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THE CROSS SECTIONS FOR FISSION OF

25, 49, 28, 11, 37, 00, 02, B and Li

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ABSTRACT

Methods are described which allow the determination of neutron flux in the energy region from 5 Kev to 2 Mev. Observations of $\sigma_f(25)$ in this energy region are described in detail. Data are presented on the comparison of the fission cross section of 49, 28, 11, 37, 00, 02, B and Li with $\sigma_f(25)$ in this energy interval and above.

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THE CROSS SECTIONS FOR FISSION OF 25, 49, 28, 11, 37, 00, 02, B and Li

INTRODUCTION

The determination of the cross section for a nuclear process such as fission is essentially dependent upon the absolute measurement of the flux of fast neutrons. It has been demonstrated in this laboratory that it is possible to determine quantitatively the number of hydrogen recoils from a known thin film of hydrogeneous material placed in a fast-neutron beam. Since the hydrogen cross section is known [1] it is therefore possible to determine the flux of fast neutrons. In this manner Hall, Koontz, and Rossi [2] have measured in a comparison chamber the relative numbers of hydrogen recoils and fission fragments from 25. Their determinations of the fission cross section of 25 for neutrons of 1 Mev energy serve as a standard of cross sections for fast neutrons in this laboratory.

DEGRADATION TESTS OF THE LONG COUNTER

It has been proved to be difficult to extend the measurements of fission cross sections by the hydrogen-recoil method with acceptable accuracy to neutron energies less than approximately 400 Kev or more than 3 Mev. However a detector has been developed which we believe has the property of a nearly uniform response to fast neutrons over the energy region from less than 10 Kev to over 2 Mev. Early models and tests on these "long counters" have been described by Hanson [3]. Further development and tests on these detectors reveal the following properties.

A model similar to that shown in Fig. 1 was first irradiated with neutrons of approximately 200 Kev energy from an Y-Be source. Then this source

1) J. H. Williams et al., CF-599
2) Hall, Koontz, and Rossi, LA-128
3) A. O. Hanson, LAMS-66

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was surrounded by a sphere of D_2O, radius 10.4 cm, to degrade the neutrons and the number of neutrons recorded was 98.5 percent of the original number. This number of neutrons recorded from the Y-Be + D_2O source is to be corrected downward by 2.5 percent since Y emits a few gamma rays of sufficient energy to disintegrate deuterium and so produce in the heavy-water sphere this fraction of the primary neutrons. Consequently the counter is 96 percent as efficient for detecting the degraded spectrum as for the 200 Kev neutrons. Chew and Konopinski have calculated that the deuterium sphere should degrade the primary neutrons to an average energy of 10 Kev, and the order of one or two percent of the neutrons will lie below the Cd cut-off. In view of the fact that the detectors are known to be of low efficiency for thermal neutrons, we feel that the test establishes our thesis that the long counter has a response independent of the neutron energy to approximately 5 percent in the region from 200 Kev to less than 10 Kev.

To eliminate the possibility that an increased sensitivity for say 100-Kev neutrons might counterbalance a decreased sensitivity for 10-Kev neutrons, or vice versa, similar tests with graphite spheres surrounding the Y-Be source were made. A typical result with a 12-cm-radius graphite sphere, estimated average neutron energy 100 Kev, was that the detector indicated an efficiency of 98.5 percent.

The evidence for the constant sensitivity of the long counter in the energy region from 200 Kev to 2 Mev will be presented below (p. 6) in the description of our measurements of $\sigma_f(25)$ in this energy region.

As a result of the above experience we have designed and built the detector shown in Fig. 1. The neutrons entering the open-front face of the inner paraffin cylinder (from the left in Fig. 1) are slowed down by the paraffin, diffuse to the central region and are captured by the enriched uranium on the inner cylinder wall. The resulting fission fragments are thus detectable with ease and so uncertainties such as amplifier gain changes which [redacted] cause

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uncertainty in other long counters where boron or BF_3 is the active ingredient are eliminated. The sensitivity of this particular counter, called "Mr. 5 by 5", is lower than that of BF_3-filled long-counter detectors. An additional feature of its design is the paraffin - B_4C - paraffin cylindrical structure which serves to prevent any large number of neutrons entering the detector from the side. This shielding is essential for quantitative measurements where an atmosphere of epithermal neutrons are present in a laboratory as a result of multiple scattering of neutrons from a primary source.

