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Inelastic Neutron Scattering by U^{238}†

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Monoenergetic neutrons in the range 0.5 to 2 Mev have been scattered from U^{238} and the spectra of scattered neutrons have been investigated by a time-of-flight method. Levels have been located at 0.044 ± 0.004, 0.146 ± 0.006, 0.30 ± 0.03, 0.73 ± 0.02, 0.98 ± 0.02, 1.06 ± 0.03, and 1.26 ± 0.04 Mev. The cross sections for excitation of these levels have been obtained corresponding to inelastic neutron scattering at 90°. An angular distribution has been obtained for the inelastically scattered neutrons corresponding to excitation of the 44-kev level by incident neutrons of 550-kev energy. This distribution is of the form $A(1-B\cos^2\theta)$ where A is 0.135 ± 0.02 barn per steradian and B is 0.45 ± 0.1. The cross section is in good agreement with calculations by Chase and Wilets which indicate compound nucleus formation is the dominant mechanism in inelastic neutron scattering by U^{238} at 550 kev, although the anisotropy is larger than that predicted.

INTRODUCTION

THE purpose of the work described here is to study the excitation of low-lying levels in U^{238} by inelastic neutron scattering. The energy spectrum of inelastically scattered neutrons yields directly the locations of levels in the target nucleus. The yields and angular distributions of inelastically scattered neutrons are pertinent to the interpretation of the mechanism of inelastic neutron scattering. Given a proper theory, the yields and angular distributions may lead to spin and parity assignments for the levels. Data on inelastic neutron scattering by U^{238} are also of considerable interest for reactor design.

The following is known about the nuclear level structure of U^{238}. From information based on the radioactive decay of Pu^{242} to U^{238} a level at about 50 kev is known.[1] From Coulomb excitation work[2] this level, the $I=2$ level of the ground-state rotational band, is known to be 44 ± 2 kev. Inelastic neutron scattering data have given indications of levels at 50 ± 20 kev and 140 ± 25 kev,[3] of another at about 700 kev[4] and of a group of levels centered at 1.18 Mev.[5] On the basis of a value of 44 kev for the $I=2$ level, the $I=4$ level is expected to be at 147 kev, so that the existence of a low-lying rotational band similar to those observed in neighboring even-even nuclei[2] has been confirmed.

From the point of view of a model for neutron-induced reactions the rotational levels of nuclei are of particular interest. The excitation of these levels in heavy nuclei by inelastic neutron scattering provides a means of studying the relative roles of a direct interaction model and the compound nucleus model. Calculations on the direct model for excitation of collective motion of a spheroidal surface have been carried out by Brink,[6] Yoshida,[7] and by Chase and Wilets.[8] The formulation of the theory for the compound nucleus process has been given by Wolfenstein[9] and by Hauser and Feshbach.[10] In previous work[5] on nuclides in the neighborhood of iron at 2.45-Mev neutron energy the compound nucleus model was strongly favored, but discrepancies from the detailed predictions of the Hauser-Feshbach theory were observed which were attributed to failure to satisfy the "statistical" assumption of the theory. The nucleus U^{239}, however, has a level spacing at neutron binding energy excitation in the neighborhood of only 15 ev,[11] so that the level spacing in the compound nucleus is very small compared to the separation of the ground and first rotational states in U^{238}. One can therefore use a band of primary neutron energies broad enough to excite sufficiently many levels in the compound nucleus (of the order of one thousand) to satisfy the statistical assumption of the Hauser-Feshbach theory while resolving the neutron groups corresponding to the levels of the ground state rotational system. Thus, nuclei like U^{238} are strategic choices from the point of view of both reaction processes.

The range of primary neutron energy used in this work, 0.5 to 2 Mev, is the range within which it is possible with our present technical capability to resolve neutrons corresponding to the excitation of some of the individual levels in U^{238}. In all cases cross sections were obtained corresponding to the neutron yield at 90°. The only case in which a detailed angular distribution could be measured with significant accuracy, however, was the case of the 44-kev level at 550-kev incident neutron energy.

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[2] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. **28**, 432 (1956).

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[7] S. Yoshida, Proc. Phys. Soc. (London) **A69**, 668 (1956).

[8] D. M. Chase and L. Wilets, Bull. Am. Phys. Soc. Ser. II, **2**, 72 (1957); also Chase, Wilets, and Edmonds, Phys. Rev. (to be published).

[9] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).

[10] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[11] *Neutron Cross Sections*, compiled by D. H. Hughes and J. A. Harvey, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).

METHOD

The method for measuring inelastically scattered neutrons from U^{238} utilized the Van de Graaff pulsed-beam time-of-flight technique described previously.[5] To resolve neutron groups corresponding to excitation of the low-lying levels in U^{238} it was necessary, however, to use lower primary neutron energy than had been used before, that is, energies in the range 0.5 to 2 Mev. This, in turn, necessitated adapting the technique and apparatus to measuring lower neutron energies than had been observed previously.

