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UNIVERSITY OF CALIFORNIA

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SUMMARY OF FAST FISSION CROSS SECTIONS

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In view of the many measurements of fission cross sections which have been carried out during the past few years, it seemed desirable to bring the summary given in LA-994[1] up to date. As in LA-994, only measurements using monoergic neutrons in the energy range from 10 kev to 20 Mev are included in the present summary. Furthermore, some of the older measurements have been omitted where more reliable recent measurements are available.

Measurement of a fission cross section involves measurement of a neutron flux and a determination of the number of fissionable nuclei. Since both these quantities are difficult to measure accurately, several of the reported measurements avoid one or the other of these determinations. Measurements in which both the neutron flux and the number of fissionable nuclei were determined will be referred to as "absolute measurements." Measurements in which two fission cross sections were determined in the same neutron flux but which do not involve the determination of this neutron flux will be referred to as "relative measurements." In addition there are measurements in which the energy dependence of a fission cross section was measured either by comparison with a known cross section or with the aid of a long counter, the sensitivity of which was assumed to depend on neutron energy in a known manner. Such measurements will be referred to as using an extrapolation of energy range.

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ABSOLUTE MEASUREMENTS

Most of the fission cross sections summarized in reference 1 were based on an absolute fission cross-section measurement performed at Los Alamos in 1944 by means of the recoil particle method.[2] This measurement became suspect, however, when it was discovered that the Li(p,n) reaction which was used as a neutron source in these measurements produces a second group of neutrons. This second group of neutrons did not show up in the pulse-height distributions reported in LA-128 so that it is probable that the flux determination was in error. The measurement was, therefore, repeated in 1952 by a similar method[3] to determine the fission cross section of U^{235} at 1.25 Mev.

At a neutron energy of 14 Mev, two absolute measurements were performed using the associated particle method on the $D(t,\alpha)n$ reaction.[4,5]

Absolute measurements by the method of total source strength were carried out by Taschek and Turner[6] for U^{235} at 250 kev, 600 kev, and 1 Mev. It is believed, however, that the measurements at the two higher energies are not as accurate as the more recent measurements using the extrapolation of energy range to the same energies. Another absolute determination of the fission cross section of U^{238} in the neutron energy range from 13.5 to 18 Mev using the associated particle method was reported by Jarvis.[7] These results disagree, however, with the measurements at 14 Mev carried out more recently, and it is believed, therefore, that the earlier measurements may be in error.

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A further measurement which involves an absolute neutron-flux determination is the measurement of the fission cross section of U^{238} for neutrons produced in the thermal fission of U^{235} (Ref. 8).

PROCEDURE FOR ARRIVING AT REPORTED FISSION CROSS SECTIONS

Almost all cross sections reported here except those at 14 Mev are based on a value of 1.27 barns for the fission cross section of U^{235} at 1.25 Mev.[3] The fission cross section of U^{235} at other neutron energies was obtained by extrapolation of the energy range. Practically all other fission cross sections have been measured relative to U^{235}. Older measurements of fission cross sections are given in this report after they were multiplied by the ratio of the U^{235} fission cross section as given in the present report to the value of the U^{235} fission cross section which was the accepted one at the time of writing of the earlier reports.

PRESENTATION OF DATA

The data are presented in the order of increasing atomic number. For each atomic number the isotopes are given in order of increasing atomic weight. For each fissionable isotope the cross section in barns is plotted against the neutron energy. If the measurements extend above 5 Mev, two curves are presented, one giving the data up to 5 Mev, the second one presenting the data above 5 Mev. On the second

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graph the measurements below 5 Mev are presented as a smooth curve.

No errors are indicated for any of the measurements. The reason for this procedure is that it is very difficult to estimate the errors in the measurements. The errors consist in most cases of the statistical error in the measurement, the error in the determination of the number of fissionable nuclei, the error in the relative flux measurement, and the error in the absolute determination of the U^{235} fission cross section on which most of the measurements are based. Since individual authors use different methods for arriving at errors, it did not appear possible to find a consistent procedure for quoting errors in the present summary. It is interesting to note that subsequent measurements have shown that the authors of earlier reports have sometimes underestimated the errors in their measurements by a factor of 10.

Th^{230}

The only attempt to observe fission in Th^{230} was reported in LA-150.[9] Measurements at 1.0 and 1.3 Mev on a foil containing both Th^{230} and Th^{232} showed no observable fissions caused by Th^{230}.

Th^{232}

The results on Th^{232} are presented in Figs. 1 and 2. Except for the 14-Mev point which is taken from LAMS-938,[*,10] the results are

* There is some question as to whether the data in this report were corrected for center of mass motion.

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unpublished measurements by R. L. Henkel et al. at Los Alamos. Relative measurements were performed at 2.8 and 4 Mev using the fission cross section of U^{235} as a standard. The fission cross section of Th^{232} was calculated employing the fission cross section of U^{235} as presented in Fig. 8. The results at all other energies were obtained by extrapolation of the energy range with the aid of a long counter. The average of the normalizations at 2.8 and 4 Mev was used to arrive at cross sections at other energies.

Pa^{231}

Apparently no measurements have been performed on Pa^{231} since 1944. The data presented in Fig. 3 of the present report were obtained from Fig. 9 of reference 9. The fission cross sections of Pa^{231} as given in reference 9 were multiplied by the fission cross section of U^{235} given in Fig. 8 of the present report and divided by the fission cross section of U^{235} as given in Fig. 5 of reference 9. A change in the accepted value of the half-life of Pa^{231} as being 34,300 years instead of the value 32,000 years used in reference 9 resulted in an additional correction of 7 percent.

U^{233}

The most extensive measurements on U^{233} were performed by R. W. Lamphere at Oak Ridge in 1954. These measurements were taken

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relative to the cross section of U^{235}. At the time of this writing only preliminary values were available. While these values are based on the U^{235} fission cross sections of references 3 and 12, it is not clear which cross sections were used at low neutron energies for calculating the U^{233} cross section. The preliminary results of Lamphere's measurements are shown in Fig. 4.

At the lower neutron energies earlier measurements[11] of the ratio of the U^{233} to U^{235} fission cross sections are also presented. These data have been recalculated using the fission cross sections of U^{235} given in Figs. 7 and 8 of the present report.

In addition, measurements[12] of the energy dependence of the fission cross section of U^{233} are shown in Figs. 4 and 5. These measurements are normalized to 1.90 barns at 3.0 Mev on the basis of reference 11.

The 14-Mev cross section shown in Fig. 5 is taken from reference 10.

$\underline{U^{234}}$

Measurements of the fission cross section of U^{234} relative to that of U^{235} were performed at Oak Ridge.[13] The ratios given in reference 13 were multiplied by the fission cross section of U^{235} as given in Fig. 8 of the present report; the cross section of U^{234} was then increased by 16 percent to take account of an error in foil weight (R. W. Lamphere, private communication). The results are presented in Fig. 6.

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In addition, measurements performed at Los Alamos[14] are shown in Fig. 6.

U^{235}

The absolute values of the fission cross section of U^{235} are based mostly on the measurements of reference 3. This reference contains both an absolute measurement at a neutron energy of 1.25 Mev and an extrapolation of the energy range by comparison with the hydrogen cross section in the energy range from 400 to 1600 kev. Another extrapolation of the energy range with the aid of a long counter has been reported in LA-1495.[12] The measurements of reference 12 were renormalized so as to give an average value of the cross section of 1.27 barns in the energy range from 1 to 1.5 Mev.[3] It is believed that the measurements of reference 12 are not reliable below a neutron energy of 250 kev because of the relatively large target thicknesses used in the production of the neutrons. The data of reference 12 below 250 kev have, therefore, not been used in the present summary.

Since the results on U^{235} are employed extensively in determinations of other cross sections, these results are presented in three figures. Figure 7 summarizes the information available below 400 kev, Fig. 8 the data from 400 kev to 5 Mev, and Fig. 9 results above 5 Mev.

Two absolute measurements have been performed at low neutron energies, a measurement using Li(p,n) neutrons and a Mn-bath,[6] and a

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determination using Sb-Be photo-neutrons.[15] The latter measurement involves a somewhat complicated inter-comparison of the Sb-Be source with a mock-fission source which in turn had been calibrated against a Ra-Be source. While the author claims 3 percent accuracy in the U^{235} fission cross section and ±5 kev uncertainty in neutron energy, these estimates do not appear realistic, since not even the absolute source strength of the Ra-Be source was known to 3 percent and since the Be in the Sb-Be source degrades the neutrons appreciably. Although the measurement of reference 15 is shown in Fig. 7, its accuracy is in doubt. The absolute measurement of reference 6 also depends on the knowledge of the absolute strength of a Ra-Be source.

In addition, Fig. 7 shows measurements based on an extrapolation of the energy range using the radioactive product method[6] and a long counter.[16] The former extrapolation was based on the fission cross section of U^{235} at 1 Mev, the latter at 500 kev. The data presented in Fig. 7 are based on the fission cross section of U^{235} at 0.5 and 1 Mev as given in reference 3.

There are also shown in Fig. 7 some preliminary data on the low energy fission cross section of U^{235} obtained by a time-of-flight method.[17] These data are based on a 1/v dependence of the cross section for the B(n,α) reaction used for the flux measurement and on the U^{235} fission cross section at 0.5 ev measured at Columbia. The data plotted in Fig. 7 were lowered by 5 percent below the preliminary values quoted in reference 17 to take into account a change in the

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thermal fission cross section of U^{235} (private communication by W. W. Havens, Jr.). The neutron energy spread is 50 percent at 20 kev so that there is some doubt as to the effective neutron energy for these measurements.

In conclusion it should be pointed out that there is considerable uncertainty about the fission cross sections in the energy range from 1 to 100 kev. This uncertainty may be as much as 50 percent around 25 kev on the basis of the difference in the results of references 15 and 17.

The fission cross section of U^{235} at 14 Mev as given in Fig. 9 is taken from reference 5.

