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by

J. J. Devaney

AN EVALUATION OF THE RADIATIVE-CAPTURE CROSS SECTION FOR TUNGSTEN

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ABSTRACT

An evaluation of the smooth neutron radiative-capture cross section for tungsten and its isotopes between 0.006 and 20 MeV is presented. Included are multiple-reaction corrections to the data which lower the cross section appreciably, especially above 1 MeV. The results are available in ENDF/B format.

I. INTRODUCTION

This paper, an interim report on the evaluation of tungsten neutron cross sections, gives the smooth radiative-capture cross sections from about 0.006 to 20 MeV. We have continued the conservative philosophy of the first paper in this series (De72a); that is, the expected fluctuations at low energy have not been displayed because they could not be substantiated from author to author nor from isotope to isotope. This remark is perhaps borderline for normal tungsten between 0.04 and 0.1 MeV (see Fig. 1 at the end of the report) where several authors (Gi61, Fr70, Ba69) partially agree on some fluctuation; however, this agreement is not substantiated by comparison of the abundance-weighted isotopic sum with natural tungsten, and it is even contradicted by others (e.g. Po67). We do find significant differences between the isotopic cross-sections, supported both by data and theory, with a reversal in relative magnitude of the isotopes at about 0.2 MeV. This reversal is caused by the differing onset and importance of inelastic-scattering competition. Beyond 3.4 MeV, we cannot justify any isotopic differences, so only the natural element is offered (See Fig. 16). The cross section above about 7 MeV is expected to result largely from direct and collective (semidirect) processes (Cl65, Br64, Gu66, Lo68, Be68, Be71, Lo70, Ve67, Be70, La59, Lo69, but see also Da64 and Sp69 who would permit higher statistical contributions). In our evaluation, we have weighted experiment according to the stated error, point scatter, comparisons with other data, age, consistency, extensiveness, and general theoretical expectations. Wherever we could determine the sample size, we made multiple reaction corrections (Dr71, De72b, De73). However, without known sample sizes and the consequent amount of the multiple reaction correction needed, we are forced to regard some of the data above 1 MeV as only upper bounds to the true cross sections. These data are so indicated in the figures by downward directed arrows.

II. RESULTS

We present the smooth capture cross sections in a series of graphs, (Figs. 1-16), together with experimental points as corrected for multiple reactions (De73) and for revised standard cross sections where appropriate. We have put error bars on only a few representative points for clarity. References to experiment are given on each graph. Above 3.4 MeV, the curve for ^{186}W (Fig. 16) is our best estimate for all isotopes. Above 1 MeV, all even isotopes are given by ^{186}W, Fig. 15. The smooth cross sections are also given in tabular form in Appendix A,(ENDF/B format - Dr70).

The smooth curve through the data was generated from weighted cross-section averages over variable energy intervals. Intervals and numbers of experimental points were varied widely as appropriate to an optimum description of the smooth curves. Initial analyses were readjusted within errors so that the abundance-weighted isotopic sums matched the normal element to within experimental error.

^{180}W [abundance 0.135% (Ni 58)] and other isotopes (0.005%) were combined with ^{182}W (26.41%) for an effective abundance of 26.55%, and ^{183}W was taken as 14.40%, ^{184}W as 30.64%, and ^{186}W as 28.41% (Ni 58). The atomic weight of natural tungsten is 183.85.

III. DISCUSSION

A. 0.1- to 3.4-MeV Neutron Energy.

Comparison of our curves for W and ^{186}W, (Fig. 6 vs Fig. 10), shows that $\sigma_{n\gamma}(^{186}W)$ crosses from below to above $\sigma_{n\gamma}(W)$ at about 0.23 MeV. Interpreting this effect to be the more successful competition of inelastic scattering of the lighter isotopes, especially the odd isotope, ^{183}W, we have constructed the curves of Figs. 7-9 and 11-14. Onset of inelastic scattering is appreciable above the first level of the target, which is 0.1001 MeV for ^{182}W (Wa66), 0.0465 MeV for ^{183}W (Ar66), 0.1112 MeV for ^{184}W (Ma66), and 0.1225 MeV for ^{186}W (Gov 66). The $(n,\gamma n')$ reaction, which also contributes below the first excited level of the target, is expected to be negligible within the accuracy of our estimates of the effect of inelastic scattering on the capture cross section, (See Ref. 14 of De73 for further discussion.) We used identities of the form

$$\sigma_{n\gamma} = \sigma_{FCN} \frac{\sigma_{n\gamma}}{\sigma_{cnn} + \sigma_{nn'} + \sigma_{n\gamma}} \qquad (1)$$

to estimate the competition of inelastic scattering. $\sigma_{FCN} \equiv \sigma_{cnn} + \sigma_{nn'} + \sigma_{n\gamma}$ is the compound-nucleus-formation cross section; σ_{cnn} is the compound elastic cross section; and $\sigma_{nn'}$ is the total inelastic scattering. These parameters were taken from experiment, extrapolated from experiment, and estimated from optical-model calculations. The results were then revised to fit σ_T (De72a), as well as the known experimental $\sigma_{n\gamma}$ self-consistently for W and ^{186}W plus ^{182}W, ^{183}W, and ^{184}W only up to 0.1 MeV. All cross sections were further adjusted within errors so that the abundance-weighted isotopic sum gave the normal tungsten cross section to well within experimental error. In the above, we used the inelastic scattering data of Lister et al. (Li67 and Gol66) for ^{182}W, ^{184}W, and ^{186}W. ^{183}W inelastic scattering was estimated on the basis of the Artna level scheme (Ar66). It might be noted that this procedure gave cross sections differing by about a factor of 2 from the high-energy capture data of Kononov et al. (Ko66), which data we argue are justifiably rejected because of the equal disagreement of Kononov et al. not only with our above described extrapolation above 0.1 MeV, but also with the ^{186}W weighted average curve at 0.1 - 0.17 MeV (see Fig. 10). Their data also disagree with the W curve (see Fig. 6).

Reliable data for ^{182}W, ^{183}W, and ^{184}W end at 0.1 MeV. We do carry the evaluations for ^{182}W and ^{184}W distinct from ^{186}W to about 1 MeV according to the foregoing prescription in order to account for the natural vs ^{186}W cross-section difference. Beyond 1 MeV, we expect a gradual equivalence in cross section for the even isotopes, but, perhaps more importantly, we have already extrapolated 0.9 MeV above any datum. Consequently, we blend ^{182}W and ^{184}W into ^{186}W at about 1 MeV. However we keep ^{183}W distinct to higher energy. Accordingly, $\sigma_{n\gamma}$ ^{183}W is predicted to be smaller than for the even isotopes until about 3.4 MeV, where lack of data forces us to one curve for all isotopes. Convergence of the $\sigma_{n\gamma}$ curves is somewhat expected since one believes that isotopic differences tend to disappear at high energy, especially for the dominant collective giant-resonance part.

B. 3.4- to 20-MeV Neutron Energy.

As noted above, we offer one curve for all isotopes in this range (Fig. 16). We have data at 3-4 MeV for ^{186}W and at 14.1 MeV for A = 181 and 197 (Dr71). We know that the compound-nucleus process dominates at low energy and the direct and giant-resonance collective processes dominate at the middle energies (Cl65, Br64, Be68, Be70, Be71, Lo68, Lo69, Lo70, Gu66, Ve67, and La59, but see also Da64 and Sp69). Therefore, for the lower energies in this range, we take as a guide the work of Lane and Lynn (theory-La59), Schmittroth for ^{197}Au (theory-Sc72), Barry et al. for ^{238}U (expt.-Ba64), and Bergqvist et al. for ^{58}Ni (expt. and theory-Be68). From 7-15 MeV we are guided by Coulomb unfolded (p,γ) cross sections ($^{142}Ce(p,\gamma)^{143}Pr$, Da64 and Ve66; $^{100}Mo(p,\gamma)^{101}Tc$, Da68; $^{82}Se(p,\gamma)^{83}Br$, Da68; $^{130}Te(p,\gamma)^{131}I$, Da64; $^{209}Bi(p,\gamma)^{210}Po$, Da64; $^{59}Co(p,\gamma)^{60}Ni$, Dr72; $^{60}Ni(p,\gamma)^{61}Cu$, Dr72; and $^{64}Zn(p,\gamma)65Ga$, Dr72); and by (n,γ) cross sections on elements other than tungsten ($^{206}Pb(n,\gamma)^{207}Pb$, Be70; $^{58}Ni(n,\gamma)^{59}Ni$, Be68; $^{40}Ca(n,\gamma)^{41}Ca$, Be72a; $^{208}Pb(n,\gamma)^{209}Pb$, Be72b; $^{165}Ho(n,\gamma)^{166}Ho$, Mc73; and $^{238}U(n,\gamma)^{239}U$, Mc73). We unfold the coulomb penetration from the proton reactions using the code PENET kindly supplied by P. G. Young (Yo72).

In estimating the trend of $\sigma_{n,\gamma}$ above 15 MeV we have been guided by Gutfreund and Rakavy (Gu66) and by Longo and Saporetti (Lo68).

