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# HEDL EVALUATION OF THORIUM CYCLE CROSS SECTIONS FOR ENDF/B-V

## Hanford Engineering Development Laboratory

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## ABSTRACT

*Four nuclei, Thorium-230 ($^{230}Th$), Protactinium-231 ($^{231}Pa$), Protactinium-233 ($^{233}Pa$) and Uranium-232 ($^{232}U$), which are important in the uranium-thorium cycle have been evaluated for the Evaluated Nuclear Data File/B-V (ENDF/B-V). $^{230}Th$, $^{231}Pa$ and $^{232}U$ are new to the ENDF/B system.*

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# HEDL EVALUATION OF THORIUM CYCLE CROSS SECTIONS FOR ENDF/B-V (FF051)

## I. SUMMARY

Three new evaluations, Thorium-230 ($^{230}$Th), Protactinium-231 ($^{231}$Pa) and Uranium-232 ($^{232}$U), have been created for the Evaluated Nuclear Data File/B-V (ENDF/B-V). The $^{233}$Pa evaluation remains basically unchanged from ENDF/B-II.

## II. INTRODUCTION

The thorium-uranium cycle is gaining attention because of its perceived role in proliferation-resistant reactor designs. Four nuclei in this cycle, $^{230}$Th, $^{231}$Pa, $^{233}$Pa, and $^{232}$U, have been reviewed by the Nuclear Analysis Section of the Hanford Engineering Development Laboratory (HEDL) for the inclusion in the fifth release of ENDF/B. This work is an extension of earlier actinide evaluations.[1]

Protactinium-233 is important because it is an intermediate step in turning fertile $^{232}$Th into fissile $^{233}$U $\left[^{232}\text{Th}(n,\gamma)\ ^{233}\text{Th}(\beta-)\ ^{233}\text{Pa}(\beta-)\ ^{233}\text{U}\right]$. Although $^{233}$Pa participates through its decay, because of its relatively long half-life (27 days), siphoning off of $^{233}$Pa through reactions can play a significant role in the breeding or conversion ratio of a reactor.

$^{230}$Th, $^{231}$Pa, and $^{232}$U are important in the production and destruction of $^{232}$U which is an important source of gamma radiation.[2] The evaluations are new to the ENDF/B system.

## III. GENERAL PROCEDURE

Unlike other actinides evaluated by HEDL, there exists scant experimental information for these isotopes. Where possible, experimental information, guided by the CINDA bibliography,[3] was used. However, in most cases, statistical model calculations based on the computer code HAUSER*4[4] were used above the resonance region. Resolved parameters were taken from BNL-325[5] for each of the isotopes. For $^{231}$Pa and $^{232}$U, unresolved parameters were based on the given resolved parameters.

The parameters used in HAUSER*4 were adjusted, in most cases, to agree with known experimental cross sections. In these cases, great confidence can be placed on the extrapolation from known values based on the calculations. In cases where no experimental data exists, systematics had to be used.

The calculations are most sensitive to the optical potential used, the level structure assumed, and fission barrier specified. The optical potential is based on the work of Lindsay,[6] who varied potential depth and shapes to achieve agreement with known *s* and *p* wave strength functions. The parameters do vary from nucleus to nucleus, but the set given in Table 1 provided an accurate representation of the potentials.

Much information is known concerning the lowest states of the actinide nuclei since, for the most part, in a given nucleus they are members of rotational bands. Using the knowledge of bands heads, complete level structures could often be constructed. In some cases this construction provided a significant addition to the very scanty experimental information available. Because of the high density of states, even at low energies, a level density description had to be used. Level density parameters based on the back shifted Fermi gas formula (with $U = E - \Delta = aT^2$, E being the excitation energy, $\Delta$ a pairing energy, and T the nuclear temperature) were obtained from known and systematically postulated low-lying discrete states and experimentally determined level spacings at the neutron separation energy. This latter quantity depends on the distribution of angular momentum at the separative energy and a function of the spin cutoff factor. This factor is often taken as a linear function of mass, which works very well for $A < 100$. But as seen later in this report, a much reduced value fits experimental data better for $A \sim 200$ and higher. The obtained level density parameters shown in Figure 1 clustered about values shown in Table 2 and were used where no other information was available.

Fission barrier heights were estimated first from the work of Weigman and Theobald,[7] but, because of the sensitivity of the prediced cross sections to barrier heights, slight modifications were sometimes needed. Capture cross sections, based on the work of Holmes et al.,[8] consisted of E1 and M1 transitions.

## IV. SPECIFIC ISOTOPES

### Thorium-230

The only experimental information available in the fast region is on the fission cross section. The evaluation follows the data of Muir and Vesser[9] which results from Los Alamos Scientific Laboratory (LASL) bomb test data, see Figure 2. Above 1.2 MeV, these results differ from Lynn et al.[10] Below 300 keV and above 3 MeV, the fission evaluation follows the results of HAUSER*4. The other cross sections, (total and capture are shown in Figures 3 and 4 respectively) result from computer calculation.

### Protactinium-231

The only experimental information available in the fast region is the fission data of Muir and Vesser resulting from LASL bomb test data (see Figure 5). Below 300 keV and above 3 MeV, the fission evaluation follows the results of HAUSER*4. The other cross sections entirely result from statistical model computer codes. Total and capture are shown in Figures 6 and 7 respectively.

### Protactinium-233

No new data have been measured since the last evaluation for ENDF/B-II by Young.[11] The evaluation was checked against resonance data and systematics of near-by nuclei. The evaluation was made consistent with ENDF/B-V procedures.

### Uranium-232

Again, the only experimental information is the fission cross section resulting from LASL bomb tests.[12,13] All cross sections are calculated by HAUSER*4 which agrees well with the known experimental data (the fission, total and capture are shown in Figures 8 through 10).

