than for the 3.92→ground transition. The reverse was in fact observed, and consequently a spin of $\frac{5}{2}$ or $\frac{7}{2}$ and even parity are suggested for the 3.92-Mev level.

These conclusions are summarized in the level scheme (Fig. 9). It was not possible to calculate any absolute transition probabilities or gamma-ray widths because of the total lack of knowledge of the Ne^{22} concentration on the target.

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Correlation of the Competition between Neutron Emission and Fission*†

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Values of the ratio of the fission cross section divided by the total cross section for 3-Mev neutrons are correlated with the fission parameter Z^2/A. For compound nuclei excited 8 to 12 Mev above their ground states, the fission width Γ_f derived from neutron- and gamma-induced fission data increases linearly with Z^2/A. The quantity Γ_f/Γ_n is independent of energy for a particular nuclide excited between 8 and 12 Mev.

INTRODUCTION

BOHR and Wheeler[1] in their classical paper on nuclear fission show a schematic diagram (Fig. 5 of reference 1) of the partial transition probabilities for fission, neutron emission, gamma emission, etc., for various excitation energies of a typical heavy nucleus. For the compound nuclei U^{239} and Th^{233}, formed by the capture of 2-Mev neutrons on U^{238} and Th^{232}, the above authors calculated ratios of the fission width to neutron emission width (Γ_f/Γ_n), of 0.25 and 0.04, respectively. These early estimates are in rather good agreement with experimental values.

It is the purpose of this paper to (1) point out a correlation between the fissionability of heavy compound nuclei formed by 2- to 5.5-Mev neutrons with the nuclear parameter Z^2/A, (2) compare values of $\Gamma_f/(\Gamma_f+\Gamma_n)$ derived from photofission and photoneutron experiments with similar values from neutron fission experiments, and (3) discuss the dependence of Γ_f and Γ_n on excitation energy and the fission parameter Z^2/A.

RESULTS AND DISCUSSION

A number of experimenters[2] have shown that the fast neutron fission cross sections of heavy nuclei are relatively constant in the neutron energy interval 2 to 5.5 Mev. Another striking feature of the cross section *vs* neutron energy curves is the uniform rise in the fission cross section at neutron energies of about 5.5 Mev. This increase in fission cross section can be explained by the onset of the $(n,n'f)$ reaction. At neutron energies of about 5.5 Mev, the product nucleus after neutron emission begins to have sufficient excitation energy to fission. This interpretation is consistent with data showing the fission thresholds of heavy nuclei with $Z=90$ to 94 to be about 5.3 Mev.[3]

It is interesting to note that the values of the fission cross sections of those nuclei measured with neutrons of energy greater than 5.5 Mev reach a second plateau at neutron energies of 7 to 8 Mev and show a second break at neutron energies of approximately 13 Mev. In the present discussion the fission cross section plateau will refer to the first region in which the values of the fission cross section are relatively constant, i.e., neutron energies of 2 to 5.5 Mev. The magnitude of the neutron fission cross section in the plateau region varies from one nuclide to another and is related to the fission parameter, Z^2/A. Neutron fission cross sections and total cross sections for 3-Mev neutrons and the calculated ratios of the neutron fission cross sections divided by the total cross sections for several heavy nuclides are given in Table I. A plot of the $\sigma_{n,f}/\sigma_{n,t}$ values *vs* Z^2/A is shown in Fig. 1. The neutron fission to total cross-section ratios increase smoothly with Z^2/A, although the five uranium isotopes are better represented by a line of slightly

* Based on work performed under the auspices of the U. S Atomic Energy Commission.

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[1] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).

[2] Results and references are given in *Neutron Cross Sections*, compiled by D. J. Hughes and J. A. Harvey, Brookhaven National Laboratory, Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 1955); R. W. Lamphere, Phys. Rev. **104**, 1654 (1956); Smith, Henkel, and Nobles, Bull. Am. Phys. Soc. Ser. II, **2**, 196 (1957).