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APPENDIX

ENDF/B-FORMAL LISTING OF TUNGSTEN CROSS SECTIONS

The capture cross section of tungsten and its isotopes from about 0.005 MeV to 20 MeV are listed in ENDF/B format. Hollerith descriptive information is omitted here because it is included in the text.

```
TUNGSTEN SMOOTH RADIATIVE CAPTURE CROSS SECTION  MATERIAL 740       740 1451     7
 7.40000+04 1.82213+02           0           0                      740 3102    46
 0.00000+ 0+5.4661 +06           0                      2        53 740 3102    47
          17           2          53           4                    740 3102    48
 5.8       +03 7.       -01 7.       +03 5.98     -01 9.       +03 5.21     -01 740 3102    49
 1.1       +04 4.65     -01 1.5      +04 3.94     -01 1.8      +04 3.54     -01 740 3102    50
 2.2       +04 3.17     -01 2.5      +04 2.9      -01 3.       +04 2.67     -01 740 3102    51
 3.5       +04 2.45     -01 4.       +04 2.28     -01 5.       +04 2.02     -01 740 3102    52
 6.        +04 1.91     -01 7.       +04 1.87     -01 8.       +04 1.815    -01 740 3102    53
 9.        +04 1.71     -01 1.       +05 1.55     -01 1.2      +05 1.31     -01 740 3102    54
 1.4       +05 1.12     -01 1.6      +05 9.95     -02 1.8      +05 9.12     -02 740 3102    55
 2.        +05 8.37     -02 2.4      +05 7.11     -02 2.6      +05 6.67     -02 740 3102    56
 3.        +05 6.07     -02 3.4      +05 5.68     -02 4.       +05 5.21     -02 740 3102    57
 4.6       +05 4.81     -02 5.0      +05 4.65     -02 6.       +05 4.44     -02 740 3102    58
 8.        +05 4.11     -02 1.0      +06 3.92     -02 1.5      +06 3.36     -02 740 3102    59
 1.8       +06 3.05     -02 2.0      +06 2.79     -02 2.5      +06 2.06     -02 740 3102    60
 3.        +06 1.46     -02 3.4      +06 1.09     -02 5.       +06 2.39     -03 740 3102    61
 6.        +06 1.07     -03 6.3      +06 9.1      -04 6.5      +06 8.8      -04 740 3102    62
 6.7       +06 8.7      -04 7.0      +06 8.9      -04 8.       +06 1.06     -03 740 3102    63
 9.        +06 1.33     -03 1.       +07 1.48     -03 1.1      +07 1.51     -03 740 3102    64
 1.2       +07 1.35     -03 1.3      +07 1.22     -03 1.4      +07 1.0      -03 740 3102    65
 1.7       +07 4.6      -04 2.0      +07 2.0      -04                           740 3102    66
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TUNGSTEN-182 SMOOTH RADIATIVE CAPTURE CROSS SECTION  MATERIAL 742   742 1451     6
 7.41820+04 1.80385+02           0           0                      742 3102    29
 0.00000+ 0+6.19140+06           0                      2        51 742 3102    30
          17           2          51           4                    742 3102    31
 4.85      +03 7.       -01 1.       +04 5.83     -01 1.5      +04 4.85     -01 742 3102    32
 2.        +04 4.       -01 2.5      +04 3.31     -01 3.       +04 2.8      -01 742 3102    33
 3.5       +04 2.46     -01 4.       +04 2.19     -01 4.5      +04 2.0      -01 742 3102    34
 5.        +04 1.95     -01 6.       +04 1.915    -01 7.       +04 1.93     -01 742 3102    35
 7.5       +04 1.93     -01 8.       +04 1.89     -01 8.5      +04 1.81     -01 742 3102    36
 9.        +04 1.715    -01 1.       +05 1.56     -01 1.2      +05 1.233    -01 742 3102    37
 1.4       +05 1.16     -01 1.6      +05 1.03     -01 1.8      +05 9.37     -02 742 3102    38
 2.        +05 8.64     -02 2.6      +05 6.87     -02 3.       +05 6.1      -02 742 3102    39
 3.4       +05 5.6      -02 4.       +05 5.13     -02 5.       +05 4.65     -02 742 3102    40
 6.0       +05 4.37     -02 7.       +05 4.23     -02 1.       +06 3.99     -02 742 3102    41
 1.5       +06 3.4      -02 1.8      +06 3.12     -02 2.       +06 2.82     -02 742 3102    42
 2.5       +06 2.09     -02 3.       +06 1.49     -02 3.4      +06 1.12     -02 742 3102    43
 5.        +06 2.39     -03 6.       +06 1.07     -03 6.3      +06 9.1      -04 742 3102    44
 6.5       +06 8.8      -04 6.7      +06 8.7      -04 7.0      +06 8.9      -04 742 3102    45
 8.        +06 1.06     -03 9.       +06 1.33     -03 1.       +07 1.48     -03 742 3102    46
 1.1       +07 1.51     -03 1.2      +07 1.35     -03 1.3      +07 1.22     -03 742 3102    47
 1.4       +07 1.0      -03 1.7      +07 4.6      -04 2.       +07 2.0      -04 742 3102    48
```

TUNGSTEN-183 SMOOTH RADIATIVE CAPTURE CROSS SECTION MATERIAL 743 743 1451 6

7.41830+04	1.81379+02		0	0			743 3102	27
0.00000+ 0	+7.4111 +06		0		2	48	743 3102	28
	13	2	48	4			743 3102	29
1.6	+04 7.01	-01 2.	+04 6.34	-01 2.5	+04 5.72	-01	743 3102	30
3.	+04 5.23	-01 4.	+04 4.45	-01 5.	+04 3.79	-01	743 3102	31
5.5	+04 3.51	-01 6.	+04 3.32	-01 7.	+04 3.025	-01	743 3102	32
8.	+04 2.725	-01 9.	+04 2.43	-01 9.5	+04 2.35	-01	743 3102	33
1.	+05 2.3	-01 1.4	+05 1.535	-01 1.8	+05 1.05	-01	743 3102	34
2.	+05 8.97	-02 2.2	+05 7.85	-02 2.4	+05 7.15	-02	743 3102	35
2.6	+05 6.59	-02 3.	+05 5.89	-02 3.4	+05 5.41	-02	743 3102	36
4.	+05 4.9	-02 5.	+05 4.315	-02 6.	+05 3.95	-02	743 3102	37
7.	+05 3.71	-02 9.	+05 3.49	-02 1.1	+06 3.31	-02	743 3102	38
1.5	+06 2.9	-02 1.8	+06 2.61	-02 2.	+06 2.39	-02	743 3102	39
2.4	+06 1.89	-02 3.	+06 1.28	-02 3.4	+06 9.7	-03	743 3102	40
5.0	+06 2.39	-03 6.	+06 1.07	-03 6.3	+06 9.1	-04	743 3102	41
6.5	+06 8.8	-04 6.7	+06 8.7	-04 7.0	+06 8.9	-04	743 3102	42
8.	+06 1.06	-03 9.	+06 1.33	-03 1.	+07 1.48	-03	743 3102	43
1.1	+07 1.51	-03 1.2	+07 1.35	-03 1.3	+07 1.22	-03	743 3102	44
1.4	+07 1.0	-03 1.7	+07 4.6	-04 2.0	+07 2.0	-04	743 3102	45

TUNGSTEN-184 SMOOTH RADIATIVE CAPTURE CROSS SECTION MATERIAL 744 744 1451 6

7.41840+04	1.82371+02		0	0			744 3102	30
0.00000+ 0	+5.7497 +06		0		2	49	744 3102	31
	16	2	49	4			744 3102	32
4.	+03 7.07	-01 6.	+03 5.25	-01 8.	+03 4.08	-01	744 3102	33
1.	+04 3.29	-01 1.2	+04 3.12	-01 1.5	+04 2.77	-01	744 3102	34
2.	+04 2.32	-01 2.5	+04 2.06	-01 3.	+04 1.86	-01	744 3102	35
3.5	+04 1.75	-01 4.	+04 1.72	-01 4.5	+04 1.73	-01	744 3102	36
6.	+04 1.66	-01 8.	+04 1.54	-01 9.	+04 1.48	-01	744 3102	37
1.	+05 1.37	-01 1.6	+05 9.84	-02 2.	+05 8.15	-02	744 3102	38
2.4	+05 6.88	-02 2.6	+05 6.45	-02 3.	+05 5.86	-02	744 3102	39
3.6	+05 5.46	-02 4.	+05 5.05	-02 5.	+05 4.6	-02	744 3102	40
6.	+05 4.34	-02 7.	+05 4.3	-02 8.	+05 4.3	-02	744 3102	41
1.	+06 4.02	-02 1.5	+06 3.4	-02 1.8	+06 3.12	-02	744 3102	42
2.	+06 2.82	-02 2.5	+06 2.09	-02 3.	+06 1.49	-02	744 3102	43
3.4	+06 1.12	-02 5.	+06 2.39	-03 6.	+06 1.07	-03	744 3102	44
6.3	+06 9.1	-04 6.5	+06 8.8	-04 6.7	+06 8.7	-04	744 3102	45
7.	+06 8.9	-04 8.	+06 1.06	-03 9.	+06 1.33	-03	744 3102	46
1.	+07 1.48	-03 1.1	+07 1.51	-03 1.2	+07 1.35	-03	744 3102	47
1.3	+07 1.22	-03 1.4	+07 1.0	-03 1.7	+07 4.6	-04	744 3102	48
2.0	+07 2.0	-04					744 3102	49

TUNGSTEN-186 SMOOTH RADIATIVE CAPTURE CROSS SECTION MATERIAL 746 746 1451 6

7.41860+04	1.84357+02		0	0			746 3102	40
0.00000+ 0	5.46610+06		0		2	46	746 3102	41
	15	2	46	4			746 3102	42
1.4	+03 7.	-01 1.8	+03 5.5	-01 2.8	+03 4.5	-01	746 3102	43
4.5	+03 3.8	-01 6.3	+03 3.4	-01 9.	+03 3.07	-01	746 3102	44
1.4	+04 2.65	-01 2.	+04 2.32	-01 3.	+04 1.98	-01	746 3102	45
4.	+04 1.76	-01 5.	+04 1.62	-01 6.	+04 1.59	-01	746 3102	46
7.5	+04 1.57	-01 8.2	+04 1.49	-01 1.	+05 1.25	-01	746 3102	47
1.2	+05 1.11	-01 1.6	+05 9.1	-02 2.	+05 7.99	-02	746 3102	48
2.4	+05 7.25	-02 3.	+05 6.5	-02 4.	+05 5.13	-02	746 3102	49
5.	+05 5.04	-02 6.	+05 4.8	-02 8.	+05 4.34	-02	746 3102	50
1.	+06 4.01	-02 1.5	+06 3.4	-02 1.8	+06 3.12	-02	746 3102	51
2.	+06 2.82	-02 2.5	+06 2.09	-02 3.	+06 1.49	-02	746 3102	52
3.4	+06 1.12	-02 5.	+06 2.39	-03 6.	+06 1.07	-03	746 3102	53
6.3	+06 9.1	-04 6.5	+06 8.8	-04 6.7	+06 8.7	-04	746 3102	54
7.0	+06 8.9	-04 8.	+06 1.06	-03 9.	+06 1.33	-03	746 3102	55
1.	+07 1.48	-03 1.1	+07 1.51	-03 1.2	+07 1.35	-03	746 3102	56
1.3	+07 1.22	-03 1.4	+07 1.0	-03 1.7	+07 4.6	-04	746 3102	57
2.0	+07 2.0	-04					746 3102	58