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TABLE 1

NEUTRON-ACTINIDE OPTICAL POTENTIALS

Real Potential (Woods-Saxon):

$V_o$ = 43.0 MeV, r = 1.28 $A^{1/3}$f, a = 0.65 fm

Imaginary Potential (derivative Woods-Saxon):

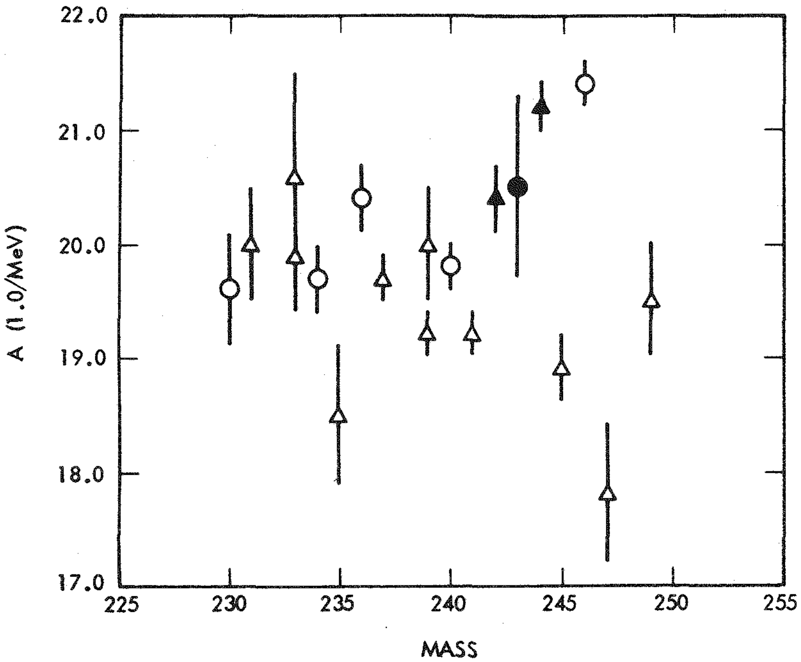
$W_s$ = 13 MeV, r = 1.28 $A^{1/3}$f, a = 0.47 fm

TABLE 2

GLOBAL LEVEL DENSITY PARAMETERS

FOR ACTINIDE NUCLEI

| | |
|---|---|
| a = 19.5 | |
| $\sigma^2 = 32.5 \left[(E-\Delta)/a\right]^{1/2}$ | |
| $\Delta$ = 0.04 | even-even nucleus |
| -0.63 | odd-even |
| -0.63 | even-odd |
| -1.26 | odd-odd |



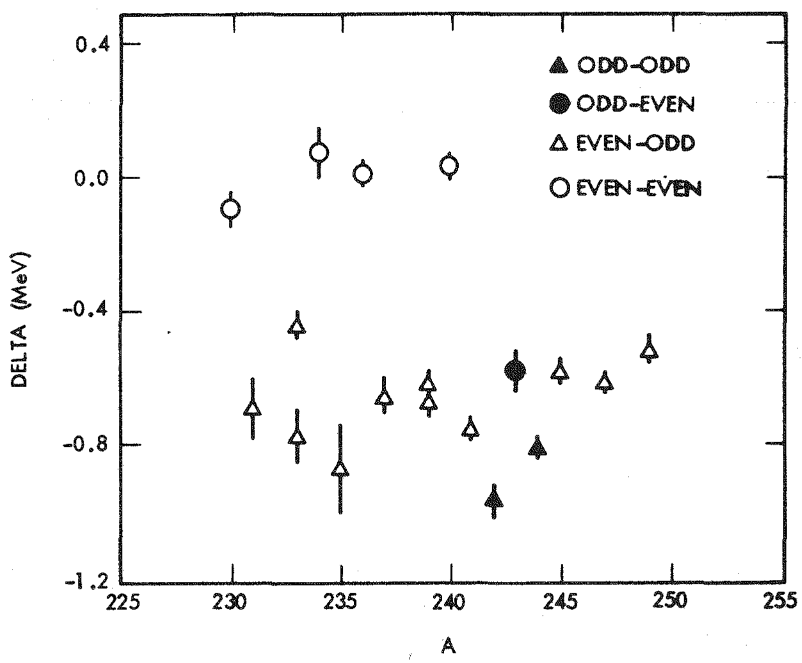




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FIGURE 1-a. Level Density Parameter for Spin Cutoff Factor = 32.5T.

