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

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

ABSTRACT

Previous studies by Behrens have provided evidence of systematic behavior in neutron-induced fission cross sections in the incident neutron energy range 3 to 5 MeV. Recently measured fission cross-section ratios revealed this behavior. In this report, we used these measurements and those of others to illustrate the behavior of fission cross sections over the neutron energy range 0.1 MeV to 15 MeV. Similar trends are seen at 0.0253 eV, as revealed by thermal cross-section measurements.

INTRODUCTION

Studies of fission systematics date back to Huizenga¹ (1953) and Batzel² (1954) who correlated σ_f/σ_T and Γ_n/Γ_f ratios with the fissionability parameter, Z^2/A . Similar studies and discussions of fission systematics appear in Refs. 3 to 5. Behrens⁶ recently observed that measured fission cross-section ratios⁷⁻¹¹ on the first fission plateau (3 to 5 MeV incident neutron energy) exhibit straightforward systematic behavior with constant proton and neutron number for isotopes of thorium through californium. We extend these observations by summarizing in this report the behavior of fission cross sections over the energy range 0.1 MeV to 15 MeV, and at 0.0253 eV. Since this informal report is a summary that will be updated periodically, the reader may wish to refer to Ref. 6 for details.

DISCUSSION

References 7 through 11 describe the cross-section measurements of Behrens, et al. Neutron-induced fission cross sections of ²³²Th, ²³³U, ²³⁴U, ²³⁶U, ²³⁸U, ²³⁷Np, ²³⁹Pu, ²⁴⁰Pu, ²⁴¹Pu, ²⁴²Pu, ²⁴⁴Pu, ²⁴¹Am, and ²⁴³Am were measured relative to the fission cross section of ²³⁵U over the incident neutron energy range 1 keV to 30 MeV. Details of our experimental method appear in Ref. 7. Measurements by others¹²⁻²³ within this high-energy range provided fission cross-section data on ²³⁰Th, ²³¹Th, ²³³Th, ²³¹Pa, ²³²U,

^{235}U , ^{237}U , ^{239}U , ^{238}Pu , ^{243}Pu , ^{242}Cm , and ^{244}Cm . We used the $^{235}\text{U}(n,f)$ cross-section values from Refs. 21 to 23 to calculate fission cross-section ratios. The values reported in Refs. 24 to 27 were used to compare neutron-induced fission cross sections at 0.0253 eV.

The neutron energy range 0.1 to 15 MeV was divided into 35 arbitrarily chosen intervals of neutron energy. To illustrate the trends over the entire energy range, we use only 11 of these intervals. Figures 1 to 11 illustrate relative values for fission cross sections. These data represent averages over these energy intervals plotted as a function of the atomic mass number of the target nucleus. The symbols represent the actinide elements from thorium through californium. Fissile isotopes are shown as solid symbols, nonfissile isotopes as open symbols. On Figs. 1-5 and 11, these data are plotted to indicate exponential [part (a)] and linear [part (b)] behaviors.

Figures 1 through 3 represent the relative cross sections over the neutron energy range 0.1 to 1 MeV. The intervals (0.1 to 0.2 MeV, 0.5 to 0.6 MeV, and 0.8 to 0.9 MeV) clearly illustrate differences in the behavior of fission cross sections for fissile and nonfissile isotopes. The cross sections for fissile isotopes tend to increase linearly with increasing proton number, Z , as the number of neutrons, N , is held constant; generally they tend to decrease exponentially with increasing N as Z is held constant. The cross sections of nonfissile isotopes, however, behave consistently with the Hill-Wheeler formula²⁸ for transmission through the fission barrier.

As shown in Figs. 4 and 5, the energy range 1 to 5 MeV is represented by the neutron intervals 1.25 to 1.50 MeV and 4 to 5 MeV. The behavior of the cross sections for nonfissile isotopes tends to be similar with that of the fissile isotopes within this energy range. This is because the kinetic energy of the incident neutron becomes large enough to raise the excitation energy of the compound nucleus above the fission barrier. This threshold behavior characterizes the nonfissile isotopes; kinetic energy compensates for the neutron-pairing energy in the fissile isotopes. In the energy range 4 to 5 MeV, target nuclei differing by $\Delta A = 2$, ($\Delta Z = 1$, $\Delta N = 1$), and integer multiples of these are connected by straight lines (the dashed lines in Fig. 5).

