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A CORRELATION OF FAST NEUTRON FISSION CROSS SECTIONS

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by

John R. Huizenga

CHEMISTRY DIVISION

November 1953

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by

John R. Huizenga

November 1953

Abstract

A relationship is shown to exist between the fast (3 Mev) neutron fission cross sections and the nuclear parameter Z^2/A . Some comments are made on the competition between fission and neutron emission. Gamma induced fission results are correlated with neutron induced fission data and the predictions of neutron scattering cross sections from the relative (γ, f) and (γ, n) cross sections are discussed.

The excitation functions for the fission of several nuclides have been measured at Los Alamos as a function of neutron energy up to 7 Mev using monoenergetic neutrons.¹ These experiments show that the fast neutron fission cross section for each examined nuclide is relatively constant in the neutron energy interval 2-5 Mev. One other striking feature of these curves is that all the cross sections rise at neutron energies of about 5.5 Mev. This increase in fission cross section can be explained by assuming that at neutron energies of about 5.5 Mev, the product after neutron emission begins to have sufficient excitation energy to undergo fission. This interpretation is consistent with the hypothesis that nuclides with $Z > 90$ have fission thresholds of approximately 5.3 Mev.² Measured photofission thresholds³ and those calculated from other nuclear data⁴ also indicate that fission thresholds are relatively constant in the heavy element region.

It is the purpose of this report to point out a relationship between the magnitude of the fast neutron fission cross section and the nuclear parameter Z^2/A . Since the neutron fission cross sections are approximately independent of neutron energy in the 2-5 Mev interval, the values of the

¹R. L. Hinkel, LA-1495.

²J. R. Huizenga and R. B. Duffield, Phys. Rev. 88, 959 (1952).

³H. W. Koch, J. McElhinney, and E. L. Gasteiger, Phys. Rev. 77, 329 (1950).

⁴J. R. Huizenga, Unpublished data discussed in NNES, Div. IV, Vol. 14A, McGraw-Hill Book Co., Inc. New York, N. Y., 1953 Chapter 20.

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fission cross sections given in Table I are for 3 Mev neutrons. The ratios of the fast neutron fission cross sections to total cross sections for nine nuclides are also given in Table I and plotted in Figure 1.

The total neutron cross section, σ_T , is given by

$$\sigma_T = \sigma_C + \sigma_{esc} \quad (1)$$

where σ_C is the compound nucleus formation cross section which includes the fission, σ_f , neutron capture, σ_{cap} , and inelastic scattering cross section σ_{insec} , (we shall include in the inelastic scattering cross section those events in which the target nucleus changes its internal state in such a way that there is no energy transfer between the target nucleus and the neutron); and σ_{esc} is the elastic scattering cross section.

The compound nucleus formation cross sections for the nuclides being discussed are approximately constant.⁵ Equation (1) can then be written in the following form

$$\sigma_{esc}/\sigma_C = (\sigma_T/\sigma_C) - 1 \approx K \quad (2)$$

since the total cross sections for the heavy elements considered are also approximately constant. K is the ratio of the elastic scattering cross section to the compound nucleus formation cross section and will be assumed to be an unknown constant for the nuclides in Table I.

Rearrangement of equation (2) and multiplication of both sides of the equation by σ_f gives

$$\sigma_f/\sigma_T \approx [1/(K+1)] [\sigma_f/\sigma_C] \quad (3)$$

From Figure 1, it can be seen that the cross section ratios, σ_f/σ_T , increase with increasing values of Z^2/A . Equation (3) simply states that the ordinate in Figure 1 is proportional to the probability that the compound nucleus decay by fission. With increasing Z^2/A values the probability for decay by fission also increases. The 3 Mev neutron capture cross sections, σ_{cap} , are small compared to the fission and inelastic scattering cross sections, so that

$$\sigma_C \approx \sigma_f + \sigma_{insec} \quad (4)$$

It can thus be readily shown that for compound nuclei formed with 3 Mev neutrons, the competition between fission and neutron emission is directly related to Z^2/A . A similar relation for the competition between fission and

⁵Blatt and Weisskopf, "Theoretical Nuclear Physics," John Wiley and Sons, Inc., New York, N. Y. (1952) Figure 4.2, p. 438.

