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SYSTEMATICS OF NEUTRON-INDUCED FISSION CROSS SECTIONS OVER THE ENERGY RANGE 0.1 THROUGH 15 MeV, AND AT 0.0253 eV

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November 11, 1977

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Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

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ABSTRACT

Recent studies have shown straightforward systematic behavior as a function of constant proton and neutron number for neutron-induced fission cross sections of the actinide elements in the incident-neutron energy range 3-5 MeV. In this report, the second in a series, fission cross-section values are studied over the MeV incident-neutron energy range, and at 0.0253 eV. Fission-barrier heights and neutron-binding energies are correlated by constant proton and neutron number; however, these systematic behaviors alone do not explain the trends observed in the fission cross-section values.

INTRODUCTION

In 1939, immediately following the discovery of nuclear fission by Hahn and Strassman,¹ Meitner and Frisch² qualitatively described the fission process in terms of the competition between Coulomb energy ($\propto Z^2/A^{1/3}$) and surface energy ($\propto A^{2/3}$), analogous to a charged liquid drop. Theoretical development of the liquid-drop model was also published in 1939 by Bohr and Wheeler.³ In the following years, many researchers studied fission phenomena in terms of the fissionability parameter Z^2/A . Some of these earliest studies have been published (Refs. 4 to 6). Recently, straightforward systematic behavior as a function of constant proton and neutron number was observed in measured neutron-induced fission cross sections averaged from 3 through 5 MeV incident-neutron energy for the actinide elements.⁷ In this series of informal reports, we present the results of studies on the fission process over a broad range of nuclear excitation energy. In the first report of this series,⁸ we showed the behavior of neutron-induced fission cross sections for the actinide elements from 0.1 through 15 MeV, and at 0.0253 eV. While continuing these studies, we also have begun to investigate nuclear phenomena relevant to these behaviors. Fission-barrier heights and neutron-binding energies are shown to be correlated by constant proton and neutron number; however, these findings alone do not explain the behaviors observed in fission cross-section values. The reader may wish to refer to Refs. 7 and 8 for further details concerning this work.

DISCUSSION

Neutron-Induced Fission Cross Sections in the MeV Range

Neutron-induced fission cross-section values for the actinides are plotted as a function of compound nucleus mass number in Figs. 1-4 for incident-neutron energies in the MeV range. Figure 1 shows the first three fission plateau regions, i.e., 2-5 MeV, 9 through 10 MeV, and 14 through 15 MeV. Figures 2-4 show the energy ranges 0.9-1.0 MeV, 0.5-0.6 MeV, and 0.2-0.3 MeV, respectively. Values of neutron-induced fission cross sections for ^{232}Th , ^{233}U , ^{234}U , ^{236}U , ^{238}U , ^{237}Np , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , ^{244}Pu , ^{241}Am , and ^{243}Am were taken from Refs. 9-11. From Refs. 12-35, we obtained the fission cross-section data on ^{230}Th , ^{231}Th , ^{233}Th , ^{231}Pa , ^{232}U , ^{235}U , ^{237}U , ^{239}U , ^{236}Np , ^{238}Np , ^{238}Pu , ^{243}Pu , ^{242}Am , ^{242}Cm , ^{243}Cm , ^{244}Cm , ^{245}Cm , ^{246}Cm , ^{247}Cm , ^{248}Cm , ^{249}Bk , ^{249}Cf , and ^{252}Cf .

In Fig. 1, we show that measured fission cross-section values on the first three fission plateaus for both even-N compound nuclei (solid symbols in Fig. 1) and odd-N nuclei (open symbols) exhibit straightforward behavior as a function of constant proton number (isotopes connected by dashed curves) and constant neutron number (isotones connected by solid straight lines). Below the neutron energy range of the first fission plateau, different systematic trends are observed. These trends can be summarized as a function of nuclear excitation energy.

For neutron-induced fission, the nuclear excitation energy is the sum of the neutron separation energy (i.e., neutron binding energy) S_n and the incident-neutron energy E_n . Fission barrier height E_B and the excitation energy E^* are quantities found in the Hill-Wheeler³⁶ formula for fission barrier penetrability $P_B(E^*)$:

$$P_B(E^*) = \left[1 + \exp 2\pi \left(\frac{E_B - E^*}{\hbar \omega_B} \right) \right]^{-1}, \quad (1)$$

where $\hbar \omega_B$ is a quantity that characterizes the curvature of the fission barrier. In Fig. 2, we compare the fission cross-section values for E_n from 0.9 through 1.0 MeV. In Fig. 3, we illustrate cross-section values from 0.5 through 0.6 MeV and in Fig. 4, we illustrate values from 0.2 through 0.3 MeV. For incident neutrons in these three energy ranges, the observed difference in

Fig. 1. Neutron-induced fission cross sections of the actinides as a function of compound nucleus mass number for (a) the incident-neutron energy range 14 through 15 MeV, (b) the energy range from 9 through 10 MeV, and (c) the range from 2 through 5 MeV. Odd-N compound nuclei are represented by open symbols; closed symbols represent even-N nuclei.