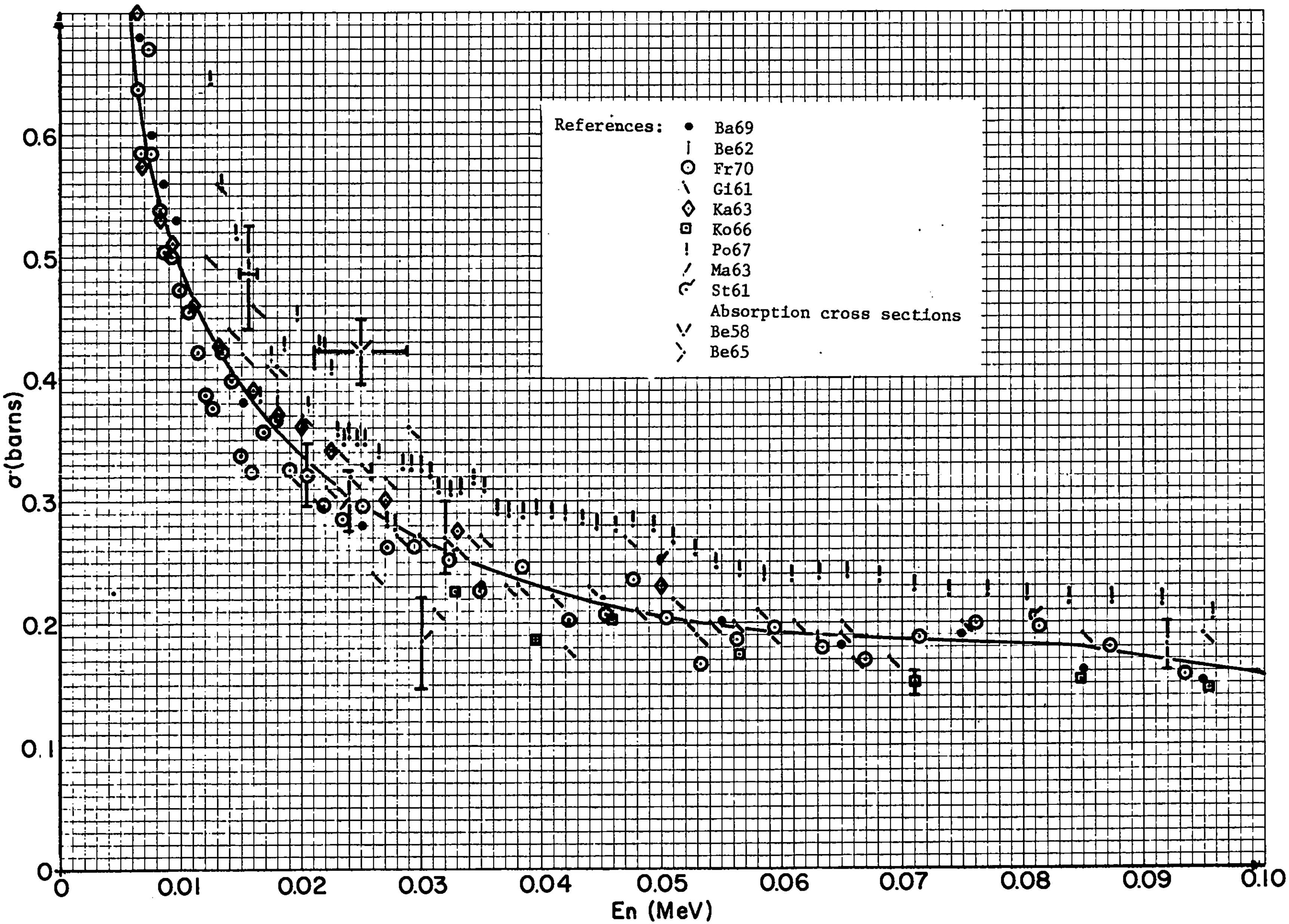

Fig. 1. Natural tungsten smooth radiative capture cross section.

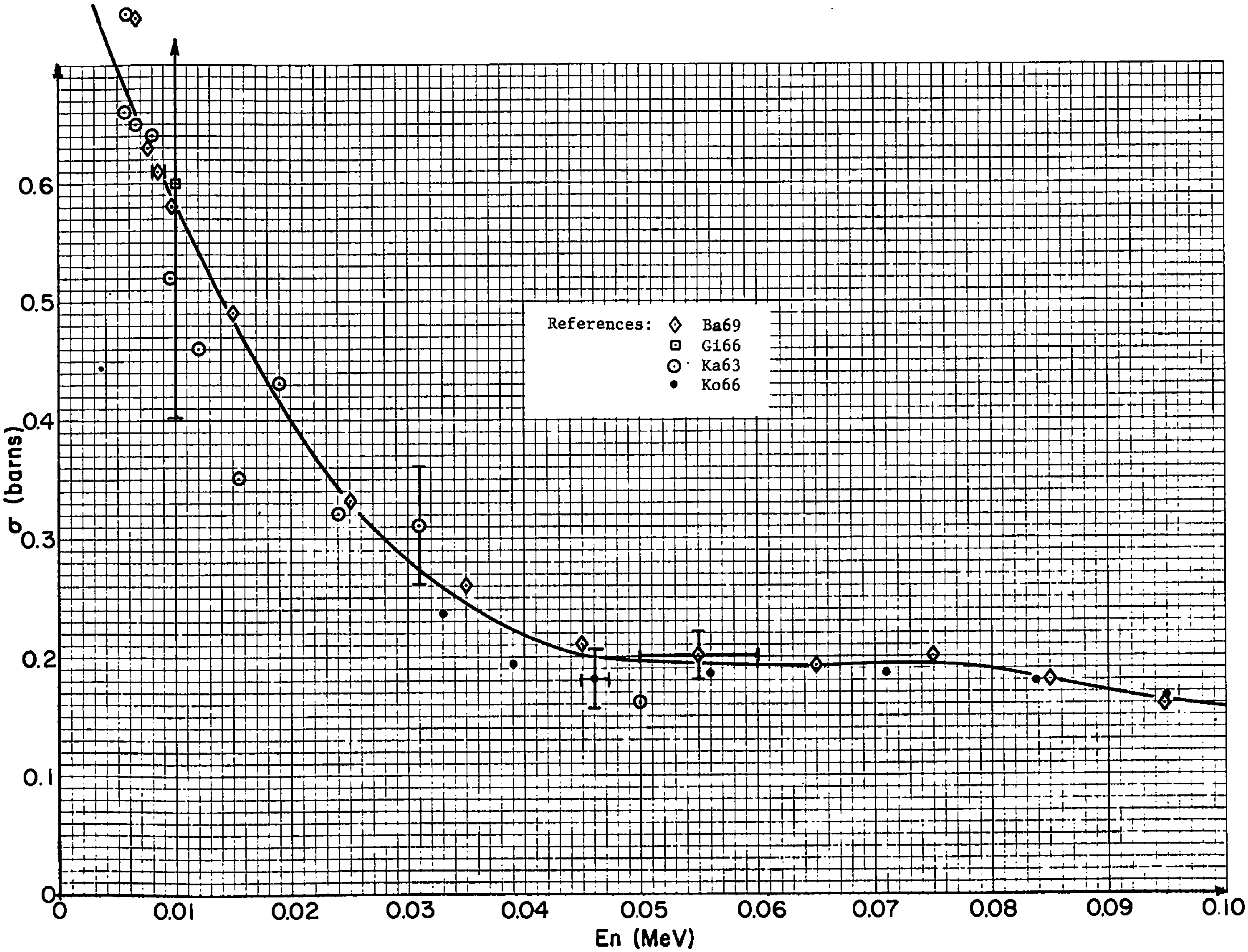

Fig. 2. Tungsten-182 smooth radiative capture cross section.

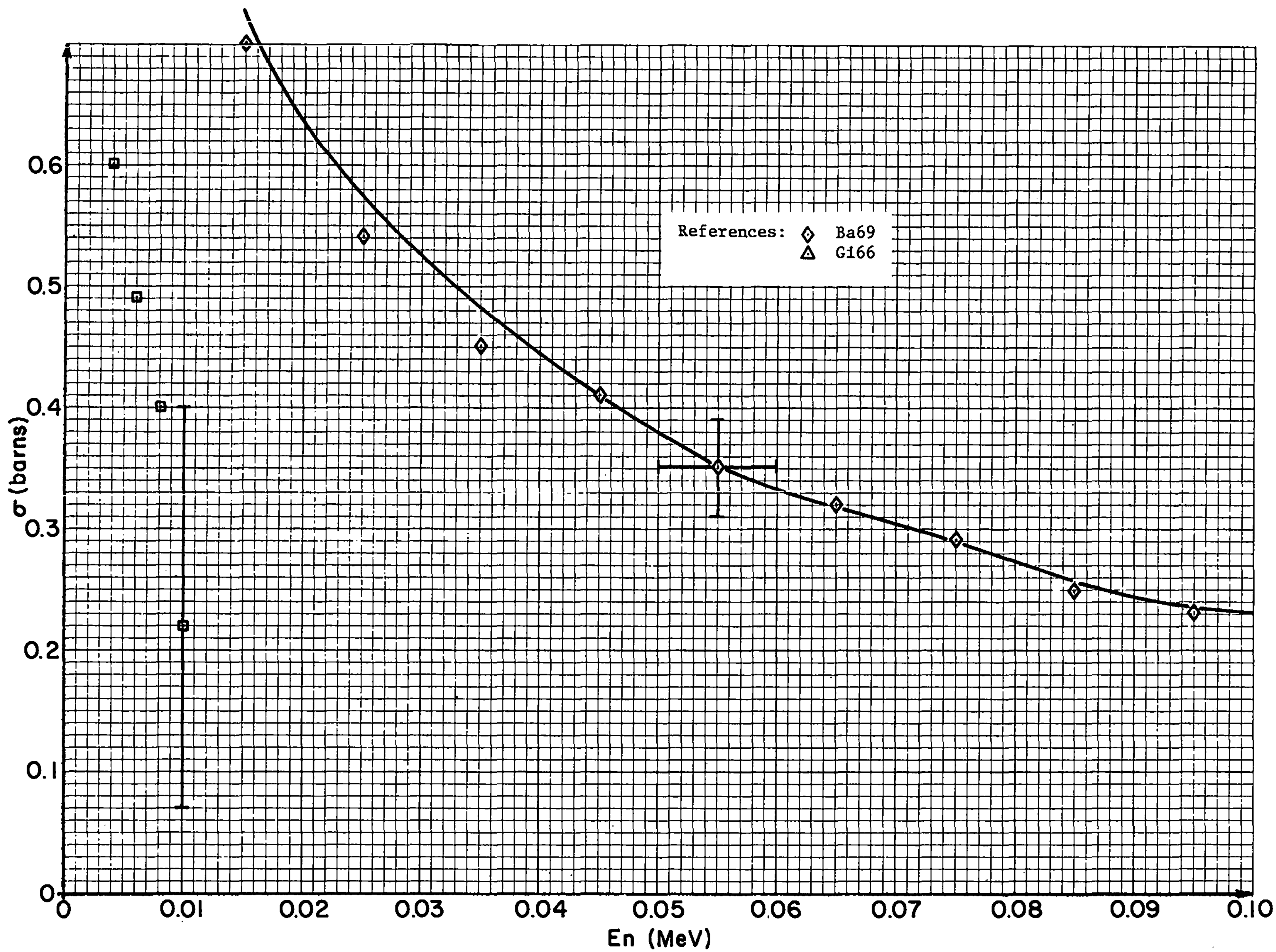

Fig. 3. Tungsten-183 smooth radiative capture cross section.