[3] J. R. Huizenga, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 2, p. 208.

steeper slope indicating that the number of excess neutrons may also be an influencing factor.

The total neutron cross section $\sigma_{n,t}$ is given by

$$\sigma_{n,t}=\sigma_{n,c}+\sigma_{n,\mathrm{esc}}, \qquad (1)$$

where $\sigma_{n,c}$ is the compound nucleus formation cross section which includes the fission $\sigma_{n,f}$, neutron capture $\sigma_{n,\gamma}$, and the inelastic neutron scattering $\sigma_{n,\mathrm{insc}}$ cross sections; and $\sigma_{n,\mathrm{esc}}$ is the elastic neutron scattering cross section. Since the capture cross section is small for 3-Mev neutrons compared to the fission and inelastic scattering cross sections, the compound nucleus formation cross section is adequately given by

$$\sigma_{n,c}=\sigma_{n,f}+\sigma_{n,\mathrm{insc}}. \qquad (2)$$

The fission width Γ_f is proportional to the neutron fission cross section. The sum of the fission width and the neutron emission width Γ_n is proportional to the compound nucleus formation cross section. From these relationships it follows that $\Gamma_f/(\Gamma_f+\Gamma_n)=\sigma_{n,f}/\sigma_{n,c}$. For the limiting case of a "black" nucleus whose radius R is much larger than the neutron wavelength λ, the compound nucleus formation cross section equals the elastic scattering cross section,

$$\sigma_{n,c}=\sigma_{n,\mathrm{esc}}=\pi R^2. \qquad (3)$$

Even though the neutron wavelength λ for a 3-Mev neutron is approximately 30% of the radius of a heavy-element nucleus, for the present calculations we assume the elastic scattering cross section equal to the compound nucleus formation cross section. With this assumption it follows that

$$\Gamma_f/(\Gamma_f+\Gamma_n)=2\sigma_{n,f}/\sigma_{n,t}. \qquad (4)$$

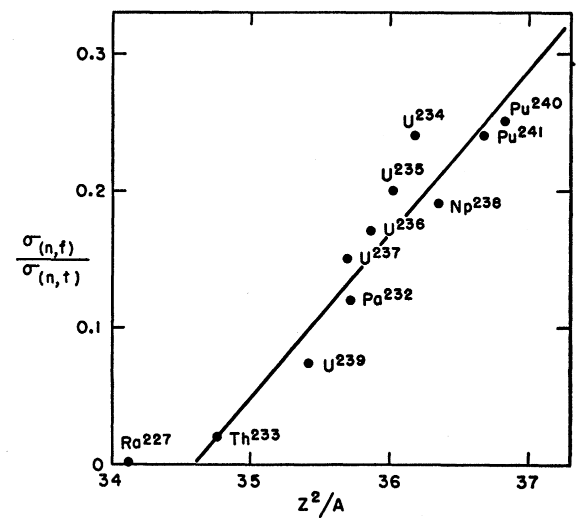

FIG. 1. Values of the ratio neutron fission cross section over the total neutron cross section ($\sigma_{n,f}/\sigma_{n,t}$) are plotted as a function of Z^2/A of the compound nucleus (A of target nucleus plus one). The cross-section data are for 3-Mev neutrons.

TABLE I. Total neutron cross sections and neutron fission cross sections of several heavy nuclide targets with 3-Mev neutrons. The values in parentheses are estimated.

