Low-Lying Levels in U^{238} Excited by Inelastic Neutron Scattering*

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Analysis of neutrons inelastically scattered by U^{238} indicates that the first two excited states in U^{238} are at 50 ± 20 kev and 140 ± 25 kev. The inelastic collision cross sections, the total inelastic scattering cross sections, and the partial inelastic scattering cross sections for the excitation of these levels are presented for neutron energies of 150, 250, and 500 kev.

IN an even-even nucleus the rotational energy level spectrum is given by[1]

$$E_{\mathrm{rot}}=\frac{\hbar^2}{2\mathcal{I}}I(I+1),\quad I=0,\,2,\,4,\text{ even parity},$$

where $\mathcal{I}$ is the effective moment of inertia of the deformed nucleus and I is the spin. For heavy nuclei with many particles outside closed shells, these predictions are well verified.[1,2]

The first excited state of U^{238} has been observed as a 2+ state at 45 kev by Coulomb excitation.[3] The second excited state is predicted to be a 4+ state with an energy of about 150 kev. Because of the large spin change, this level has not been observed by Coulomb excitation. Batchelor[4] observed considerable inelastic scattering to low-lying levels in U^{238} but was unable to resolve the levels. This experiment was undertaken to look for these levels by observing inelastically scattered neutrons and to measure the inelastic collision cross sections and the inelastic scattering cross sections for the excitation of these levels at neutron energies of 150, 250, and 500 kev.

A hydrogen recoil proportional counter[5] was placed 60 cm from a 10-kev thick $Li^7(p,n)Be^7$ neutron source. The pulse-height distributions from the counter were recorded on an 18-channel analyzer. With a heavy metal sphere around the counter, the pusle-height distribution is essentially the same as that of the bare counter provided only elastic scattering occurs in the metal, since the amounts of in and out scattering tend to balance and there is very little energy loss in elastic scattering. However, inelastic processes in the sphere either remove the neutron or lower its energy. The pulse-height distribution in this case consists of fewer pulses due to full-energy neutrons and pulses due to lower-energy neutrons. The total inelastic collision cross section can be computed from the transmission of the primary neutrons,[6] and the level structure of the target nucleus and the inelastic scattering cross sections for the excitation of these levels can sometimes be determined from the pulses due to lower-energy neutrons.

Consider the 150-kev data shown in Fig. 1. The response with the sphere off was produced by the 150-kev primary neutrons only. The sphere-on distribution (the U^{238} sphere had an outer diameter of 10 cm and a thickness of 2 cm) was due to primary neutrons (some of which had been elastically scattered) and to inelastically scattered neutrons. A small correction has been applied to this distribution to account for the nonuniformity of the counter response as a function of the direction of the incident neutrons. The magnitude of this correction was determined experimentally by measuring the distortions introduced when spheres of Pb and Bi with no inelastic scattering were used. This

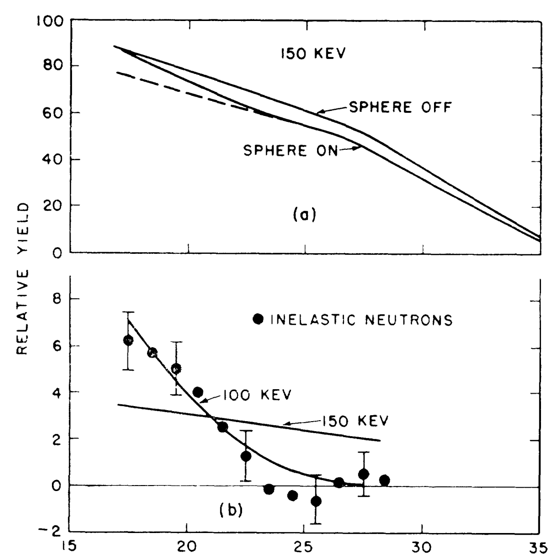

FIG. 1. Proton recoil pulse-height distributions obtained with 150-kev incident neutrons with and without a U^{238} shell around the detector.

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[1] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953); Phys. Rev. **90**, 717 (1953).

[2] G. Scharff-Goldhaber, Phys. Rev. **103**, 837 (1956); F. Asaro and I. Perlman, Phys. Rev. **91**, 763 (1953).

[3] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **93**, 906 (1954); Divatia, Davis, Moffat, and Lind, Phys. Rev. **100**, 1266 (1955); R. B. Day (private communication).

[4] R. Batchelor, Proc. Phys. Soc. (London) **A69**, 214 (1956).

[5] A description of this counter is given by R. F. Taschek, *Proceedings of the International Conference on Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, Paper 573, p. 64.