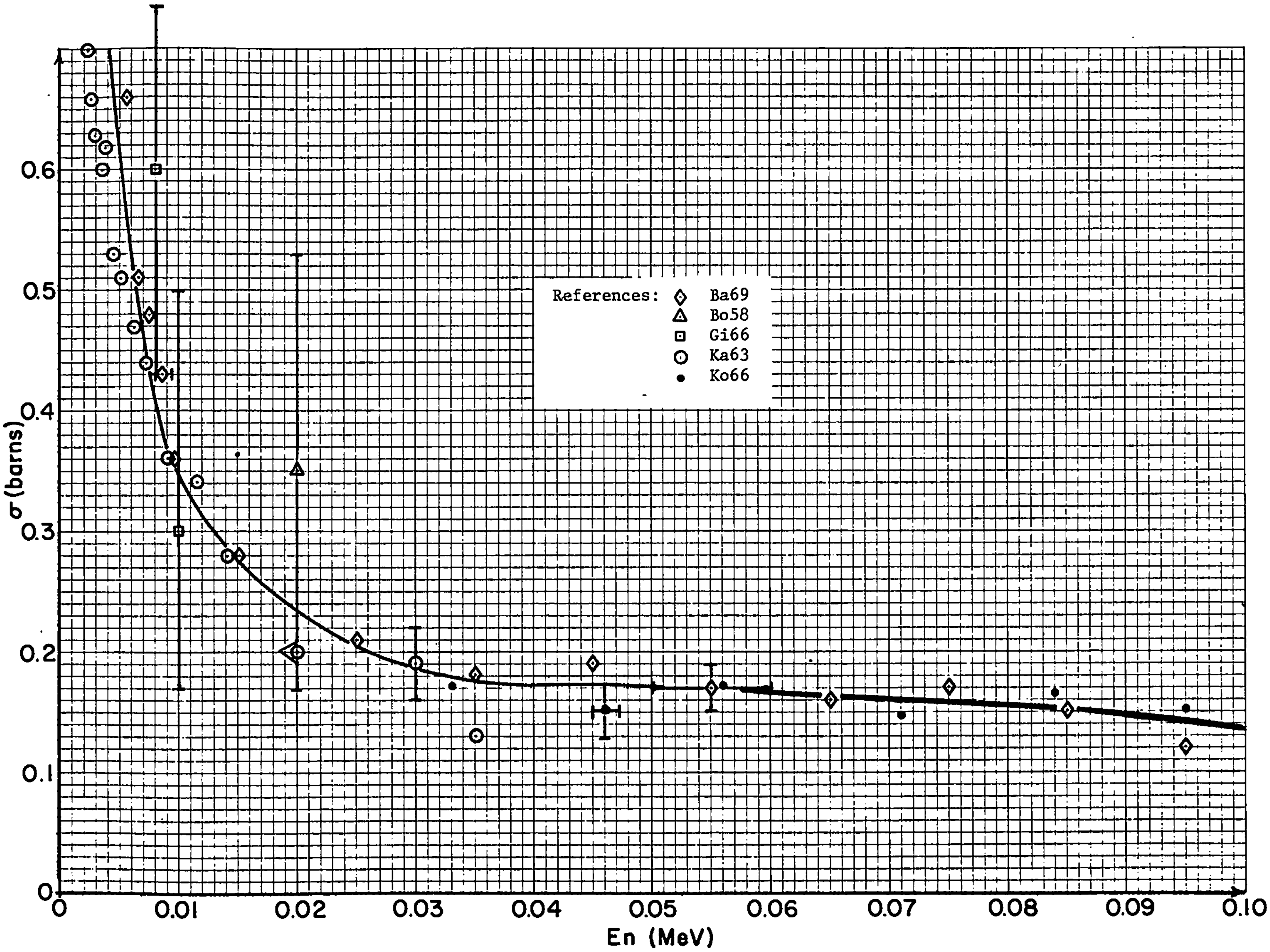

Fig. 4. Tungsten-184 smooth radiative capture cross section.

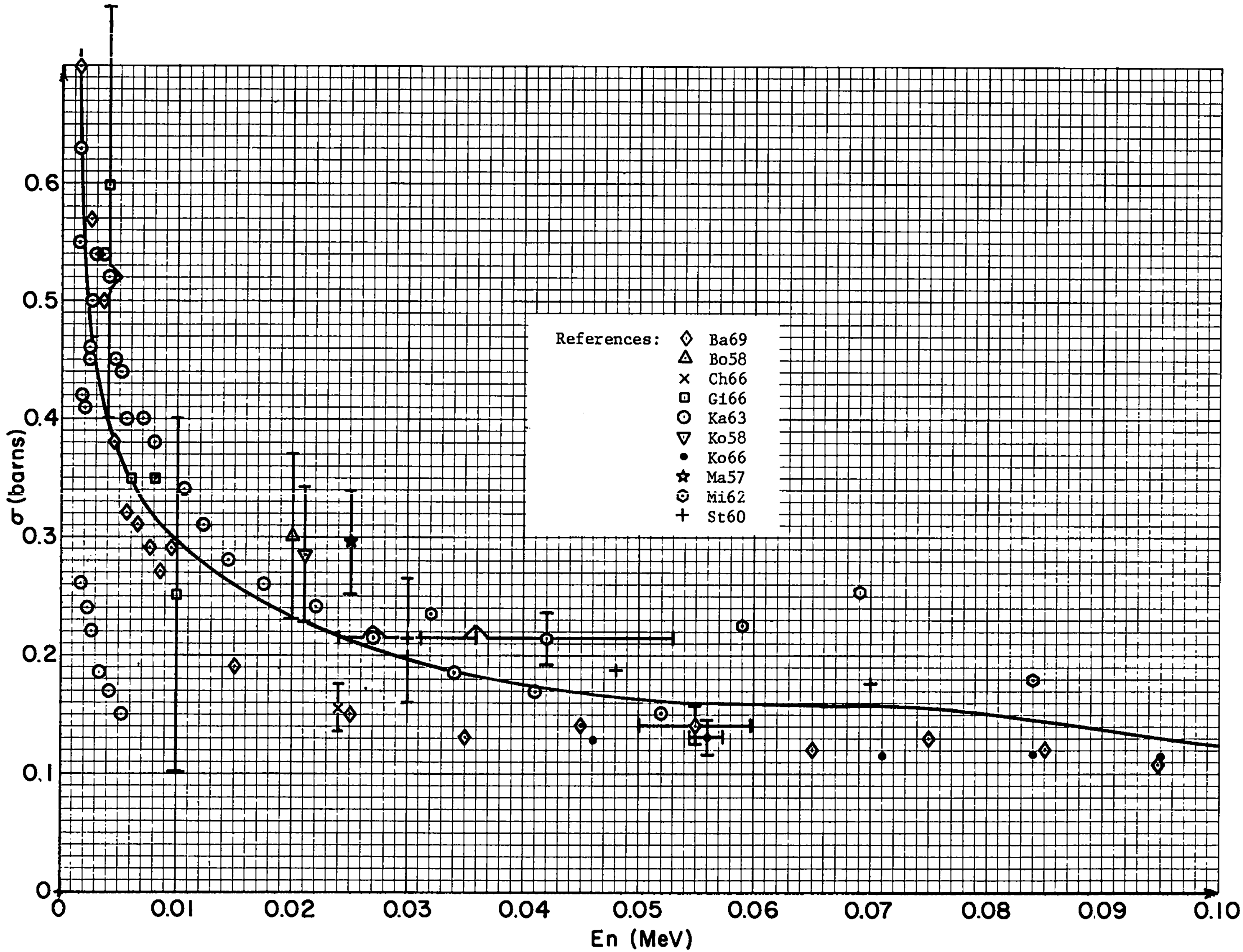

Fig. 5. Tungsten-186 smooth radiative capture cross section.

