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# TABLES OF NEUTRON

# CROSS SECTIONS FOR ELEMENTS Po - Cm.

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# TABLES OF NEUTRON CROSS SECTIONS FOR ELEMENTS Po - Cm.

Compiled by G. Haines and K. Way

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# TABLES OF NEUTRON CROSS SECTIONS FOR ELEMENTS Po - Cm.

Compiled by G. Haines and K. Way

## Sources of Information and Acknowledgments.

This summary of neutron cross sections for the heavy elements lists all data available in the Oak Ridge National Laboratory in June 1948. The compilers have based their work on the lists of project and non-project cross sections started by Hilda Castle Uchiyamada in 1943. Mrs. Uchiyamada kept up these lists until the spring of 1945. From that time until the present they have been added to successively by Mr. Harold Schweinler, Mrs. Nancy Dismuke, and the present compilers.

From Aug. 1946 - Oct. 1947 cross section data were reported regularly from both the secret and open literature by the Isotope Information Committee (CL-IIC-#1-10). The non-secret items collected by this committee amounted to about three quarters of the total number and have recently been published as a supplement to the May issue of Nucleonics. Since the time of the last report of this committee (Oct. 1947) the compilers have relied upon their own surveys of quarterly reports, library lists, and upon checking of the Physical Review for new cross section data. The present list can be considered as an addition to Mon P-405 and Mon P-405 Supplement and Errata which form a compilation of cross section data for the elements H - Bi. For this reason it is labelled as covering the elements Po - Cm although no cross sections are at present known for the elements $Po_{84}$ - $Fr_{87}$.

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Graphs have been included when possible. Many of these are identical with curves given by H. H. Goldsmith and H. C. Ibser in the "wall paper book" MUC-HHG-#7. These have been repeated here for the sake of completeness. In cases where the curves of the wall paper book were found not to agree exactly with those of original reports, the reports were followed.

Explanation of Tables

The designations SLOW and FAST appearing at the upper left hand corner of a page refer to the neutron energy at which the cross sections appearing on that page were measured. Slow neutron energies include those in the thermal and resonance regions. Neutron energies given on SLOW pages are in ev. Those on FAST pages are in mev.

For purposes of orientation the isotopes for each element covered have been listed and information given on their abundances or radioactive characteristics. This data has been taken from the table of G. T. Seaborg and I. Perlman, BC-59, supplemented by recent project reports and open literature results.

All cross sections are given per atom of isotope or element unless otherwise stated.

All cross sections are given in barns ($10^{-24}$ cm$^2$).

When $\alpha$ decay can proceed by the emission of $\alpha$ particles of different energies only the energy of the most energetic and most intense $\alpha$ ray are given. These are designated $\alpha_0$ and $\alpha_m$ respectively.

Energies of photo neutrons have been taken to have the values estimated in CLM-KW-5 for 20% degradation.

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ABBREVIATIONS

$\sigma_s$ scattering cross section $\sigma_{tr}$ transport cross section

$\sigma_f$ fission cross section

$\sigma_c$ cross section for radiative capture by a target nucleus (Z, A) resulting in production of the nucleus (Z, A+1)

$\sigma_a$ absorption cross section $\sigma_a = \sigma_f + \sigma_c$

$\sigma_t$ total cross section as found from transmission measurements $\sigma_t = \sigma_s + \sigma_f + \sigma_c$

$\sigma(\theta)$ scattering cross section per unit solid angle at angle $\theta$ with direction of incident beam

$\sigma_i$ inelastic scattering cross section

$\alpha_m$ energy of the $\alpha$ particle of greatest intensity emitted by an $\alpha$ active nucleus

$\alpha_e$ energy of the most energetic $\alpha$ particle emitted by an $\alpha$ active nucleus

P pile

TC thermal column

Ra-Be-Par Ra-Be neutron source surrounded by paraffin

MC modulated cyclotron used in measuring neutron time of flight

CS crystal spectrometer

C energy of thermalized neutrons for which Cd differences were taken

T energy of neutrons produced by a thermal column or energy of neutrons designated by experimenters as thermal without additional information

$\nu$ neutrons emitted per fission

$\eta$ neutrons emitted per neutron absorbed $\eta = \nu/(1+\alpha)$

$\alpha$ $\sigma_c/\sigma_f$

[redacted]

88 Radium (Ra)

| 222 | 223 (AcX) | 224 (ThX) | 225 | 226 | 227. | 228 (MsTh1) |
|---|---|---|---|---|---|---|
| 38 s<br>$\alpha$ 6.5 | 11.2 d<br>$\alpha_{om}$ 5.717<br>(55%)<br>$\gamma$ ? | 3.64 d<br>$\alpha$ 5.661 | 14.8 d<br>$\beta^-$ ~0.2<br>< 0.05<br>$\alpha$ ? | 1622 y<br>$\alpha$ 4.793<br>6 shorter<br>$\alpha$'s ?<br>$\gamma$ 0.19 | $\beta^-$ | 6.7 y<br>$\beta^-$ 0.053 |

| | Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| FISSION | | | | |
| $Ra^{223}$ | P | C | < 100 | Peterson and Ghiorso, P-3, '47. |
| $Ra^{226}$ | P | C | $\leq 1 \times 10^{-4}$ | Ames and Ghiorso, A-2, '47. |
| $Ra^{226}/U^{233}$ | Ra-Be-Par | C | $< 1 \times 10^{-4}$ | Pontecorvo and West, P-6, '45. |
| $Ra^{226}/U$ | Ra-$\alpha$-Be | ~ 4 mev | $\leq 9 \times 10^{-4}$ | Cook et al, C-1, '45. |
| $Ra^{226}/Th^{232}$ | " | " | $\leq 0.003$ | Pontecorvo and West, P-6, '45. |
| $Ra^{228}$ | P | C | < 2 | Peterson and Ghiorso, P-3, '47. |
| CAPTURE | | | | |
| $Ra^{226}$ | | T | ~ 12 | Seaborg and Manning, private comm. |

[redacted]

89 Actinium (Ac)

| 225 | 226 | 227 | 228 ($MsTh_2$) |
|---|---|---|---|
| 10.0 d<br>$\alpha$ 5.80 | | 13.5 y<br>$\beta^-$ ~.01 (99%)<br>$\gamma$ .037, .015<br>$\alpha$ 5.0 (1%) | 6.13 h<br>$\beta^-$ 1.55<br>$\gamma$ 0.97<br>8 less energetic $\gamma$'s<br>$\alpha$ 4.5 |

| | Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| FISSION | | | | |
| $Ac^{227}$ | P | C | < 2 | Peterson and Ghiorso, P-3, '47. |
| CAPTURE | | | | |
| $Ac^{227}$ | P | C | 18-20 | Peterson, P-5, '47. |

[redacted]

SLOW

90 Thorium (Th)

| 226 | 227 (RdAc) | 228 (RdTh) | 229 | 230 (Io) | 231 (UY) | 232 | 233 |
|---|---|---|---|---|---|---|---|
| | | | | | | 100 | |
| 30.9 m<br>$\alpha$ 6.3 | 18.6 d<br>$\alpha_o$ 6.049<br>$\alpha_m$ 5.988<br>$\gamma$ complex | 1.90 y<br>$\alpha$ 5.333, 17%<br>5.418, 83%<br>$\gamma/\alpha = 1$<br>Origin of $\gamma$ not clear | 7,000 y<br>$\alpha_m$ 4.85<br>$\alpha_o$ 5.05 | $8.0 \times 10^4$ y<br>$\alpha$ 4.66<br>$\gamma$ | 25.8 h<br>$\beta^-$ 0.055<br>0.2<br>$\gamma$'s | $1.39 \times 10^{10}$ y<br>$\alpha$ 4.00 | 23.5m<br>$\beta^-$ 1.6<br>No $\gamma$ |

See decay scheme for $UX_1$ on page 12.

| | Neutron Source | Neutron Energy | $\sigma$ Measured | $\sigma$ at 0.025 | Reference |
|---|---|---|---|---|---|
| TOTAL | | | | | |
| $Th^{232}$ | | T | | 19.8 | Anderson and Bistline, A-1, '44. |
| | CS | 0.04-15 | graph | | Sturm and Turkel, S-1, '46. Figure 1. |
| SCATTERING | | | | | |
| $Th^{232}$ | | T | 12.78 | | LA-140A. |
| ABSORPTION | | | | | |
| $Th^{232}$ | P | | | 7.2 | Wattenberg et al, W-1, '44. |
| | | C | 6.0 | | Meitner, M-1, '40. |
| | Rn-Be-$H_2O$ | C | 7.1 | 9.4 | Volz, V-1, '43. |
| | P | | | 7.0 | Pomerance, private comm. May '48. Oscillator. |
| CAPTURE | | | | | |
| $Th^{232}$ 23.5 m | TC | T | | 7.58 ± 10% | Seren et al, S-6, '44. |
| | Ra-Be-Par | T | | 6.8 | Grummitt et al, G-7, '44. From $\sigma(Th)/\sigma(I) = 0.975$. |
| | " | " | | 6.75 | Grummitt et al, G-7, '44. From $\sigma(Th)/\sigma(U) = 2.64$ |
| $\int \sigma dE/E$ | | | 81.3 for infinite dilution | | Hughes and Eggler, H-5, '45. Curve given for values as function of $\sigma_s$. |

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— FIGURE I. —

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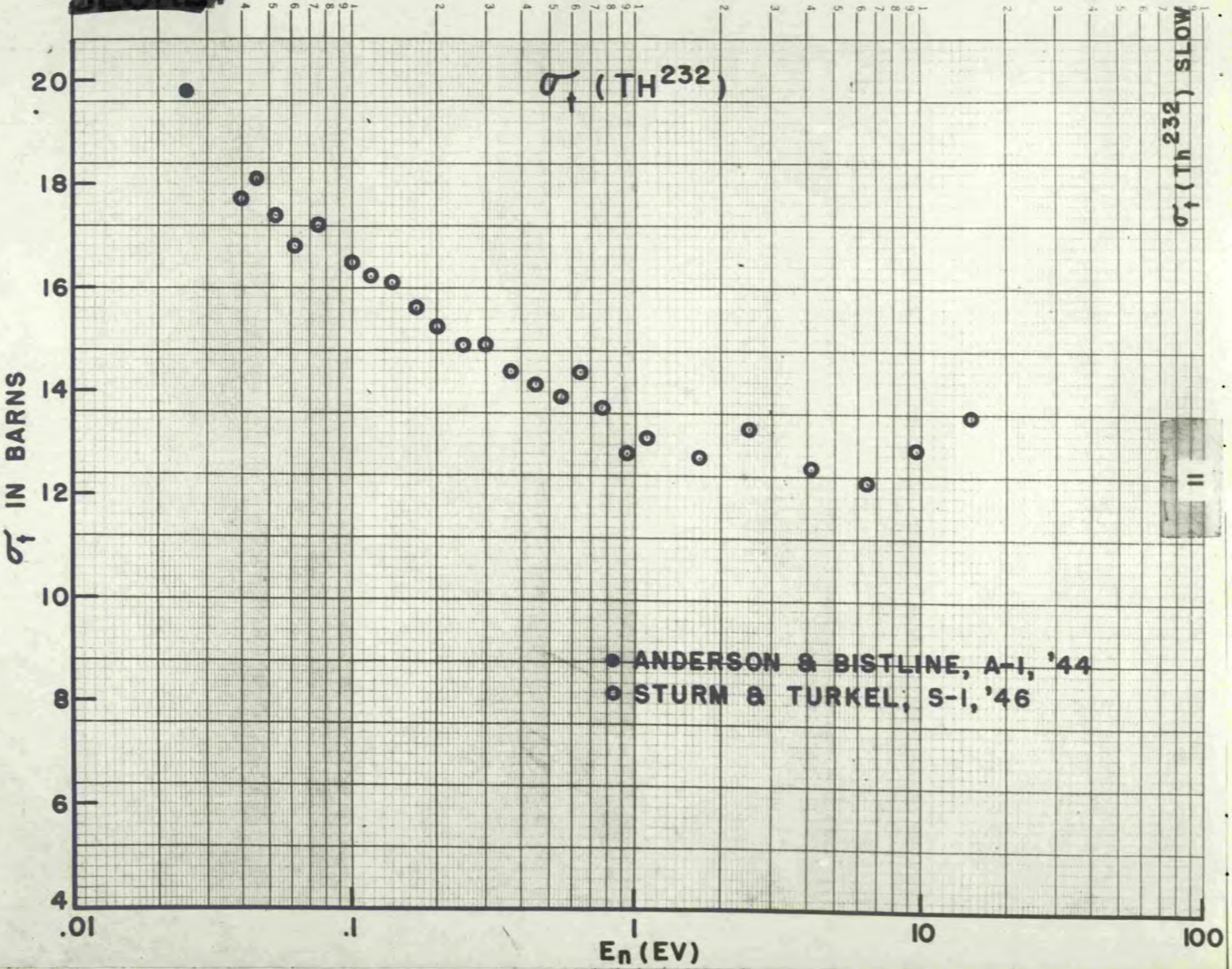
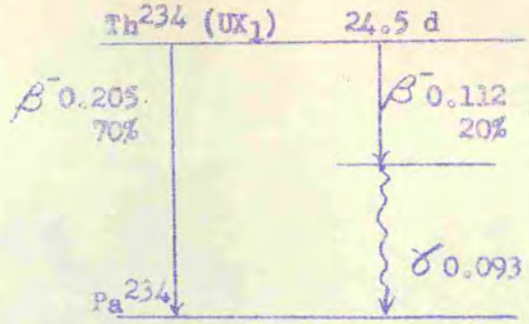