With this detector (calibrated by the standard $\sigma_f(25)$ at 1 Mev, as mentioned above) we have measured the flux of neutrons from various neutron sources and from simultaneous measurements on the fission rate in a known-mass foil of 25 have determined $\sigma(25)$ as a function of neutron energy.

MEASUREMENTS OF $\sigma_f(25)$

The sources of neutrons used in the determination of the fission cross sections of 25 and other isotopes are thin lithium targets bombarded by mono-energetic protons accelerated in Van de Graaff generators. The evidence that the neutrons arising from the Li (p,n) reaction are monoenergetic is presented later in this report (p. 20). The energy of the neutrons is determined by the bombarding-proton energy and the angle of observation. The uncertainty in the neutron energy is determined by the uncertainty in the proton energy, the thick-ness of the lithium target, and the solid angle subtended by the neutron detector. By a proper choice of these parameters the uncertainty in the neutron energy can be reduced for practical reasons to less than 1 percent for energies greater than 500 Kev, less than 2 percent for energies greater than 200 Kev, less than 5 percent for energies greater than 50 Kev, less than 10 percent for energies greater than 20 Kev, less than 30 percent for energies greater than 10 Kev, and less than 50 percent for energies greater than 4 Kev.

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The experimental arrangement used in measuring $\sigma_f(25)$ is shown in Fig. 2. The long counter and fission chamber receive simultaneously neutrons of the same energy and nearly the same energy uncertainty. The observations consist of recording the relative counting rate in the two detectors as a function of the neutron energy. The result is a determination of the relative values of $\sigma_f(25)$ as a function of neutron energy. This conclusion is of course based on the validity of our assumption of the flat energy response of the long counter.

<u>Test With Calibrated Ra-Be Source</u>

In order to test this assumption in a higher energy region and to normalize the data to an absolute value of $\sigma_f(25)$ we performed the following experiment. A Ra-Be source of known strength [4] was put in the exact position of the Li(p,n) source. The counting rate of the long counter in its original position will give a measure of the overall efficiency of this detector for Ra-Be neutrons. Assuming this measured efficiency to be the same as the efficiency for 1 Mev neutrons we can normalize the relative fission-to-long-counter data taken at 1 Mev. The result is that $\sigma_f(25)$ at 1 Mev is 1.37 barns. This result is in excellent agreement with the more precisely determined value of 1.33 barns obtained by Hall, Koontz, and Rossi [2]. Furthermore the relative data reveal that $\sigma_f(25)$ at 1.6 Mev is essentially equal to that at 1 Mev. This is again in complete agreement with Hall, Koontz, and Rossi. We are therefore led to believe our assumption about the energy response of the long counter.

In the intermediate energy region the agreement between our relative cross section at 400, 600 and 1000 Kev with measurements by the above observers increases our confidence.

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4) Calibrated by A. Graves of the R-3 group.

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Tests With Compensating Pair of Ionization Chambers

In order that our conclusions regarding the fission cross section of 25 in the energy region below 400 Kev should not rest entirely upon the tested assumption that the long counter possesses a flat energy response, further instrumentation to determine relative neutron flux in this energy region has been made.

Since it is clear that the elastic-scattering cross section of hydrogen is fairly well established both from theoretical [5] and experimental [1] considerations the following instrument was developed. Two identical high-pressure ionization chambers [6] with a well-defined collecting volume were built as shown in Fig. 3. For neutron-flux measurements below 500 Kev one of these chambers is filled with argon to a pressure of approximately 15 psi and the other is filled with a mixture of hydrogen and argon to pressures of approximately 150 psi and 15 psi, respectively. The choice of pressures is determined by the neutron-energy region one wishes to investigate. For high neutron energies the argon pressure is increased to insure a minimum wall effect for the hydrogen recoils. The high-voltage electrodes of these chambers are kept at sufficiently high potentials of opposite polarity to insure saturation collection of ionization within the collecting volumes. The collecting electrodes are connected in parallel and the net ionization due to both gamma rays and proton recoils is detected by means of a DC amplifier. When the chambers are exposed to a strong source of γ rays which is symmetrically located with respect to the chambers it is possible to adjust the argon pressure in the chamber containing only argon to such a value that the net current from the two chambers in parallel is not detectable, i.e., the net current is less than 1/10 percent of the ionization current due to proton recoils. When the chambers are exposed with symmetrical geometry to a mixed source of neutrons and gamma rays, which is the case for the