$\underline{U^{236}}$

The ratio of the fission cross section of U^{236} to that of U^{235} is reported in reference 13. The cross sections given in Fig. 10 were obtained by multiplying these ratios by the fission cross section of U^{235} of Fig. 8. In addition, relative measurements were performed at 2.5 and 14 Mev.[5] The results of these measurements are shown in Figs. 10 and 11. The energy dependence of the fission cross section of U^{236} was studied in reference 12. These measurements were normalized so as to give a value of 0.85 barn at 2.75 Mev, which yields the best agreement with the relative measurements in this energy range. Finally the results of relative measurements at several neutron

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energies as reported in LA-1258 are shown in Figs. 10 and 11.[18] The value at 2.55 Mev has been omitted since it is almost certainly in error. The 14-Mev point has also been omitted because it is not clear how the U^{236} cross section was obtained from the U^{236}/U^{235} fission cross section ratio given in LA-1258. The cross sections at the other energies were adjusted by using the fission cross section of U^{235} shown in Figs. 8 and 9.

U^{238}

The most recent relative measurement of the fission cross section of U^{238} is reported in LA-1571.[19] The fission cross section of U^{238} was obtained by multiplying the ratio reported in LA-1571 by the fission cross section of U^{235} as shown in Fig. 8. A value of 0.55 barn at 2.5 Mev was obtained in this manner. The energy dependence of the cross section as reported in reference 12 is shown in Figs. 12 and 13. These measurements are normalized to give a cross section of 0.55 barn at 2.5 Mev. Unpublished measurements by M. G. Ennis at Los Alamos of the energy dependence of the fission cross section of U^{238} near threshold are shown by the solid line in Fig. 12. The measurements were normalized to agree with the results of reference 12 at higher energies. The 14-Mev point is the absolute determination of reference 4. The reliability of the data in the energy range from 13.5 to 18 Mev as reported in reference 7 is sufficiently doubtful that these

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data are not shown in Fig. 13.

The absolute measurement of the fission cross section of U^{238} for fission neutrons reported in reference 8 is in excellent agreement with the value obtained by combining the results shown in Figs. 12 and 13 with measurements of the distribution in energy of neutrons produced in the thermal fission of U^{235}.

Np^{237}

Data on the fission cross section of Np^{237} are presented in Figs. 14 and 15. The energy dependence of the cross section is that reported in reference 12. Data in reference 12 were normalized to a cross section of 1.44 barns at 1.50 Mev.[20] Since the currently accepted value of the fission cross section of U^{235} at 1.5 Mev is not appreciably different from that used in reference 20, the same normalization is used for the present report as was used in reference 12. Some of the data of reference 20 are also shown in Fig. 14.

The first determination of the Np^{237} cross section was reported in reference 9. In this measurement the amount of Np on the foil was obtained from an alpha count using a half-life of 3×10^6 years. If one corrects these data to the currently accepted half-life of 2.2×10^6 years, the results do not agree with those of reference 20. It is assumed that the earlier measurement was in error.

A preliminary measurement of the Np^{237} fission cross section at

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14 Mev is quoted in reference 12. This measurement is not considered sufficiently firm to be included in this summary.

Pu^{239}

Figure 16 summarizes the available data on the fission cross section of Pu^{239}. Most of the low-energy data are taken from LA-520.[21] These data were corrected for the change in fission cross section between that reported in reference 21 and Figs. 7 and 8 of the present report. In addition, Fig. 16 shows the results of relative measurements performed at Los Alamos by Henkel and Nobles of the fission cross section of Pu^{239} with respect to that of U^{235}. These cross sections are calculated using the fission cross section of U^{235} as given in Figs. 7 and 8. The point at 14 Mev is taken from reference 5. It is believed that the determination of the Pu^{239} fission cross section at 14 Mev reported in reference 10 is in error.

SUMMARY

In Fig. 17 the results shown in the previous figures are summarized except for the 14-Mev measurements. Smooth curves were drawn through the experimental points.

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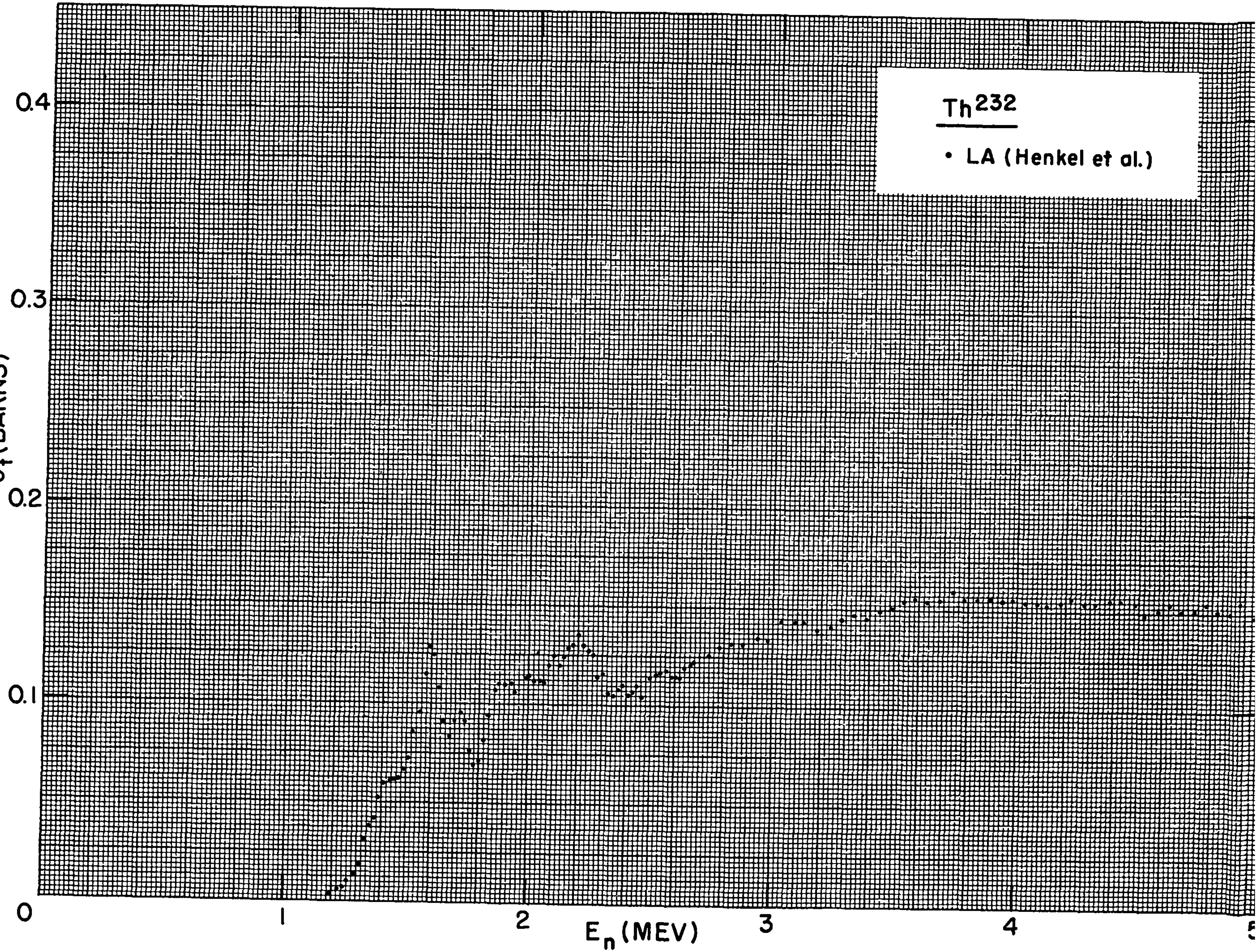

Fig. 1

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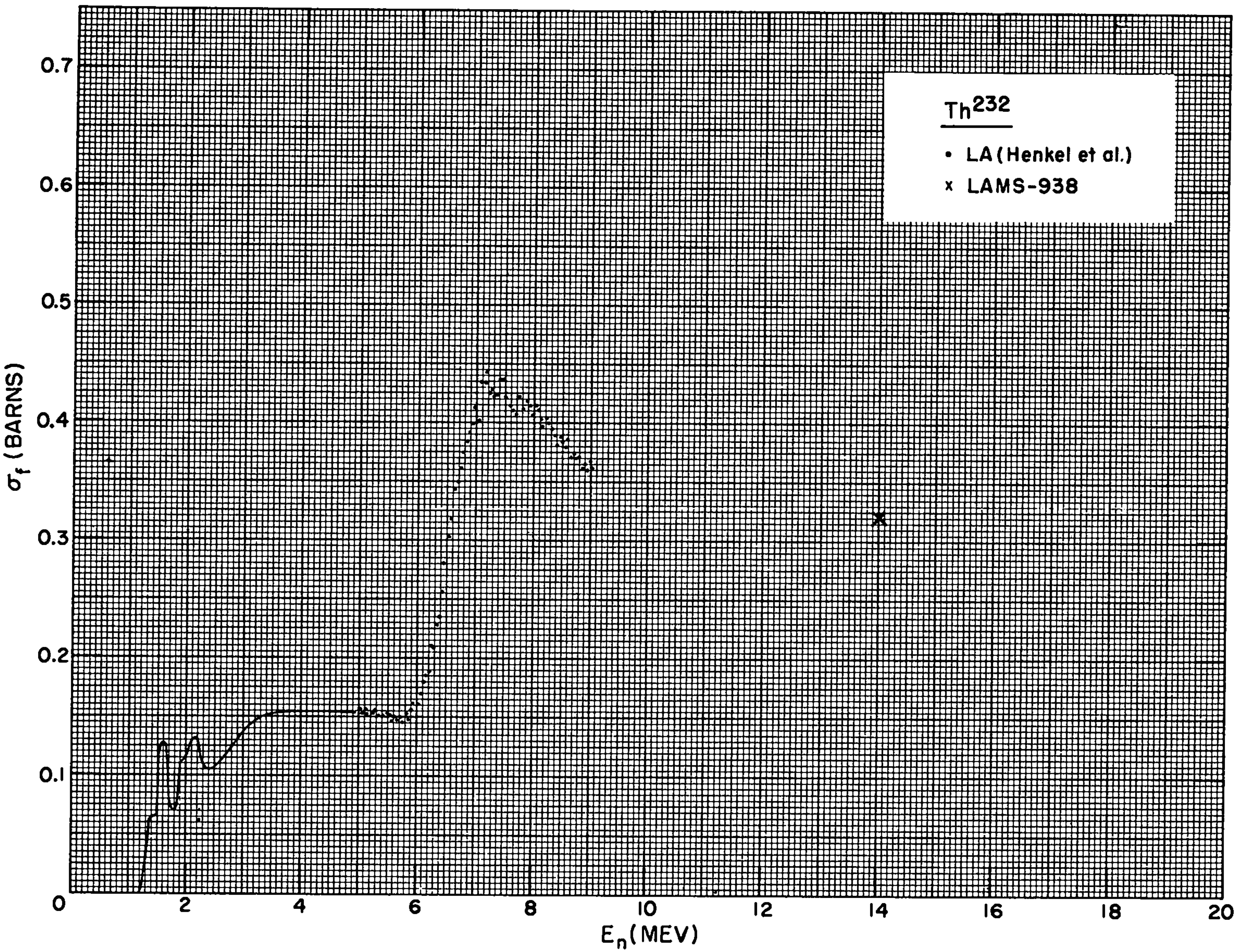