Target nucleus	σ_f (barns)	σ_t (barns)	Z^2/A (of compound nucleus)	σ_f/σ_t
Ra^{226}	0.0003	(7.3)	34.115	4×10^{-5}
Th^{232}	0.14	7.5	34.764	0.02
Pa^{231}	1.13	(7.5)	35.694	0.15
U^{233}	1.80	(7.5)	36.171	0.24
U^{234}	1.53	(7.6)	36.017	0.20
U^{235}	1.28	7.6	35.864	0.17
U^{236}	0.90	(7.6)	35.713	0.12
U^{238}	0.57	7.7	35.414	0.074
Np^{237}	1.48	(7.7)	36.340	0.19
Pu^{239}	1.95	7.9	36.817	0.25
Pu^{240}	1.9	(7.9)	36.664	0.24

Values of $\Gamma_f/(\Gamma_f+\Gamma_n)$ calculated from the 3-Mev neutron cross section data of Table I by Eq. (4) are given in Table II and plotted as solid circles in Fig. 2.

Data from photofission and photoneutron emission experiments are used to derive the remaining values of $\Gamma_f/(\Gamma_f+\Gamma_n)$ in Table II. These quantities are plotted as open circles in Fig. 2. In the case of U^{238} and Th^{232} the photofission and the photoneutron emission cross sections were measured at several gamma energies. Since the fission width and neutron emission width are proportional to the photofission and photoneutron emission cross sections respectively, one obtains

$$\Gamma_f/(\Gamma_f+\Gamma_n)=\sigma_{\gamma,f}/(\sigma_{\gamma,f}+\sigma_{\gamma,n}). \qquad (5)$$

The photofission to photoneutron emission cross-section ratios of U^{238} and Th^{232} are, within experimental error, independent of excitation energy in the energy range 8 to 12 Mev. If one assumes an average neutron binding energy of 6 Mev, compound nuclei formed by

TABLE II. Values of $\Gamma_f/(\Gamma_f+\Gamma_n)$ and Γ_n/Γ_f are given for nuclei excited in the energy range 8 to 12 Mev. At these excitation energies the ratios listed are independent of energy.

Compound nucleus	Method of formation	$\Gamma_f/(\Gamma_f+\Gamma_n)$	Γ_n/Γ_f
Ra^{226}	n	8×10^{-5}	10^4
Th^{233}	n	0.04	24
Th^{232}	γ	0.08	12
Th^{230}	γ	0.17	4.9
Pa^{232}	n	0.30	2.3
U^{239}	n	0.15	5.7
U^{238}	γ	0.20	5.0
U^{237}	n	0.24	3.2
U^{236}	γ	0.32	2.1
U^{236}	n	0.34	1.9
U^{235}	γ	0.38	1.6
U^{235}	n	0.40	1.5
U^{234}	γ	0.38	1.6
U^{234}	n	0.48	1.1
U^{233}	γ	0.49	1.0
Np^{238}	n	0.38	1.6
Np^{237}	γ	0.51	1.0
Pu^{241}	n	0.48	1.1
Pu^{240}	n	0.50	1.0
Pu^{239}	γ	0.70	0.4

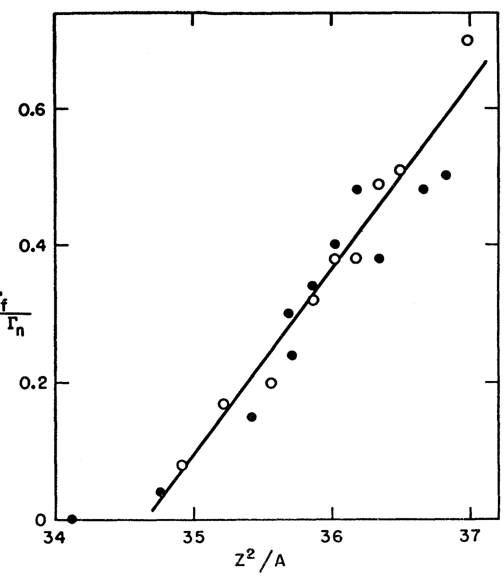

FIG. 2. Values of $\Gamma_f/(\Gamma_f+\Gamma_n)$ are plotted as a function of Z^2/A. For a particular compound nucleus $\Gamma_f/(\Gamma_f+\Gamma_n)$ is independent of excitation energy for energies between 8 and 12 Mev. The data in this figure is restricted to this energy range. The quantities plotted as solid circles (●) and open circles (○) are derived from 3-Mev neutron cross sections and photofission and photoneutron emission cross sections, respectively.