Fig. 2. Neutron-induced fission cross sections of the actinides as a function of compound nucleus mass number for the incident-neutron energy range 0.9 through 1.0 MeV. Odd-N compound nuclei are represented by open symbols; closed symbols represent even-N nuclei.

Fig. 3. Neutron-induced fission cross sections of the actinides as a function of compound nucleus mass number for incident-neutron energy 0.5 through 0.6 MeV for (a) even-N nuclei and (b) odd-N nuclei.

Fig. 4. Neutron-induced fission cross sections of the actinides as a function of compound nucleus mass number for incident-neutron energy 0.2 through 0.3 MeV. Odd-N compound nuclei are represented by open symbols; closed symbols represent even-N nuclei.

behavior of $\sigma(n,f)$ values for even- and odd-N isotopes is explained in terms of $E_B - E^*$ from Eq. 1. This quantity is $E_B - S_n - E_n$ for neutron-induced fission. For a given element, even-N compound nuclei have S_n values that are ~1.5 MeV greater than S_n values for odd-N nuclei. This difference in S_n accounts for the threshold behavior observed in $\sigma(n,f)$ values of odd-N nuclei for $E_n \cong 1$ MeV. Differences in the behavior of odd-Z relative to even-Z nuclei from N equal to 141 through 153 are also shown in Figs. 2 through 4.

Neutron-Induced Fission Cross Sections at Thermal Neutron Energy

Several features observed in the MeV incident-neutron energy range are also found at thermal neutron energy. Figures 5 and 6 show fission cross-section values at 0.0253 eV plotted as a function of compound nucleus mass number for radium through fermium. The values of $\sigma_{th}(n,f)$ were taken from Refs. 37 through 40.

Even-N, even-Z compound nuclei (closed symbols in Fig. 5) appear to be correlated by smooth curves connecting isotones. However, thermal cross-section values for even-N, odd-Z nuclei (open symbols) tend to lie well above these curves, perhaps forming their own set of smooth curves connecting isotones of odd-Z nuclei. These differences between odd- and even-Z isotones may, in part, be attributed to the proton-pairing energy component of nuclear-excitation energy.

Odd-N compound nuclei are often more difficult to study because only upper limits on $\sigma_{th}(n,f)$ are available. In Fig. 6, we compare the available data on these nuclei; upper limits on $\sigma_{th}(n,f)$ values are indicated in Fig. 6 by parentheses around the symbol. Odd-N, even-Z compound nuclei appear to be correlated by lines connecting isotones. Comparing Fig. 4 with Fig. 6 reveals additional similarities, shown by lines connecting isotopes and isotones.

Fission Modeling

The fission process at low energy was originally expressed³ in terms of the equation

$$\langle \Gamma_f \rangle = \frac{\langle D \rangle}{2\pi} N_f ,$$

where $\langle \Gamma_f \rangle$ is the mean fission width, $\langle D \rangle$ is the mean resonance spacing, and N_f is the number of levels in the transition state at the saddle point. Today,

Fig. 5. Neutron-induced fission cross sections for thorium through fermium as a function of compound nucleus mass number for 0.0253 eV incident-neutron energy for even-N compound nuclei. Odd-Z nuclei are represented by open symbols; closed symbols represent even-Z nuclei.

Fig. 6. Neutron-induced fission cross sections for radium through californium as a function of compound nucleus mass number for 0.0253 eV incident-neutron energy for odd-N compound nuclei. Parentheses indicate upper limits.

the number N_f is called the number of channels effective for fission. The reaction-rate formula⁴¹ is

$$\langle \Gamma_f \rangle = \frac{\langle D \rangle}{2\pi} \frac{1}{1 + \exp 2\pi \left(\frac{E_B - E^*}{\hbar \omega_B} \right)}. \quad (2)$$

Neglecting proton emission and γ -ray de-excitation, the neutron-induced fission cross section can be expressed by

$$\sigma_f = \sigma_R \langle \Gamma_f \rangle / (\langle \Gamma_f \rangle + \langle \Gamma_n \rangle)$$

for incident-neutron energies below the threshold for second-chance fission. Here, σ_R is the reaction cross section. This formula expresses the competition between neutron re-emission $\langle \Gamma_n \rangle$ and fission $\langle \Gamma_f \rangle$, i.e.,

$$\frac{\langle \Gamma_n \rangle}{\langle \Gamma_f \rangle} = \frac{\sigma_R}{\sigma_f} - 1. \quad (3)$$

To understand the fission process, the quantities $\langle D \rangle$, E_B , $\hbar \omega_B$, and E^* ($=S_n + E_n$) from Eq. 2 should be studied. Systematics of fission-barrier height and neutron-separation energy are discussed in Appendices A and B. Nuclear level density ($=\langle D \rangle^{-1}$) as a function of excitation energy should also be studied.