Fig. 2

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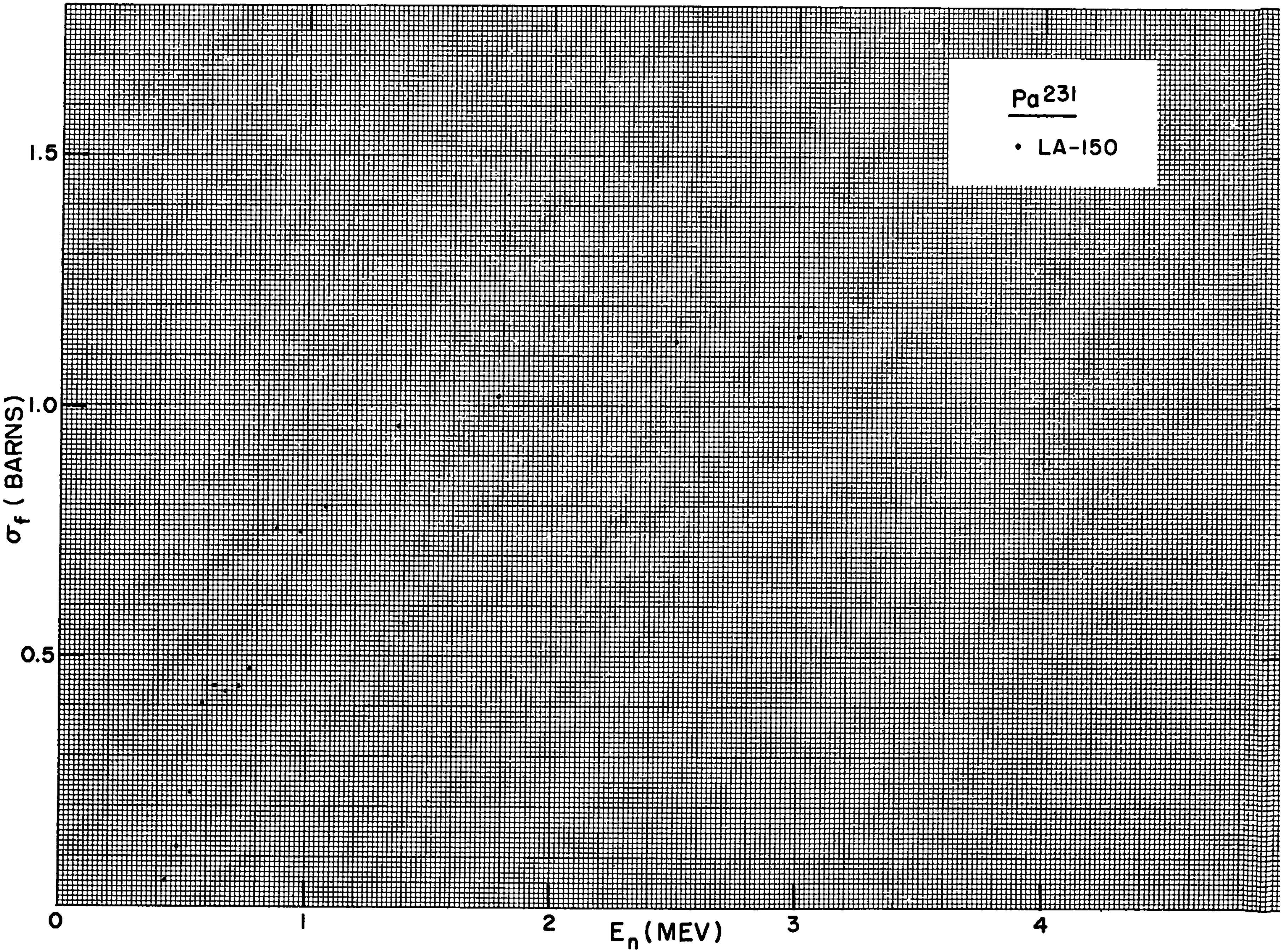

Fig. 3

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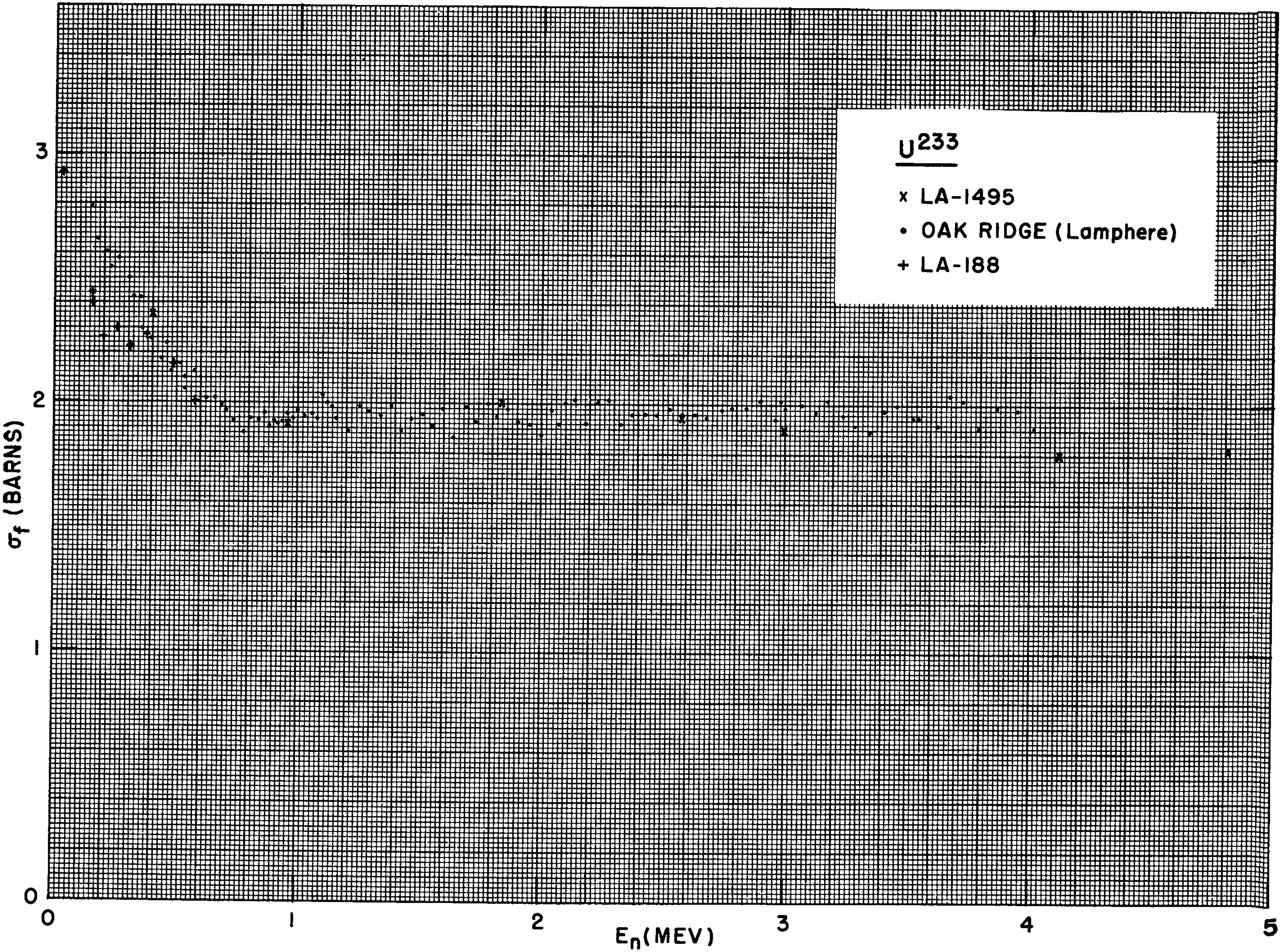