SLOW and FAST

Thorium (Th)




Bradt and Scherrer, B-1, '46.

| | Source | Neutron Energy | σ Measured | σ at 0.025 | Reference |
|---|---|---|---|---|---|
| CAPTURE | | | | | |
| $Th^{230}$ | P | C | | 50 | Seaborg and Manning, private communication. |
| $Th^{233}$ 24.5 d | P | C | | 1500-2000 | Hyde et al, H-1, '47. |
| FISSION | | | | | |
| $Th^{227}$ | P | C | $1000^{+1500}_{-500}$ | | Peterson and Ghiorso, P-3, '47. |
| $Th^{228}$ | TC | T | < 0.3 | | Studier and Ghiorso, S-4, '47. |
| $Th^{229}$ | P | C | 45 ± 25% | | Studier et al, S-2, '47. |
| $Th^{230}$ | P | C | ≤ 0.0012 | | Seaborg and Manning, S-7, '46. |
| $Th^{230}/Th^{232}$ | Rn-Be | | 2.7 ± 15% | | Jentschke et al, J-1. |
| $Th^{232}$ | P | C | $\leq 6.8 \times 10^{-4}$ | | Farwell and Kahn, F-1, '46. |
| | P | C | $\sim 2 \times 10^{-5}$ | | Seaborg and Manning, S-7, '46. |
| | 1-6 mev | | see graph | | Figure 2. |
| $Th^{232}/U^{238}$ | 25 fission n's | | 0.22 | | Moak et al, M-2, '45. |
| " " | Ra-α-Be | ~ 4 | 0.25 | | Cook et al, C-1, '45. |

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—FIGURE 2—

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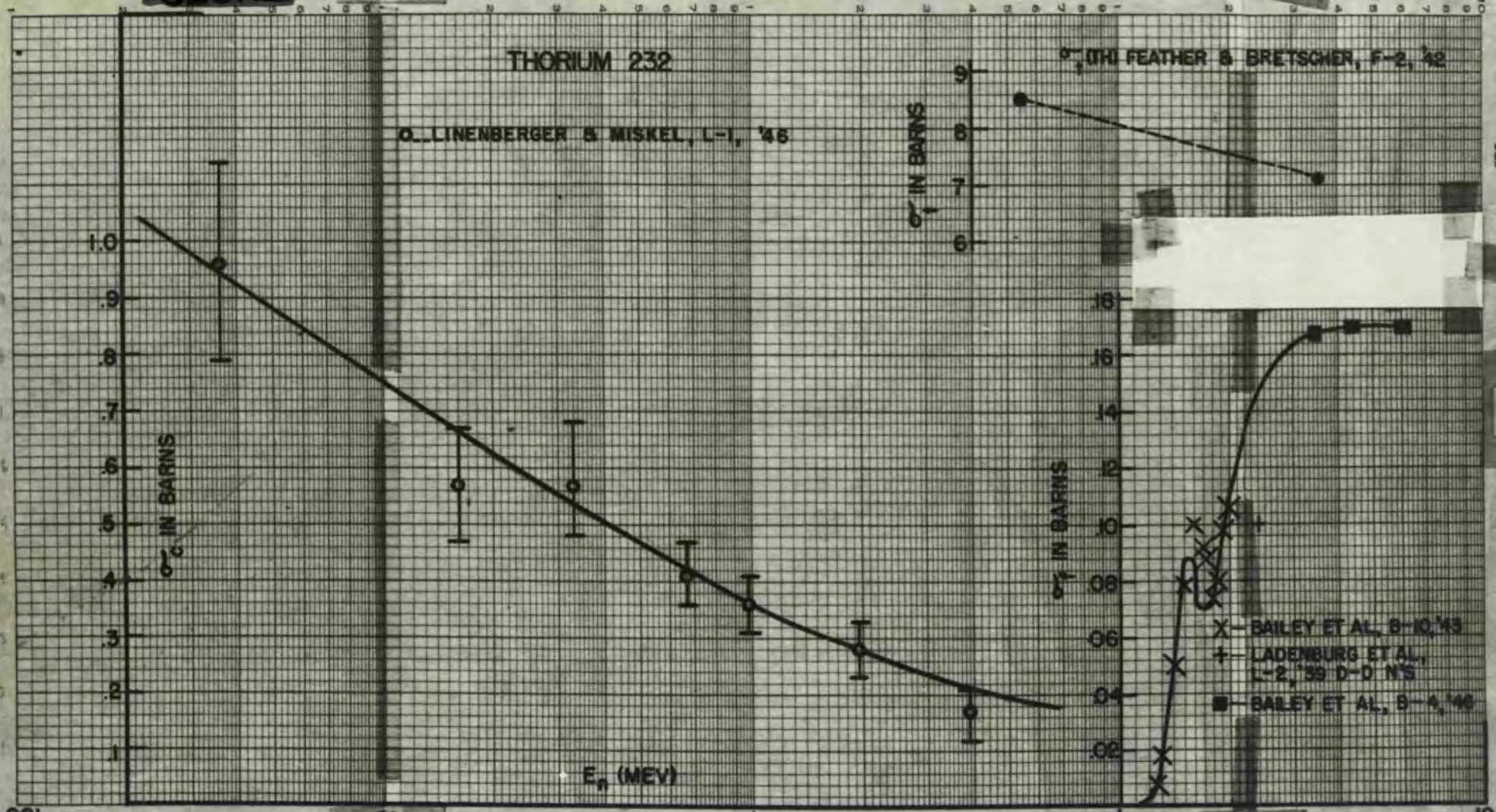



TH232 FAST

[redacted]



91 Protoactinium (Pa)

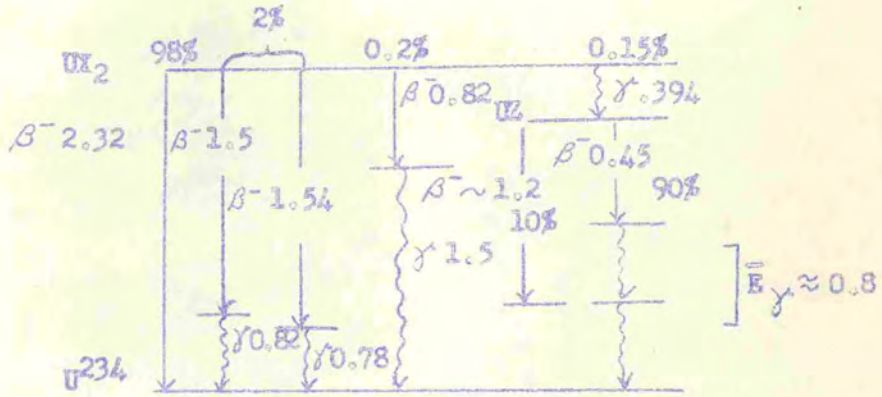
| 229 | 230 | 231 | 232 | 233 | 234 ($UX_2$ and UZ) |
|---|---|---|---|---|---|
| 1.5 d | 17.0 d | $3.43 \times 10^4$ y | 1.32 d | 27.4 d | 1.14 m 6.7 h |
| $\alpha$ 5.6 | $\beta^- \sim 1.1$ | $\alpha$ 5.012 (87%) | $\beta^-$ 0.14 (75%) | $\beta^- \sim 0.2$ | See decay scheme on next page. |
| K? | $\gamma$ 0.94 | 4.736 (13%) | 0.4 (20%) | $\gamma$ 0.084 | |
| | | $\gamma$ 0.095 | 1.0 (5%) | 0.298 | |
| | | 0.294 | $\gamma$ 1.2 | 0.309 | |
| | | 0.323 | | 0.337 | |

| | Neutron Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| FISSION | | | | |
| $Pa^{230}$ | P | C | 19,000 | Ghiorso et al, G-3. |
| $Pa^{231}$ | P | C<br>0.15-3.0 mev | $\leq$ 0.092<br>graph | Farwell and Kahn, F-1, '46.<br>Figure 3. |
| $Pa^{232}$ | P | C | 700 | Perlman, P-1, '46. |
| $Pa^{233}$ | P | C | < 1<br>< 0.1 | Hagemann et al, H-2, '47.<br>L. Borst, private connumication. |
| | Ra-Be-Par | | < 1.5 | Pontecorvo and West P-6, '45. |
| $Pa^{233}/U^{233}$ | Ra-Be | ~ 4 mev | 0.21 | Pontecorvo and West, P-6, '45 |
| $Pa^{234}$ | TC | T | $\sim 10^3$-$10^4$ | Bentley et al, B-2, '46. |
| $Pa^{234}$($UX_2$)<br>(UZ) | P | | $\leq$ 500<br>$\leq$ 5000 | E. Barney et al, B-9, '46.<br>" " " " " |

[redacted]

SLOW and FAST

91 Protoactinium




H. L. Bradt, private communication to R. W. Stoughton, Feb. 1947.

| | Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| CAPTURE | | | | |
| $Pa^{231}$ | P | | 290 ± 20% | Elson and Sellers, E-1, '47. |
| $Pa^{233}$ | TC | T | 37 ± 14 | Katzin and Hagemann, K-1, '46. |

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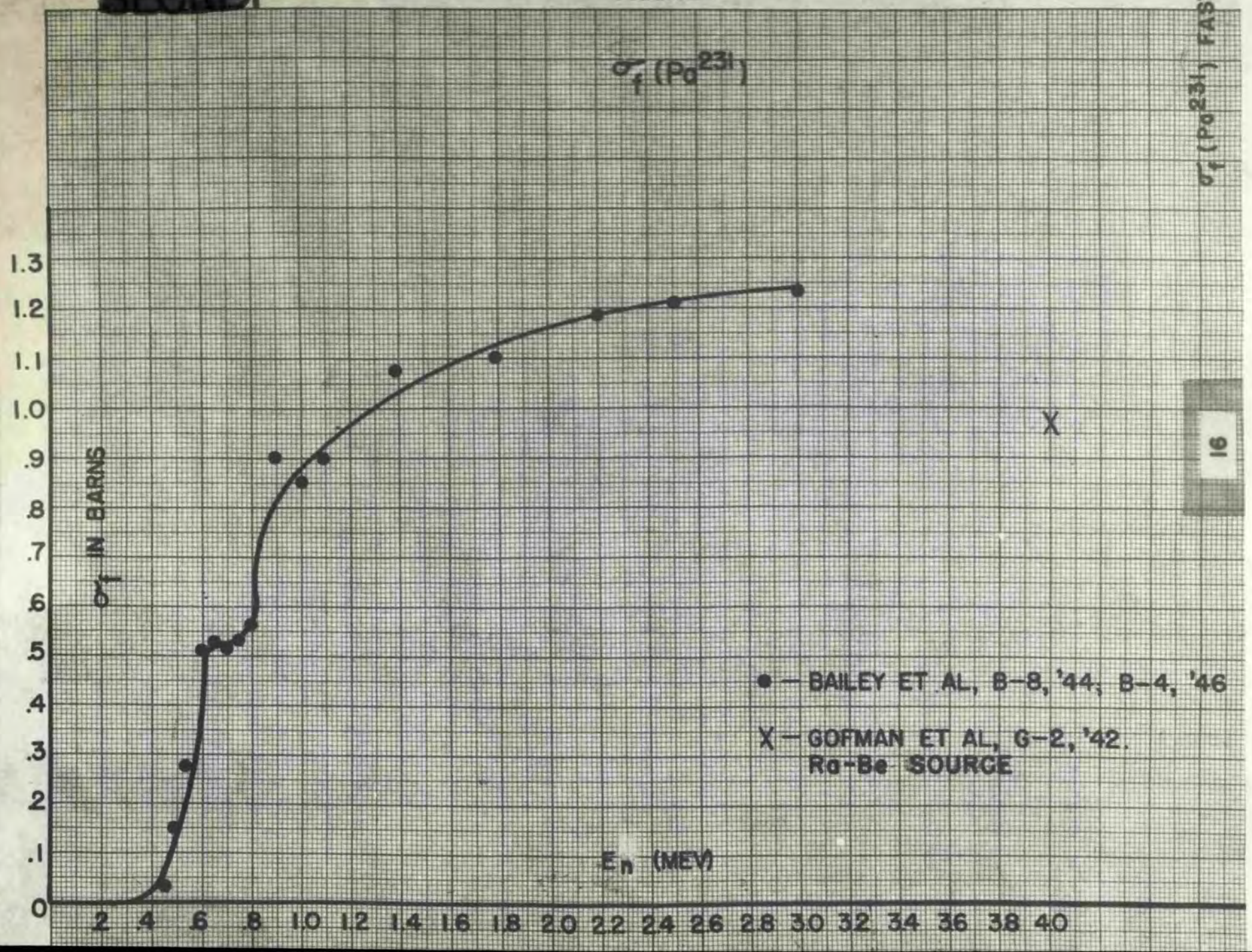
—FIGURE 3—