FIGURE 1-b. Pairing Energy Parameter for Spin Cutoff Factor = 32.5T

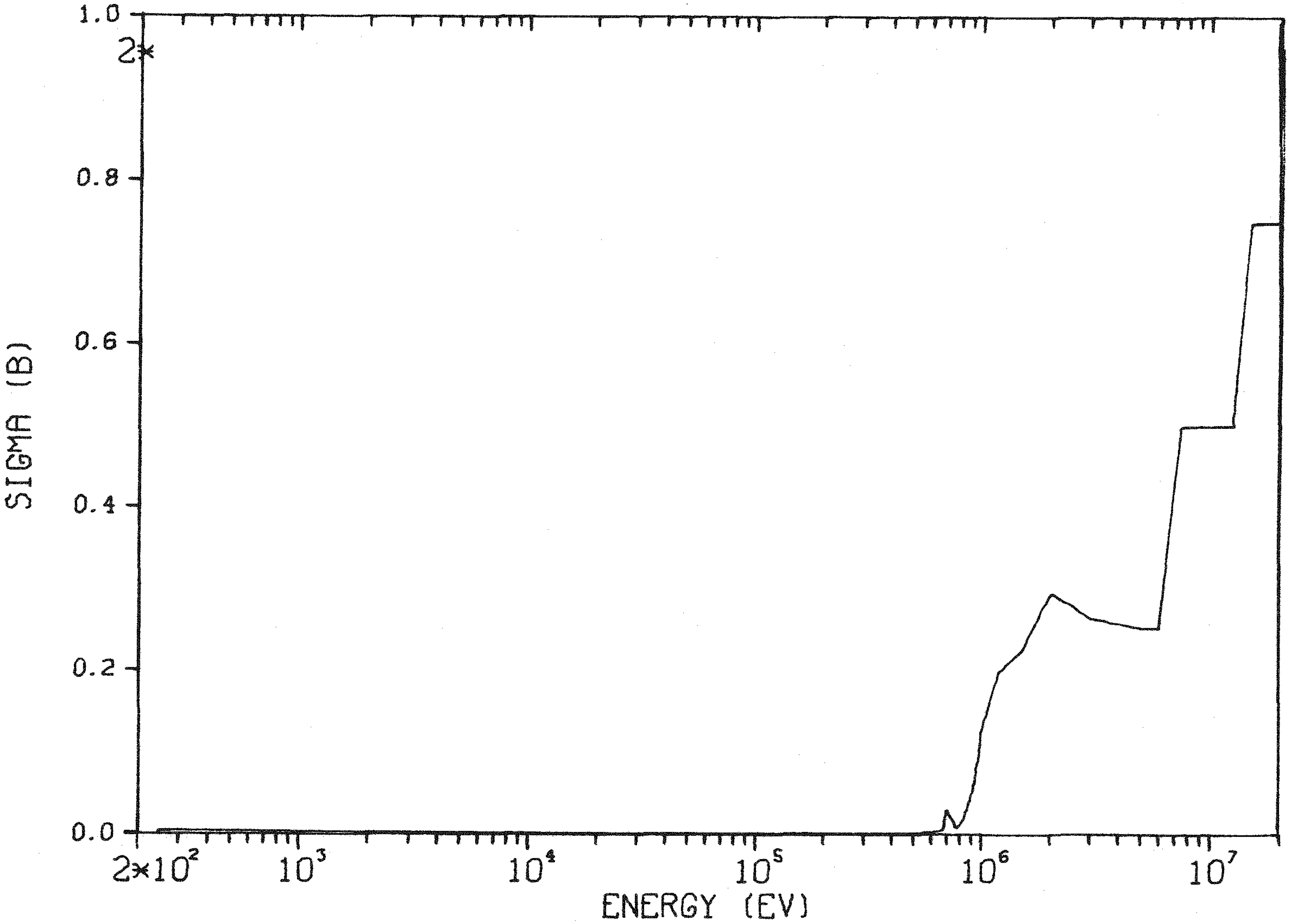


FIGURE 2. Thorium-230 (n,f).