To improve the efficiency and signal-to-background ratio for the detection of neutrons of energy less than 500 kev a detector was developed which utilizes coincident observation of the light produced in a plastic scintillator, together with upper- and lower-bound discriminators on the coincident photomultipliers. These features, together with refrigeration of the photomultipliers to ice-water temperature, make it possible to detect neutrons down to an energy of 200 kev with an efficiency of about 40% with a background of only 2 counts per second due to noise, cosmic rays, etc. A description of this detector has been given in connection with its use for the measurement of total neutron cross sections.[12]

In the course of the measurements of low-energy neutron groups it was observed that the lower the neutron energy the more the centroid of a neutron line shifts to lower energy. The effect becomes noticeable below about 1.5-Mev energy and amounts to about 9 mμsec at 300 kev under typical conditions. This effect may be accounted for by a combination of factors, the most important of which appear to be the increased role of variation in geometrical flight path at lower neutron energy, and tardiness of discriminator response for smaller pulses. The effect is not eliminated by basing calculations on an extrapolated "fastest time of arrival" or other characteristic feature of the line structure. To infer the values of energy levels with greatest accuracy by the method of measuring inelastically scattered neutrons by time-of-flight the most practical expedient seems to be to make a comparison with a known level of very nearly equal energy. Thus, for the lowest lying level in U^{238}, the one at 44 kev, the elastic line itself is a suitable comparison line. For the next level at 147 kev the level in Ta^{181} at 136 kev proved suitable.

Cross sections have been obtained, as previously, from a knowledge of the relative sensitivity of the detector[13] as a function of energy and a normalization to the n-p cross section by observing the scattering from hydrogen in a polythene sample. The size of the polythene sample was adjusted at each primary energy to give a transmission of about 80%. Where multiple scattering corrections were expected to be important, Monte Carlo calculations have been made to determine the corrections.

To resolve adequately the 44-kev level in U^{238} from elastically scattered neutrons, it proved necessary to use a target thickness of only 20 kev and a flight path of 2.5 meters. The most suitable source of primary neutrons, considering the limitation on energy spread and the flux requirement, proved to be the reaction $Li^7(p,n)Be^7$, which has a resonance at 2.3-Mev proton energy yielding neutrons of 550-kev energy with a

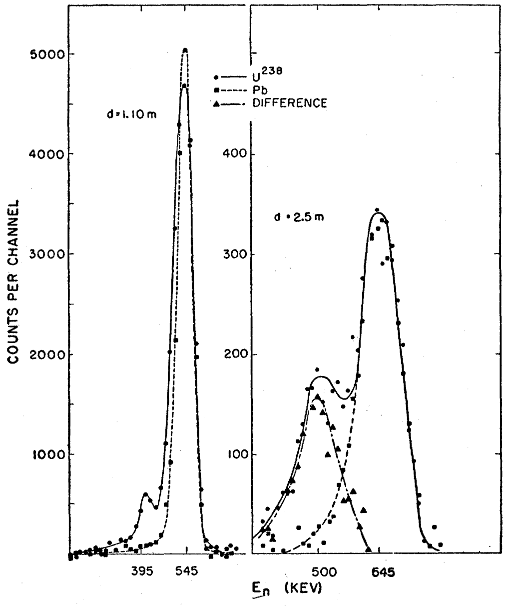

FIG. 1. Time spectra for a primary neutron energy of 550 kev at each of two flight paths. The solid curve is for a U^{238} scatterer, the dashed curve is for Pb normalized to the uranium elastic peak, and the dot-dash curve is the difference between U^{238} and Pb. The scattering angle was 90°.

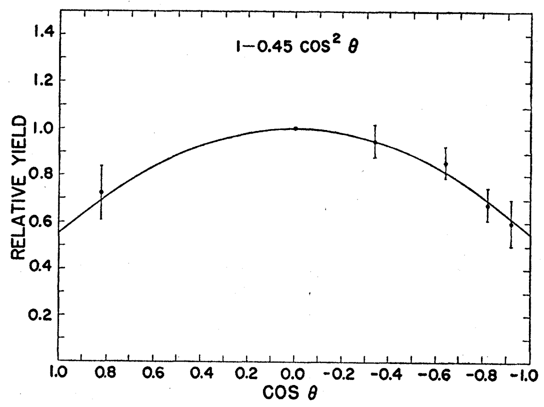

FIG. 2. Relative angular distribution of neutrons corresponding to excitation of the 44-kev level for 550-kev neutrons incident on U^{238}. The value 1.0 on the vertical scale corresponds to 0.135 barn/steradian.

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[12] Cranberg, Beauchamp, and Levin, Rev. Sci. Instr. 28, 89 (1957).

[13] The authors are indebted to W. D. Allen and A. T. G. Ferguson of Atomic Energy Research Establishment, Harwell, for furnishing the data on the low-energy portion of the zero-degree $Li^7(p,n)Be^7$ and $T(p,n)He^3$ excitation functions on which our relative detector calibrations are based.

TABLE I. Cross sections (barns per steradian) for inelastic neutron scattering from U^{238} at 90°.