16

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U (natural) and $U^{238}$

| 230 | 231 | 232 | 233 | 234 | 235 | 236 |
|---|---|---|---|---|---|---|
| | | | | 0.005 | 0.71 | |
| 20.8 d<br>$\alpha$ 5.86 | 4.2 d<br>K | 70 y<br>$\alpha$ 5.31 | $1.62 \times 10^5$ y<br>$\alpha$ 4.82<br>$\gamma$ 0.040<br>0.080<br>0.31<br>$e^-$ | $2.35 \times 10^5$ y<br>$\alpha$ 4.76 | $8.6 \times 10^8$ y<br>$\alpha$ 4.36 (70%)<br>$\gamma$ 0.187 (70%) | $2 \times 10^7$ y<br>$\alpha$ 4.5 |

Continued on next page

| | Neutron Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| TOTAL U | Ra-Be-Par | ? | 23 | Whitaker et al, W-2, '39. U metal. |
| | Rn-Be-Par | ? | 20 | Goldsmith et al, G-8, '39. $U_3O_8$. Value used for $\sigma$(O) not given. |
| | 23 cm C filter | ~0.0018 | 31.4 | H. L. Anderson et al, A-5, '43. |
| | 23 " Be " | ~0.0042 | 25.7 | Fermi and Marshall, F-6, '44. |
| | D-D-Par | C | 16.0 | Carlson et al, C-3, $U_3O_8$. $\sigma$(O) = 4.1. |
| | TC | 0.025 | 15.3 | Fermi and Marshall, F-5, '44. |
| | " | " | 15.3 | Anderson and Bistline, A-1, '44. |
| | MC | " | 15.7 | Havens and Rainwater, H-6, '44. |
| | " | .015-3 ev | graph | " " . Figure 4. |
| | P | InRes 1.44ev | 9.3 | Bragdon and Marshall, B-11, '44. Values vary slightly with absorber thickness. |
| | " | Ga " | ~14 | |
| | MC | 1.4~4 ev | 9.6 | E. E. Anderson et al, A-6, '44. |
| $U^{238}$ | TC | 0.025 | 10.75 | H. L. Anderson et al, A-8, '44. |
| SCATTERING U | Ra-Be-Par | ? | ~12 | Whitaker et al, W-2, '39. |
| | TC | T | 8.5 | Bragdon, B-16, '44. Based on $\sigma$(C) = 4.8. |
| | P | AgRes | 9.6 | Langsdorf, L-4, '44. " " $\sigma$(C) = 4.6. |
| | " | Epi Cd | 17 | " " . $BF_3$ chamber. |

[redacted]

U (natural) and $U^{238}$

| 237 | 238 | 239 | 240 |
|---|---|---|---|
| | 99.28 | | |
| 6.8 d | $4.50 \times 10^9$ y | 23.5 m | 10 h |
| $\beta^-$ 0.14 | $\alpha$ 4.180 | $\beta^-$ 0.56 (10%) | |
| 0.35 | | 1.20 (90%) | |
| $e^-$ | | $\gamma$ 0.076 | |
| $\gamma$ 0.14 | | 0.3 | |
| 0.23 | | | |
| 0.53 | | | |

| U | Neutron Source | $\sigma_s$/U atom | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| $\int \sigma dE/E$ | Rn-Be | $\infty$ | 239 | Anderson and Fermi, A-11, '41. |
| | " | " (C) | 253 | Anderson, A-12, '42. |
| | " | " ($H_2O$) | 255 | " " " |
| | | " | 240 | Anderson, A-13. |
| | Cyclotron | ~10-1000 | graph | Creutz et al, C-4. |
| | " | 17-1600 | " | Mitchell et al, M-5, '44. |
| | P | 8.2-400 | " | Goldstein and Hughes, G-10, '46. Based on $\int \sigma dE/E$ for In = 3,000. |
| | " | $\infty$ | 221 | |
| | | | See also | Graham et al, G-9, '44. |
| | | | " " | Dancoff et al, D-5, '46. |

| $U^{238}$ | Neutron Source | Neutron Energy | $\sigma$ Measured | |
|---|---|---|---|---|
| ABSORPTION | | 0.025 | 2.58 | Anderson et al, A-7, '44. Danger method. Based on $\sigma$(B) = 703. |
| ACTIVATION 23.5 m | TC | " | 2.53 | Seren, S-6, '44. |
| | " | " | 2.6 | Hill and Nagle, H-4, '44. From $\sigma_c(28)/\sigma_f(25) = 0.66 \pm 0.02$. (Natural U) |
| | Ra-Be-Par | " | 2.86 | Based on $\sigma$(Mn) = 13.0 } Grummitt et al, G-7, '44. |
| | | | 2.59 | " " $\sigma$(I) = 7.0 } |
| | | | 2.66 | " " $\sigma$(Th) = 7.0 } |
| Consistent set for U | | $\sigma_a(28)$ = | 2.59 | |
| | | $\sigma_a(25)$ = | 4.60 | |
| | | $\sigma_a(U)$ = | 7.2 | |
| | | $\sigma_t(U)$ = | 15.3 | |
| | | $\sigma_s(U)$ = | 8.1 | |

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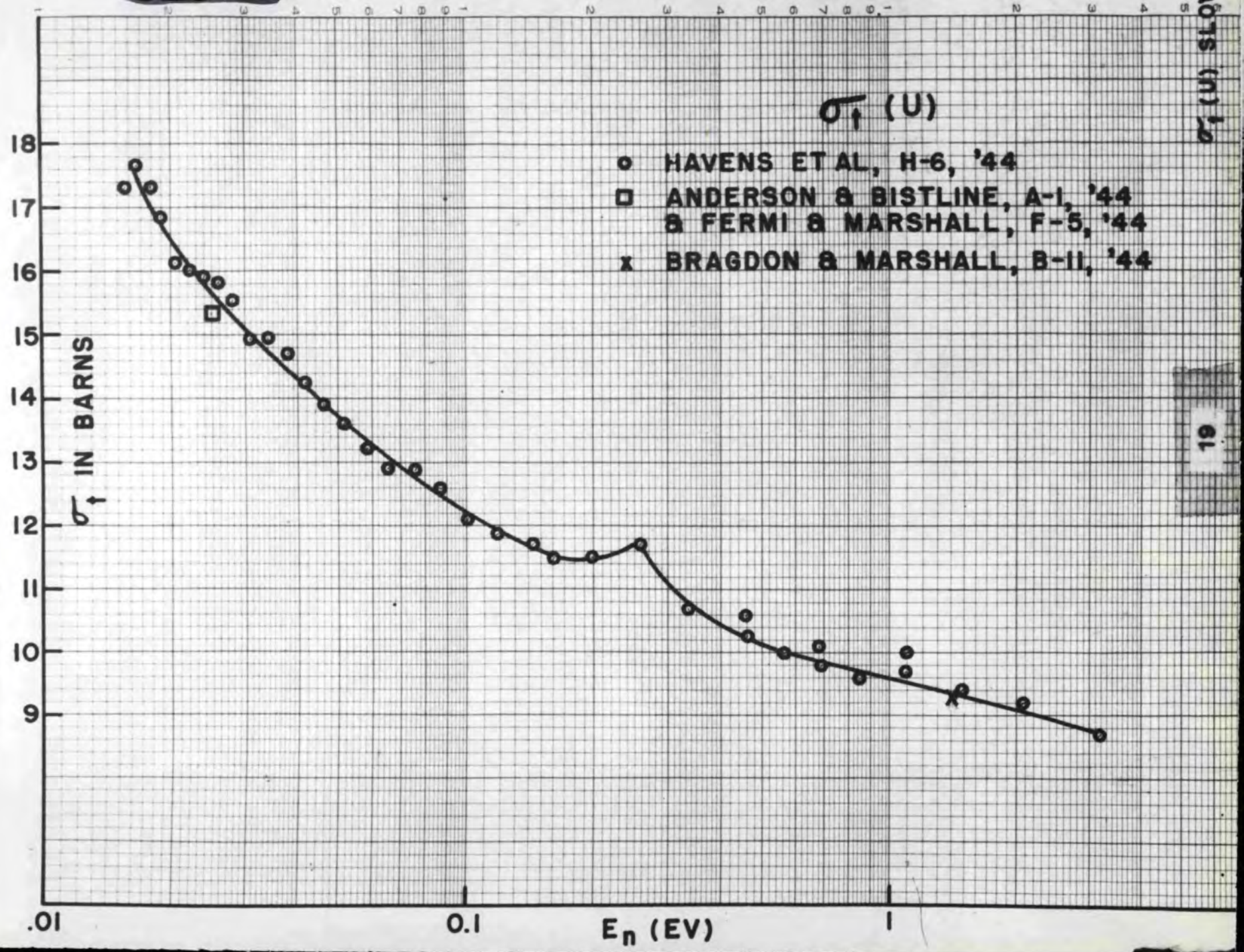
— FIGURE 4 —




$\sigma_t$ (U) SLOW

19

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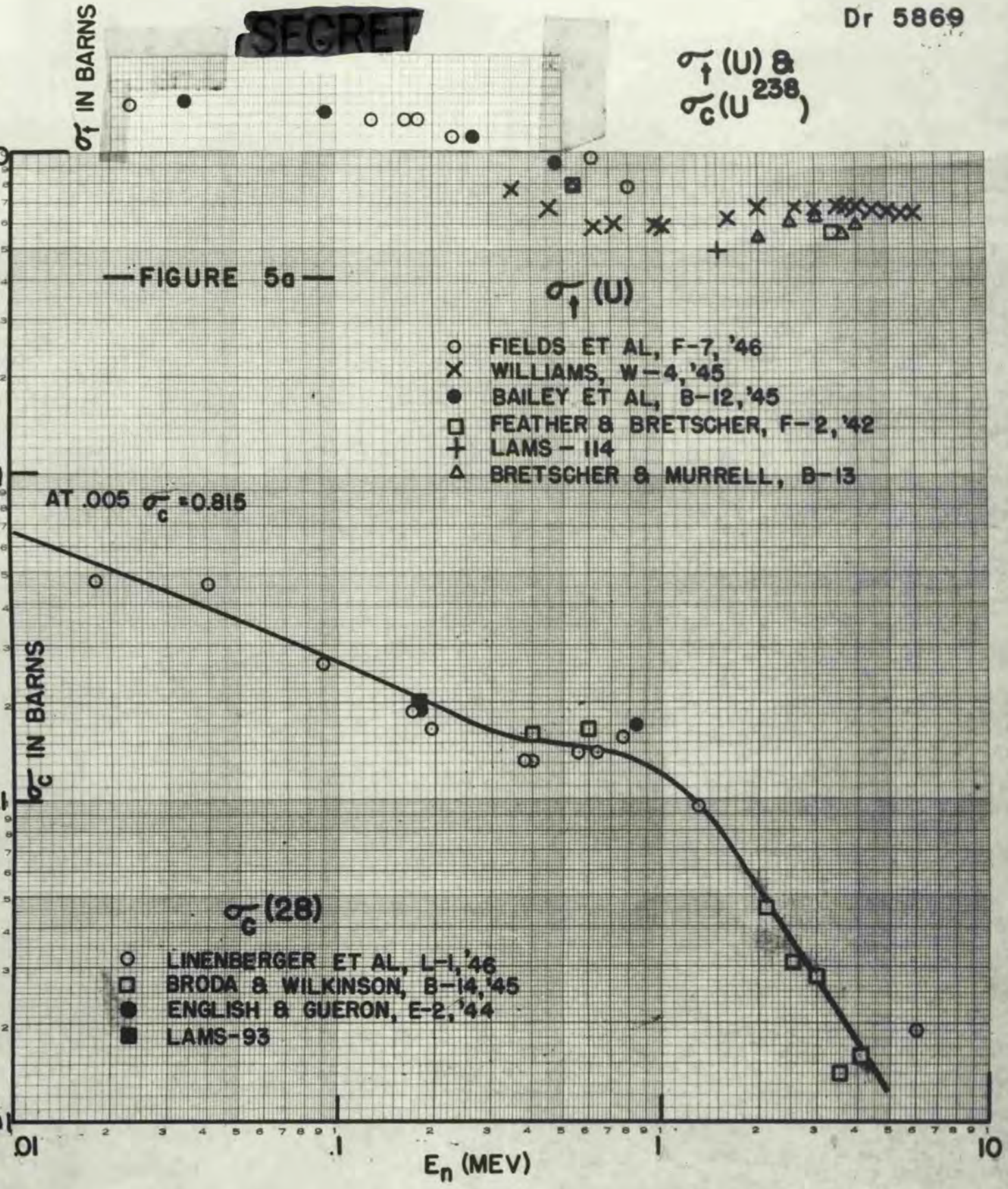