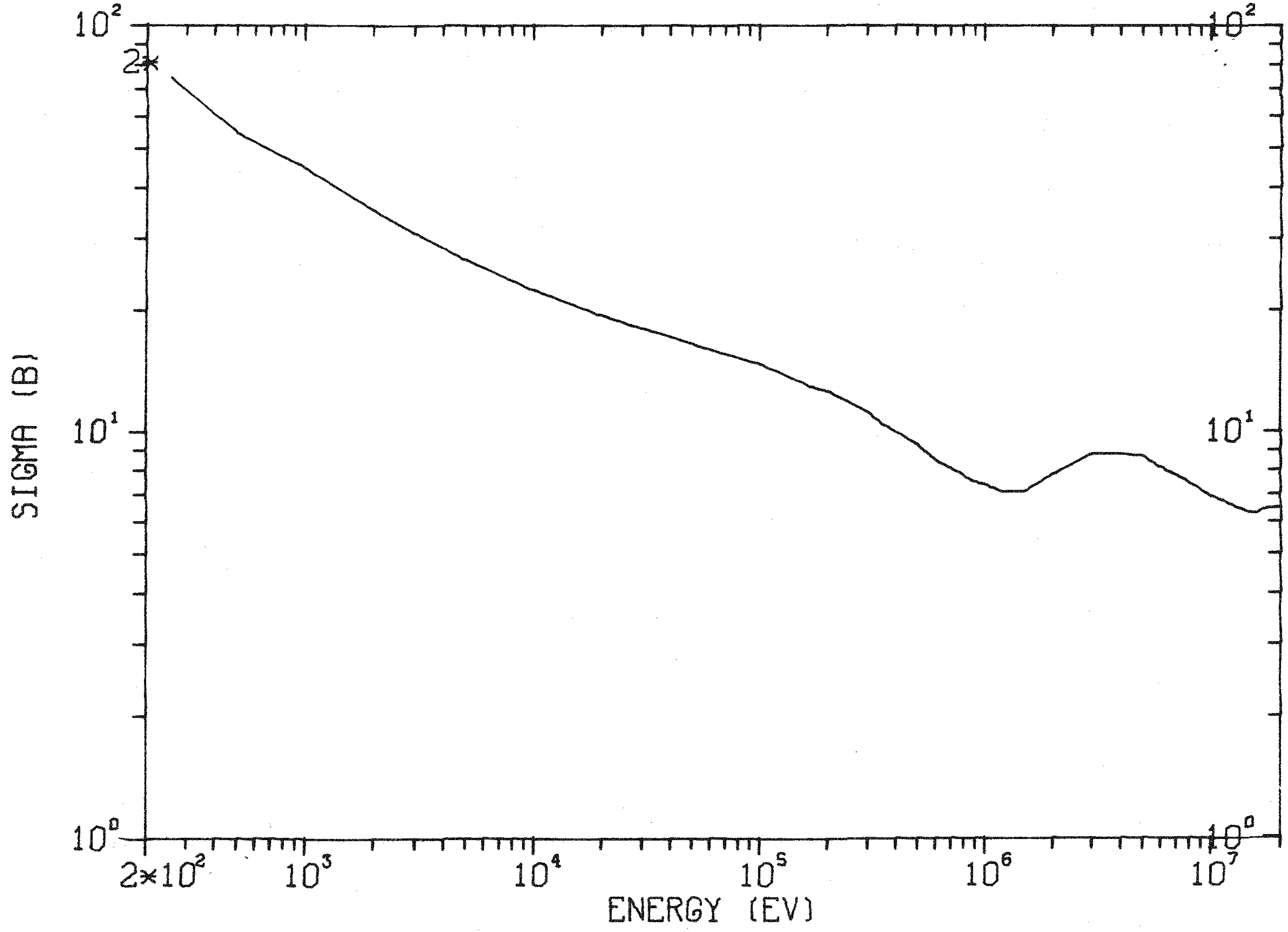


FIGURE 3. Thorium-230 Total.

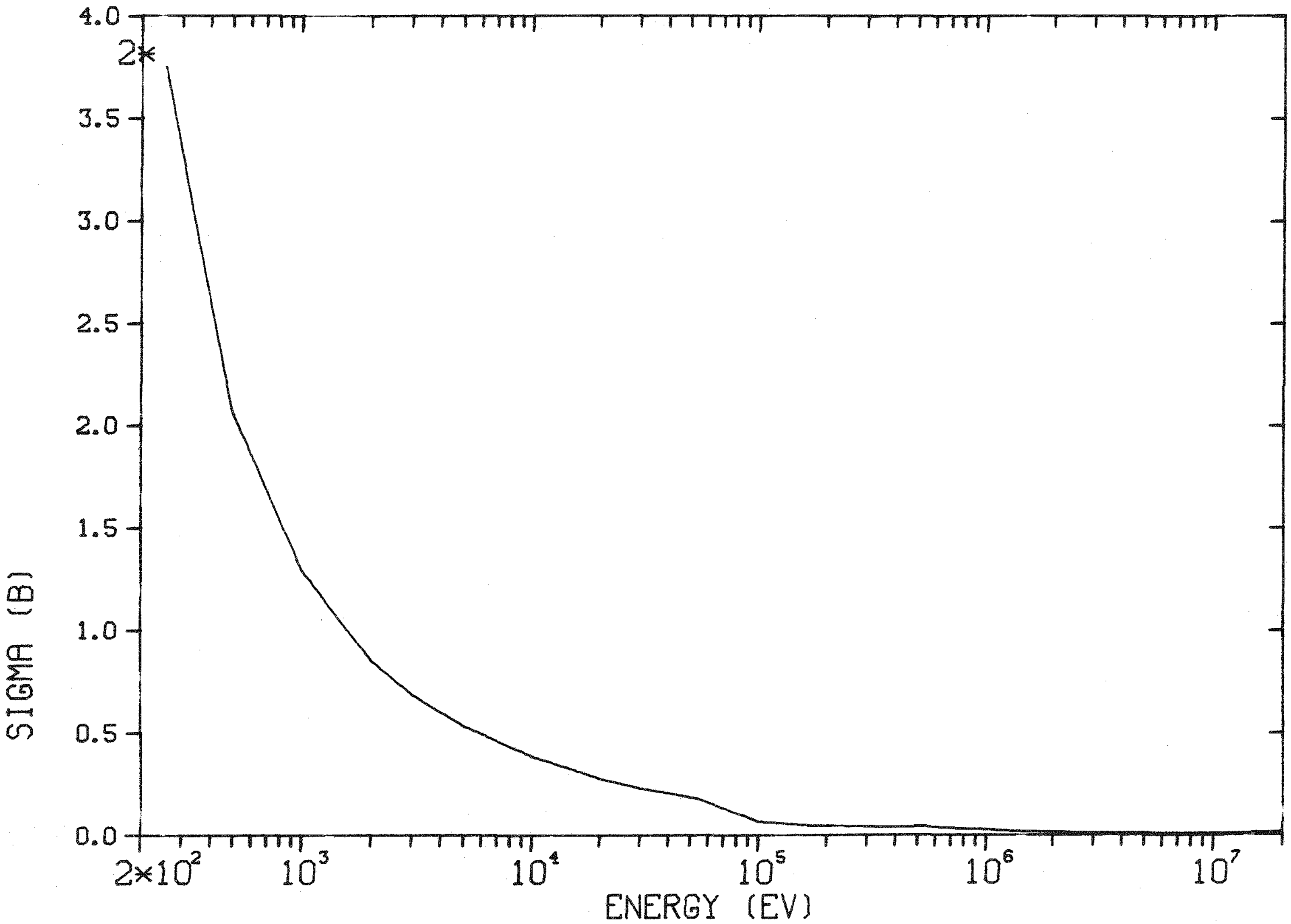


FIGURE 4. Thorium-230 Capture.