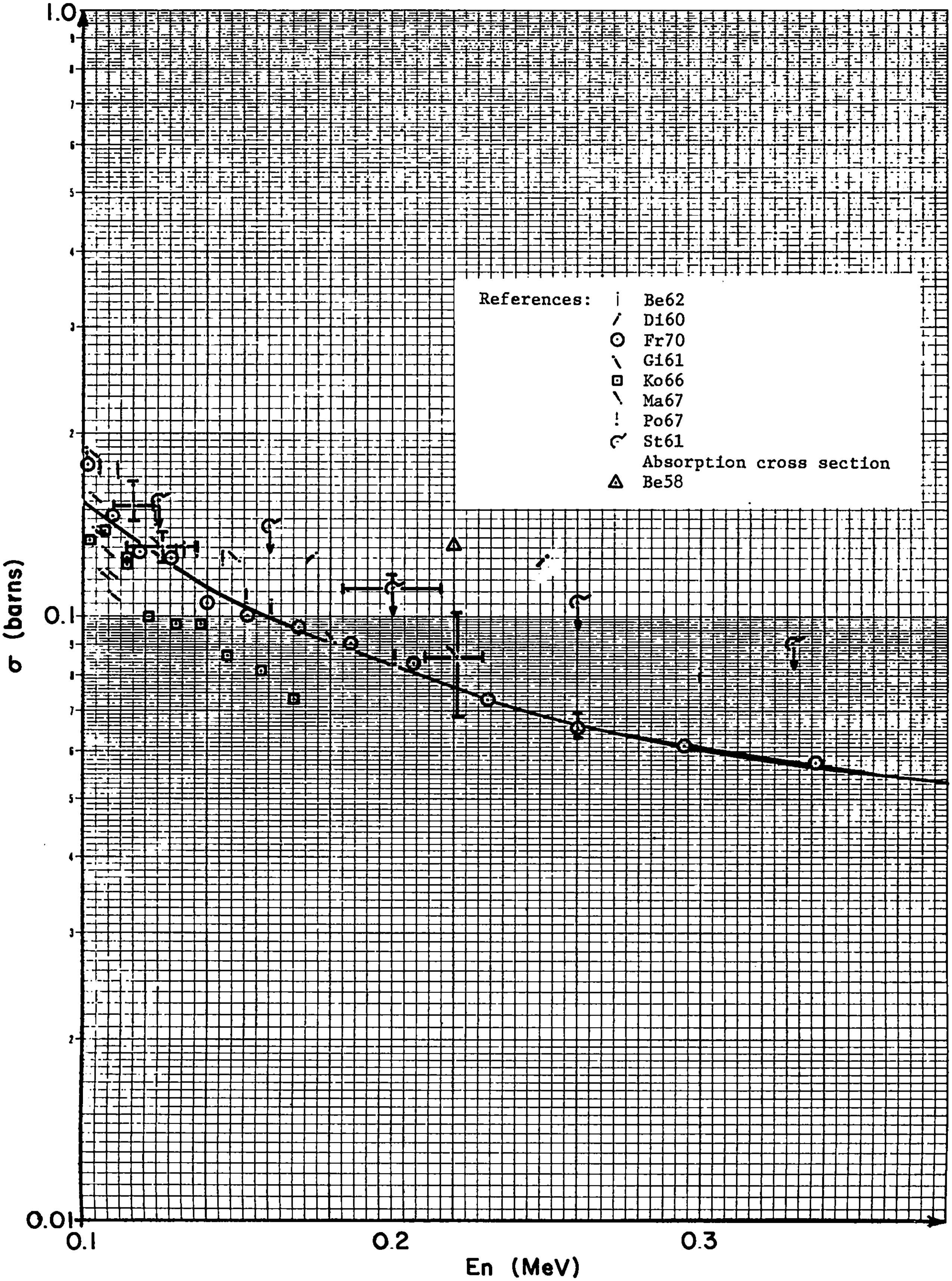

Fig. 6. Natural tungsten smooth radiative capture cross section.

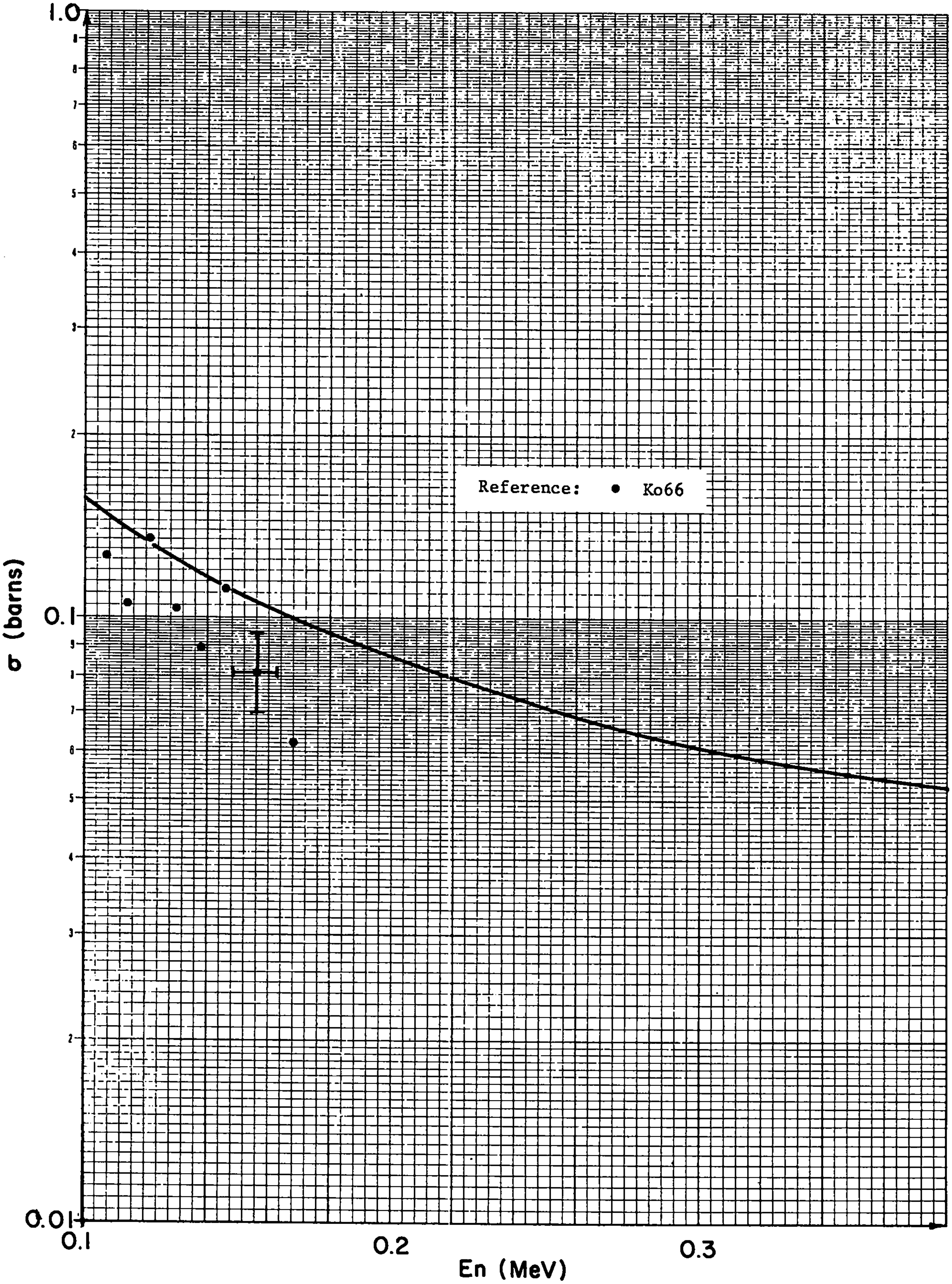

Fig. 7. Tungsten-182 smooth radiative capture cross section.

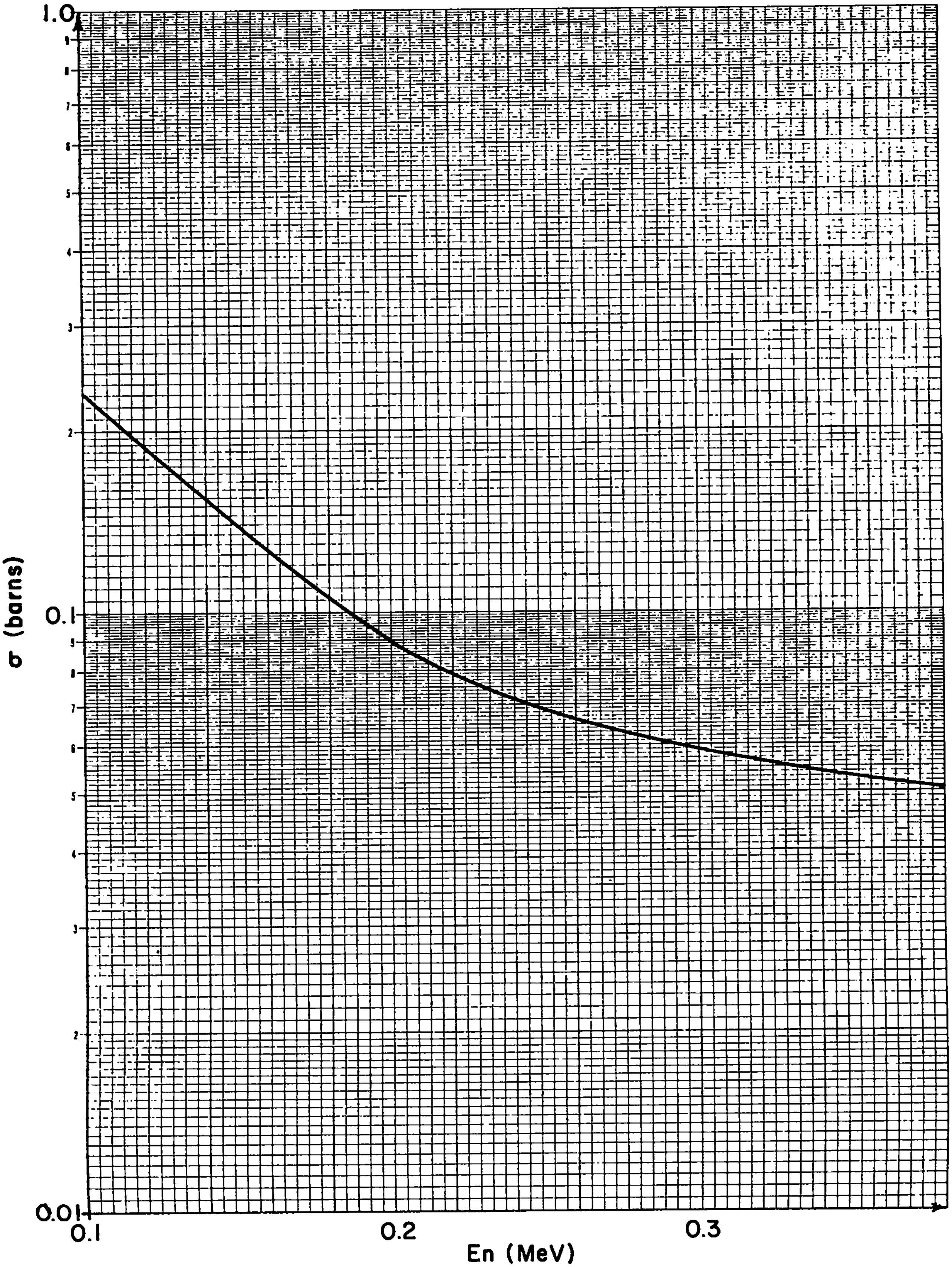

Fig. 8. Tungsten-183 smooth radiative capture cross section.