Spin	$I=2$	$I=4$	$I=6$					
$-Q$ (kev) E_n (kev)	44±4	146±6	300±30	730±20	980±20	1060±30	1260±40	1400−1750
550±10[a]	0.135±0.02	0.023±0.005	<0.01					
1000±24	0.07 ±0.02	0.05 ±0.015	0.007±0.004	0.041±0.006				
1500±36				0.022±0.002	0.037±0.004	0.037±0.004		
1890±30				0.007±0.003	0.041±0.004	0.035±0.004	0.008±0.004	
2000±40					← — —	0.10 ±0.01	— — →	0.087±0.008

[a] Plus and minus values indicate spread in incident neutron energy.

cross section of about 120 mb/steradian in the forward direction. The T(p,n)He^3 reaction was the neutron source used at higher energies. At lower energies it also proved to be important to adjust the geometry of the scatterer in relation to source and detector so as to minimize the time spread of the scattered neutrons due to geometrical variations in flight path. Thus, disk scatterers proved to be significantly superior to the cylindrical scatters used previously.[5] Final inelastic data were taken with disks 1 in. in diameter $\frac{1}{4}$ in. thick oriented with their faces at 45° to the direction of the incident neutron beam. Two one-hundred-channel analyzers, each covering half the time range, were useful for furnishing the fullest details of the observed spectra.

RESULTS

Illustrative time spectra are shown in Fig. 1 for the scattering of 550-kev primary neutrons at 90° for each of two flight paths "d," using a U^{238} disk scatterer. These spectra represent the difference between "scatterer-in" and "scatterer-out" runs. To resolve the neutrons corresponding to excitation of the 44-kev level from the elastically scattered neutrons the true elastic line shape was obtained by use of a lead scatterer whose geometry was identical to that of the uranium sample. Figure 1 shows such a line shape normalized to the high-energy side of the uranium line. On the shorter flight path only an indication of the 44-kev level is obtained, but the $I=4$ level at about 150 kev is seen clearly. On the longer flight path the 44-kev level is resolved quantitatively by subtracting the normalized curve for lead from the uranium curve. The cross section for excitation of the 44-kev level amounts to about 40% of the elastic yield for uranium at 90°.

The 44-kev level excited by 550-kev neutrons proved to offer the most favorable situation for detailed investigation that was encountered in the course of this study, and an angular distribution was obtained for the inelastically scattered neutrons corresponding to excitation of this level. The results for the relative angular distribution are given in Fig. 2. The curve drawn represents $1-0.45\cos^2\theta$. In Fig. 2 the error in the 90° point is absorbed in the errors assigned to the data at other angles. Cross-section data are summarized in Table I. On the assumption that the angular distribution is of the form $A(1-B\cos^2\theta)$ the results are adequately described by the values $A=0.135\pm0.02$ barn per steradian and $B=0.45\pm0.1$.

The errors assigned the data points at each angle in Fig. 2 are 50% greater than the standard deviation due to the statistical uncertainty alone. This 50% increase represents an attempt to estimate the contribution to the error arising from slight shifts which take place in the time spectra from run to run and affect the accuracy of the elastic subtraction. These shifts are of electronic origin and are the main source of error other than the statistical one so far as relative values at various angles are concerned. The cross section value was obtained by comparison with the scattering from a rod of polythene, and it is corrected for errors arising from geometrical and multiple scattering effects. Multiply scattered neutrons, as calculated by the Monte Carlo method, were isotropic and accounted for 26% of the inelastically scattered neutrons. Correction for these decreased the 157°/90° ratio from an observed value of 0.73 to 0.60. The angular resolution of the measurements was ±10° and the angular accuracy was ±2°.

Figure 3 illustrates the comparison between Ta^{181} and U^{238} under the conditions which are most favorable for determining the energy of the $I=4$ level by comparison with the 136-kev level[2] in tantalum. The dashed portion of the curve for uranium represents an extrapolation of the data corresponding to the ground-state and $I=2$ neutron groups. The energy and cross-section data for the $I=4$ level are given in Table I. The anisotropy of the neutrons corresponding to excitation of this level, as measured by the 145°/90° ratio of yields, was 1.0±0.2. At 550 kev no level was detectable at the expected position for $I=6$ corresponding to $Q=-309$ kev.