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$\sigma_f$(U) & $\sigma_c$ ($U^{238}$) FAST

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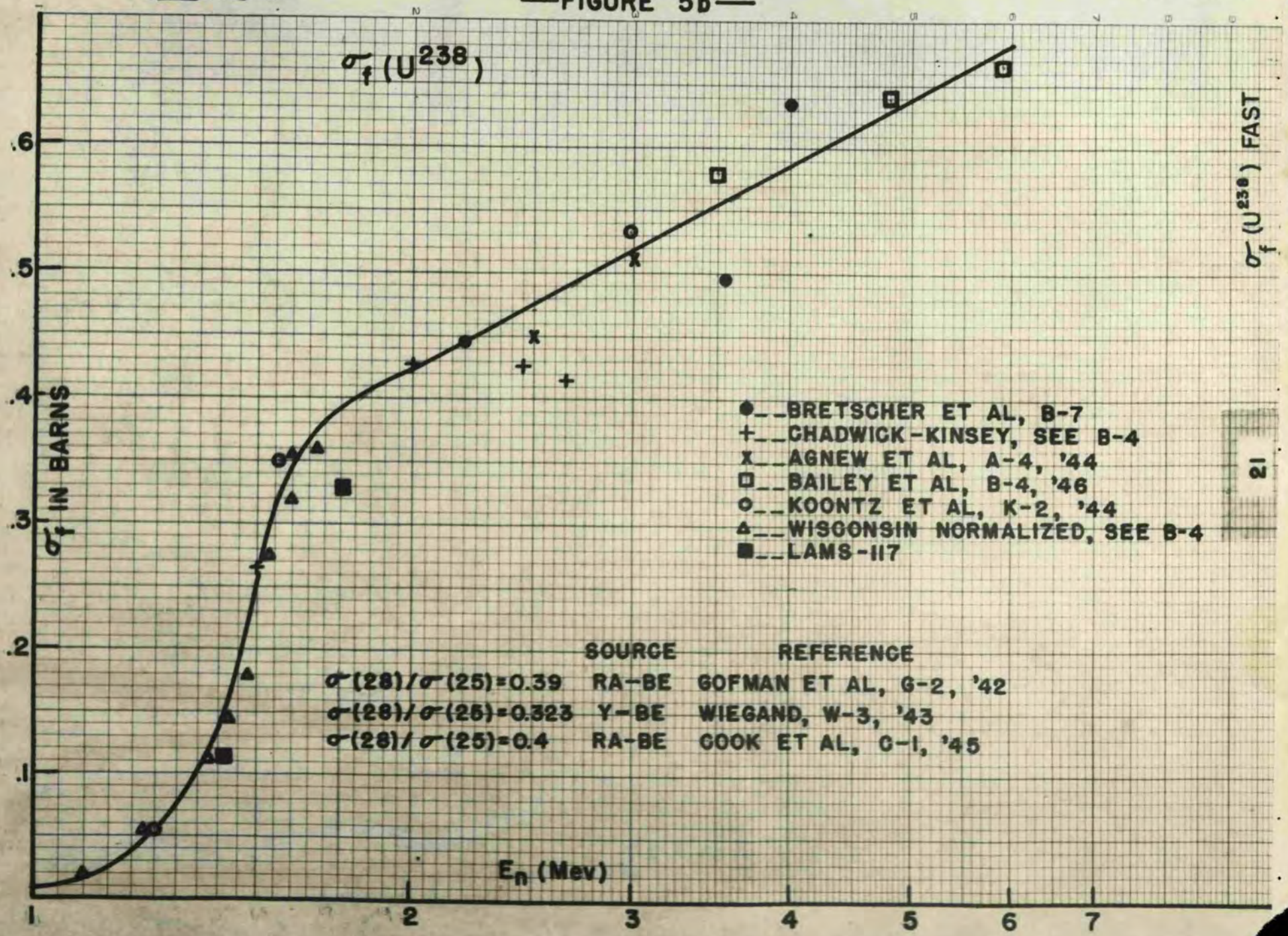
—FIGURE 5b—



[redacted]

U (natural) For graphs for $\sigma_t(U)$ and $\sigma_c(U)$ and $\sigma_f(28)$, see Figures 5a and 5b.

| | Neutron Source | E(initial) | E(bias) | $\Theta$ | $4\pi\sigma(\Theta)$ | Reference |
|---|---|---|---|---|---|---|
| DIFFERENTIAL | Li-p | .200 | | 90°-180° | 6.0 | Olum et al, 0-2, '45. |
| | Li-p | .600 | 0.160 | 30°- 60° | 11.2 | |
| n energy after scattering > E(bias) | | | 0.350 | " | 11.9 | |
| | | | 0.16 | 60°-90° | 7.3 | |
| | | | 0.35 | " | 6.5 | |
| | | | 0.16 | 90°-180° | 4.0 | " " " " |
| | | | 0.35 | " | 3.8 | |
| | Li-p | 1.5 | 0.50 | 30°-60° | 8.2 | |
| | | | 0.75 | " | 6.5 | |
| | | | 1.20 | " | 7.5 | |
| | | | 0.50 | 60°-90° | 3.4 | |
| | | | 0.75 | " | 3.6 | " " " " |
| | | | 1.20 | " | 1.8 | |
| | | | 0.50 | 90°-180° | 2.6 | |
| | | | 0.75 | " | 2.1 | |
| | | | 1.20 | " | 2.2 | |
| | D-C | 1.6 | ~1.0 (28 fission threshold) | 115° | 3.2 | Frisch and McKibben, F-15, '43. |
| | | | | 138° | 1.9 | |
| | | | | 148° | 1.7 | |

$\sigma(\Theta)$ is the cross section per unit solid angle for scattering at an angle $\Theta$ with the direction of the incident beam. The values given are averages for the angular ranges indicated.

[redacted]

FAST

U (natural)

| | Neutron Source | E(initial) | E(bias) | $\theta$ | $4\pi\sigma(\theta)$ | Reference |
|---|---|---|---|---|---|---|
| DIFFERENTIAL | D-D | 3.0 | 0.75 | 30°-60° | 7.8 | Olum et al, O-2, '45. |
| | | | 1.30 | | 6.1 | |
| | | | 2.25 | | 6.0 | |
| | | | 0.75 | 60°-90° | 2.5 | " " " |
| | | | 1.30 | | 1.3 | |
| | | | 2.25 | | 0.6 | |
| | | | 0.75 | 90°-180° | 1.8 | " " " |
| | | | 1.30 | " | 0.95 | |
| | | | 2.25 | " | 0.95 | |
| | D-D | 5.1 | ~1.0 | 45° | 2.3 | Frisch and McKibben, |
| | | | 28 fission | 115° | 1.8 | F-15, '43. |
| | | | threshold | 138° | 1.5 | |
| | | | | 148° | 1.3 | |

| | Neutron Source | E(initial) | E(bias) | $\sigma_i$ | Reference |
|---|---|---|---|---|---|
| INELASTIC | Y-Be | 0.18 | $\Delta E$ = 40kev | 0.4 | Fischer et al, F-17, '45. |
| | Li-p | 0.2 | | 0-0.75 | Barschall et al, B-18, '44. |
| | " | 0.6 | 0.16 | 0 | |
| n energy after scattering <E(bias) | " | " | 0.35 | 0.4 | |
| | " | 1.5 | 0.50 | 1.6 | |
| | | | 0.75 | 1.9 | " " " " |
| | | | 1.2 | 2.0 | |
| | D-D | 3.0 | 0.75 | 1.8 | |
| | | | 1.3 | 2.7 | " " " " |
| | | | 2.25 | 2.7 | |
| | Ra-B | | ~1.0 | 2.5 | Feld, F-16, '43. |
| | $H^3$-D | 14 | ~12 | 1.65 | Barschall et al, B-19, '47. Cu |
| | | | ~3 | 1.65 | and Al used as threshold detectors |

[redacted]

U (natural)

| | Neutron Source | Neutron Energy | $\sigma_s > 30^\circ$ | $\sigma_{tr}$ | Reference |
|---|---|---|---|---|---|
| SCATTERING and TRANSPORT | Li-p | 0.20 | 8.4 | 7.5 | Olum, O-2, '45. |
| | " | 0.60 | 6.3 | 5.2 | $\sigma_s$ and $\sigma_{tr}$ include $\sigma_f$. |
| | " | 1.50 | 4.7 | 4.3 | |
| | D-D | 3.00 | 4.3 | 3.8 | |
| | Be-D | 3 - 5 | $\sigma_t(U_2O_5)_{\frac{1}{2}} = 13.0$ | | May and Powell, M-3. |
| $U^{238}$ | | | | | |
| n,2n | P | P | (yield of 37)/(yield of 49) = 0.003 ± 50% | | T. J. La Chapelle, L. B. Magnusson, private communication. Beard, B-20, '45. |

[redacted]



| | Neutron Source | Neutron Energy | $\sigma$ | Reference |
|---|---|---|---|---|
| ABSORPTION | | 0.025 ev | 566 | E. Fermi et al, F-12. |
| | TC | " | 559 | Anderson and May, A-9, '44. Assumed $\sigma_s = 8.3$. |
| | TC | " | 566 | Lichtenberger, Zinn et al, L-6, '46. Assumed $\sigma_s = 8$. |
| | | Average = | 564 | |
| FISSION | MC | 0.02-500 | graph | E. E. Anderson et al, A-10, '44. Figure 6. |