5) C. Richman
6) Code designation 2 PG.

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Li(p,n) source of the electrostatic generators, the measured ionization current is due to the recoil-hydrogen nuclei in the chamber containing hydrogen.

The magnitude of this current can be translated into neutron flux if one knows the pressure of H_2, the effective volume, the geometry with respect to the neutron source, the scattering cross section of H, the neutron energy and the average energy loss per ion pair formed in the H_2 - A mixture by the hydrogen recoil nucleus. The only piece of information which is not immediately available is the average energy loss per ion pair in the particular gas mixture used. Considerable information is however available in standard texts about the average energy loss per ion pair of alpha particles traversing certain unmixed gases, including argon and hydrogen.

The information appropriate to our gas mixtures was obtained by including within the mixed-gas chamber a foil of Pt covered with a very thin layer of polonium. The number of polonium alpha particles emitted per second was counted by using the ionization chamber as a pulse chamber connected to a fast amplifier. The ionization current arising from these α particles (approximately 100/sec) was also measured. Since the energy of the individual polonium alphas is known, the energy loss per ion pair for polonium alphas was determined. The agreement with the values extrapolated from published measurements on single gases was to within 5 percent.

Some of the information listed above such as the pressure and volume of H_2 or the energy loss per ion pair for hydrogen recoils cannot be determined with exceedingly high accuracy. However with a given gas filling it is possible to use these compensated chambers to determine relative flux at two different neutron energies to a much higher degree of accuracy. In practice we have made use of these chambers in the latter way although the absolute flux measurements agree to within 10 percent with those determined by fission measurements with the "standard" cross sections of Hall, Koontz, and Rossi. The experimental

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arrangement to determine $\sigma_f(25)$ with these chambers is shown in Fig. 4. Neutrons of the same energy and intensity impinge on both ion chambers and on a fission foil encased in a separate chamber. Both ion chambers are subject to the same gamma-ray flux from the target and the electrostatic generator. Simultaneous measurements of the fission rate and net ionization current due to neutrons are recorded for a given neutron energy. Without changing the geometry of the detectors the neutron energy is changed and the ratio of number of fissions per unit time and ion current is again recorded. Since one knows the neutron energy and the cross section of hydrogen as a function of neutron energy it is possible to transfer the relative ion-current measurements at the two neutron energies into relative flux measurements at the two neutron energies. Thus the relative fission cross sections for 25 at the two energies are obtained.

In the above manner we have measured $\sigma_f(25)$ as a function of neutron energy in the energy region between 50 Kev and 500 Kev. The results are shown as open circles in Fig. 5, normalized to the long-counter cross section at 500 Kev.

Also shown in Fig. 5 as solid points, are the results of our observations with the long counter over the wider energy range from 5 Kev to 1.9 Mev. These measurements are normalized to a value of 1.33 barns at 1 Mev. Also indicated in this figure are the results of other observers as well as the absolute values of σ_f that we have determined by the instruments and methods outlined above.

The general form of $\sigma_f(25)$ as a function of neutron energy is fairly well established by the measurements shown in Fig. 5. We believe that $\sigma_f(25)$ as measured is trustworthy to approximately 15 percent throughout the entire energy range above 15 Kev and is known to be between 5 and 10 percent from 200 Kev to 2 Mev.

It is clear that once $\sigma_f(25)$ is known as a function of neutron energy the problem of investigating the dependence of other cross sections is greatly simplified. A known mass of 25 in the form of a thin foil can then be exposed to the same flux as the isotope in question and will serve to determine the flux. Our practice has been to mount two foils, one of 25 and the other the substance under investigation, back to back in a comparison ionization chamber similar to that shown in Fig. 6. Observations on the relative counting rate from these foils and a knowledge of their masses allows an immediate determination of the unknown cross section.