Time spectra illustrating the results for 1.00-Mev neutron energy are given in Fig. 4. Because of neutron flux limitations it was not worthwhile to try to resolve the 44-kev level. From the time spectrum for the long flight path, however, it is apparent that the 44-kev level is still strongly excited, with a cross section in the neighborhood of 1 barn. Excitation of the $I=4$ level is now appreciably stronger than at 550 kev, and a just-detectable peak is apparent in the neighborhood in which the level at $I=6$ is expected. The short flight-path result brings in a level at 730 kev which is clearly

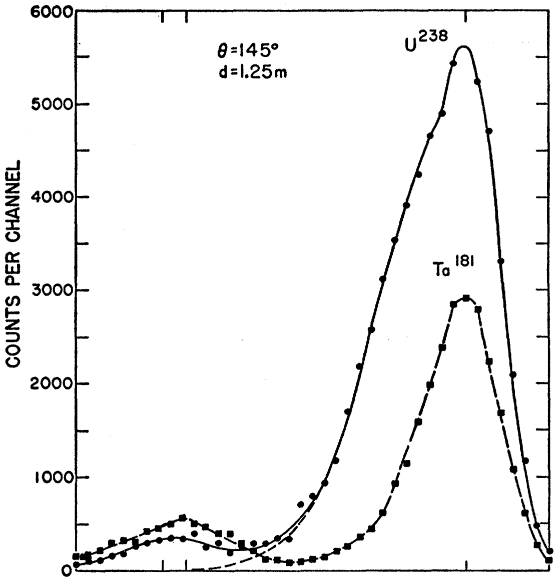

FIG. 3. Time spectra showing a comparison of the scattering from U^{238} and Ta^{181} for neutrons of 550-kev energy.

to be identified with the level reported earlier[4] at 700 kev.

At 1.50-Mev neutron energy (Fig. 5) the ground-state rotational band is no longer resolvable. A continuum of neutrons is observed due to fission, and the most prominent inelastic features are the 730-kev level, with cross section reduced from the value observed at 1.00 Mev, and a broad structure in the neighborhood of $Q=-1.0$ Mev. This structure is most simply interpreted as due to two levels, about equally excited, corresponding to $Q=-0.98$ Mev and $Q=-1.06$ Mev. The 730-kev level shows an anisotropy of 1.06±0.07, as measured by the 155°/90° ratio of yields.

At 1.89 Mev (Fig. 6) excitation of the 730-kev level is substantially reduced, a new feebly excited level appears at $Q=-1.26$ Mev, and fission neutrons are more prominent. It is surmised that the levels at 1.26, 1.06, and 0.98 Mev coalesce to form the unresolved broad line centered at 1.18 Mev which was previously reported[5] for a neutron energy of 2.45 Mev. This trio of levels appears to be relatively isolated or excited with exceptional strength at 2.45 Mev. The analysis of the 2.45-Mev spectrum previously given[5] implied that the trio is superimposed on a feeble continuum of unresolved, weakly excited levels in addition to the fission-neutron continuum. It would be consistent with the earlier data and the uncertainty in the procedure for subtracting a normalized fission spectrum, however, to suggest that this inelastic continuum is in fact negligible and that these three levels are indeed the only ones in their energy region. Much improved data are needed to settle this point. With present techniques no levels can be resolved at energies above 1.3 Mev, and no attempt has been made to obtain the entire yield of inelastically scattered neutrons for primary neutron energies of 1.50 and 1.89 Mev.

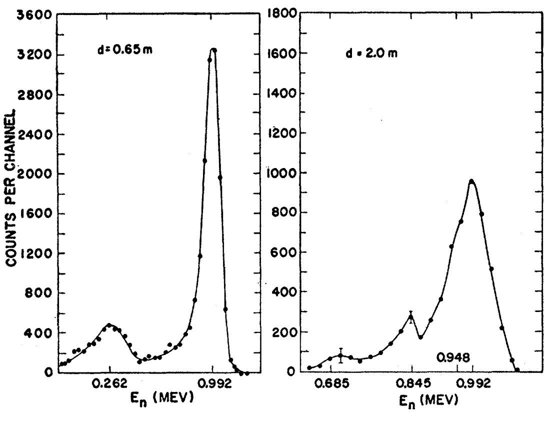

FIG. 4. Time spectra for scattering of 1.00-Mev neutrons by U^{238} at 90° for each of two flight paths.

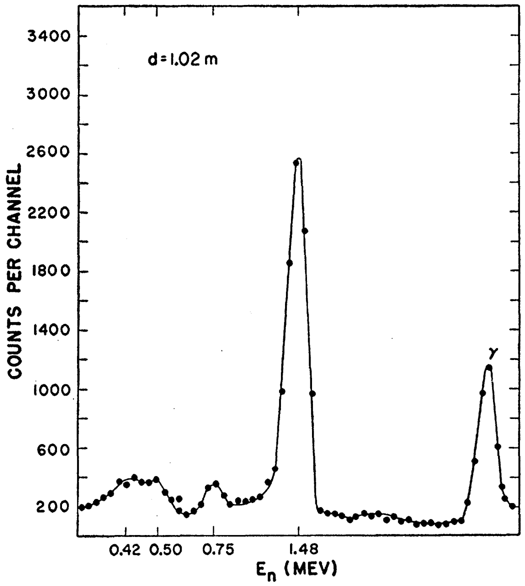

FIG. 5. Time spectrum for scattering of 1.50-Mev neutrons by U^{238} at 90°.