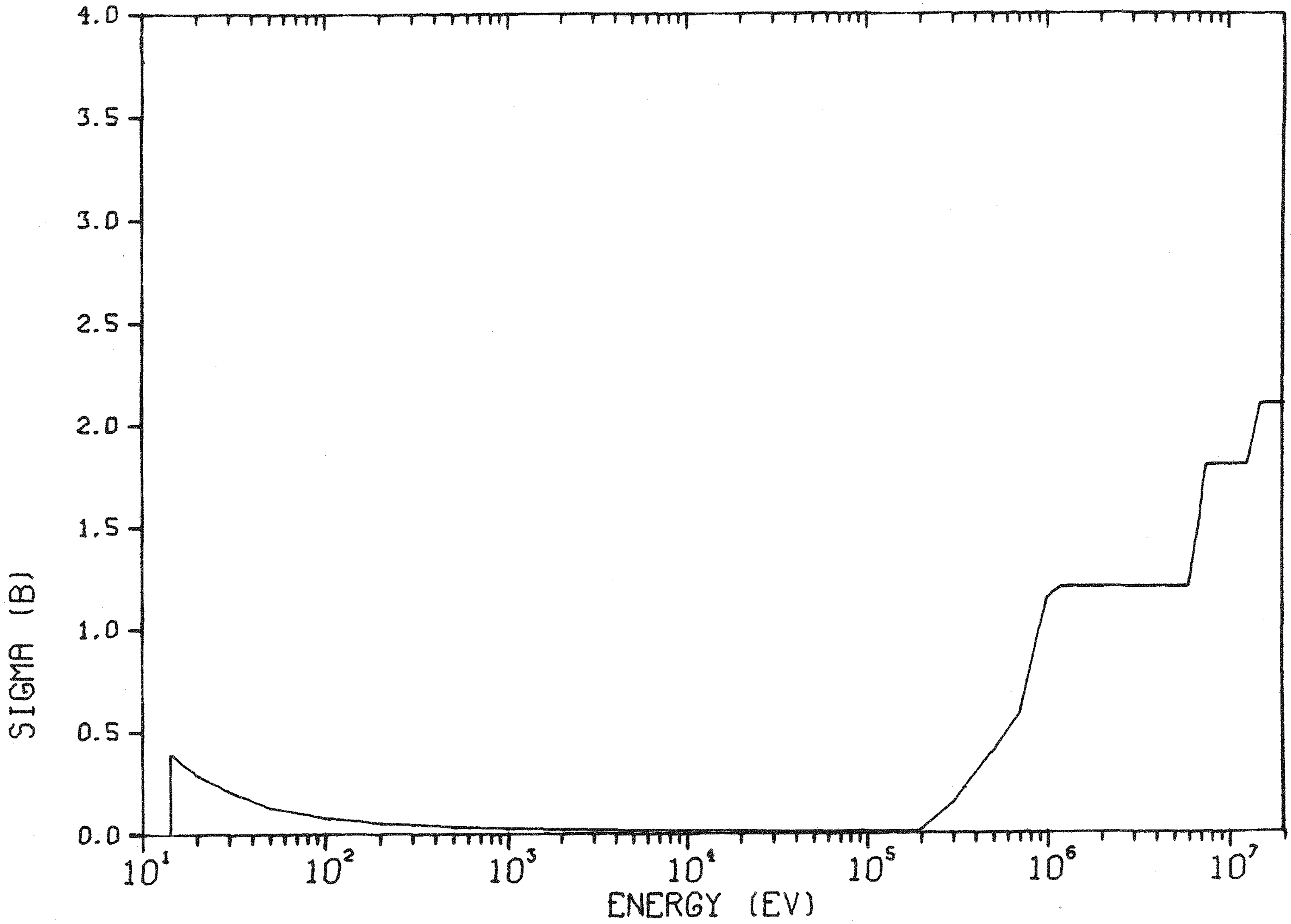


FIGURE 5. Protactinium-231 (n,f).