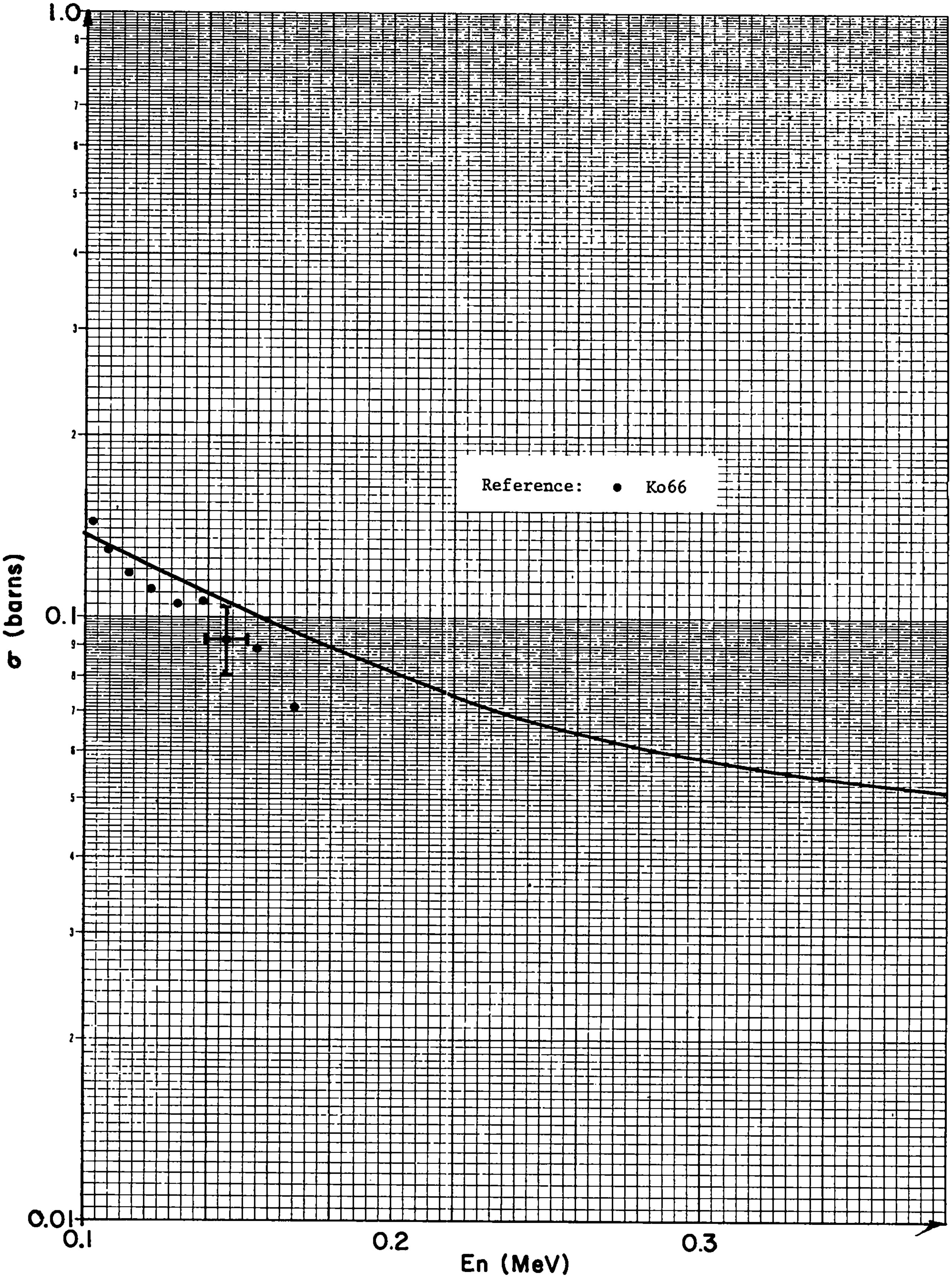

Fig. 9. Tungsten-184 smooth radiative capture cross section.

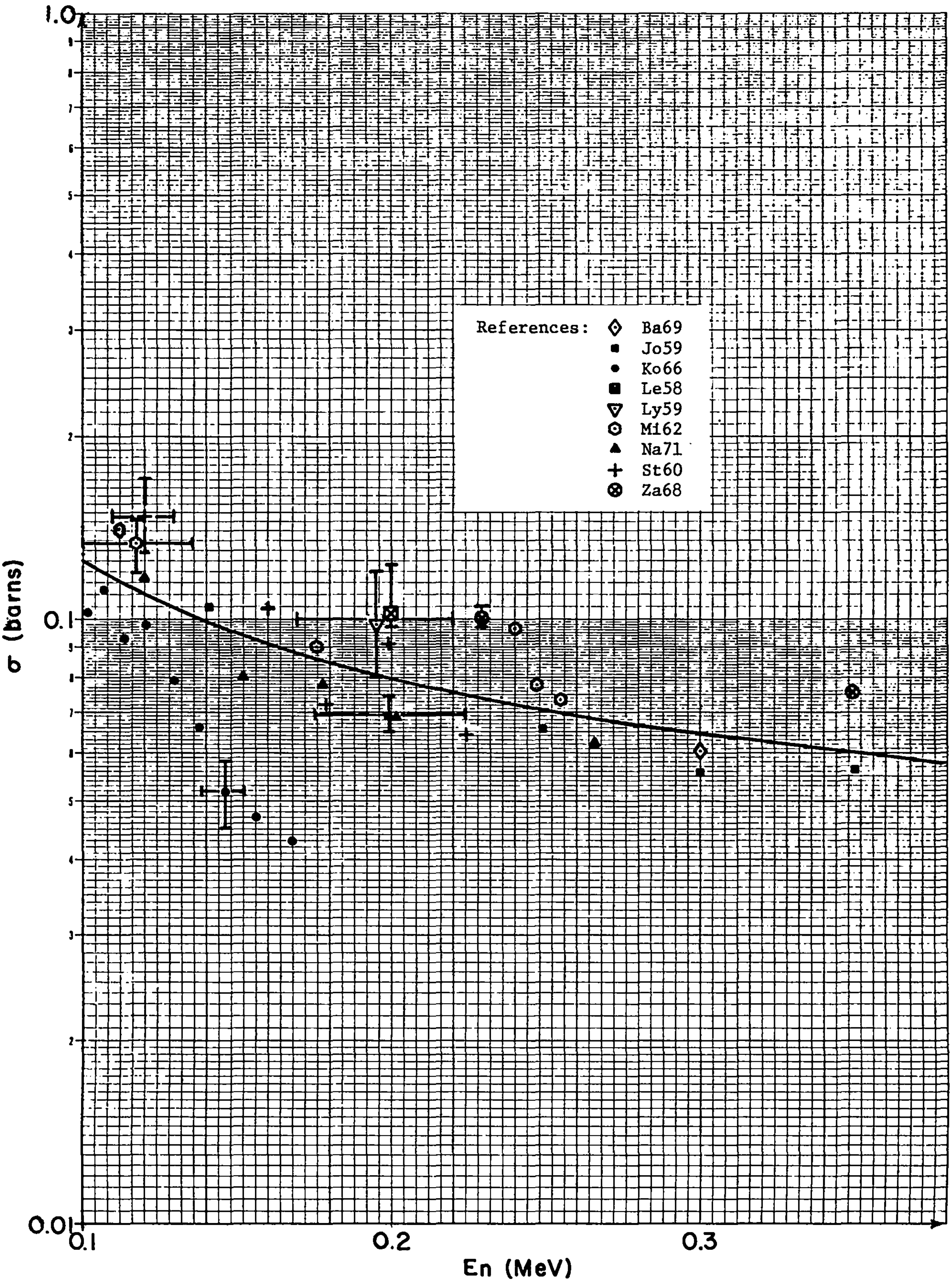

Fig. 10. Tungsten-186 smooth radiative capture cross section.

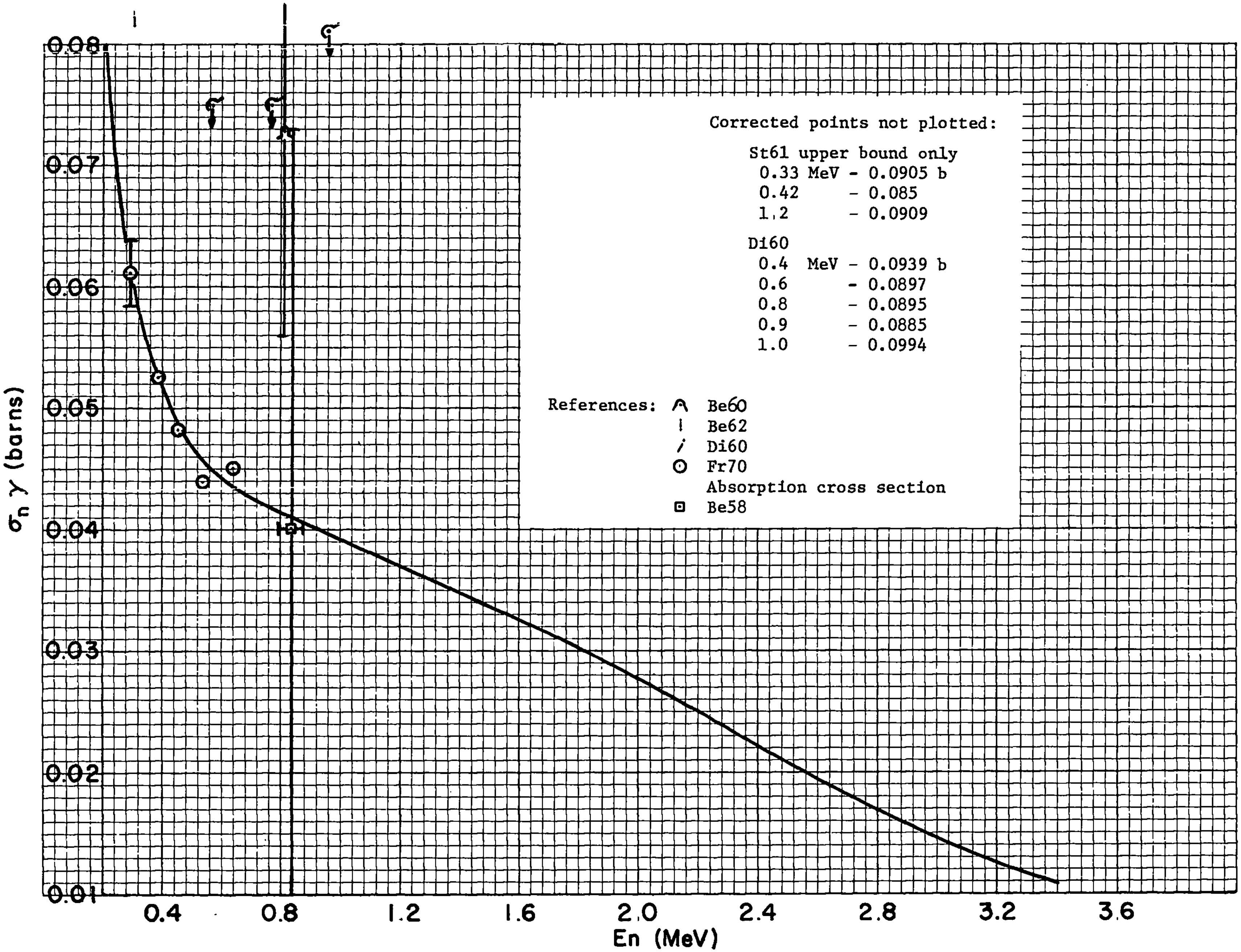

Fig. 11. Natural tungsten radiative capture cross section.

