of Pu^{239} having dimensions of 0.5-in. diameter and 0.125-in. thick.[4] The C2 nuclear emulsion plates were placed at right angles to the thermal neutron beam at a distance of 20 cm from the plutonium sample. Good geometry was emphasized in the experiment and effort was directed toward eliminating factors which might modify neutron energies such as nearby scattering objects, collimating devices, etc. A 35-hr irradiation at a power of 5.5 kw gave a suitable proton recoil track density in the nuclear plates. Other details of the experimental arrangement are similar to those of reference 3.

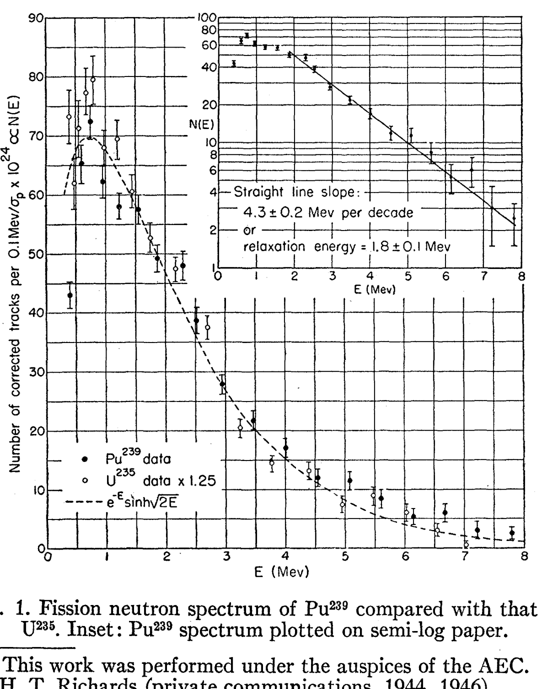

FIG. 1. Fission neutron spectrum of Pu^{239} compared with that of U^{235}. Inset: Pu^{239} spectrum plotted on semi-log paper.

The spectrum data were accumulated from a total of approximately 5500 proton recoil tracks measured by two microscopists working independently. The nuclear plate analysis has been discussed previously[3] and only the final results are presented here. The data are shown in Fig. 1 where the relative neutron intensity, $N(E)$, is given as a function of the neutron energy, E; the tracks per unit energy interval have been divided by the scattering cross section of hydrogen, σ_p, and corrected for tracks leaving the emulsion surfaces. The fission spectrum data from U^{235} and Watt's[5] empirical relation, $e^{-E}\sinh(2E)^{\frac{1}{2}}$, where E is in Mev, are given in the figure for comparison purposes. The latter two items were normalized to the Pu^{239} data at 1.5 Mev. This region of the data is considered most reliable since here the statistical errors are quite small, the tracks are of sufficient length to eliminate difficulties associated with the measurement of short tracks, and no correction is required for tracks leaving the emulsion surfaces.

The results show that the fission neutron spectra of Pu^{239} and U^{235} are identical within the statistical errors of the two experiments. Each of these spectra attains a maximum intensity in the 0.6- to 0.8-Mev region and possesses an exponential slope at energies beyond 2 Mev. The slope of the Pu^{239} spectrum data is 4.3±0.2 Mev per decade of intensity, whereas the U^{235} spectrum gave 3.9±0.2 Mev; the two values are just within the limits of experimental error. The average energy, $\bar{E}=\int N(E)EdE/\int N(E)dE$, of the spectrum is 2.0 Mev. The point for Pu^{239} at 0.4 Mev seems unusually low although it has been corrected for emulsion inefficiency at this low energy. Probably this point is not

† This work was performed under the auspices of the AEC.
[1] H. T. Richards (private communications, 1944, 1946).
[2] H. Staub and D. Nicodemus (private communication, 1944).
[3] N. Nereson, Phys. Rev. **85**, 600 (1952).
[4] A thin foil would have provided a better sample geometry but at the time was not available.
[5] B. Watt, Phys. Rev. **87**, 1037 (1952).

too reliable since it represents the lower energy limit at which nuclear emulsion data can be used. Both spectra are represented quite well by the function $e^{-E}\sinh(2E)^{\frac{1}{2}}$. However, there is a tendency for the two sets of data to show somewhat more high energy neutrons than the above empirical relation. It is difficult to know if this is a real effect on account of the small number of proton recoil tracks measured in the high energy region.

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Nuclear Photoprocesses at High Energy*

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In view of recent interest in the influence of pion production on the high energy photonucleon cross sections, an attempt is made to give a systematic discussion of the background effects, i.e., those high energy effects which are not directly concerned with either the production of pions or relativistic corrections to the nucleon motion. An appropriate definition of each high energy (irreducible) multipole moment is given. It is shown that the Siegert theorem does not apply, so even the electric dipole transition may be affected by (adiabatic) exchange currents. These and other high energy effects are found to contribute about 5 percent to the electric dipole photodisintegration cross section of the deuteron. Larger corrections are anticipated for heavier nuclei. It is shown that the corrections are calculated most readily by using the usual form of the multipole moment operators, rather than the formally correct irreducible operators.

1. INTRODUCTION

IT is generally recognized that the possibility of pion photoproduction should have a marked influence on nuclear photodisintegration cross sections at photon energies of the order of 140 Mev or larger.[1] The separation of this influence from the "ordinary" process of photodisintegration can be accomplished only if a reliable theoretical value of the cross section for the ordinary process is available. The natural procedure, and the one that has recently been followed,[2] is to use the electric dipole cross section for this purpose. The dipole moment operator is usually[3] taken to be the static moment operator $D=\sum_\alpha e_\alpha(\mathbf{u}\cdot\mathbf{r}_\alpha)$, where $\mathbf{u}$ is the direction of polarization of the photon. Justification of this procedure has been based on the Siegert theorem, which asserts that that form of the electric moment may be used as long as the dynamics of the nuclear system can be described in terms of nuclear variables alone. Thus any observed deviation from the calculated curve is interpreted as an indication of the effects that depend explicitly on the pion variables, in other words, as the influence of the "pion polarizability" of the system. In particular, this interpretation has recently been given[2] to the deviation of the observed photodisintegration cross section of the deuteron from the calculated curves of Schiff[4] and of Marshall and Guth,[5] curves which are based on the deuteron electric moment, $\frac{1}{2}e(\mathbf{u}\cdot\mathbf{r})$.

Our purpose is to point out that the Siegert theorem is *not* valid at high energy; in fact, for the deuteron it breaks down at energies in the neighborhood of 50 Mev. Therefore, the above interpretation of the data could in principle be erroneous, but we shall see below that the errors are quite small.

2. REDUCIBLE MULTIPOLE MOMENTS

To understand the failure of the Siegert theorem, it is necessary to reconsider the problem of defining the multipole moments of a system. The most elementary definition involves an expansion of its interaction with the electromagnetic field in powers of kr, where k is the propagation vector of the radiation and r is a distance of the order of the linear dimensions of the radiating nucleus. At low energies, this expansion converges rapidly, so only the lowest of the terms which contribute to a given transition need be considered. That term is fixed by the specification of the angular momentum and parity change associated with the transition. Thus the lowest term contributing to a transition $\Delta j=l$ with parity change equal to $(-1)^l$ is defined as the electric 2^l pole moment, and that contributing with the opposite change of parity is the magnetic 2^l pole moment. These are the definitions for which the proof of the Siegert theorem has been given.[6]

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