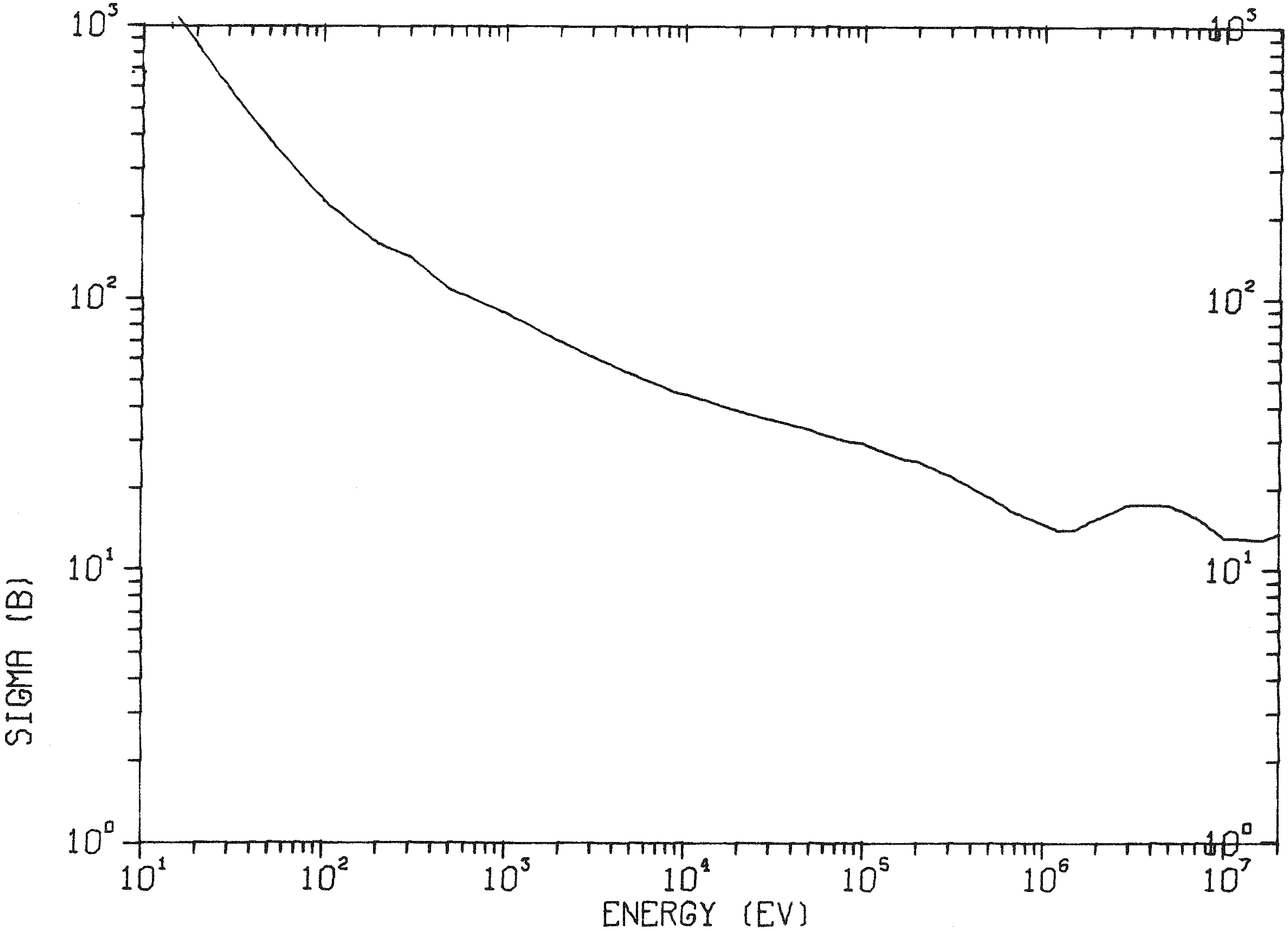


FIGURE 6. Protactinium-231 Total.

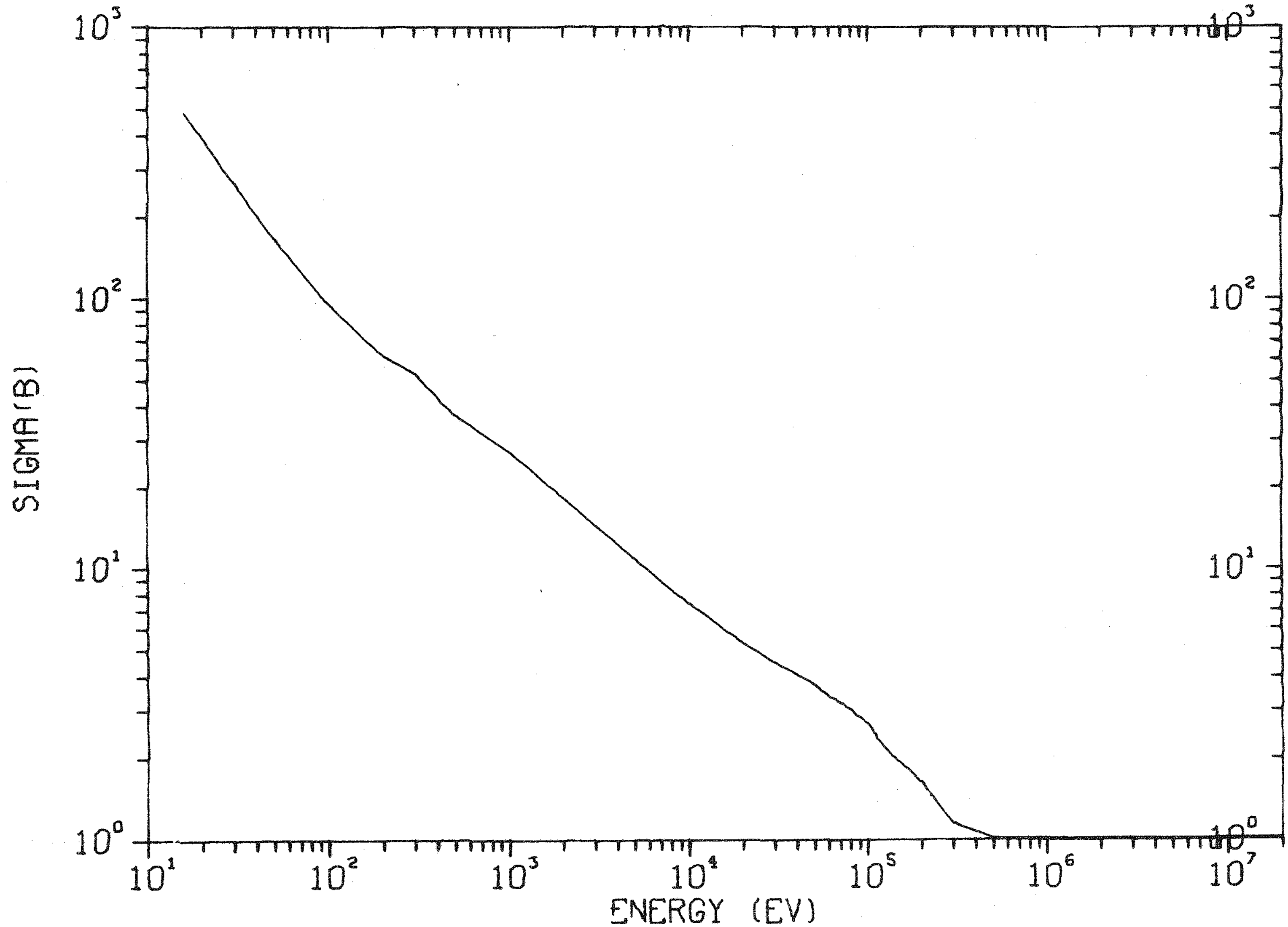


FIGURE 7. Protactinium-231 Capture.