2- to 5.5-Mev neutrons have approximately the same excitation energy as if produced directly by excitation with 8- to 12-Mev gamma rays. In either case the product nucleus formed by neutron emission, (n,n') or (γ,n), has excitation energy below its fission and neutron emission thresholds. Secondary reaction cross sections such as $(n,n'f)$ and (γ,nf) are negligible at the above energies. From the gamma-ray experiments on U^{238} and Th^{232} one concludes that the fission to neutron emission width (Γ_f/Γ_n) is independent of excitation energy in the energy range 8 to 12 Mev. The constancy of the neutron-induced fission cross section for a particular nuclide with neutrons of 2 to 5.5 Mev is also consistent with a constant Γ_f/Γ_n ratio.

Values of the quantity $\Gamma_f/(\Gamma_f+\Gamma_n)$ given in Table II for U^{238} and Th^{232} of 0.2 and 0.08, respectively, are average values derived from cross-section data for 8- to 12-Mev gamma rays.[4,5] Magnitudes of $\Gamma_f/(\Gamma_f+\Gamma_n)$ given in Table II for Th^{230}, U^{236}, U^{235}, U^{234}, U^{233}, Np^{237}, and Pu^{239} are derived from relative photofission yield experiments with 12-Mev bremsstrahlung.[6] In calculating values of $\Gamma_f/(\Gamma_f+\Gamma_n)$ for these latter nuclides, the assumption is made that the photofission and photoneutron cross sections make up all the total cross section (Γ_p and other widths are negligible) and the sum of $\sigma_{\gamma,f}$ and $\sigma_{\gamma,n}$ for these isotopes is equal to the corresponding sum for U^{238}. It follows then that

$$[\Gamma_f/(\Gamma_f+\Gamma_n)]_X = F[\Gamma_f/(\Gamma_f+\Gamma_n)]_{U^{238}}, \tag{6}$$

where $X = Th^{230}$, U^{236}, etc., and F is the fissionability of the nuclide X relative to U^{238} with 12-Mev bremsstrahlung. Values of F used in the present calculations are 0.46, 0.85, 1.00, 1.58, 1.88, 1.88, 2.44, 2.53, and 3.51 for the isotopes Th^{232}, Th^{230}, U^{238}, U^{236}, U^{235}, U^{234}, U^{233}, Np^{237}, and Pu^{239}, respectively.[6] The value of 0.09 for the ratio of $\Gamma_f/(\Gamma_f+\Gamma_n)$ calculated for Th^{232} from equation (6) is close to the directly measured value[5] of 0.08 and establishes the validity of Eq. (6).

Values of $\Gamma_f/(\Gamma_f+\Gamma_n)$ derived from nuclei excited with neutrons (solid circles of Fig. 2) and gamma rays (open circles) increase linearly with the Z^2/A value of the compound nucleus. The 3-Mev neutron data are, within experimental error, consistent with the data obtained from nuclei excited with gamma rays. This agreement indicates that the assumption of equal cross sections for compound nucleus formation and elastic neutron scattering for 3-Mev neutrons is valid within our experimental errors.

From Fig. 2 it is evident that values of $\Gamma_f/(\Gamma_f+\Gamma_n)$ vary from 0.04 for Th^{233} to 0.70 for Pu^{239} and that Γ_f is dependent on the fission parameter Z^2/A and increases linearly with increasing values of Z^2/A.

[4] R. B. Duffield and J. R. Huizenga, Phys. Rev. **89**, 1042 (1953).
[5] Gindler, Huizenga, and Schmitt, Phys. Rev. **104**, 425 (1956).
[6] Huizenga, Gindler, and Duffield, Phys. Rev. **95**, 1009 (1954).