At 2.00-Mev primary neutron energy no effort has been made to resolve individual levels. An attempt has been made, however, to subtract a fission neutron spectrum and so to obtain some idea of the distribution in energy of the inelastically scattered neutrons. Before this can be done, however, account must be taken of the following fact. The difference between a "sample-in" and "sample-out" run for a primary neutron energy in excess of the fission threshold always gives a non-vanishing result, and this is true even in the time region corresponding to neutron energies at which the detector has negligible neutron sensitivity. This result is interpreted to mean that the detector is observing gamma rays associated with the decay of fission products. For the most part these should be too long-lived[14] to give observable structure in the time scale of the observations, which was 0.2 μsec. Consequently they have been treated as random in time, and are corrected for by subtracting a time-independent background which forces the yield to zero in the region of low neutron energy for which the detector sensitivity is negligible. This procedure was followed also in earlier work.[5]

To subtract a fission-neutron spectrum it has been assumed as before[5] that the spectrum of fission neutrons for U^{238} at the energy of interest is the same as for U^{235} for thermal and epithermal energies. To make the subtraction as straightforward as possible the time spectrum of fission neutrons for U^{235} has been obtained directly by the pulsed-beam method using neutrons produced at the threshold of the $Li^7(p,n)Be^7$ reaction. To reproduce multiple scattering effects the U^{235} sample was identical in size to the sample of U^{238}.

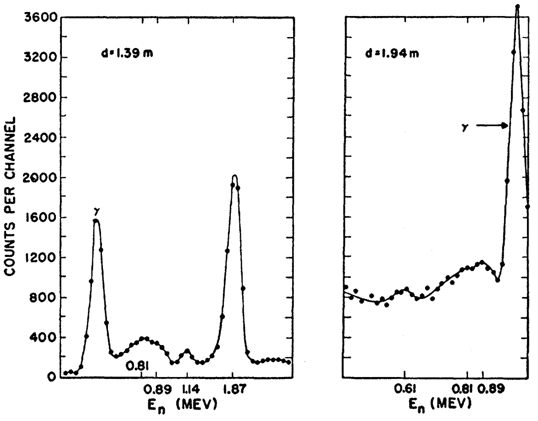

FIG. 6. Time spectra for scattering of 1.89-Mev neutrons by U^{238} at 90°. In the right-hand figure the background, which was structureless in the interesting region, has not been subtracted.

Figure 7 shows the time spectrum observed for U^{238} after the "sample-out" background had been subtracted, together with the level of background which is ascribed to fission-product decay. The U^{235} fission spectrum is also shown. It has been normalized to the U^{238} spectrum on the high-energy side of the elastic peak. By subtracting the fission neutrons normalized in this way the inelastic scattering has been obtained. In addition to levels seen at lower energies there is evidence of numerous strongly excited levels at $Q=-1.5$ Mev and above. The distribution of the yield in intervals suggested by the structures observed is given in Table I. No attempt has been made to estimate the contribution due to levels within 500 kev of the ground state or within 250 kev of the primary neutron energy.

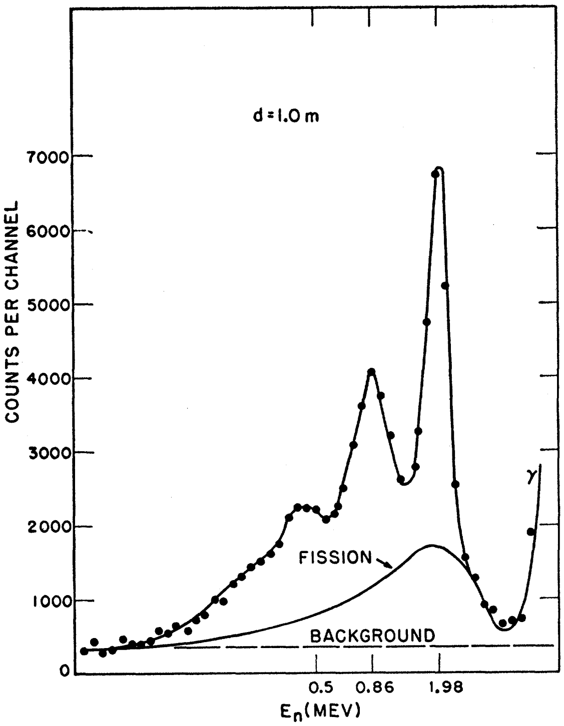

FIG. 7. Time spectrum for scattering of 2.00-Mev neutrons by U^{238}. Also shown is the background due to fission-product decay and the normalized time spectrum of fission neutrons. This was obtained with threshold neutrons from the $Li^7(p,n)Be^7$ reaction incident on U^{235}.

It has seemed worthwhile to check the integral inelastic cross section by measuring the total elastic scattering and subtracting it and the reaction cross section from the total neutron cross section. Data on the cross section for elastic scattering at 1.0 Mev are already available.[15] Figures 8 and 9 give the elastic angular distributions obtained at $E_n=550$ kev and 2.00 Mev, respectively, using a cylindrical tube of U^{238} which was 2 inches long, $\frac{3}{4}$ inch o.d. with $\frac{1}{16}$-inch wall.