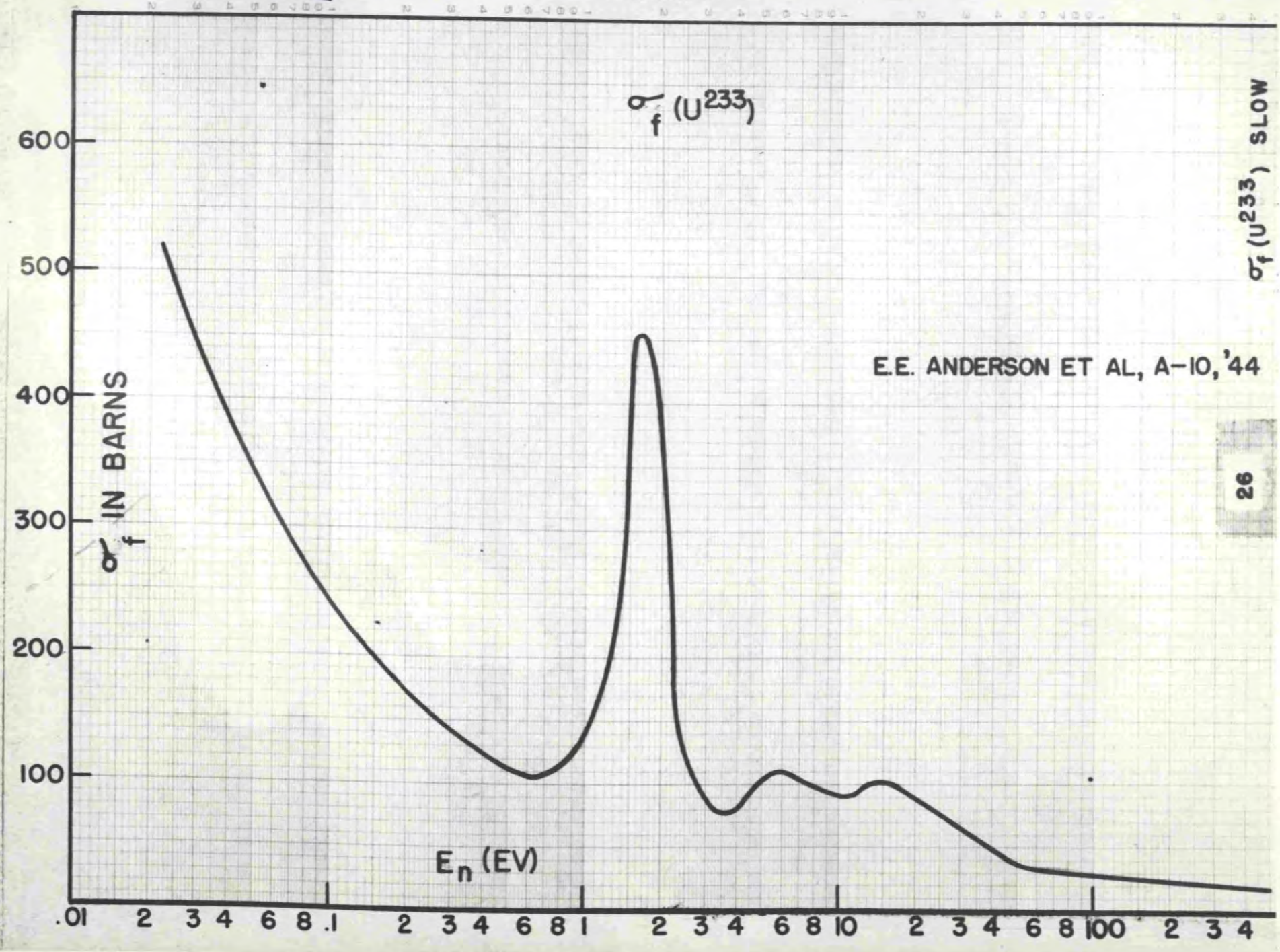
This experimental work gives only relative values of $\sigma_f$. An absolute value at 0.025 ev of 488 was assigned by taking the average of the following cross sections which were found by comparison with 25. It was assumed that $\sigma_{23}(0.025\ ev) = 1.13\ \overline{\sigma_{23}}$ and that $\sigma_{25}(0.025\ ev) = 1.15\ \overline{\sigma_{25}}$ where the bars indicate averages over Maxwellian distributions for which kT = 0.025 ev. (See Figure 10 for variation of the 25 factor with kT.) $\sigma_f(25)$ at 0.025 ev was taken to be 527.

| | | | |
|---|---|---|---|
| TC | 0.025 | 498 | Lichtenberger, Zinn et al, L-6, '46. |
| TC | " | 487 | Anderson and May, A-9, '44. |
| Cyclotron + graphite | " | 481 | De Wire et al, D-3, '46. |
| | Average = | 488 | |

SECRET

Dr 5871

—FIGURE 6—




$\sigma_f$ ($U^{233}$) SLOW

26

[redacted]

| | Neutron Source | Neutron Energy | $\sigma$ | Reference |
|---|---|---|---|---|
| $\nu$ | Based on | $\nu(25)$ = | 2.50 | |
| | Cyclotron +graphite | | 2.57 | DeWire et al, D-4, '44. From $\nu(23)/\nu(25)$ prompt = 1.033, 0.76% delays 25, 0.24 delays 23. |
| | TC | | 2.70 | Anderson and May, A-9, '44. Compared n emission and fission rates in foils of 23 and 25. |
| $\eta = \nu/(1+\alpha)$ | | | 2.38 | Anderson and May, A-9, '44. From n emission rates and $\sigma_a(23)/\sigma_a(25) = 564/644$. |
| | P | | 2.33 | Lichtenberger, Zinn et al, L-6, '46. Oscillator used to compare reactivity change due to 23 and B samples. |
| | | | 2.35 | Lichtenberger, Zinn et al, L-6, '46. From comparison with 25 assuming $\eta(25) = 2.12$. |
| | | Average = | 2.35 | |
| | Consistent set | $\sigma_a = 564$ at 0.025 ev<br>$\sigma_f = 490$ at 0.025 ev<br>$\sigma_c = 74$ | | $\nu = 2.70$ $\eta = 2.35$ $1+\alpha = 1.15$ |

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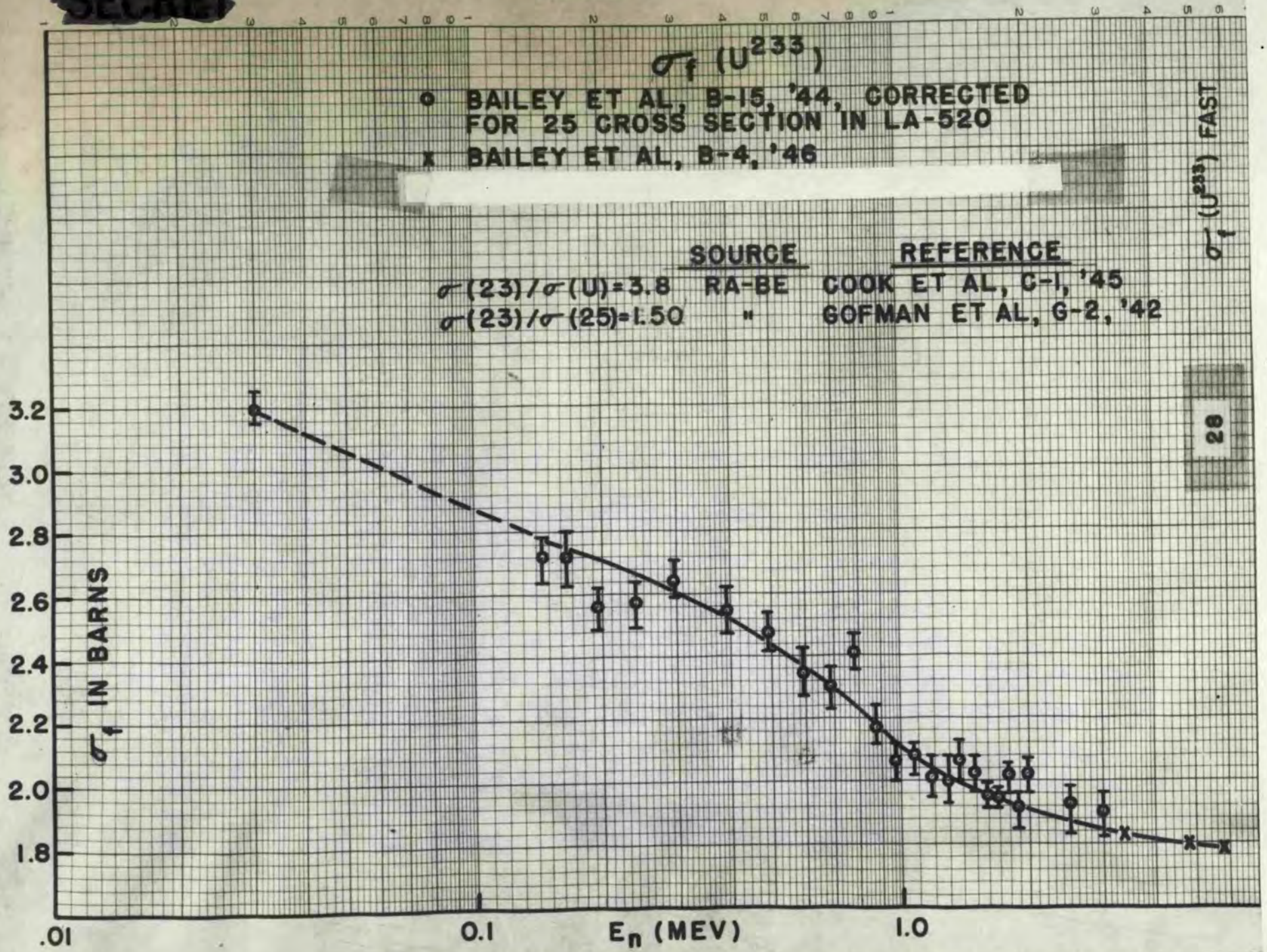
—FIGURE 7—



[redacted]

| | Neutron Source | Neutron Energy | $\sigma$ | Reference |
|---|---|---|---|---|
| TOTAL | MC | 0.004-1000 | graph | Rainwater et al, R-2, '48. Figure 9. From measurements on special samples enriched to ~95% in $U^{235}$. Cross sections on graphs are per atom of sample rather than per atom of $U^{235}$. |
| ABSORPTION | MC | 0.015-200 | graph | E. E. Anderson et al, A-6, '44. Figure 8. |
| | | 0.025 | 653 | Assumed $\sigma_s = 9.2$. |
| | TC | 0.025 | 645 | Fermi et al, F-10, '43. |
| | " | " | 640 | Fermi and Marshall, F-6, '44. |
| | " | " | 642 | Lichtenberger, Zinn et al, L-6, '46. |
| | " | " | 642 | Fermi and Marshall, F-11, '44. From $\sigma_a(25)/\sigma_a(Li) = 9.86$ |
| | | Average | 644 | |

Assumed $\sigma_a = 8.5$

[redacted]

| | Neutron Source | Neutron Energy | $\sigma$ | Reference |
|---|---|---|---|---|
| FISSION | MC | 0.01-1000 | graph | E. E. Anderson et al, A-6, '44. Figure 8. |

The experimental work gives only relative values of $\sigma_f$. An absolute value at 0.025 ev of 546 has been assigned from the consistent set on page 34.

The values below are based on the assumption that $(\sigma_f/\sigma_b$ at 0.025 ev$) = \bar{\sigma}_f/\bar{\sigma}_b$ where $\sigma_b$ is the cross section of the comparison material and the bars indicate the experimental averages.

| | | | | |
|---|---|---|---|---|
| | Ra-Be-Gr | 0.025 | 541 | Snyder and Williams, S-10, '44. Modified for $Q = 0.900 \times 10^7$ sec$^{-1}$. From p 22, $\sigma_f = (640 \times .867)/(1.14 \times 0.90)$ |
| | Cyclotron + graphite | " | 552<br>554 | Based on $\sigma_a(B) = 703$<br>" " $\sigma_a(Li) = 64.9$ } Bailey et al, B-17, '44. |
| | " | " | 547<br>510 | " " $\sigma_a(Mn) = 13.0$<br>" " $\sigma_a(Au) = 95$ } Deutsch and Linenberger, D-2, '44. |
| | Boron absorption curve | | | Fermi et al, F-13, '45. |
| CAPTURE | X and W piles | 0.025 | 101 ± 8 | Williams and Yuster, W-5, '46. Mass spect. measurement. Flux from fissions, $\sigma_f = 540$. |

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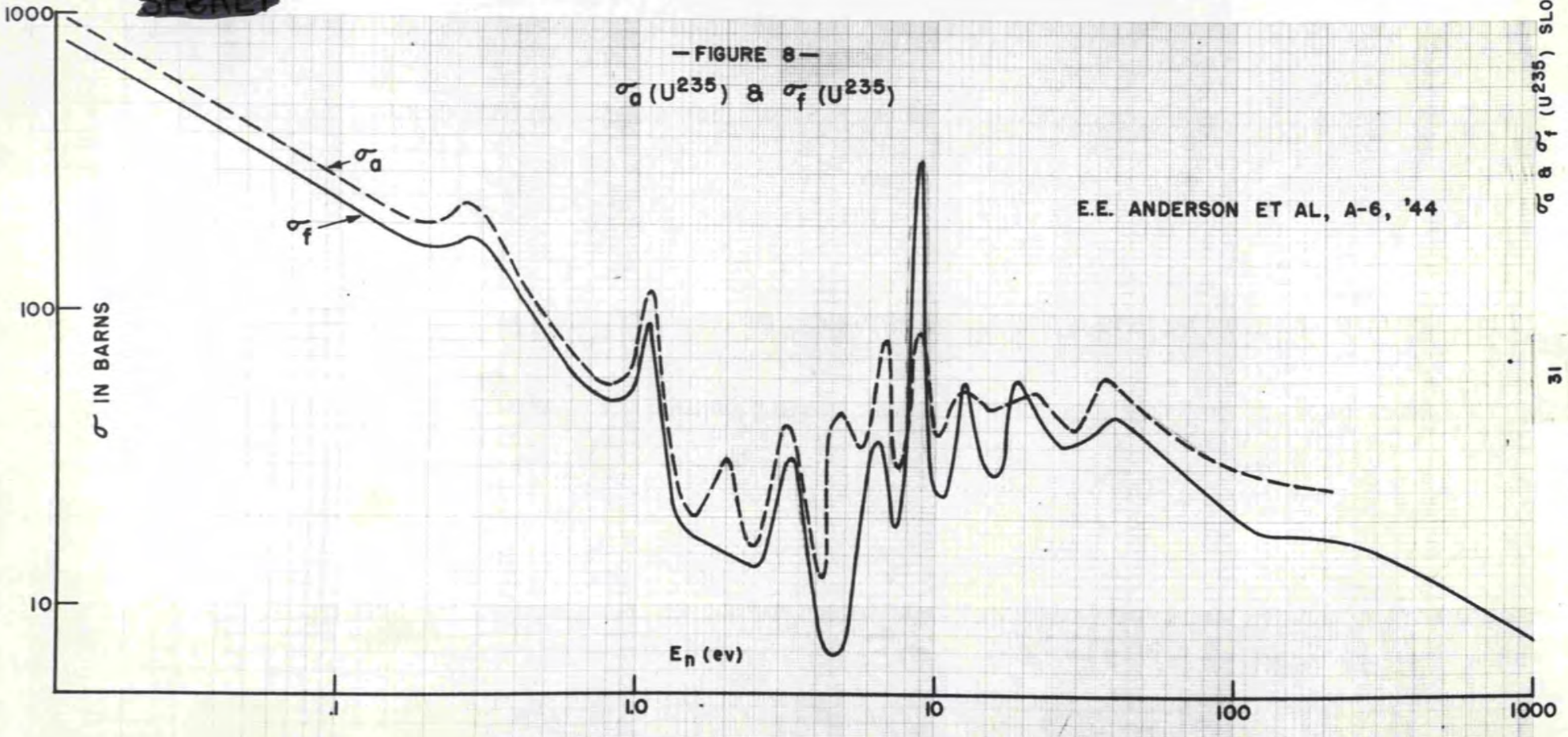
Dr 5873