Table I

Bombarded Nucleus	σ_f (3 Mev neutrons)	σ_T (3 Mev neutrons)	Compound Nucleus	σ_f/σ_T^*	Z^2/A
Pa ²³¹	1.2 ^(a)	-	Pa ²³²	0.16	35.694
Th ²³²	0.17 ^(a)	7.4 ^(a)	Th ²³³	0.02	34.764
U ²³³	1.8 ^(b)	- (c)	U ²³⁴	0.24	36.171
U ²³⁴	1.4 ^(d)	-	U ²³⁵	0.18	36.017
U ²³⁵	1.25 ^(b)	7.6 ^(e)	U ²³⁶	0.16	35.864
U ²³⁶	0.85 ^(b)	-	U ²³⁷	0.11	35.713
U ²³⁸	0.55 ^(b)	7.7 ^(f)	U ²³⁹	0.07	35.414
Np ²³⁷	1.5 ^(d)	-	Np ²³⁸	0.20	36.340
Pu ²³⁹	1.9 ^(b)	7.8 ^(g)	Pu ²⁴⁰	0.25	36.817

*Since the total cross sections for 3 Mev neutrons on some of the nuclei are not known, and the values of the measured cross sections are approximately constant within experimental error, a constant total cross section of 7.6 barns is used in the calculation of these ratios.

(a)U. S. Atomic Energy Commission Unclassified Document AECU-2040.

(b)U. S. Atomic Energy Commission Secret Document BNL 170A.

(c)Secret Document BNL 170 gives a 14 Mev neutron value of 6.1 Barns.

(d)Supplement 1 to Unclassified Document AECU- 2040.

(e)Secret Document BNL 170 gives values up to ~ 4 Mev.

(f)Secret Document BNL 170 (14 Mev neutron value ~ 5.9 barns).

(g)Secret Document BNL 170, values up to ~ 3.5 Mev neutrons.

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Figure 1

Plot of the ratios of the neutron fission cross section, σ_f , to the total neutron cross section, σ_T , as a function of Z^2/A . These cross sections are all measured with 3 Mev neutrons. σ_T is assumed to be 7.6 barns for the nuclides considered (see explanation in Table I). The points plotted are the compound nuclei (Target nucleus + n).

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neutron emission has also been observed for gamma ray excitation.⁶ The objection may be raised that the even A compound nuclei are more excited with 3 Mev neutrons than the odd A compound nuclei due to the differences in neutron binding energies. It must be remembered that the fission cross sections are approximately constant out to 5 Mev neutrons. The competition between fission and neutron emission is therefore relatively constant over the neutron energy interval 2-5 Mev. This is also consistent with photo-fission and photoneutron emission cross sections of U^{238} as a function of gamma energy.⁷ It was observed⁷ that the U^{238} cross section ratios, $(\gamma, f)/[(\gamma, f) + (\gamma, n)]$, for 8 to 11 Mev gamma rays had an average value of 0.20 to 0.25.

The interpolated neutron cross section ratio, σ_f/σ_T , from Figure 1 for the compound nucleus U^{238} is ~ 0.1 . Since the gamma ray bombardments⁷ of U^{238} give the competition between fission and neutron emission for the U^{238} compound nucleus in the energy range under consideration in this report, it is interesting to substitute this information and the interpolated σ_f/σ_T value for U^{238} into equation (3). This gives

$$0.1 \approx [1/(k + 1)] [0.2 \text{ to } 0.25] \quad K \approx 1 \text{ to } 1.5 \quad (5)$$

The calculated elastic neutron scattering cross section is 1 to 1.5 times the compound nucleus formation cross section. For a black nucleus whose radius, R, is much larger than the neutron wavelength, λ , the total cross section is twice the geometrical cross section, and

$$\sigma_C = \sigma_{esc} \approx \pi R^2 \quad (6)$$

With 3 Mev neutrons, where $R/\lambda \approx 4$, the result that the elastic scattering cross section is 1 to 1.5 times the compound nucleus formation cross section indicates that the gamma and neutron excitation results are consistent with each other within the experimental errors.

In the energy range being considered in this report, the above discussion has illustrated that information on competition between fission and neutron emission from gamma excitation is valuable in predicting neutron fission and inelastic scattering cross sections. The correlation of gamma and neutron bombardments can also yield elastic neutron scattering cross sections by an independent method which does not depend on differentiating the energies of the emitted neutrons.

⁶J. R. Huizenga, J. Gindler, and R. B. Duffield, Phys. Rev. To be submitted for publication.

⁷R. B. Duffield and J. R. Huizenga, Phys. Rev. 89, 1042 (1953).