Fig. 4

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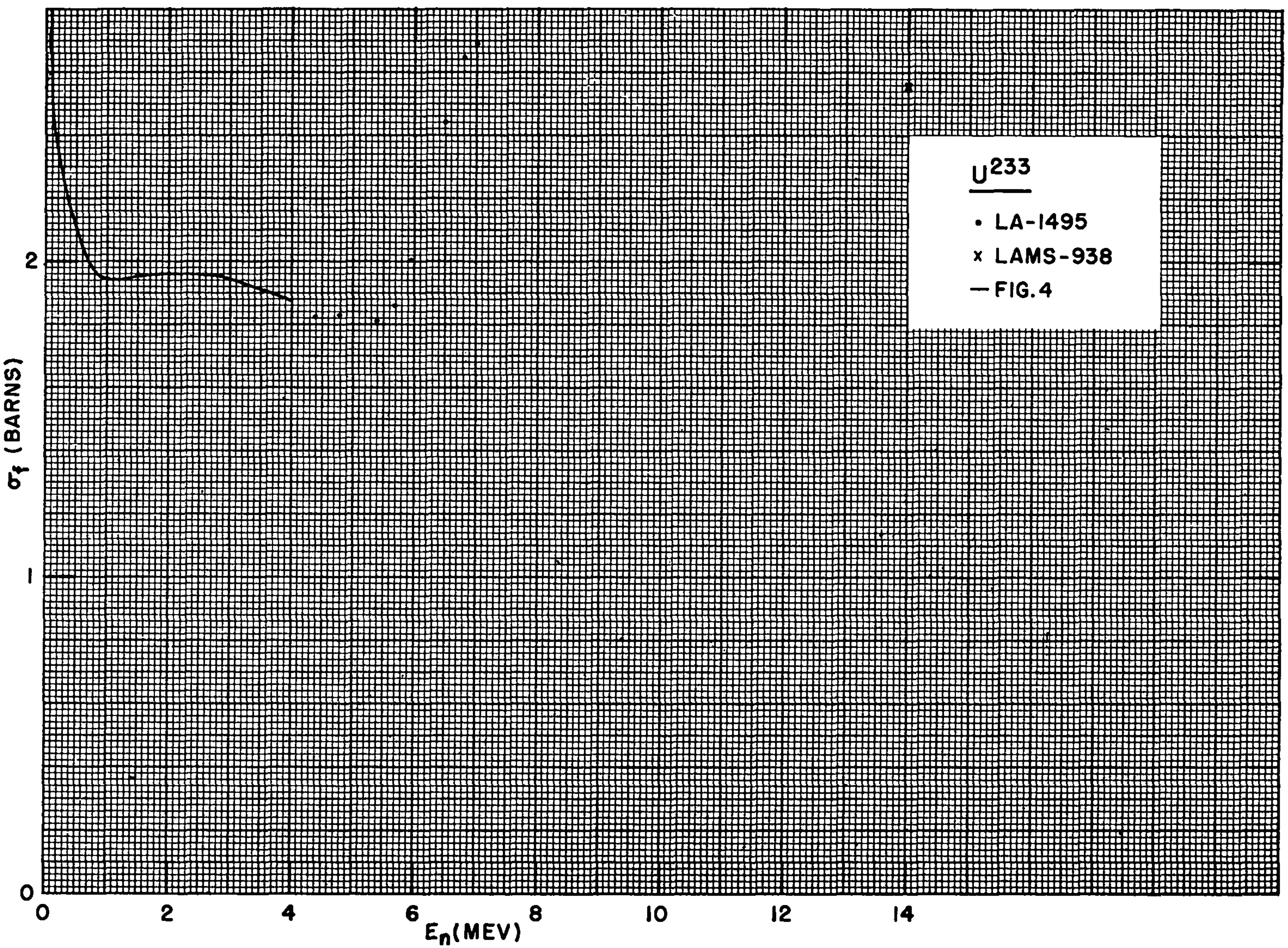

Fig. 5

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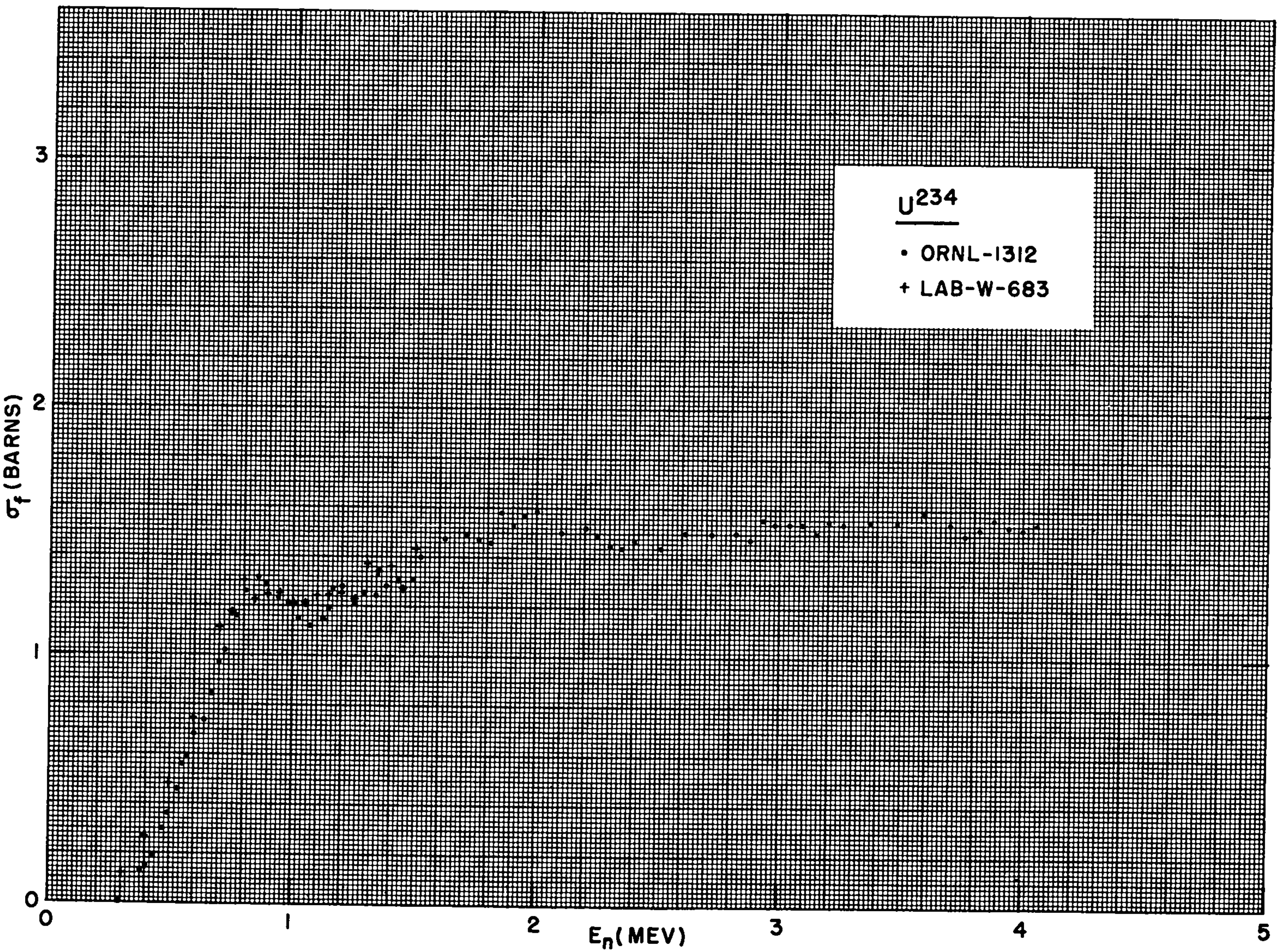

Fig. 6

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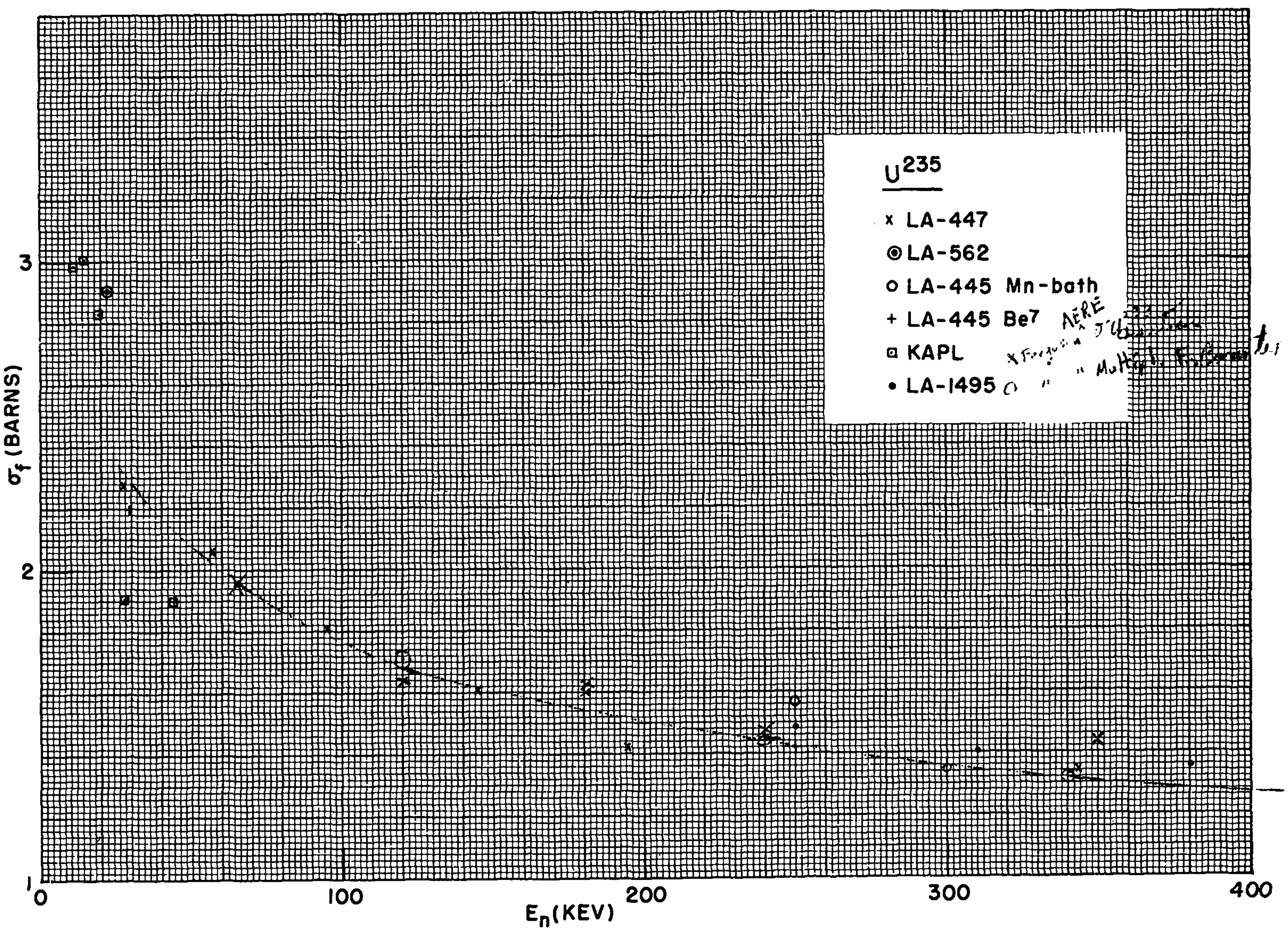
U^{235}
x LA-447
⊚ LA-562
o LA-445 Mn-bath
+ LA-445 Be^7
⊡ KAPL
• LA-1495
AERE
σ_f (BARNS)
3
2
1
0
100
200
300
400
E_n (KEV)