— FIGURE 8 —

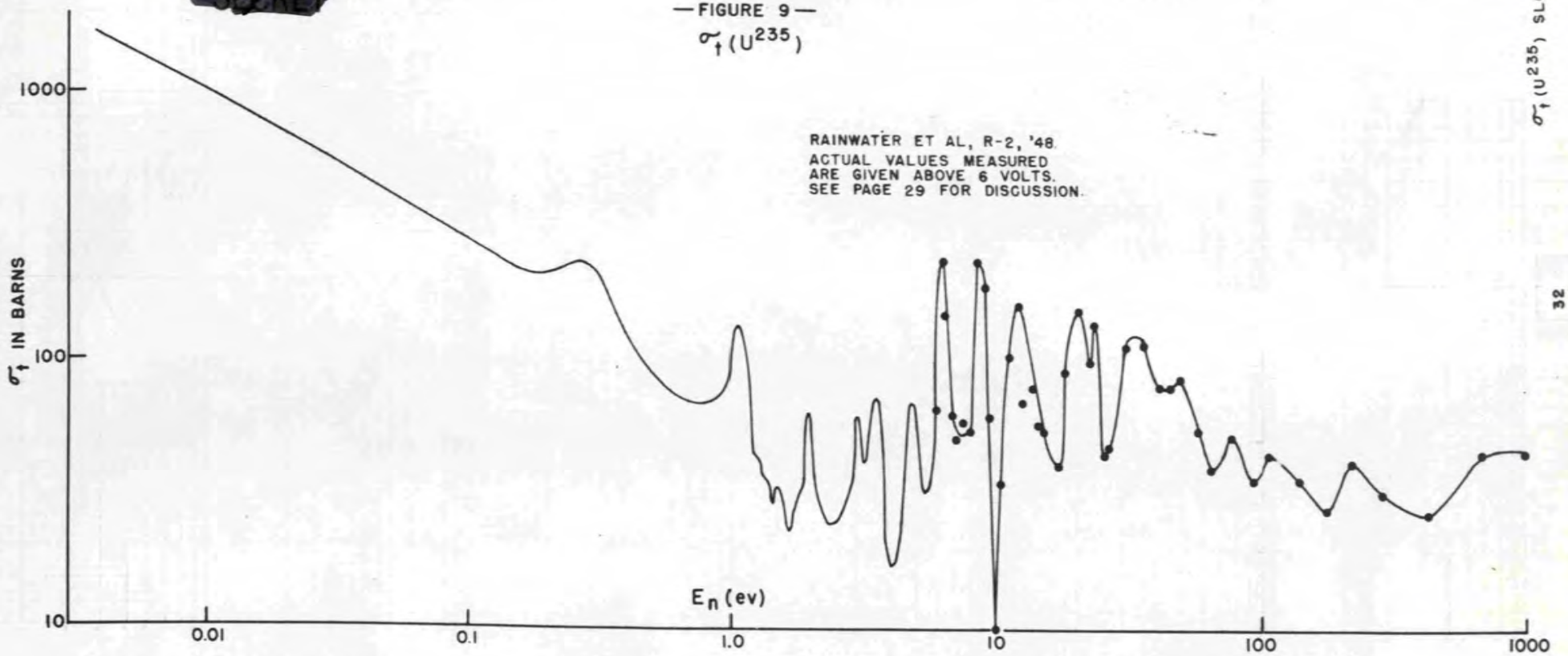
$\sigma_a (U^{235})$ & $\sigma_f (U^{235})$

$\sigma_a$ & $\sigma_f$ $(U^{235})$ SLOW

[redacted]

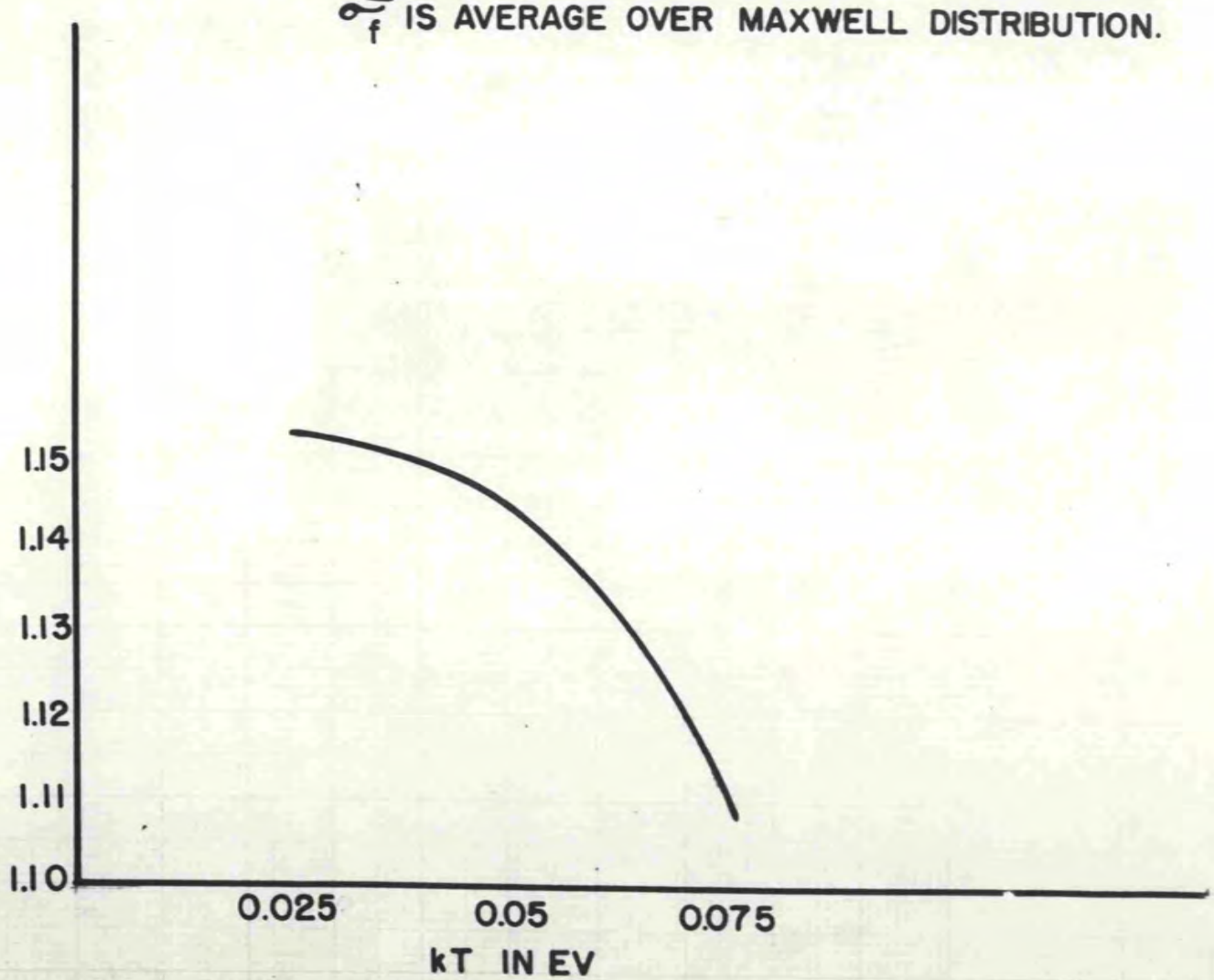
— FIGURE 9 —

$\sigma_f(U^{235})$



— FIGURE 10 —

$\sigma_f(kT)/\bar{\sigma}_f$ FOR $U^{235}$ FROM DATA OF FIGURE 8.
$\bar{\sigma}_f$ IS AVERAGE OVER MAXWELL DISTRIBUTION.




$\sigma_f(kT)/\bar{\sigma}_f(U^{235})$ SLOW

[redacted]

| | Neutron Source | Neutron Energy | Value Measured | Reference |
|---|---|---|---|---|
| $\alpha = \sigma_c / \sigma_f$ | TC | T | 0.18 | Fermi and Marshall, F-11, '44. Measured $\sigma_f(25)/\sigma_a(Li)$ and $\sigma_a(25)/\sigma_a(Li)$. |
| | | | 0.183±.006 | Williams and Tuster, W-5, '46. Mass spect. meas. Flux not involved. |
| | $\alpha$ = const. to 10% from 0.025 to 2 ev | | | E. E. Anderson et al, A-6, '44. |
| $\nu$ | Cyclotron + graphite | T | 2.54 | Snyder and Williams, S-10, '44. Modified for $Q = 0.900 \times 10^{7}$ $sec^{-1}$. From comparison with n's emitted from standard source. |
| $\eta = \nu/(1+\alpha)$ | | | 2.14 | Fermi et al, F-10, '43. From effect on pile reactivity of sample of 25 and B sample of equal absorbing power. |
| | | | 2.15 | Fermi and Marshall, F-6, '44. Same method. |
| | | | 2.11 | Lichtenberger, Zinn et al, L-6, '46. Oscillator used to find reactivity change. |
| | Consistent set | $\sigma_a = 644$ | at 0.025 ev | $\nu = 2.50$ $1+\alpha = 1.18$ |
| | | $\sigma_f = 546$ | " " | $\eta = 2.12$ |
| | | $\sigma_c = 98$ | " " | |

[redacted]

$U^{235}$ Curve for $\sigma_f$ given on Figure 11.

| | Neutron Source | E(initial) | E(bias) | $\sigma_i$ | Reference |
|---|---|---|---|---|---|
| INELASTIC | Li-p | 0.2 | | 0.7 | Barschall et al, B-18, '44. |
| n energy after scattering < E(bias) | " | 0.6 | 0.175 | 0.8 | |
| | | | 0.360 | 1.1 | |
| | " | 1.5 | 0.47 | 1.3 | " " " " |
| | | | 0.75 | 1.7 | |
| | D-D | 3.0 | 0.75 | 1.8 | |
| | | | 1.50 | 1.8 | " " " " |
| | | | 2.25 | 1.8 | |

| | | | | $\sigma_{tr}$ | |
|---|---|---|---|---|---|
| TRANSPORT | Li-p | 0.2 | | 8.1 | Barschall et al, B-18, '44. |
| | " | 0.6 | | 5.4 | Includes $\sigma_f$. |
| | " | 1.5 | | 4.9 | |
| | D-D | 3.0 | | 4.3 | |