Figure 7 shows values of $\langle \Gamma_n \rangle / \langle \Gamma_f \rangle$ plotted as a function of compound nucleus mass number for the incident-neutron energy range of the first fission plateau deduced from Eq. 3 by assuming σ_R to be 2.9 b, and by using measured $\sigma(n,f)$ values from Refs. 9 through 35. Behaviors as a function of both constant proton and neutron number are included in Fig. 7.

Neutrons are not the only projectiles that cause fission, and the actinide elements are not the only elements that have been observed to fission. Behaviors from in Refs. 7 and 8 and this work may also be found in (γ,f) , (p,f) , (d,f) , and (α,f) reactions. For example, Figs. 8 and 9 illustrate (α,f) cross sections plotted as a function of compound nucleus mass number for tantalum through bismuth. In the figures, the cross-section values were taken from Ref. 42 and the incident-alpha-particle energy was 38 MeV.

Further study is needed to explain the trends that have been observed in fission cross-section values, e.g., studies of nuclear-level densities. We

Fig. 7. Values of $\langle \Gamma_n \rangle / \langle \Gamma_f \rangle$ for the actinides as a function of compound nucleus mass number for the incident neutron energy range of the first fission plateau for (a) thorium through neptunium and (b) thorium through californium.

Fig. 8. Alpha-particle-induced fission cross sections for tantalum through bismuth as a function of compound nucleus mass number for 38 MeV incident alpha-particle energy. Subscripts on symbols are compound nucleus proton numbers.

Fig. 9. Alpha-particle-induced fission cross sections for tantalum through bismuth as a function of compound nucleus neutron number for 38 MeV incident alpha-particle energy. Proton numbers Z are for the compound nucleus.

hope that these studies will eventually lead to a clearer understanding of the fission process, and perhaps other nuclear phenomena as well.

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APPENDIX A: SYSTEMATICS OF FISSION BARRIER HEIGHTS

Figures A-1 and A-2 show fission barrier heights plotted as a function of compound nucleus mass number for thorium through einsteinium. We assumed the Strutinsky^{A-1, A-2} model of the fission barrier. Values for the inner barrier height E_a and outer barrier height E_b were taken from Refs. A-3 through A-6. Straight lines appear to connect isotones (solid lines in figures) and isotopes (dashed lines). For the inner barrier, E_a values (Fig. A-1) appear to be correlated by lines of constant neutron number that change from negative to positive slope near neutron number 146. Interestingly, neutron number 148 has been calculated by Strutinsky as being that for optimum development of the secondary well in the fission barrier. E_a values also appear to be correlated by lines of constant proton number that change from positive to negative slope near neutron number 146. The outer barrier height E_b (Fig. A-2) appears to decrease linearly with increasing proton number and constant neutron number over the range $N = 139$ through 150. Dashed straight lines appear to correlate E_b values for nuclei of constant Z , as shown in Fig. A-2. Parentheses around symbols indicate estimates of barrier heights (as discussed in Refs. A-3 through A-6).

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Fig. A-1. Inner fission barrier heights of the actinides as a function of compound nucleus mass number. Odd-N compound nuclei are represented by open symbols; closed symbols represent even-N nuclei. Graphs overlap but are separated for simplicity.

Fig. A-2. Outer fission barrier heights of the actinides as a function of compound nucleus mass number. Odd-N compound nuclei are represented by open symbols; closed symbols represent even-N nuclei.

APPENDIX B: SYSTEMATICS OF NEUTRON SEPARATION ENERGIES AND PROTON SEPARATION ENERGIES

In Figs. B-1 and B-2, we have taken experimentally determined values of neutron separation energy S_n and proton separation energy S_p and plotted them as a function of compound nucleus mass number for thorium through fermium. Values of S_n and S_p were taken from Ref. B-1.

In Fig. B-1, solid straight lines connect S_n values for isotones, whereas dashed smooth curves connect isotopes. Solid symbols represent even-N compound nuclei; open symbols represent odd-N nuclei. Neutron pairing energy produces the observed difference between even and odd-N isotopes of the same element. Other odd, even effects are also illustrated in these figures.

Solid straight lines in Fig. B-2 connect S_p values for isotones; dashed straight lines connect isotopes. Solid symbols represent even-Z compound nuclei, and open symbols represent odd-Z nuclei. Proton pairing energy produces the difference between even- and odd-Z isotones; neutron pairing energy accounts for differences between even- and odd-N isotopes. Other combinations of odd, even effects are illustrated in Fig. B-2.

The behaviors of S_n and S_p values shown in Figs. B-1 and B-2 are not unique to the actinide elements.

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Fig. B-1. Neutron separation energies of the actinides as a function of compound nucleus mass number. Odd-N compound nuclei are represented by open symbols; closed symbols represent even-N nuclei.

Fig. B-2. Proton separation energies of the actinides as a function of compound nucleus mass number. Odd-Z compound nuclei are represented by open symbols; closed symbols represent even-Z nuclei.

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