Fig. 7

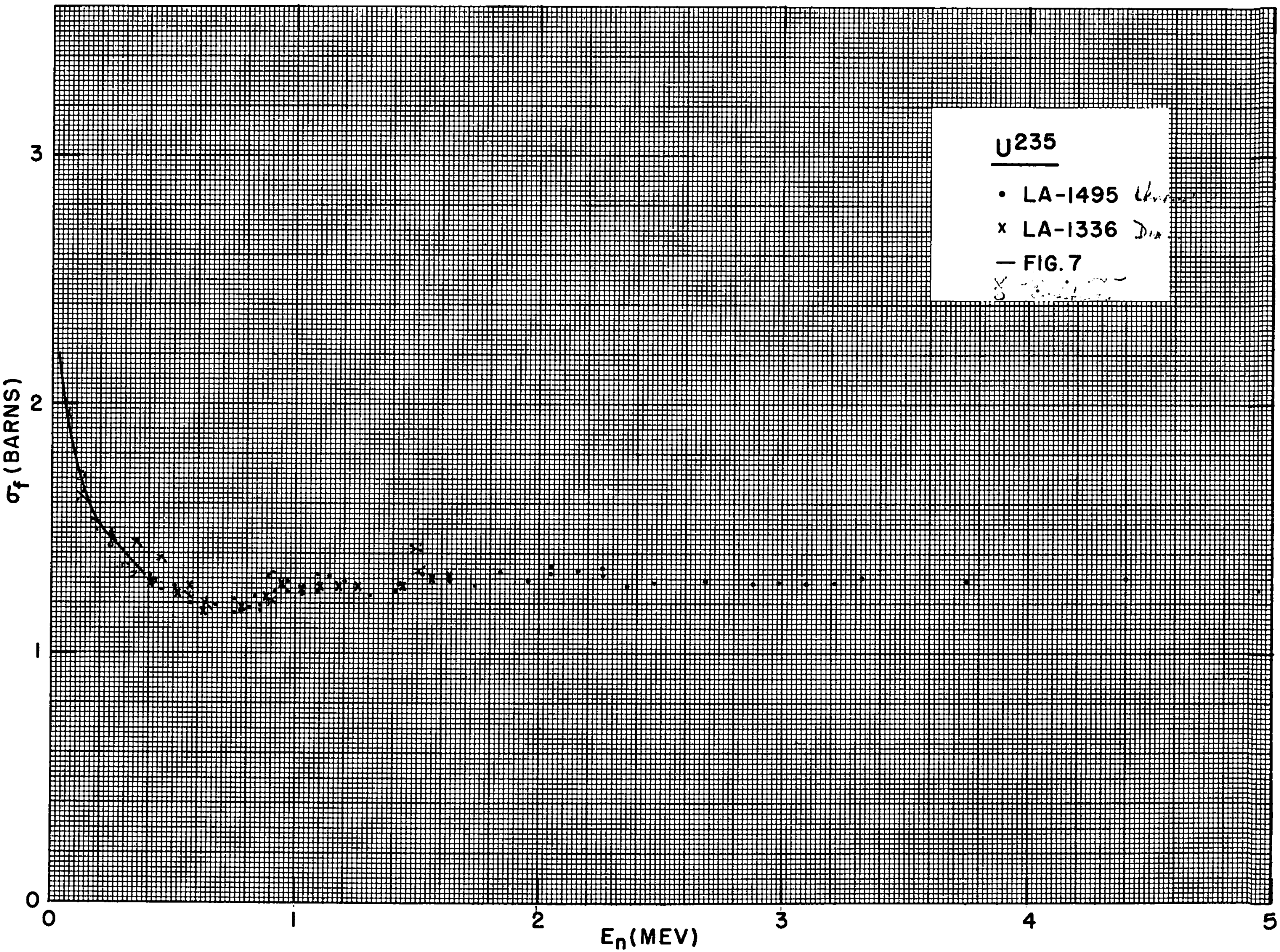

Fig. 8

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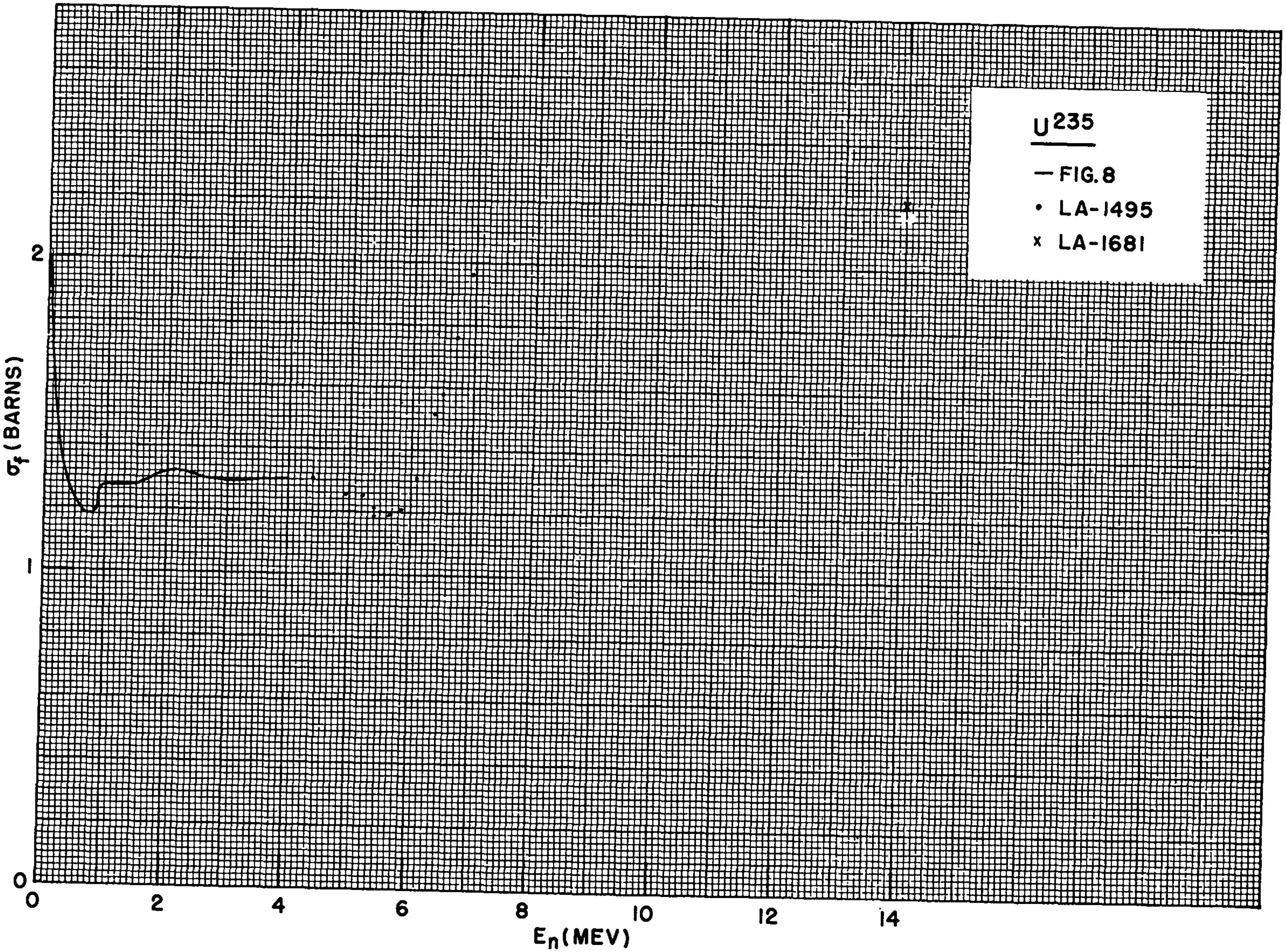