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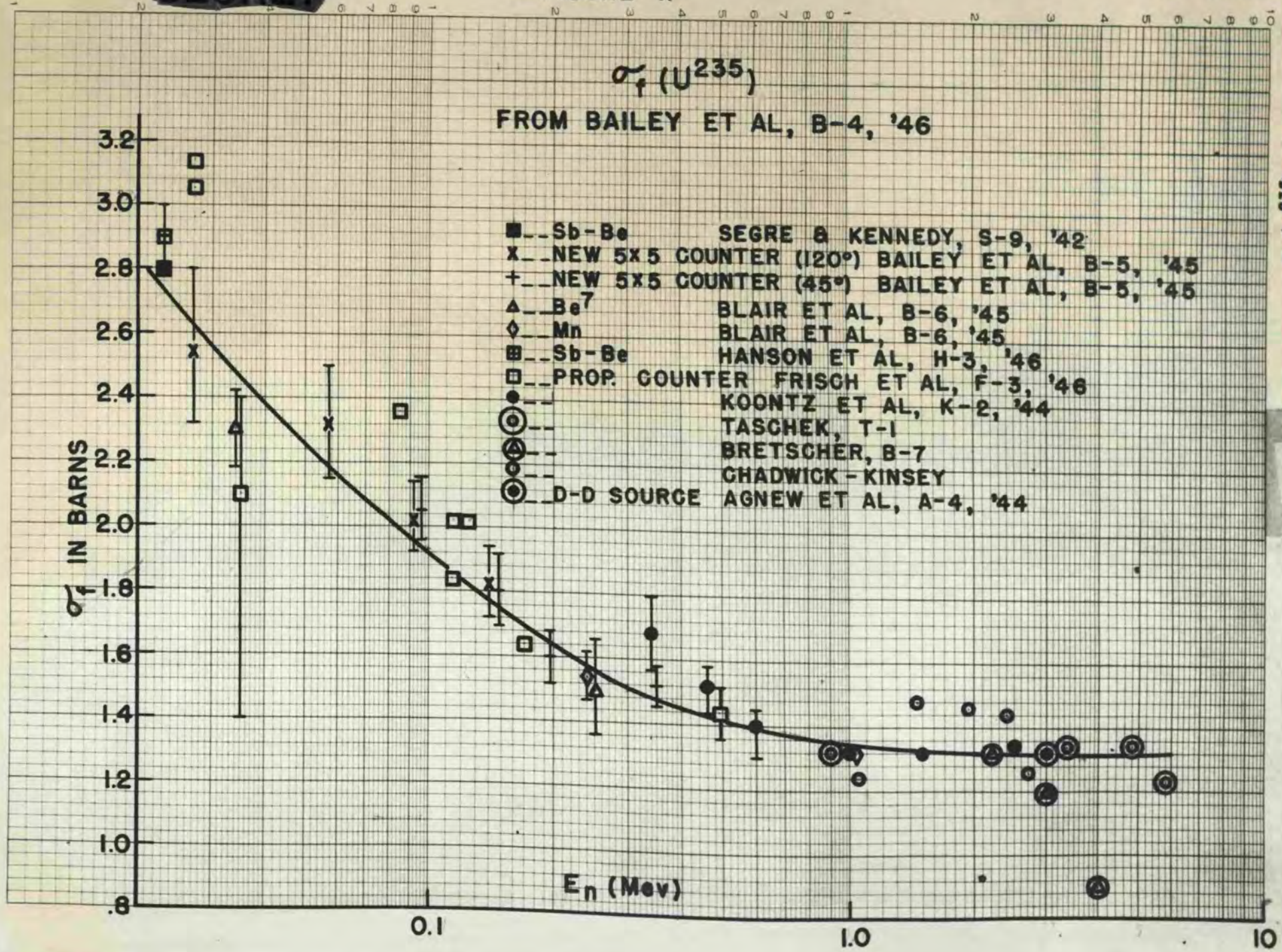
—FIGURE 11—

Dr 5876




$\sigma_f$ ($U^{235}$) FAST

36

[redacted]

| | Neutron Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| FISSION | | | | |
| $U^{230}$ | TC | T | ~25 | Bentley et al, B-2, '46. |
| $U^{231}$ | TC | T | ~250 | " " " " |
| $U^{232}$ | TC | T | 83 | Van Winkle et al, V-2, '47. |
| $U^{234}$ | | T | 2.7 | Linenberger, L-5. |
| | TC | T | 1.9 | Farwell and Kahn, F-1, '46. |
| | P | T | < 0.65 | Shapiro, S-11, '48. |
| | | T | 3.5 | $\sigma_f(24)/\sigma_f(25) = 0.064$ |
| | | 40 kev | 0.047 | " = 0.02 |
| | | 220 kev | 0.065 | " = 0.04 |
| | | Ra-Be | 0.73 | " = 0.56 |
| | | | | LA-140 |
| CAPTURE | | | | |
| $U^{236}$ | TC | T | < 30 | Finklestein and Turkevich, F-14, '45. |

[redacted]

93 Neptunium (Np)

| 234 | 235 | 236 | 237 | 238 | 239 |
|---|---|---|---|---|---|
| 4.40 d | 400 d | 22 h | $2.25 \times 10^6$ y | 2.10 d | 2.33 d |
| K | K | $\beta^- > 0.1$ | $\alpha$ 4.72 | $\beta^-$ 0.2 (60%) | $\beta^-$ 0.48, 0.70 |
| $\gamma$ 1.9 | $e^-$ | < 1.2 | | 1.4 (40%) | $\gamma$ 0.5, 0.208 |
| $e^-$ | | $\gamma$ | | $\gamma$ 1.2 | 0.226, 0.276 |
| | | | | 0.075 | $e^-$ |
| | | | | $e^-$ | |

| | Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| FISSION | | | | |
| $Np^{234}$ | TC | T | $\approx$ 1000 | Bentley et al, B-2, '46. |
| $Np^{236}$ | P | C | $< 10^5$ | Seaborg & Manning, private communication. |
| $Np^{237}$ | P | C | 0.019 | Ghiorso et al, G-5, '47 and S-3, '46. |
| | P | C | $\leq$ 0.10 | Farwell and Kahn, F-1, '46. |
| | | 0.1-3 mev | graph | Figure 12. Blair et al, B-3, '45. |
| $Np^{238}$ | P | C | 1500 | Perlman, P-1, '46. |
| | TC | T | 1600 | Studier et al, S-5, '47. From $\sigma_f(38)/\sigma_f(23) = 3.07$. |
| $Np^{239}$ | P | C | < 20 | Deutsch et al, D-1, '46. Observed $\sigma = 14 \pm 4$ with possibility that undepleted U was introduced as impurity. |
| | P | | < 10 | Floyd and Scofield, F-8, '46. |
| CAPTURE | | | | |
| $Np^{237}$ | P | C | 144 | Jaffey and Magnusson, J-3, '46. |
| n,2n | No clear cut evidence at present for n,2n reaction with piles n's. | | | W. M. Manning, private communication July 1948. |

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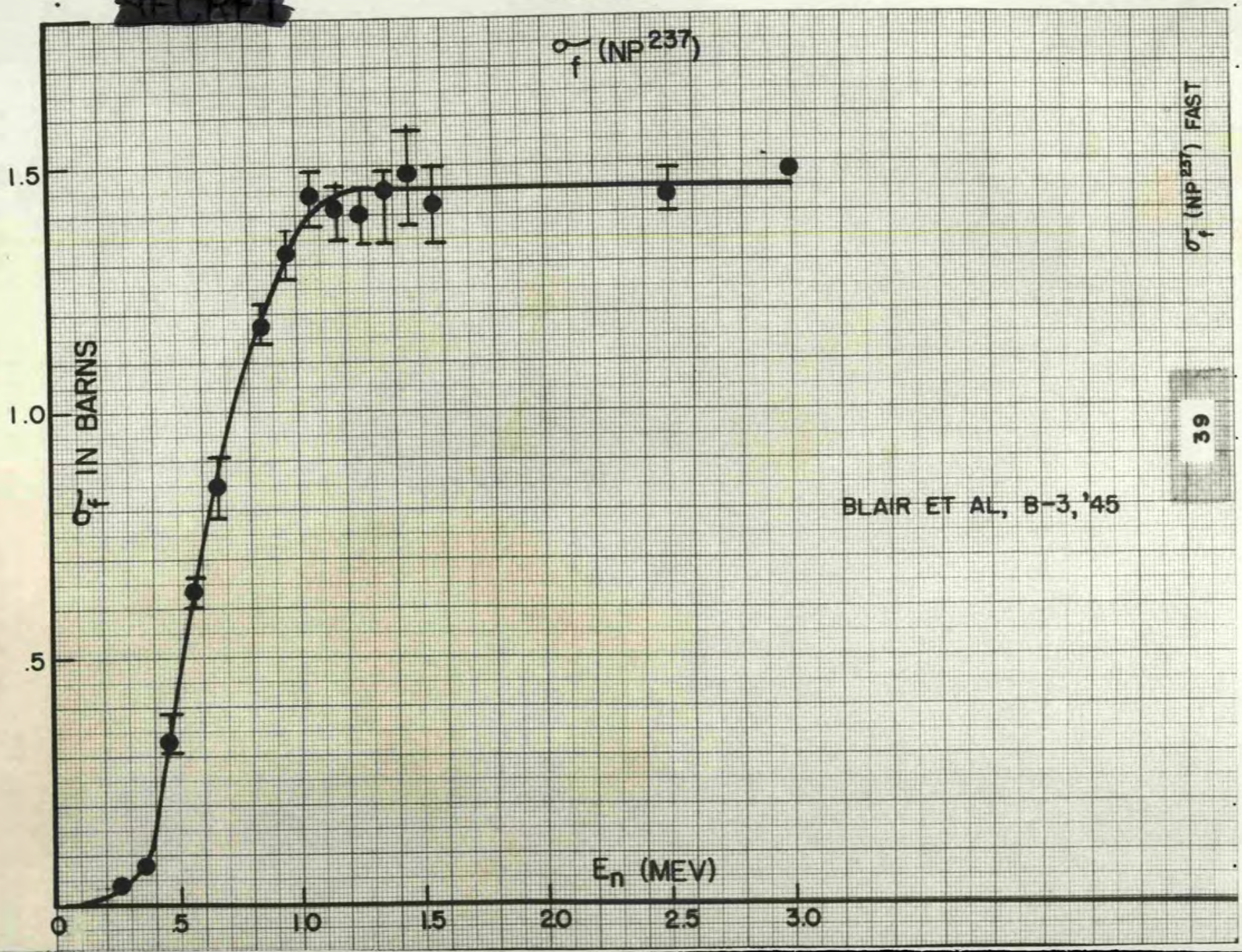
—FIGURE 12—

Dr 5877



[redacted]

$Pu^{239}$ See page 45 for Pu half lives and activities.

| | Neutron Source | Neutron Energy | $\sigma$ | Reference |
|---|---|---|---|---|
| TOTAL | MC | 0.01-65 | graph | E. E. Anderson et al, A-15, '45. Figure 13. |
| | " | 0.025 | 1045 | " " " " " " " " |
| | " | 0.025 | 1057 | E. E. Anderson et al, A-16, '44. |

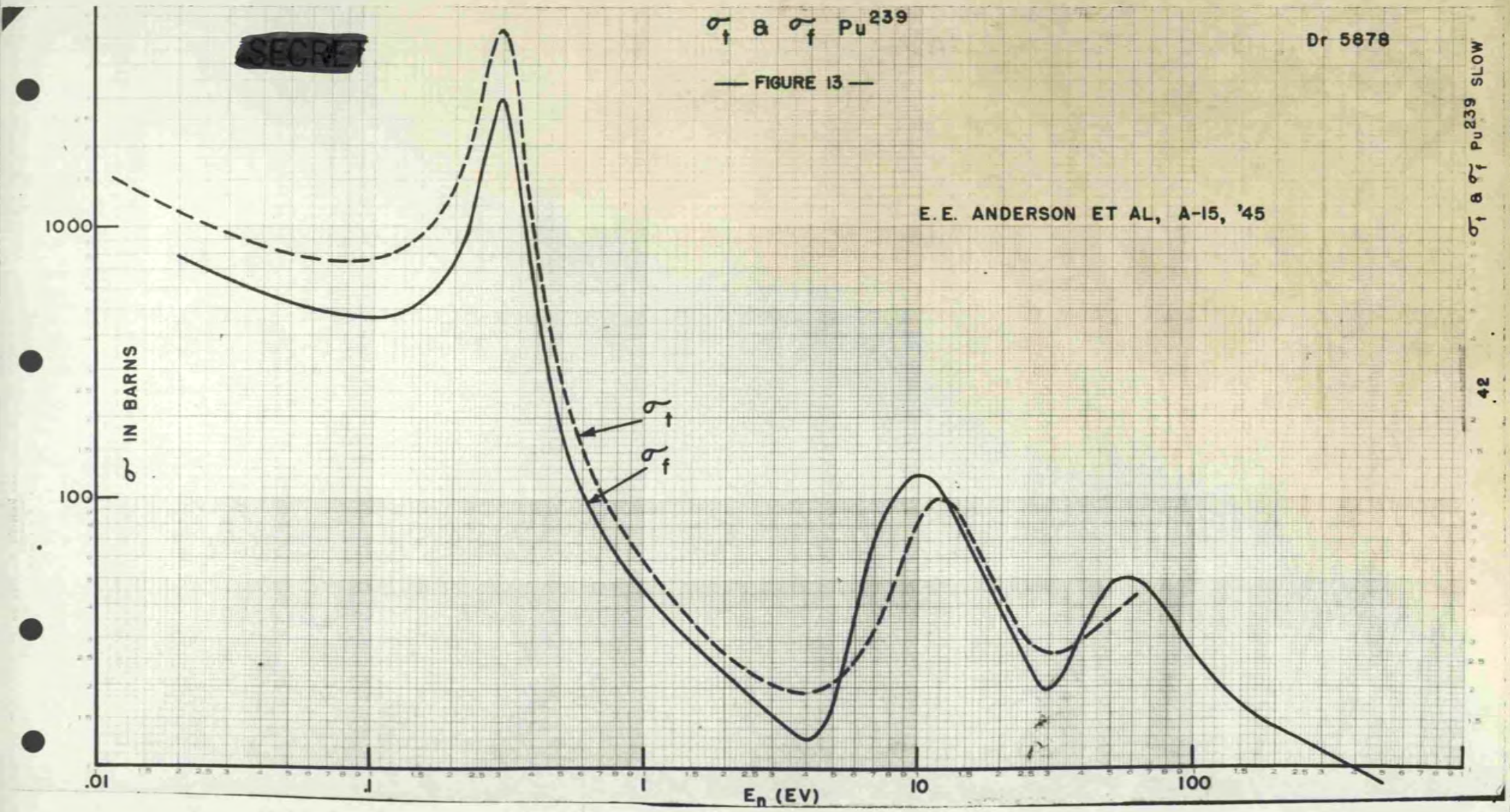
| | Neutron Source | $\bar{v}$ | $\bar{\sigma}$ | |
|---|---|---|---|---|
| | TC | 2156 m/s | 1155 | H. L. Anderson, A-17, '44. |
| | Maxwell distribution | " | 1110 | From numerical integration using curve of Anderson, A-15. |
| | " | 2480 m/s $E_{kT} = 0.025$ | 1025 | " " " " " " " " |
| 100 ev $\int \sigma dE/E$ 0.04 ev | | | 520 | Mason, M-4, '47. Calculated from curve of A-15 for infinite dispersion of Pu in Hanford pile. |