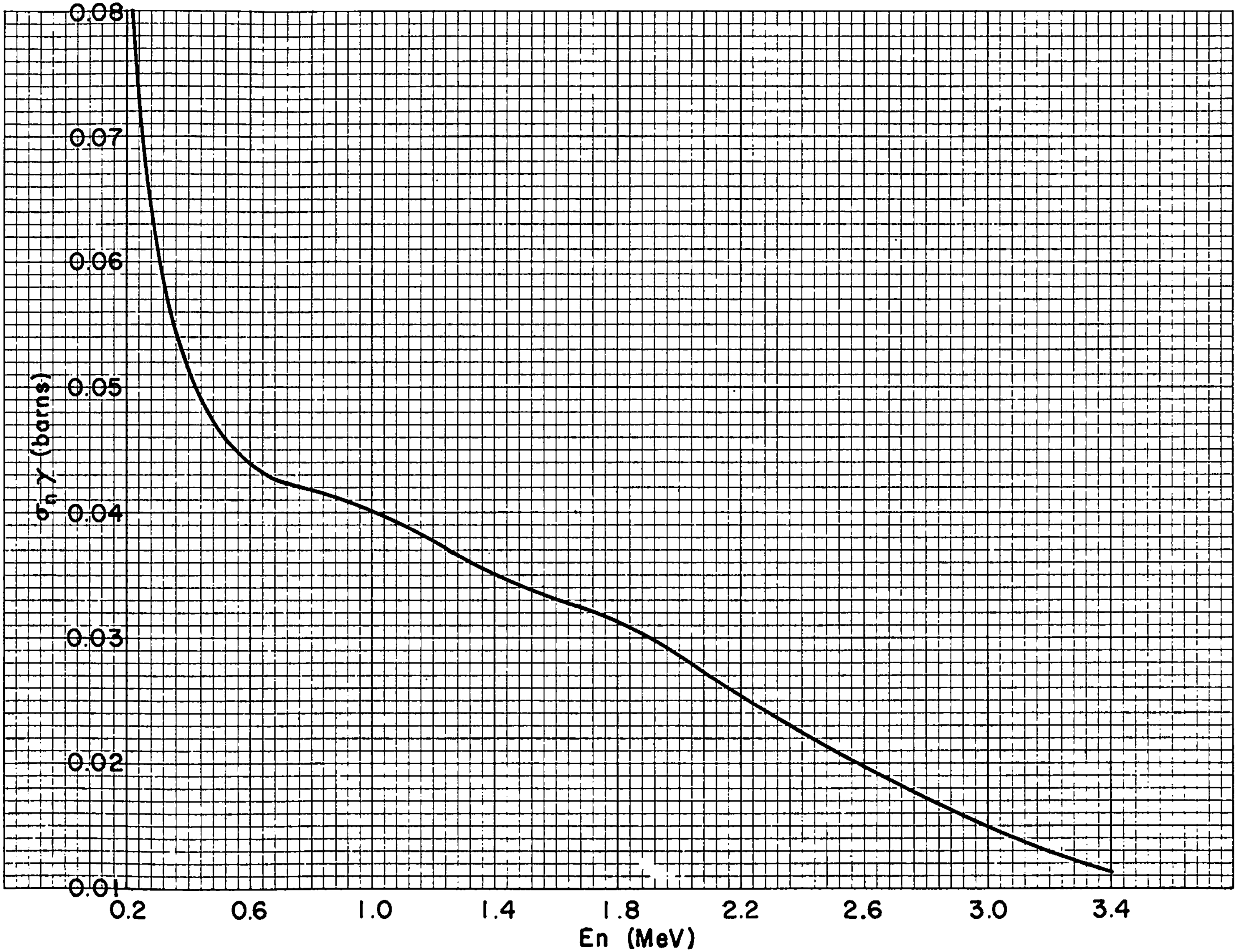

Fig. 12. Tungsten-182 radiative capture cross section.