[6] Beyster, Henkel, Nobles, and Kister, Phys. Rev. **98**, 1216 (1955); Bethe, Beyster, and Carter, Los Alamos Report LA-1429 (unpublished).

adjustment also corrected for the slight effect caused by the loss of energy of elastically scattered neutrons. Since the first level in U^{238} is at 45 kev, the higher voltage part of the sphere-on response contained pulses due to the primary neutrons only, and from this pulse-height region the sphere transmission was determined.

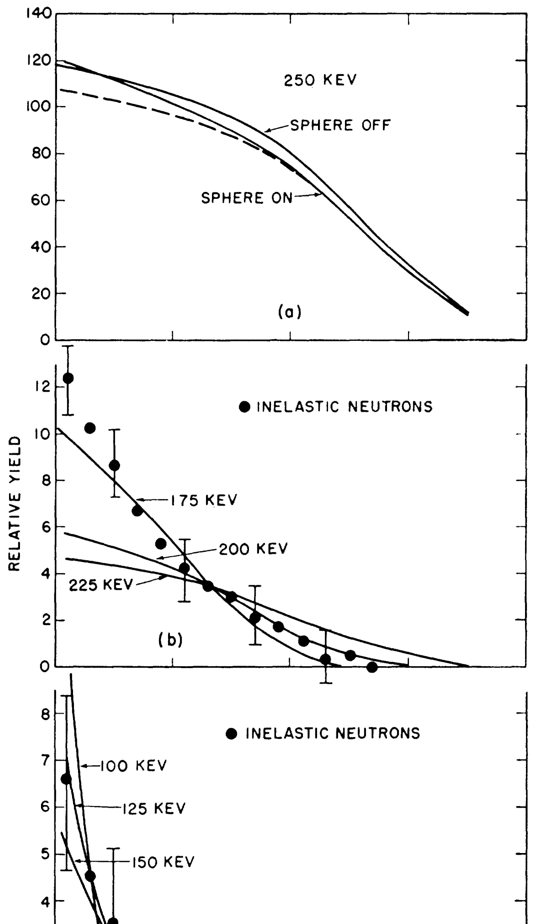

FIG. 2. Proton recoil pulse-height distributions obtained with 250-kev incident neutrons with and without a U^{238} shell around the detector.

Next, multiplying this transmission by the sphere-off distribution, the part of the sphere-on distribution resulting from primary neutrons was computed. This extension to the lower-pulse-height region is shown by the dotted line in Fig. 1(a). The difference between the observed sphere-on response and that part of the sphere-on response resulting from primary neutrons

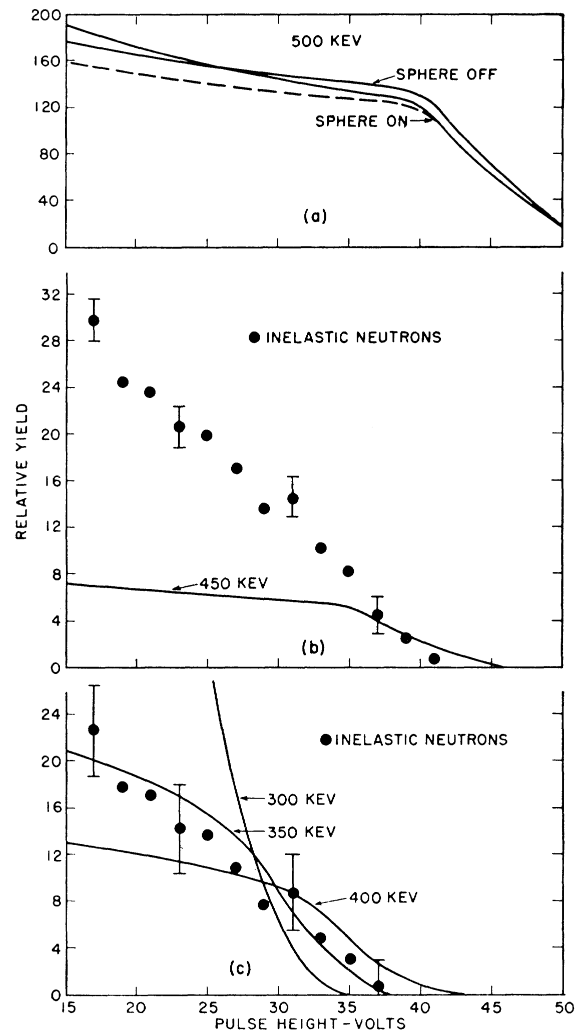

FIG. 3. Proton recoil pulse-height distributions obtained with 500-kev incident neutrons with and without a U^{238} shell around the detector.

only represented the contribution from inelastically scattered neutrons. In Fig. 1(b), the data points are a plot of this difference. Only relative errors are shown; these arise mostly from statistical fluctuations. The solid lines in Fig. 1(b) represent the pulse-height distributions observed with monoenergetic 100- and 150-kev neutrons. Since the inelastic distribution agrees with the 100-kev response, the inelastically scattered neutrons form a monoenergetic group which has lost 50-kev energy in the scattering process. This corresponds to a first level in U^{238} at 50 kev.