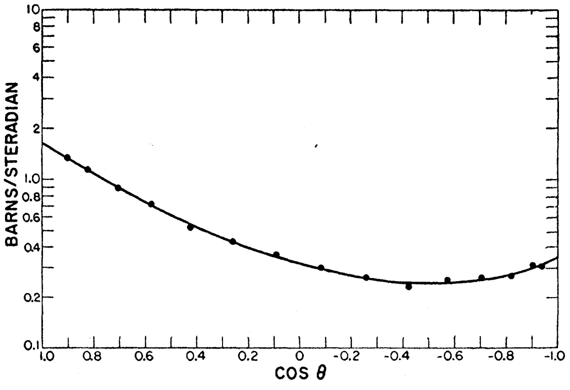

FIG. 8. The angular distribution of elastic scattering for neutrons of 550-kev energy incident on U^{238}.

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[14] K. Way and E. P. Wigner, Phys. Rev. **73**, 1318 (1948).

[15] Allen, Walton, Perkins, Olson, and Taschek, Phys. Rev. **104**, 731 (1956).

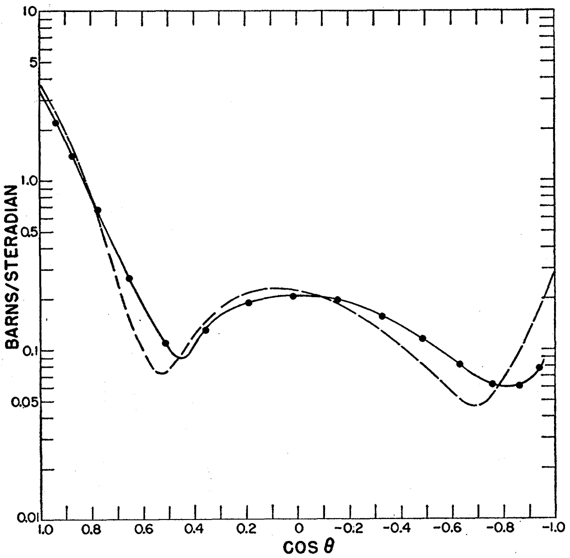

Fig. 9. The angular distribution of elastic scattering for neutrons of 2.00-Mev energy incident on U^{238}. The dashed curve is as calculated by Beyster[16] from interpolated cloudy-crystal ball parameters.

The angular resolution was ±7°. These data are uncorrected for angular resolution and multiple scattering. Both these corrections should be small, however, and should have negligible effect on the quantity of interest, which is the integral of the elastic scattering. The elastic scattering data at 2.00 Mev include inelastic scattering to the levels within 500 kev of the ground state. The statistical error at each point is less than 3%. The estimated error for the integral of the elastic cross section due to uncertainties involved in the comparison with the *n-p* cross section is 5%.

Also shown in Fig. 9 is the angular distribution calculated by Beyster[16] on the basis of the cloudy-crystal ball model[17] and the Woods and Saxon potential[18] using parameters obtained by interpolation between those values which fitted experimental data best at 1.0 and 2.5 Mev. The values of these parameters are: $R=8.05\times10^{-13}$ cm, $V_0=-44$ Mev, $\zeta=0.075$, $a=0.5\times10^{-13}$ cm, where R is the nuclear radius, V_0 is the real potential, $V_0\zeta$ is the imaginary potential, and a is the diffuseness parameter. To the shape-elastic scattering calculated on this basis has been added an isotropic contribution of 0.05 barn/steradian as the estimated contribution of "compound-elastic" scattering. This estimate was based on data at neighboring energies at which it is unlikely the lowest-lying levels were resolved from the ground state, and hence must be presumed to include some inelastic scattering. The agreement of the experimental and calculated results is about the same as was obtained at the energies at which the fits were made. The differences between calculated and experimental results follow a very similar course, except that the second observed minimum occurs at an angle which is about 20° larger than the calculated value.

Table II summarizes the data obtained on the partial cross sections. For $E_n=1.0$ Mev the value for the total elastic scattering cross section is taken from Allen *et al.*[15] after subtracting our estimate of the unresolved contribution due to the 44-kev level. The agreement of the sum of the partial cross sections and the measured total neutron cross section is always within experimental errors. These errors are large enough, however, to allow a few-tenths barn cross section to be associated with unobserved levels, i.e., those within 250 kev of the primary neutron energy.

DISCUSSION

The total cross section obtained for excitation of the 44-kev level at 550-kev neutron energy is much greater than has been reported previously.[3,4] The difference between this and the earlier results is ascribed to incomplete resolution of inelastic from elastic scattering in the earlier work. There is also a discrepancy between Batchelor's[4] value for $\sigma_{\text{inelastic}}$ corresponding to energy loss in excess of 500 kev for 1-Mev incident neutron energy and the yield reported here for the 730-kev level of 0.52±0.1 barn, which is 4π times the differential cross section given in Table I. Batchelor's value, corrected for capture and fission, is 1.0±0.2 barns. The corresponding value of Beyster *et al.*[19] is 0.9 barn with unstated uncertainty. These discrepancies may be resolved by assuming that the results are sensitive to the precise value of the primary neutron energy through the excitation of the level at 0.98±0.02 Mev. An apparent discrepancy concerns the report by Beyster *et al.*[19] at 1.0 Mev of a cross section of 0.65 barn corresponding to excitation of levels between 200 and 600 kev. The only level observed in this range is the one at 300±30 kev which is excited with a cross section of 0.09±0.05 barn. It has been suggested[20] that the difficulty here may also be due to inadequate resolution in earlier work.