Fig. 9

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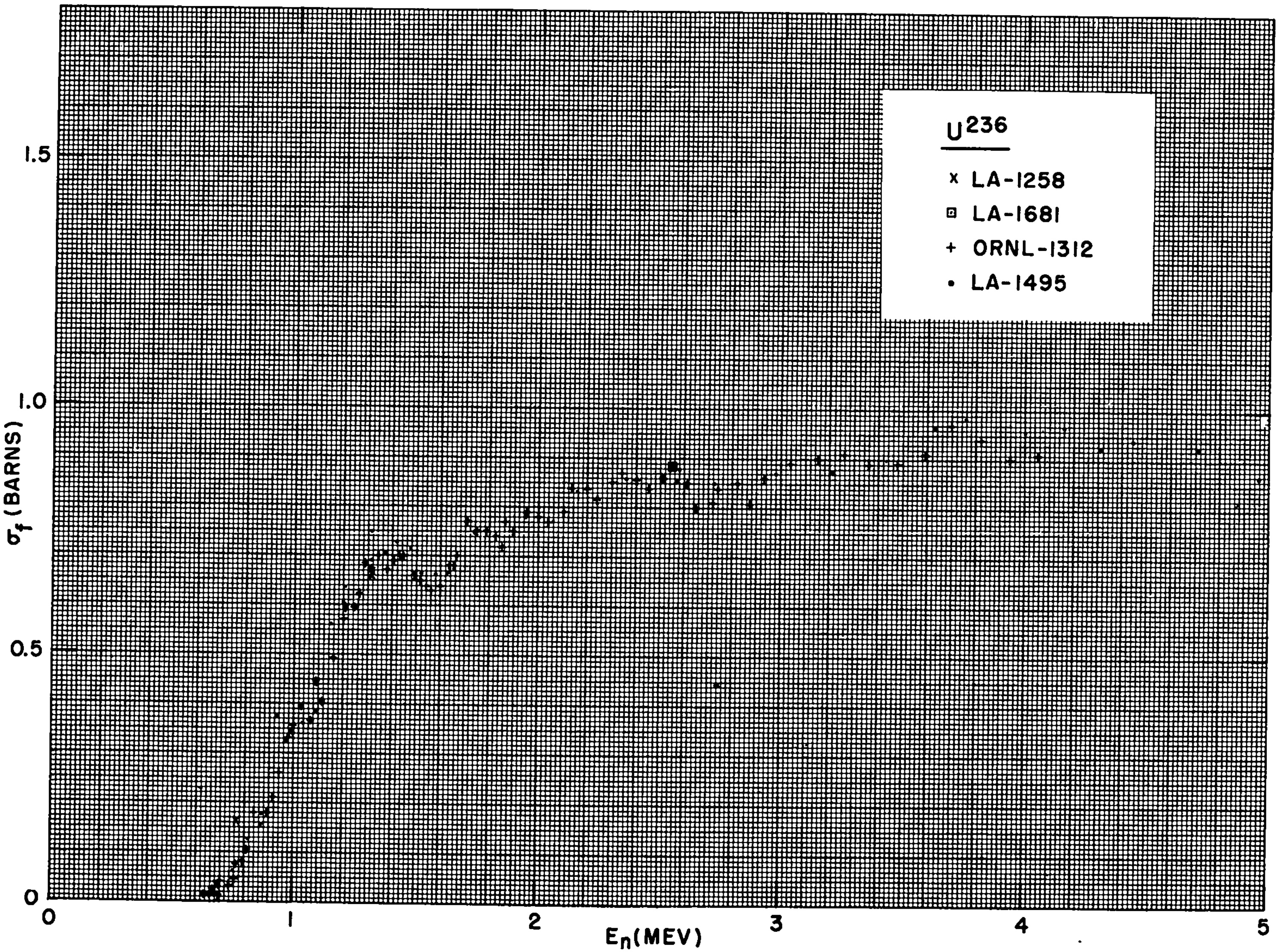

Fig. 10

Note: The cross sections taken from ORNL-1312 should be raised 2.7 percent (R. W. Lamphere, private communication).

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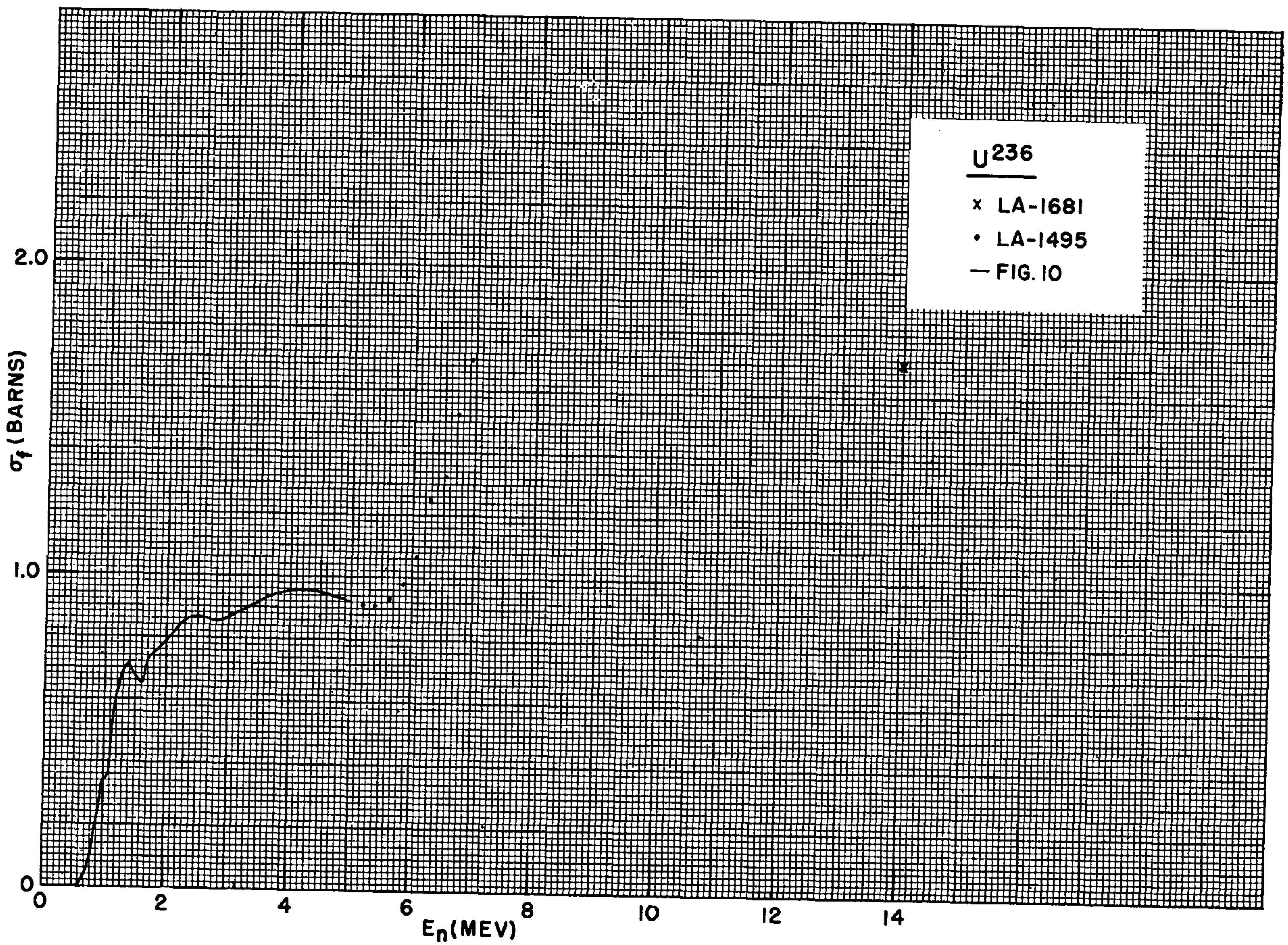

Fig. 11

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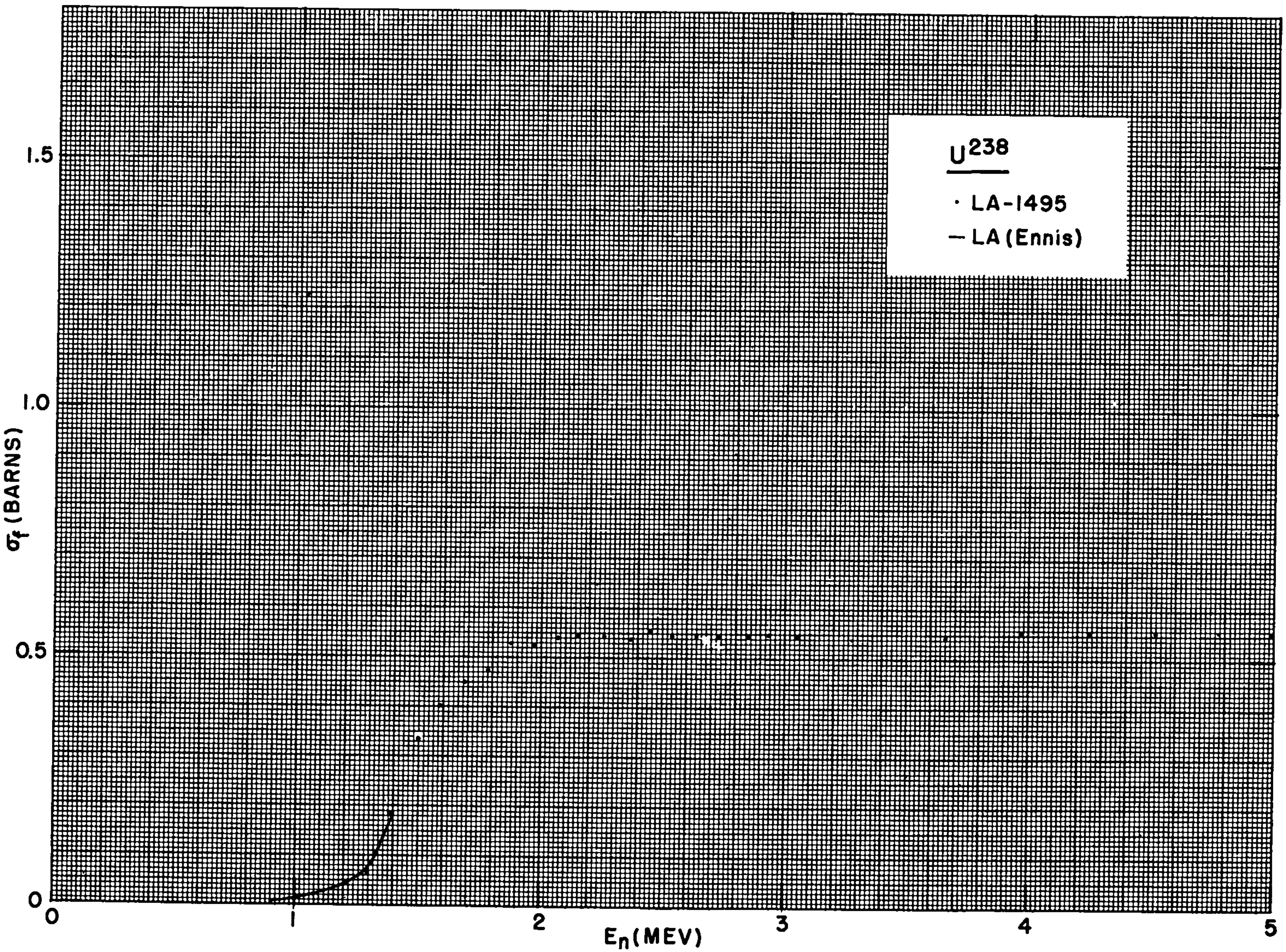