Hanson has been primarily responsible for the instrumentation of the long counter and the observations with it in the higher energy neutron range. Perry has guided the measurements with the long counter in the energy region from 100 Kev down to 5 Kev. Bailey and Hush developed the compensated ionization chambers, 2 FG, and made observations in the region from 50 Kev to 500 Kev. We are indebted to the members of Dodson's group, particularly Cpl. Miller, Ph.D., for the preparation of 25-foils used in the detectors, and to Chamberlain for analyses of the 25-content of the fission foils.

MEASUREMENTS ON 49

Early measurements on the fission cross section of 49 have been reported in LA-28. Since that time it has proved possible to use larger quantities of material in a simple comparison chamber. This improvement results from the design of faster amplifiers by the electronics group and the development of an electroplating technique for 49 by Dodson's group. Although we have found it possible to use 1.2 mg of 49, the present measurements were taken with 200 μg and 600 μg samples. The experimental conditions were such that we had approximately 100 percent efficiency for the detection of fission processes. The accuracy of the present data therefor far exceeds that of our previous [redacted]

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measurements and eliminates the existence of an anomalous dip in the cross section reported in LA-28.

The foils of 49 used in these determinations were electroplated discs, 1-3/16" diameter, on thin platinum backings. Their masses were determined by alpha counting and an assumed half life of 24,000 years. The probable error assigned to these determinations by Dodson's group is $\pm$ 1.4 percent.

Observations were made of the relative fission rate from known masses of 49 and 25 as a function of neutron energy. The accuracy of these data is limited by the statistical errors of counting, which in general were less than 3 percent for all neutron energies, and by uncertainties in the masses of the foils - possibly another 3 percent. The spread in energy about the weighted average energy plotted for each point is less than the limits set on page 5 above.

The ratio $\sigma_f(49)/\sigma_f(25)$ determined by the above observations may be multiplied by the values of $\sigma_f(25)$ obtained from the smooth curve of Fig. 5. The resulting values of $\sigma_f(49)$ are shown in Fig. 7. It is clear that the variation of this cross section with energy bears only a rough similarity to that of $\sigma_f(25)$. It is interesting to note that $\sigma_f(49)$ is less than $\sigma_f(25)$ for energies between the lowest measured point for fast neutrons and 100 Kev. The behavior of $\sigma_f(49)$ in the region from 500 volts up to 5 kilovolts remains to be investigated.

The foils of 49 used in these experiments were prepared and counted by Miller. The instrumentation for these observations were performed by Hanson, Klema, and Perry. We are indebted to members of the R-3 group for operating the D-D source of neutrons to provide the data at 2.5 Mev.

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MEASUREMENT OF $\sigma_f(28)$

For the sake of completeness a brief report of the values of $\sigma_f(28)$ as a function of neutron energy up to 2 Mev will be given here. The measurements have been described by Hanson [7] and by Taschek [8]. The independent observations were in good agreement and were of rather high accuracy but were somewhat uncertain with respect to the numerical value of the cross section. Recently Hall, Koontz, and Rossi [2] have determined $\sigma_f(28)/\sigma_f(25)$ for neutrons of 1.57 Mev. They derive a value of 0.35 barns for $\sigma_f(28)$ at this energy from their observations. We have normalized our previous results on the basis of this information and have plotted $\sigma_f(28)$ vs E_n as shown in Fig. 8.

MEASUREMENTS OF $\sigma_f(11)$

The possibility of using protoactinium as a threshold detector was recognized from early observations [9] that it did not suffer fission under thermal-neutron irradiation but fissions were detected when it was exposed to neutrons from a Ra-Be source.

Several foils of Pa mounted on thin platinum backings have been prepared for us by members of Dodson's group. The masses of these foils have been determined by alpha counting with due regard to the growth of decay products and with an assumed half life of Pa equal to 32,000 years. The chemistry involved in this preparation will be discussed under the section of this paper describing measurements of $\sigma_f(37)$.