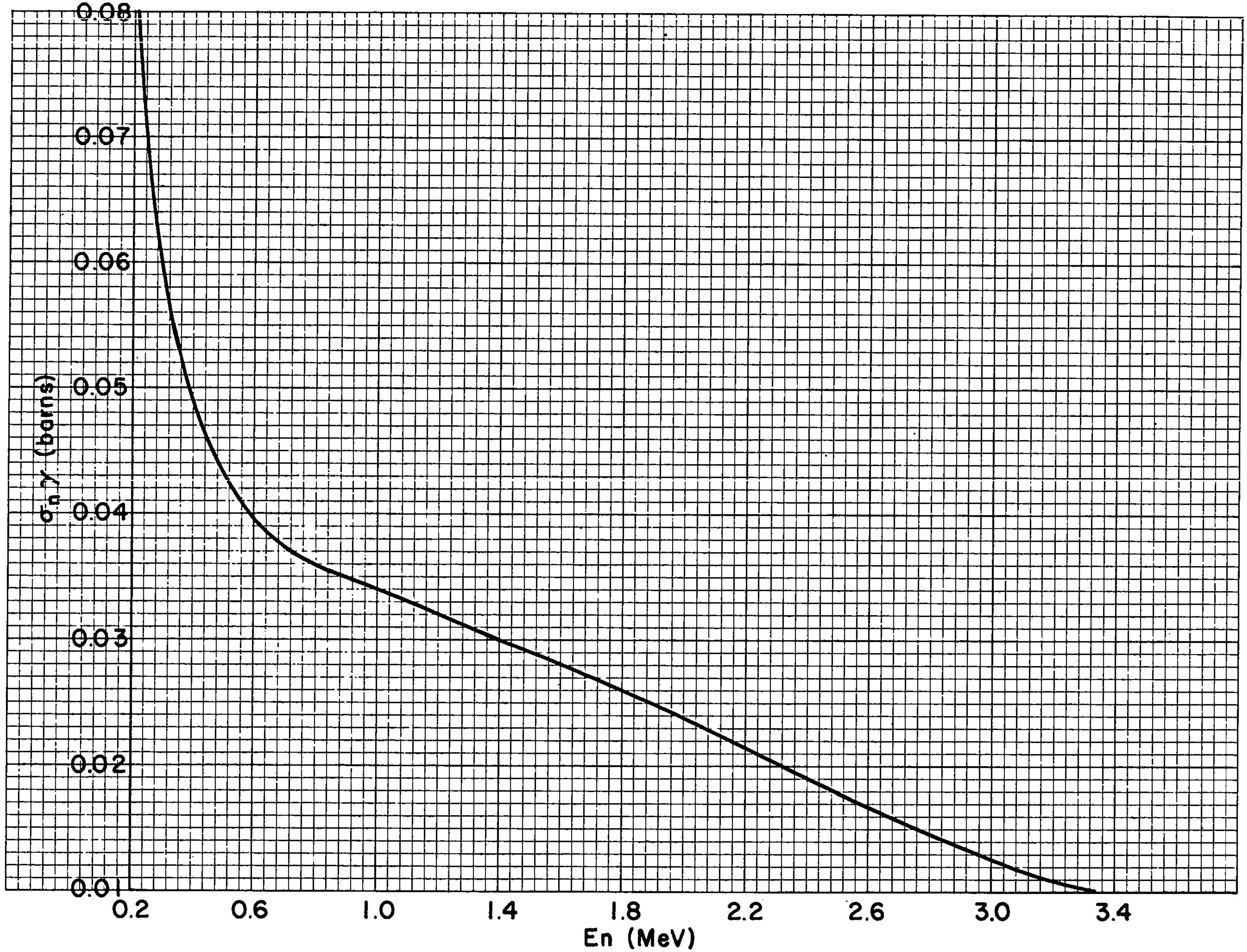

Fig. 13. **Tungsten-183 radiative capture cross section.**

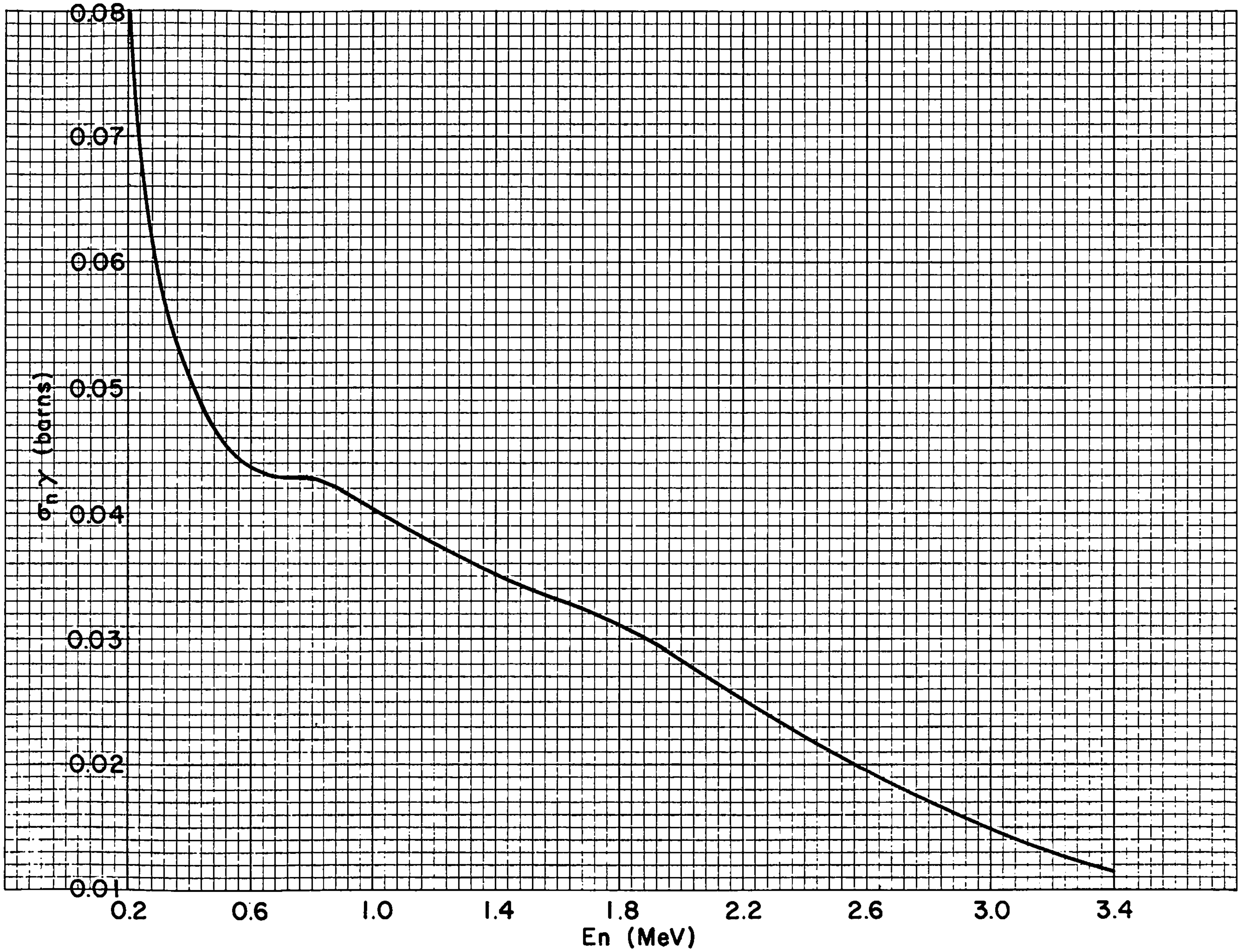

Fig. 14. Tungsten-184 radiative capture c oss section.

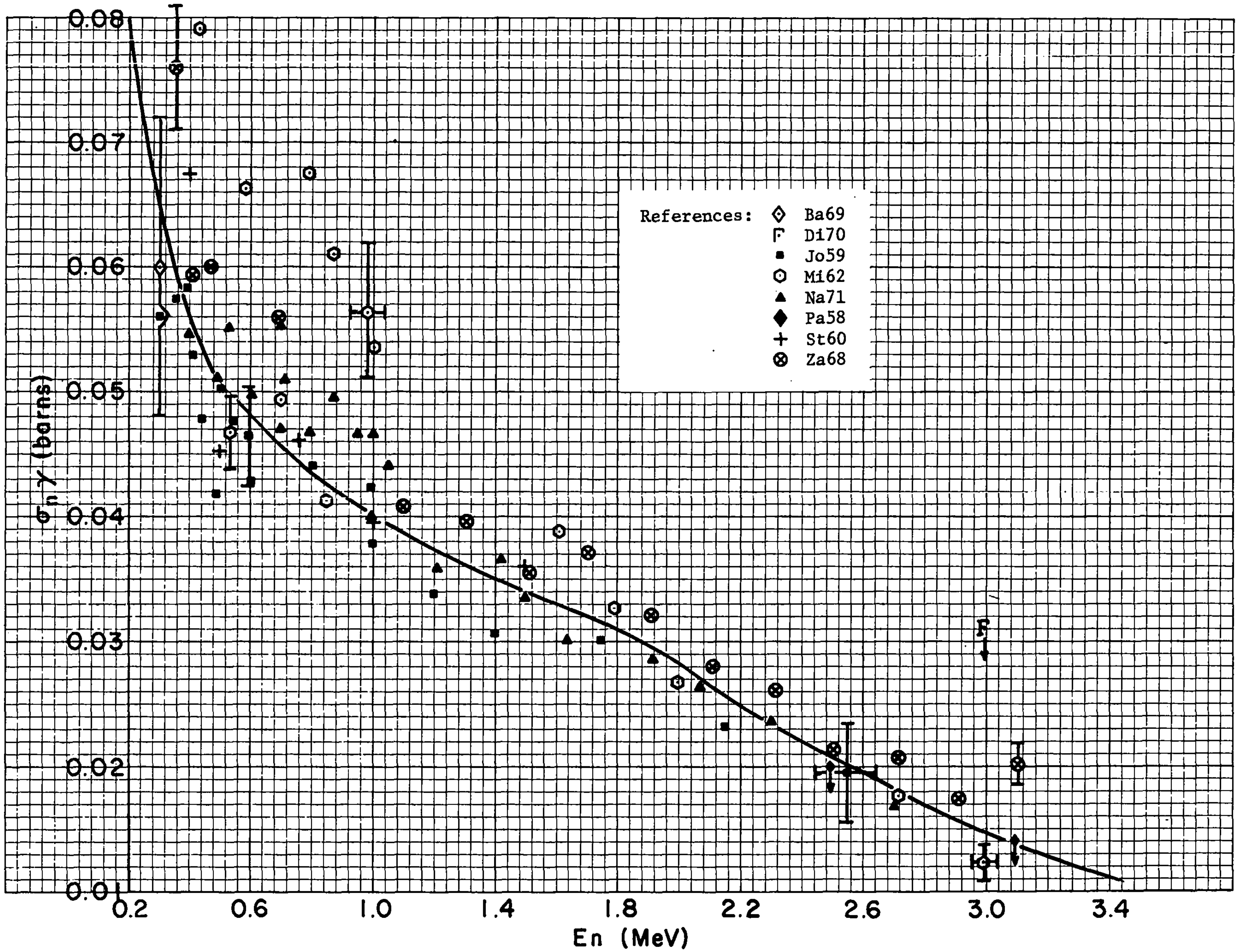

Fig. 15. Tungsten-186 radiative capture cross section.

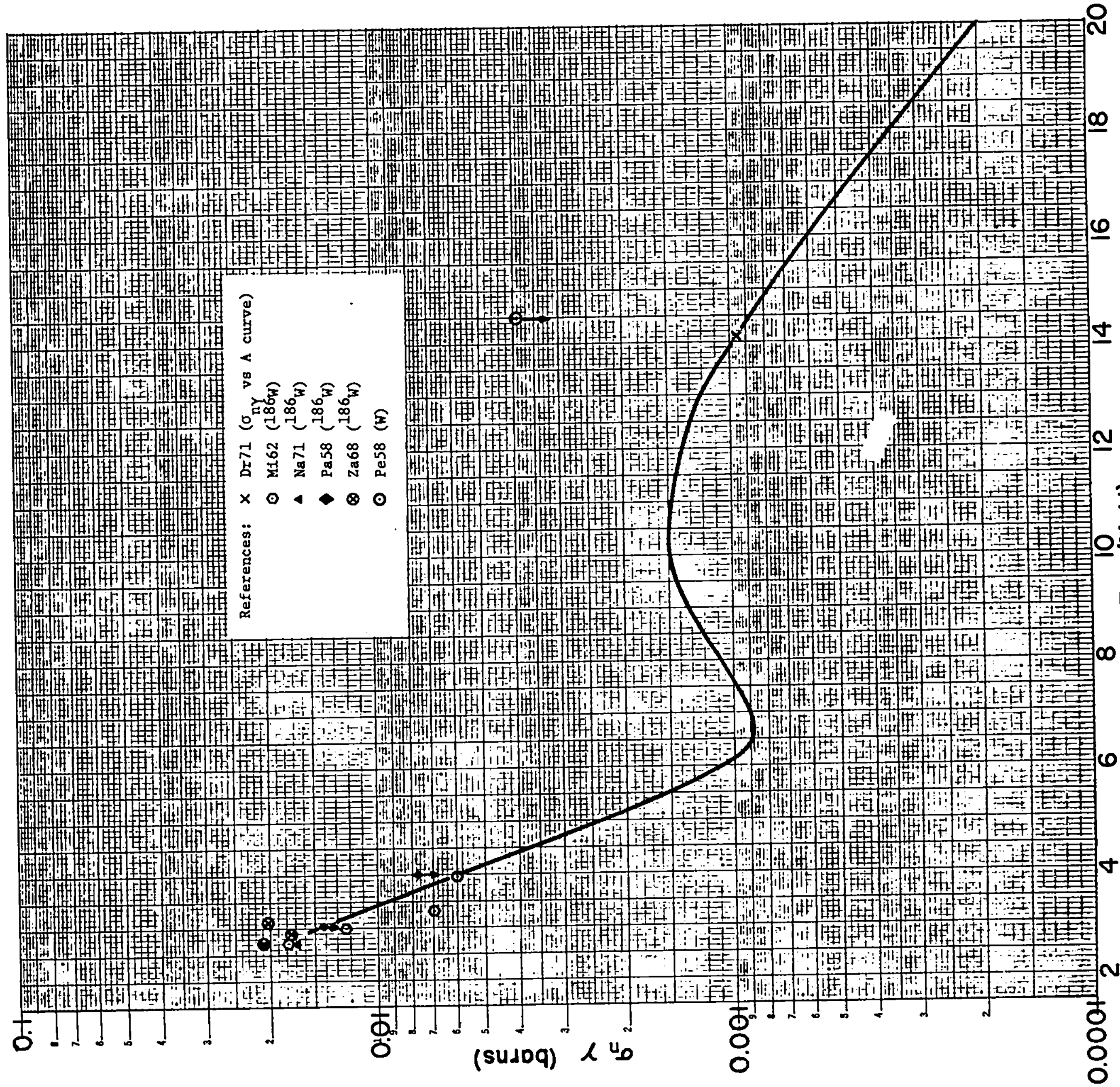

Fig. 16. Tungsten radiative capture cross section.

KT:371(110)