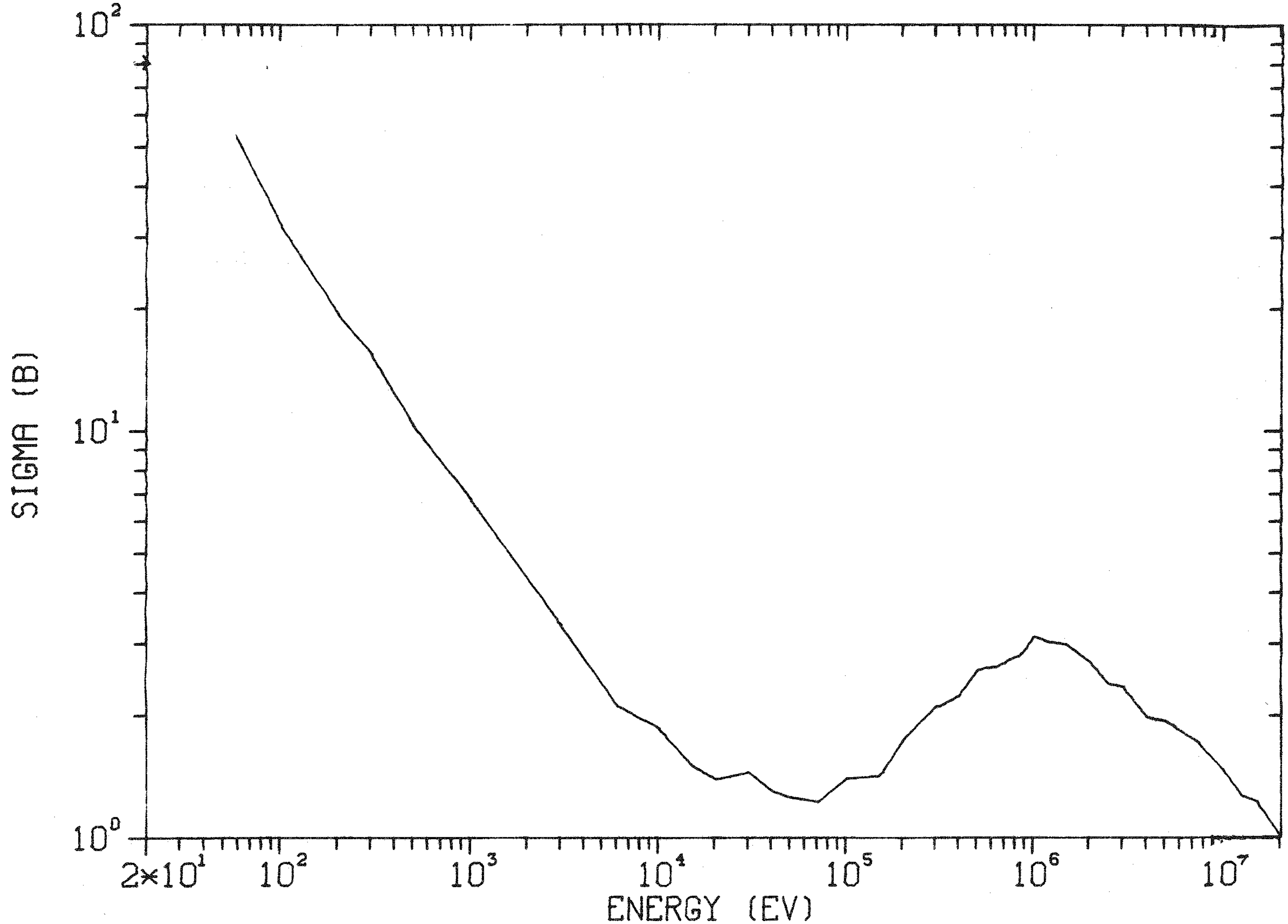


FIGURE 8. Uranium-232 (n,f).