The 250- and 500-kev data shown in Figs. 2 and 3, respectively, were analyzed in the same manner as the 150-kev data. The transmissions were determined from the higher-voltage region of the pulse-height distributions. The products of the sphere-off distributions and the transmissions gave the primary components of the sphere-on distributions; the extensions of these to the

TABLE I. Experimental values of U^{238} inelastic cross sections (barns).

E_n (kev)	$\sigma_{\text{in coll}}$	$\sigma_{n,\gamma}$	Total	$\sigma_{\text{in scat}}$ 50 kev	140 kev
150	0.63 ± 0.2	0.19	0.44 ± 0.2	0.44 ± 0.2	...
250	0.63 ± 0.15	0.15	0.48 ± 0.15	0.19 ± 0.1	0.29 ± 0.15
500	0.80 ± 0.15	0.13	0.67 ± 0.15	0.18 ± 0.1	0.49 ± 0.25

lower-voltage regions are shown by the dotted lines in Figs. 2(a) and 3(a).

For the 250-kev data, Fig. 2(b) gives the distribution due to inelastically scattered neutrons. The higher-voltage part can be explained by a group of neutrons having an energy 50 kev less than the primary energy. In addition to these neutrons, there were other lower-energy neutrons. The response due to these neutrons is given by the difference between the data points and the 200-kev response in Fig. 2(b) and is shown in Fig. 2(c). This distribution is explained by a group of neutrons of about 125-kev energy, corresponding to a level in U^{238} at about 125 kev. Thus, the 250-kev data are consistent with a 50-kev level in U^{238} as the first excited state, and, in addition, indicate the presence of a second level at about 125 kev.

For the 500-kev data, Fig. 3(b) shows the distribution due to the inelastically scattered neutrons. The 450-kev response was put in arbitrarily but it shows that the inelastic scattering cannot be explained by a single level in U^{238} at 50 kev. The difference between the data points and the 450-kev distribution in Fig. 3(b) is plotted in Fig. 3(c). Although the magnitude of the 450-kev distribution is arbitrary, its effect on the shape of the second difference is small since the 450-kev response is quite flat. This second difference can be explained by a single group of neutrons having an energy of about 350 kev, corresponding to inelastic scattering with U^{238} being left in an excited state of about 150-kev energy. Because of the large errors introduced by repeated subtractions, no effort was made to look for higher excited states.

The data at these three energies indicate that the first two excited states of U^{238} are at 50 ± 20 kev and 140 ± 25 kev. This agrees with the known first level at 45 kev and the expected second rotational level at 150 kev.

The inelastic collision, the total inelastic scattering and the partial inelastic scattering cross sections for the excitation of the levels are given in Table I. The inelastic collision cross sections were computed from the sphere transmissions using the multiple scattering corrections developed by Bethe, Beyster, and Carter.[6] The inelastic scattering cross sections were computed from

$$\sigma_{\text{in scat}}=\sigma_{\text{in coll}}-\sigma_{n,\gamma},$$

since other processes such as (n,p) have vanishingly small cross sections at these energies. The values of $\sigma_{n,\gamma}$ listed in Table I were obtained from Rose.[7] The errors in the inelastic collision and total scattering cross sections are mostly due to errors introduced by the distortion in the counter response as a function of the direction of the incoming neutrons.

For the 250- and 500-kev data, the fraction of the total inelastic collision cross section which is the inelastic scattering cross section for the excitation of each level was computed from the number of counts due to each inelastically scattered neutron group and from the relative detection efficiency for each group. At 500 kev, the sum of the scattering cross sections involving the first two excited states equals the total inelastic scattering cross section, indicating that there is very little inelastic scattering in which the U^{238} nucleus is left in an excited state greater than 140 kev in energy. The errors in the level cross sections arise from errors in the collision cross sections and detection efficiencies and from the uncertainties in fitting the inelastic distributions.

[7] B. Rose, Atomic Energy Research Establishment, Harwell Report AERE NP/R 1743 (unpublished). These values were estimated from Dr. Rose's summary of presently available data. The author is grateful to Dr. Rose for the use of his data prior to publication.