Table II. Partial and total cross sections (barns) for U^{238}.

E_n (kev)	Elastic	Inelastic	Fission[a]	Capture[a]	Sum	σ_t[a]
550	6.3±0.3	1.7±0.2	<0.01	0.14	8.2±0.4	8.2±0.1
1000	4.6±0.5[b]	2.0±0.4[c]	0.015	0.10	6.7±0.6	7.0±0.1
2000	3.9±0.2[d]	2.4±0.2[c]	0.56	0.05	6.9±0.3	7.1±0.1

[a] Reference 11.
[b] Reference 15 after subtracting 0.9 barn as the estimate for the contribution due to the 44-kev level.
[c] Does not include levels within 250 kev of the primary neutron energy.
[d] Includes levels within 500 kev of the ground state.

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[16] J. R. Beyster, Los Alamos Scientific Laboratory Report LA-2099 (unpublished).

[17] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).

[18] R. D. Woods and D. S. Saxon, Phys. Rev. **95**, 577 (1954).

[19] Beyster, Walt, and Salmi, Phys. Rev. **104**, 1319 (1956).

[20] J. R. Beyster (private communication).

Calculations of the excitation function for the 44-kev level by Chase and Wilets[8] on the direct interaction model and on the compound-nucleus model are given in Fig. 10 together with the experimental result. For the compound-nucleus calculation the penetrabilities have been calculated on the basis of the optical-model parameters determined by Beyster[16] for 500-kev neutrons. These are: $R=8.05\times10^{-13}$ cm, $a=0.50\times10^{-13}$ cm, $V_0=-44$ Mev, $\zeta=0.05$, where the quantities have been defined above. For the direct interaction the calculation was done on the basis of the values of ζ shown in Fig. 10 using $R=8.36\times10^{-13}$ cm, $\Delta=2.2\times10^{-13}$ cm, $V_0=-44$ Mev, and $\beta=0.33$. The quantity β is the nuclear distortion parameter and Δ is the 90% to 10% falloff distance of the potential.

It is clear from Fig. 10 that the dominant mechanism for the excitation of the $I=2$ level at 550-kev neutron energy is compound nucleus formation, and that the accuracy of the measurement does not permit observation of the contribution due to direct interaction.

Figure 11 gives the calculated angular distributions for inelastically scattered neutrons corresponding to excitation of the 44-kev level at 550-kev incident neutron energy on the two models. The lower solid curve is for the direct excitation with $\zeta=0.05$ and corresponds to much smaller cross sections than the upper solid curve, which is for compound nucleus formation. The dashed curve is the sum of the two normalized to the experimental data at 90°.

The experimental data exhibit an anisotropy greater than that calculated for the sum of the compound-nucleus and direct-interaction effects by an amount outside the assigned errors. It should be noted that the error assignment includes a somewhat arbitrary factor intended to take account of fluctuations of the data which were outside statistics. These data were obtained under exceptionally favorable conditions of beam intensity and represent the limit of our present technical capability. Clearly, the indication here of a significant discrepancy can be readily checked by a somewhat improved facility. It should be noted also that the angular distribution data for elastic scattering at 550-kev neutron energy given here indicate a different trend in the back direction than was estimated previously for a primary neutron energy of 500 kev. Thus, the optical-model parameters used in the calculations require adjustment to accommodate this fact and to take account of the nonspherical shape of the U^{238} nucleus.

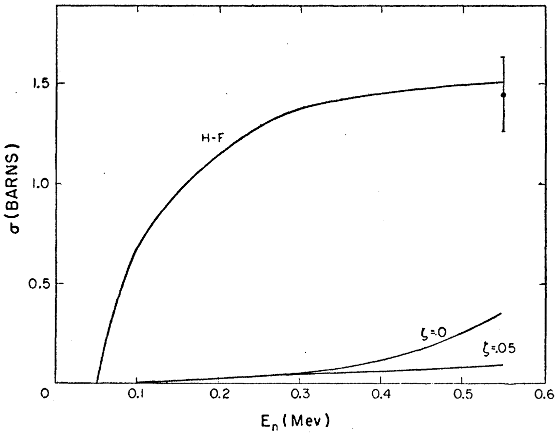

FIG. 10. Excitation functions for the 44-kev level in U^{238} as a function of primary neutron energy for the Hauser-Feshbach and direct interaction models according to Chase and Wilets.[8] The direct interaction result is given for two values of the parameter ζ which determines the imaginary part of the potential.