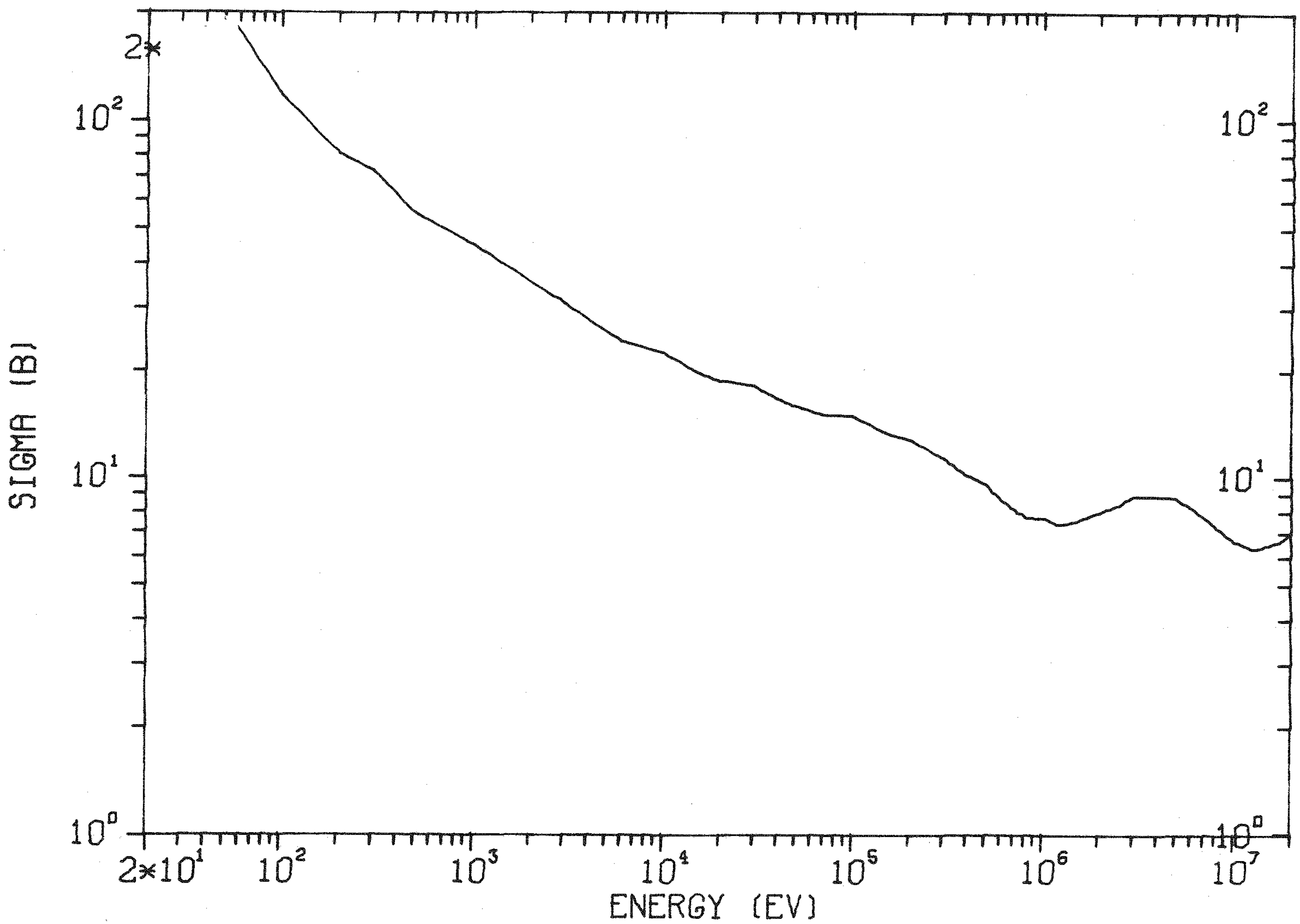


FIGURE 9. Uranium-232 Total.

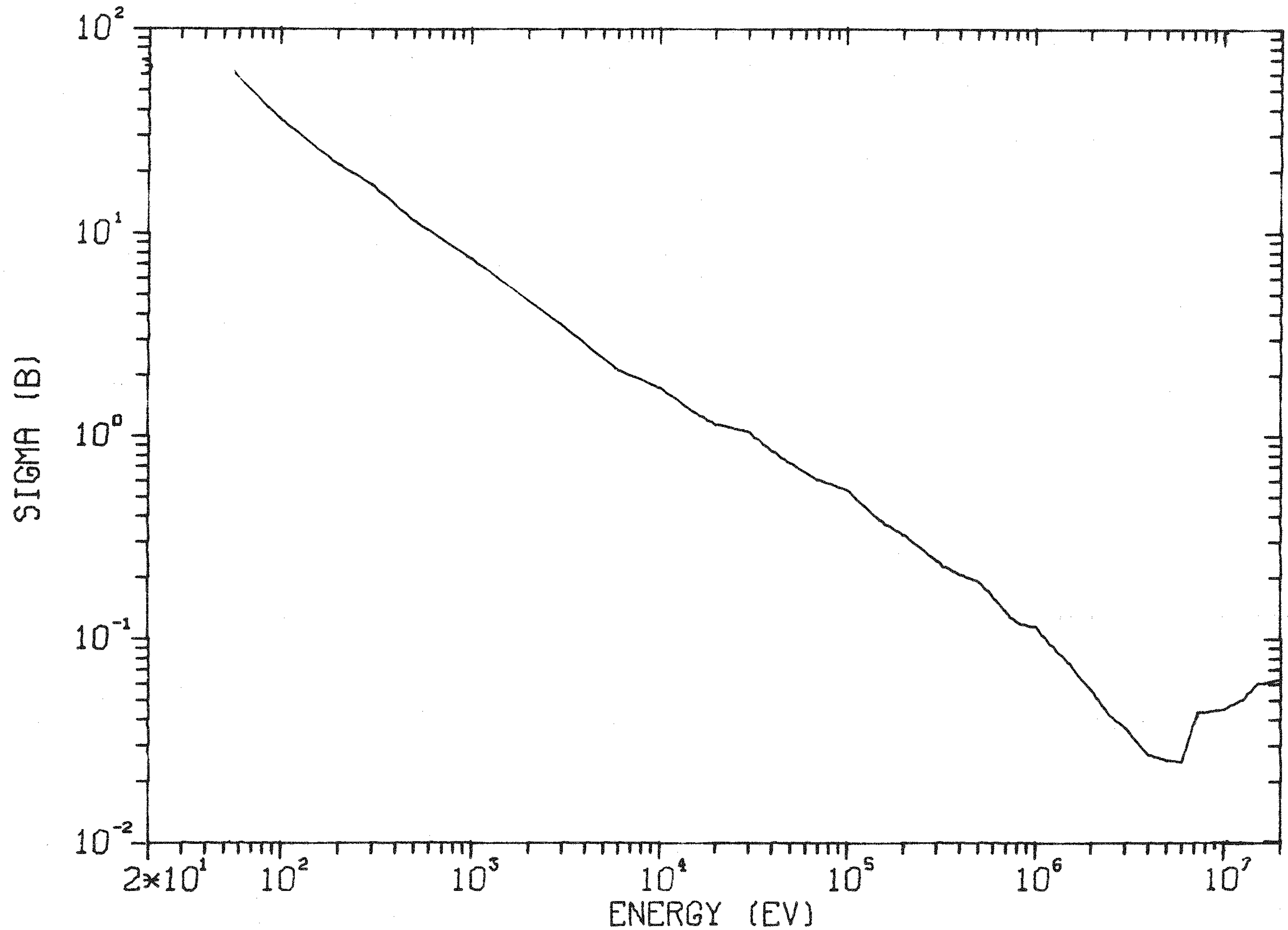


FIGURE 10. Uranium-232 Capture.

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