Fig. 12

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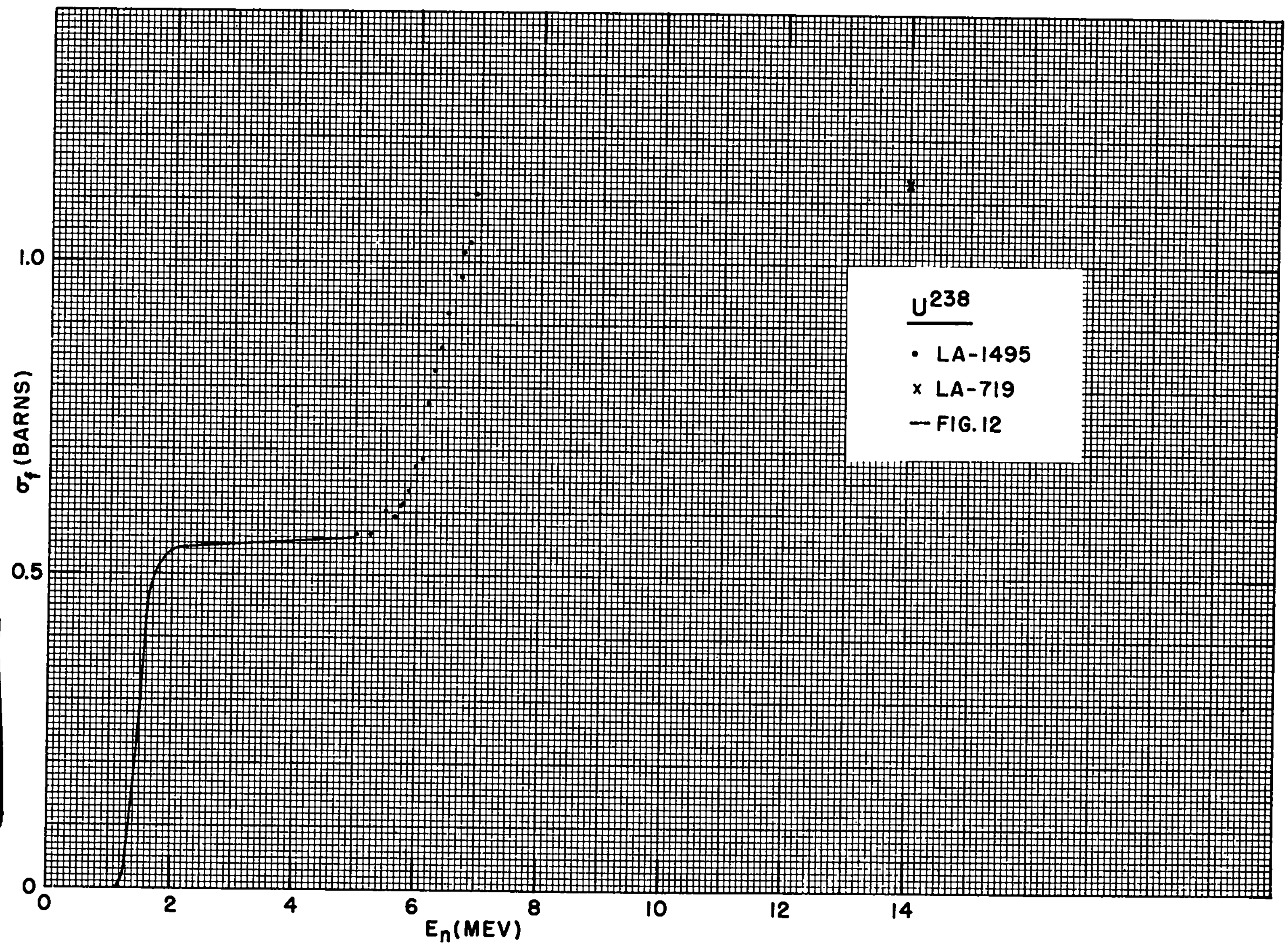

Fig. 13

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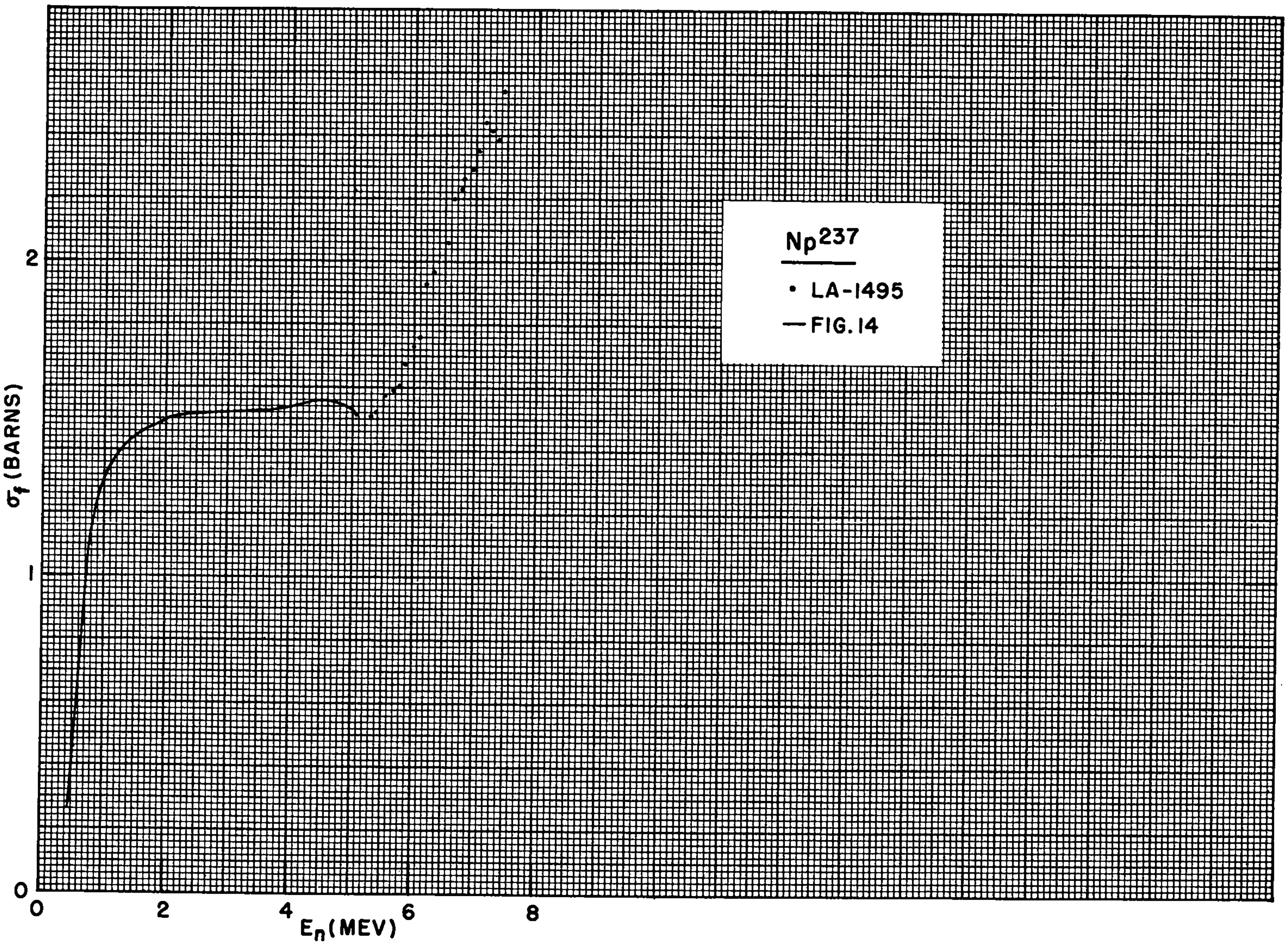