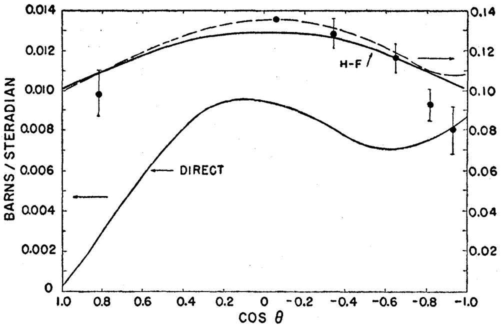

FIG. 11. Angular distributions of inelastically scattered neutrons corresponding to excitation of the 44-kev level in U^{238} by neutrons of 550-kev energy. The lower solid curve is for direct interaction and refers to the left-hand cross section scale. The upper solid curve is the Hauser-Feshbach prediction and refers to the right-hand scale. The dashed curve is the sum of the two normalized to the experimental point at 90° and also refers to the right-hand scale.

For primary neutron energies in excess of 500 kev, calculations of the excitation of low-lying levels by compound nucleus formation become difficult because of the lack of spin and parity assignments for the levels which compete with the low-lying ones. Hence nothing can be said at present about the relative roles of direct interaction and compound nucleus formation at higher energies although calculations are available for the former process alone.[8] However, the curve of elastic scattering plus inelastic scattering to low-lying levels for a neutron energy of 2.00 Mev, Fig. 9, imposes an upper limit of 60 mb/steradian on the combined effect of both mechanisms at 140° for transitions to the $I=0$, 2, 4, and 6 levels.

It is pertinent to note also, as has been pointed out by Wheeler,[21] that the competition between inelastic neutron scattering and fission may account for the well-known[11] fine structure in the excitation function for neutron-induced fission in even-even nuclei. The excitation function for fission of U^{238}, as measured by Lamphere,[22] is shown plotted on a semilogarithmic scale in Fig. 12, together with the positions of the pertinent

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[21] J. A. Wheeler, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. II, p. 155.

[22] R. W. Lamphere, Phys. Rev. **104**, 1654 (1956), and private communication.

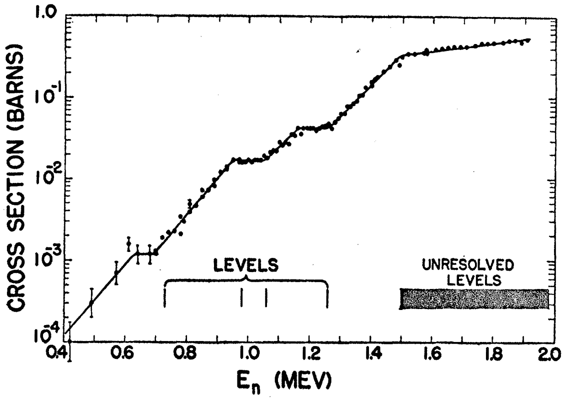

FIG. 12. The excitation function for neutron-induced fission of U^{238} according to Lamphere,[22] with the positions of levels observed in inelastic neutron scattering in U^{238}.

levels reported in this work. The excitation function is a series of exponential rises of diminishing steepness alternating with horizontal steps. It is clear that the positions and spacings of levels are in rough accord with the 0.98- and 1.06-Mev levels. The break at 1.50 Mev is in accord with the observation of strongly excited levels at this and higher energies. There is indication of a discrepancy between the position of the first break in the excitation function and the level reported at 0.73 Mev. But it should be noted that the excitation function is uncorrected for an energy resolution of about 60 kev, and that the statistical accuracy of the data in that region is very poor. A more quantitative formulation of the competition mechanism is required than is now available before one can discuss the comparison with experiment in any greater detail.

More complete experimental data are obviously desirable, particularly data at higher energies, where the direct interaction process becomes more important. It is expected that when the amount of pulsed beam available has been increased 3- to 5-fold it will be practical to improve the quality of these data and to extend results on the low-lying levels to higher incident neutron energy.

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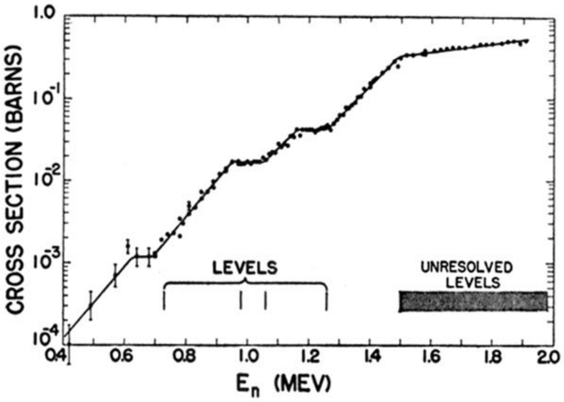

FIG. 12. The excitation function for neutron-induced fission of U^{238} according to Lamphere,[22] with the positions of levels observed in inelastic neutron scattering in U^{238}.