The behavior of the relative cross sections from 5 to 15 MeV is essentially the same as that observed in the 4 to 5 MeV interval: all fission cross sections (fissile and nonfissile) tend to increase linearly with

increasing Z as N is held constant and tend to decrease exponentially with increasing N as Z is held constant. Figures 6 through 11 illustrate the behavior in the range 5 to 15 MeV. The thresholds for the $(n,n'f)$ and $(n,2n)$ reactions are within the interval 5 to 7 MeV (Figs. 6 through 8), and target nuclei differing by $\Delta A = 2$ ($\Delta Z = 1$, $\Delta N = 1$) can no longer be connected by straight lines (the dashed lines in Figs. 6 and 7). In the interval 9 to 10 MeV (on the second fission plateau), target nuclei differing by $\Delta A = 3$ ($\Delta Z = 1$, $\Delta N = 2$), and integer multiples of these are connected by straight lines (the dashed lines in Fig. 9). Within the interval 11 to 12 MeV (Fig. 10) are the thresholds for the $(n,2n'f)$ and $(n,3n)$ reactions. The third fission plateau is represented by the interval from 14 to 15 MeV, as shown in Fig. 11.

Many of the features observed over the energy range 0.1 to 15 MeV are also found at 0.0253 eV, as shown in Fig. 12(a) and (b). This figure shows *absolute* fission cross-section values at 0.0253 eV plotted as a function of the atomic mass of the target nucleus. The behavior of the nonfissile isotopes at 0.0253 eV is similar to that observed in the energy range 0.1 to 1 MeV (Figs. 1 through 3). Figure 12(b) illustrates that fissile isotopes with even Z follow constant neutron curves at 0.0253 eV, just as they follow constant neutron lines at incident neutron energies above 0.1 MeV (Figs. 1 through 11). Studies within the thermal neutron energy range are important because, for fissile and nonfissile isotopes alike, neutron-induced fission occurs with the compound nucleus at its lowest excitation energy.

Systematic trends observed recently by Behrens⁶ exist throughout the energy range 0.1 to 15 MeV and at 0.0253 eV. These trends should give us clues to the properties that fission models of the nucleus must possess. Improved models are needed to calculate fission cross sections^{29,30} for nuclei that cannot be measured using current methods. Alternatively, predicted fission cross-section values based on empirical formulae derived from studies of systematic behavior³¹ should become more credible as cross-section measurements on more isotopes are found consistent with the trends we have discussed here.

Fig. 1. Neutron-induced fission cross sections relative to ^{235}U from 0.1 to 0.2 MeV, as a function of target-nucleus mass number: (a) semi-log, (b) linear.

Fig. 2. Neutron-induced fission cross sections relative to ^{235}U from 0.5 to 0.6 MeV, as a function of target-nucleus mass number: (a) semi-log, (b) linear.

Fig. 3. Neutron-induced fission cross sections relative to ^{235}U from 0.8 to 0.9 MeV, as a function of target-nucleus mass number: (a) semi-log, (b) linear.

Fig. 4. Neutron-induced fission cross sections relative to ^{235}U from 1.25 to 1.5 MeV, as a function of target-nucleus mass number: (a) semi-log, (b) linear.

Fig. 5. Neutron-induced fission cross sections relative to ^{235}U from 4 to 5 MeV, as a function of target-nucleus mass number: (a) semi-log, (b) linear.

Fig. 6. Neutron-induced fission cross sections relative to ^{235}U from 5 to 5.5 MeV, as a function of target-nucleus mass number.

Fig. 7. Neutron-induced fission cross sections relative to ^{235}U from 5.5 to 6 MeV, as a function of target-nucleus mass number.

Fig. 8. Neutron-induced fission cross sections relative to ^{235}U from 6 to 7 MeV, as a function of target-nucleus mass number.

Fig. 9. Neutron-induced fission cross sections relative to ^{235}U from 9 to 10 MeV, as a function of target-nucleus mass number.

Fig. 10. Neutron-induced fission cross sections relative to ^{235}U from 11 to 12 MeV, as a function of target-nucleus mass number.

Fig. 11. Neutron-induced fission cross sections relative to ^{235}U from 14 to 15 MeV, as a function of target-nucleus mass number: (a) semi-log, (b) linear.

Fig. 12. Neutron-induced fission cross sections at 0.0253 eV: (a) semi-log, (b) linear.

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