Fig. 14

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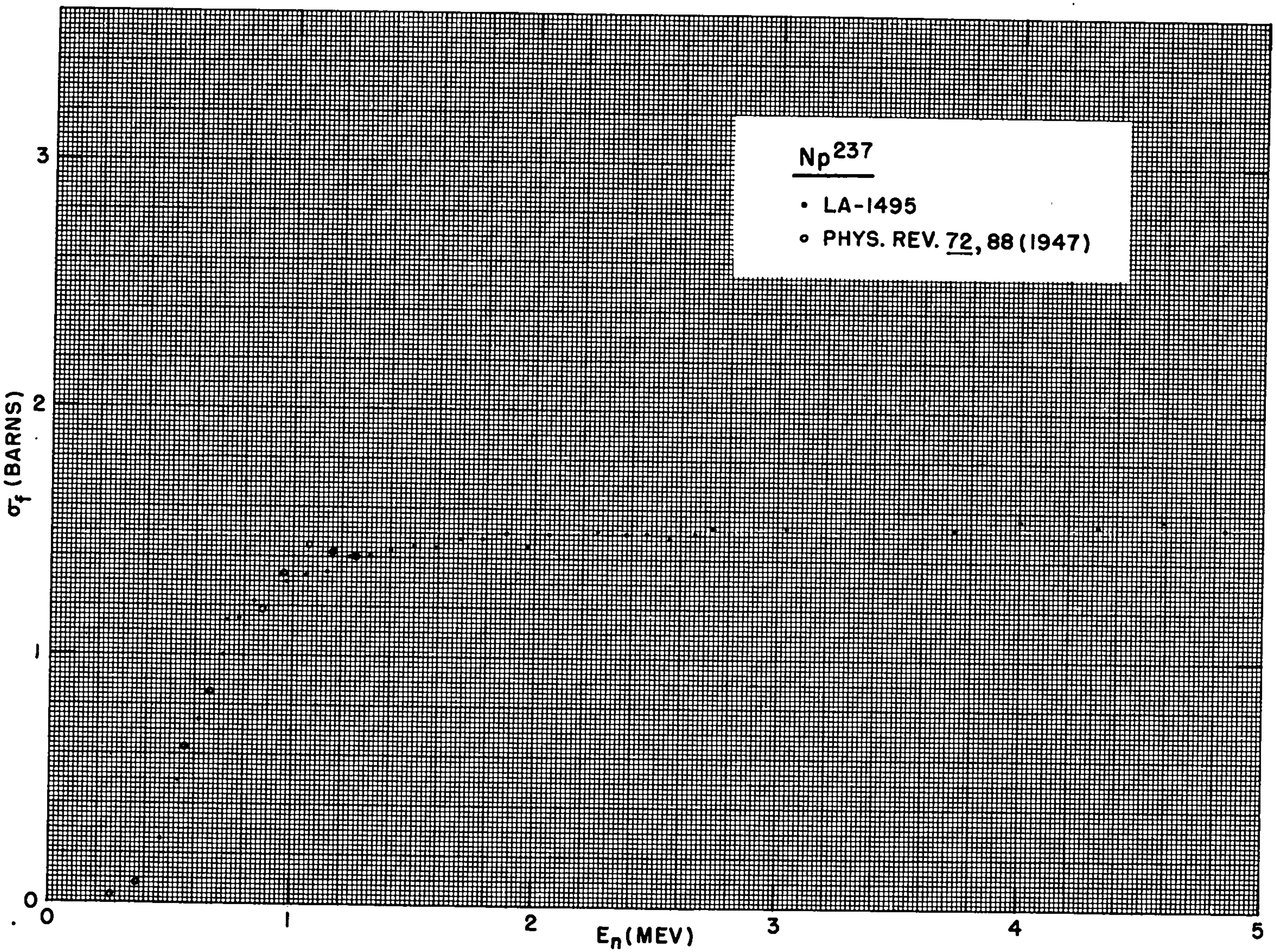

Fig. 15

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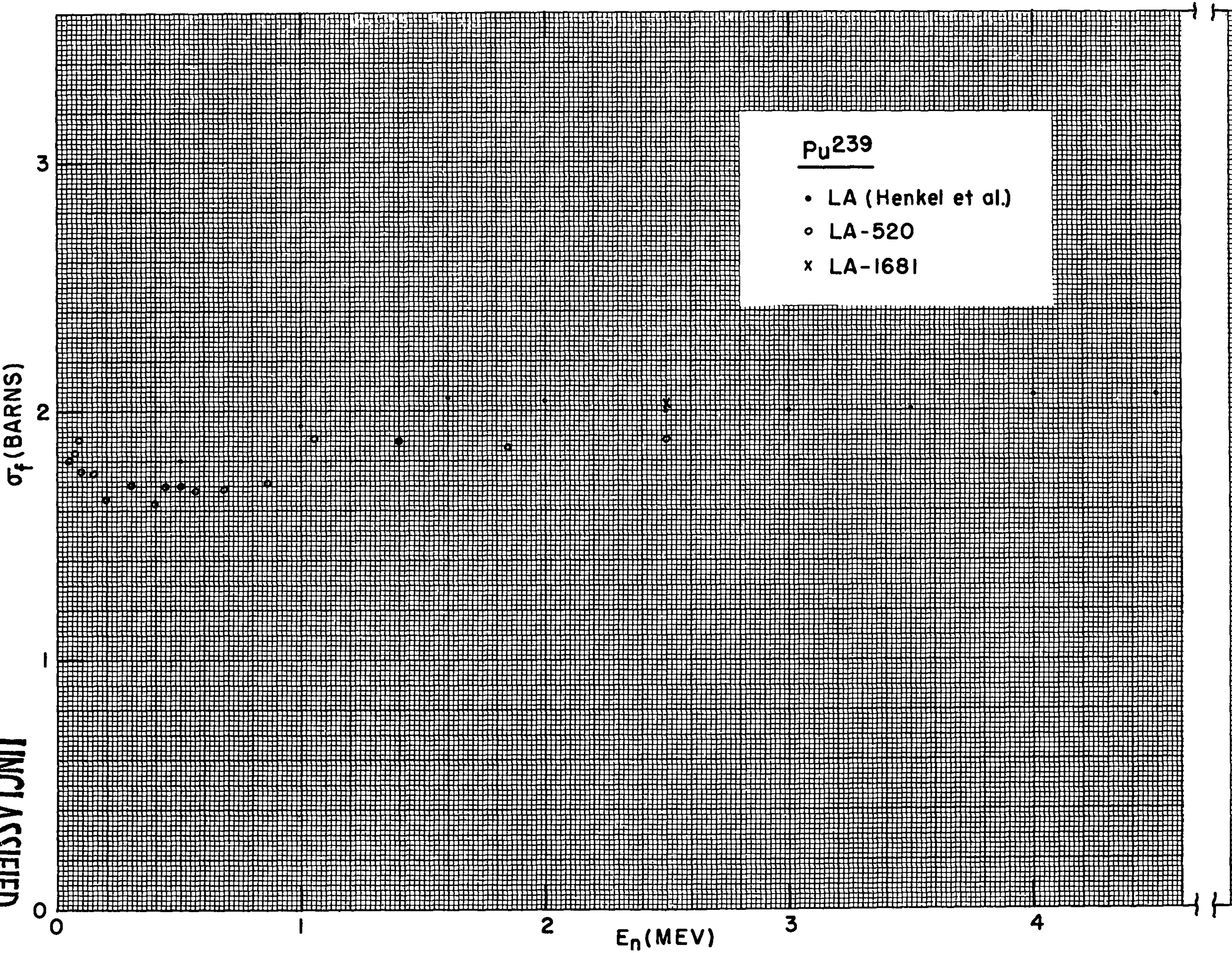

Fig. 16

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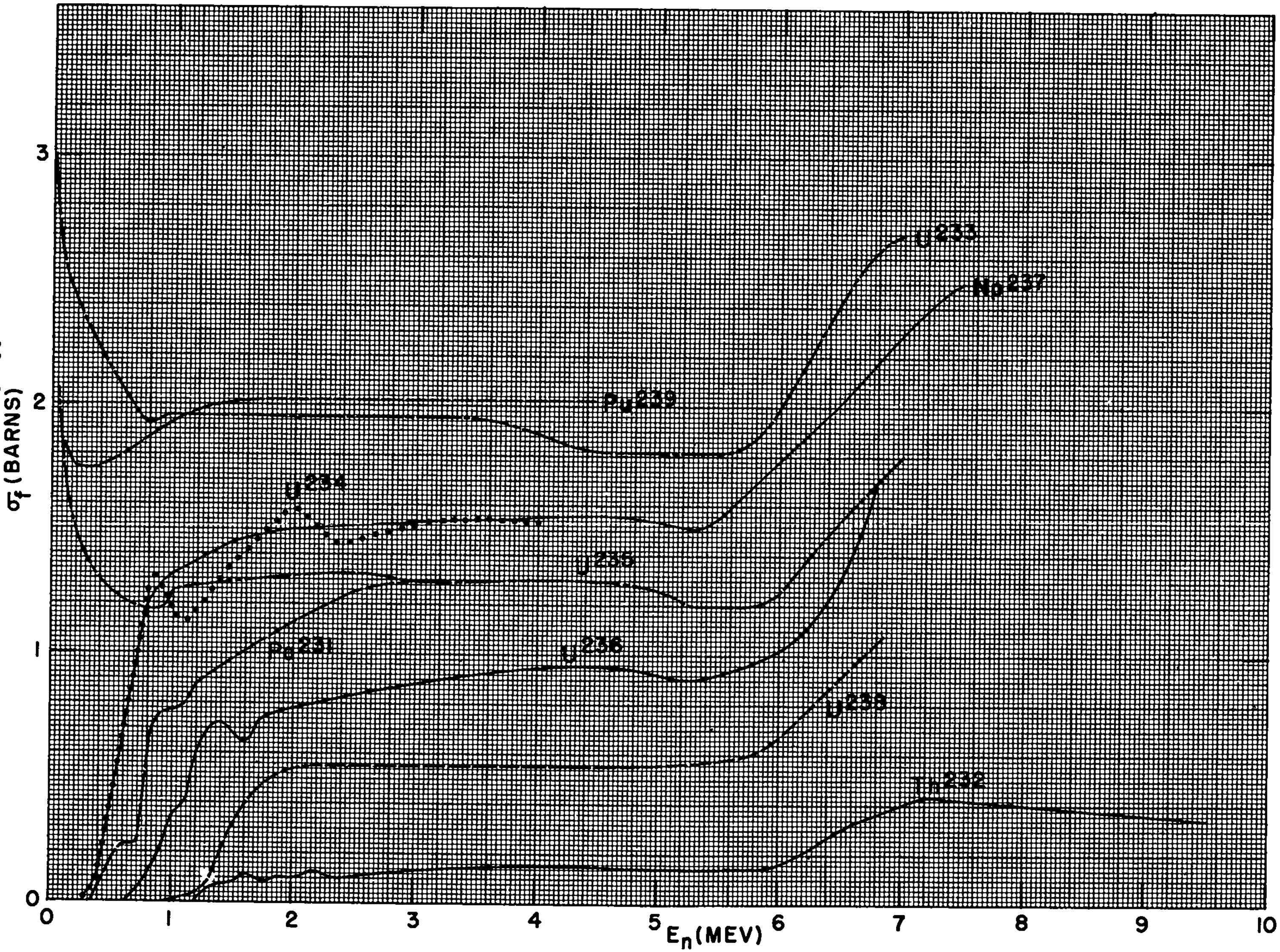

Fig. 17

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