[redacted]

| | Neutron Source | Neutron Energy | $\sigma$ | Reference |
|---|---|---|---|---|
| FISSION | MC | 0.02-500 | graph | E. E. Anderson et al, A-15, '45. Figure 13. |

The experimental work gives only relative values of $\sigma_f$. An absolute value at 0.025 ev of 701 has been found by taking the average of the following cross sections which are based on measurements of $\overline{\sigma_f}(49)/\overline{\sigma_f}(25)$. Figure 8 gives $\overline{\sigma_f}(25) = 475$ for an average over a Maxwell distribution with kT = 0.025. Figure 13 gives ($\sigma_f(49)$ at 0.025 ev) $= \overline{\sigma}(49)$ 1.058. Thus ($\sigma_f(49)$ at 0.025 ev) $= [\overline{\sigma_f}(49)/\overline{\sigma_f}(25)]\,[475 \times 1.058]$

| | | | | |
|---|---|---|---|---|
| | TC | 0.025 | 709 | H. L. Anderson and Nagle, A-14, '44. Used solution. |
| | Cyclotron + graphite | " | 689 | Snyder and Williams, S-10, '44. |
| | " | " | 704 | DeWire et al, D-6, '44. |
| | | Average | 701 | |
| | Boron absorption curve | | | Fermi et al, F-13, '45. |
| 100 ev $\int \sigma\, dE/E$ 0.04 ev | | | 325 | Mason, M-4, '47. Calculated from curve of Figure 13 for infinite dispersion of Pu in Hanford pile. |


SECRET
$\sigma_t$ & $\sigma_f$ $Pu^{239}$
— FIGURE 13 —
Dr 5878
E.E. ANDERSON ET AL, A-15, '45
$\sigma$ IN BARNS
1000
100
$\sigma_t$
$\sigma_f$
.01
.1
1
10
100
$E_n$ (EV)
$\sigma_t$ & $\sigma_f$ $Pu^{239}$ SLOW

[redacted]

SLOW

$Pu^{239}$

| | Neutron Source | Neutron Energy | Value Measured | Reference |
|---|---|---|---|---|
| $\bar{\nu}$ | From comparison with 25 assuming $\bar{\nu}(25) = 2.50$ | | | |
| | Cyclotron + graphite | T | 2.95 | DeWire et al, D-7, '44. |
| | | | 2.93 | Snyder and Williams, S-10, '44. |
| $\bar{\eta} = \bar{\nu}/(1+\alpha)$ | TC | T | 2.06 | Anderson and Nagle, A-14, '44. From $\bar{\eta}(49)/\bar{\eta}(25) = 0.97$ and $\bar{\eta}(25) = 2.12$. |
| | | | 1.99 | Snyder and Williams, S-10, '44. Modified for value of $\overline{\sigma_a \nu}$ found from Figure 13 by numerical integration. |

Consistent set for thermal distribution for which kT = 0.025 ev.

$\overline{\sigma_a} = 1025$ $\quad \bar{\nu} = 3.00$ $\quad \overline{1+\alpha} = 1.54$

$\overline{\sigma_f} = 664$ $\quad \bar{\eta} = 1.95$

$\overline{\sigma_c} = 361$

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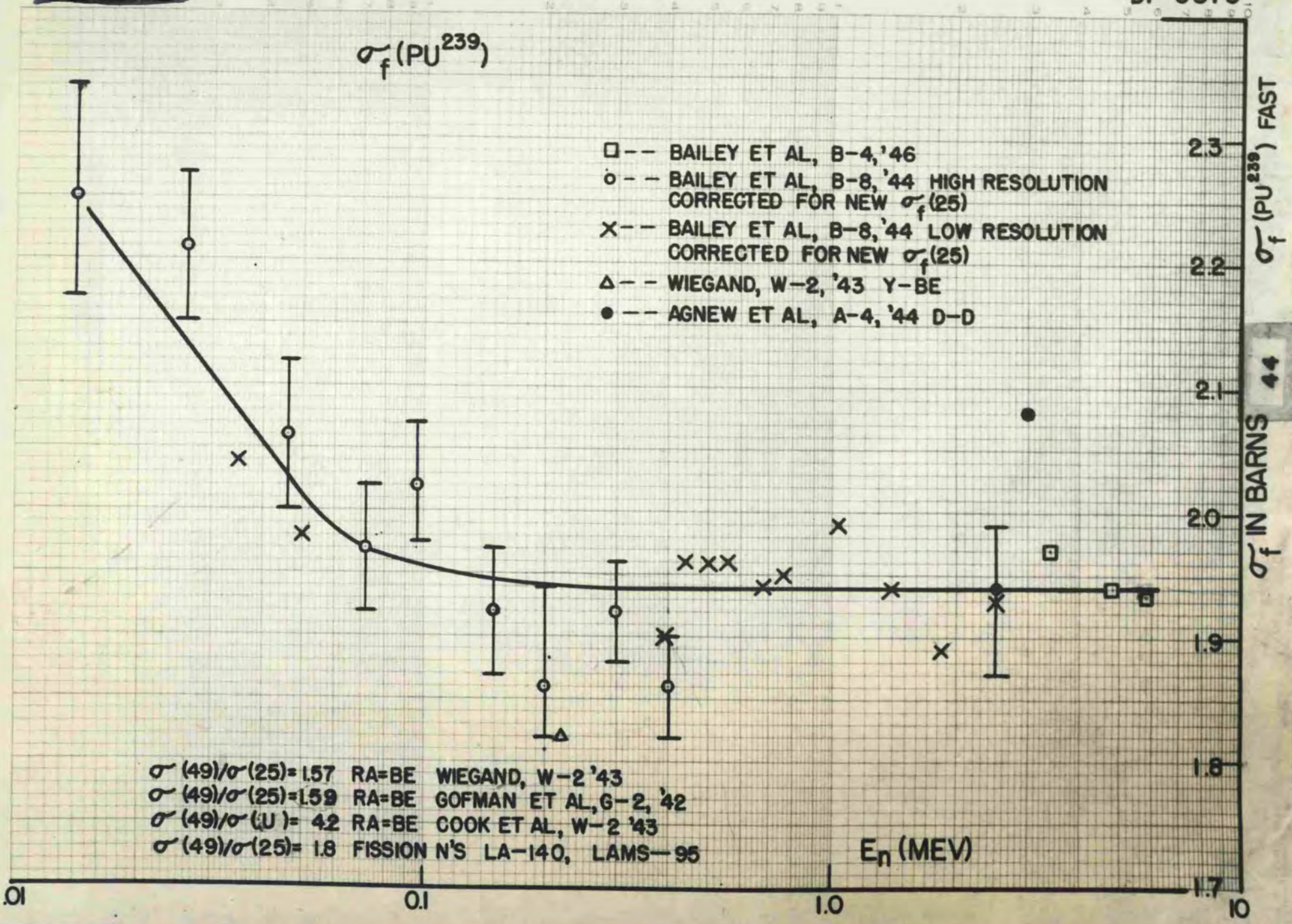
—FIGURE 14—

Dr 5879




44

[redacted]

94 Plutonium (Pu)

| 234 | 235? | 236 | 237 | 238 | 239 | 240 | 241 |
|---|---|---|---|---|---|---|---|
| 8 h<br>$\alpha$ 6.2<br>K | $\ll$12 h or<br>$>$5 y<br>K | 2.7 y<br>$\alpha$ 5.75 | 40 d<br>K<br>No $\gamma$ | 90 y<br>$\alpha$ 5.5 | $2.41 \times 10^4$ y<br>$\gamma$ 0.05<br>0.3<br>$e^-$<br>$\alpha$ 5.15<br>X-rays | $6.2 \times 10^3$ y<br>$\alpha$ 5.1 | $\sim$14 y<br>$\alpha$ $10^{-3}$ %<br>$\beta^-$ 0.01-0.02 |

| | Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| FISSION | | | | |
| $Pu^{236}$ | P | C | large | Perlman, P-1, '46. |
| $Pu^{238}$ | P | C | $\simeq$15 | Perlman, P-1, '46, and P-4, '47. |
| | P | C | 18 | Reed et al, R-1, '47. |
| | P | C | 24 | Osborne and Ghiorso, O-1, '47. |
| $Pu^{240}$ | P | C | $\leq$180 | Ghiorso et al, G-1, '46. |
| $Pu^{240}/Pu^{239}$ | P | C | 0.09 | Farwell and Kahn, F-4, '45. |
| $Pu^{241}$ | P | P | $\sim$25,000 | Mason, M-4, '47. |
| CAPTURE | | | | |
| $Pu^{238}$ | P | C | 300-800 | Reed and Bentley, R-3, '47. |
| $Pu^{240}$ | P | | $\sim$2,000 | Mason, M-4, '47. |
| | P | C | 1,500 | Seaborg and Manning, private communication |
| $Pu^{241}$ | P | C | 600 | " " " " " |

[redacted]

95 Americium (Am)

| 238 | 239 | 241 | 242 |
|---|---|---|---|
| ? | ? | | |
| 50 h | 12 h | 510 y | 17 h |
| K and L X-rays | K and L X-rays | $\alpha$ 5.5 | $\beta^-$ 0.6 |
| $e^-$ 1.2 - 1.3 | $\alpha$ | | 400 y |
| $\gamma$ 1.3 - 1.4 | $\gamma$ .285 | | $\beta^-$ ~0.5 |
| | $e^-$ .20 - .24 | | $\alpha$ (0.2%) |
| | $\alpha$/K ~0.01 | | |

| | Neutron Source | Neutron Energy | $\sigma$ Measured | Reference |
|---|---|---|---|---|
| FISSION | | | | |
| $Am^{241}$ | P | C | $3.2 \pm 0.3$ | Cunningham and Ghiorso, C-2, '47. |
| $Am^{?}$ (not $Am^{241}$) | P | C | $>10^3$ | Perlman, P-2, '47. if isotope involved has $T_{\frac{1}{2}}$ of several months. |
| CAPTURE | | | | |
| $Am^{241}$ 400 y | P | C | 400 | Seaborg, S-8 and Perlman, P-7, '48. |

SLOW

[redacted]

96 Curium (Cm)

| 240 | 241 | 242 |
|---|---|---|
| 29 d | 30-60 d | 150 d |
| α 6.3 | K | α 6.1 |

| | Neutron Source | Neutron Energy | σ Measured | Reference |
|---|---|---|---|---|
| FISSION | | | | |
| $Cm^{240}$ | P | C | ~20,000 ? | Perlman, P-4 and P-1, '46. Impurities possible. |
| $Cm^{242}$ | P | C | ~ 70 | Perlman, P-4, '46. |
| | P | C | 3,500 | Ghiorso et al, G-6, '48. |

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