The comparison of $\sigma_f(11)/\sigma_f(25)$ was carried out in a manner similar to that described above for other materials. These observations have been

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7) A. O. Hanson, CF-618
8) R. F. Taschek, LA-39
9) V. Grosse, Booth and Dunning, Phys. Rev. 56, 382 (1[redacted])

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transformed by multiplication of $\sigma_f(11)/\sigma_f(25)$ by values of $\sigma_f(25)$ read from the smooth curve of Fig. 5. The results are shown in Fig. 9 where the vertical dashes indicate the statistical uncertainties from the limited number of fissions observed.

It is clear from this figure that $\sigma_f(11)$ rises sharply from a threshold of approximately 375 Kev to a very substantial value of 1.23 barns at 3.0 Mev. This rise appears to be somewhat irregular in that the cross section is essentially constant over the energy range from 600 to 650 Kev. This anomaly is reasonably well established by the data and is not entirely unexpected in view of our earlier observations 8) on $\sigma_f(02)$ which first revealed that fission cross sections might not be monotonic functions of neutron energy.

The usefulness of Pa as a threshold detector is established by these measurements. It should, however, be pointed out that it is at present very difficult to use more than a few milligrams of Pa in a fission chamber because the large alpha activity may result in alpha coincidences equal in signal level to that of fissions.

We are indebted to the R-3 group for operating the D-D source of neutrons to provide the data at 2.5 and 3.0 Mev. The measurements of $\sigma_f(11)$ were performed by D. Frisch, E. Klema, and other members of the R-2 group.

MEASUREMENTS ON $\sigma_f(37)$

A sample of 37 prepared by the U (n,2n) reaction with Be (d,n) neutrons from the Berkeley cyclotron was made available to us through the kindness of A. Wahl. This element was separated by the following chemical procedure:

The 37 was formed along with 49, in an amount equal to a few percent of the 49 made, in the bombarded uranium metal and nitrate. Previous to bombardment the uranium had been purified roughly by ether extraction. After bombardment the 37 and 49 were extracted from the uranium by several acetate and fluoride cycles. The 37 was then separated from the 49 by a modified fluoride

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cycle, with 39 added as a tracer for the 37. The extraction was repeated until the ratio of 39 β activity to α activity of the sample remained constant to 10 percent. On the basis of its α activity this sample cannot contain more than about 0.2 μgm of 49 or 11. One milligram of normal uranium, however, would account for less than 1 percent of its α activity and could escape detection by the 39 tracer method.

The half life of 37 has been given variously as 3×10^6 and 6×10^6 years; using 3×10^6 the weight of the sample is 20 μgm and the cross sections in Fig. 11 are given accordingly.

Observations of the number of fissions observed in the 37 sample divided by the number of fissions observed in the 25 sample, i.e. $R(37)/R(25)$ were made in the usual manner. The results are shown in Fig. 10. The constant value of this ratio in the energy region from thermals up to 400 Kev and the marked increase of this ratio above 1 Mev indicate that an appreciable amount of uranium exists in the 37 sample. If one makes the reasonable assumption that all the thermal-fission rate of the "37" sample is due to a normal-uranium contamination, 6.3 μgm of 25 and 874 μgm of 28, and subtracts from the observed "37" fission rate an amount due to the mass of 25, times $\sigma_f(25)$ and the mass of 28, times $\sigma_f(28)$ for all the neutron energies employed one obtains a curve of $R'(37)/R(25)$ which is of a more reasonable shape. There is, however, a large uncertainty in the form of this curve at the higher neutron energies because the above correction to the data is several times larger than the net effect. When the net curve shown in Fig. 10 is converted to cross sections by assuming a mass of 20 μgm of 37 and by using the values of $\sigma_f(25)$ given in Fig 5 the values of $\sigma_f(37)$ shown in Fig. 11 are obtained. It should be emphasized that the absolute value of $\sigma_f(37)$ given in this figure is uncertain to the extent that the mass of 37 in the foil is unknown.

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A comparison of Fig. 11 and Fig. 9 reveals a surprising similarity between the behavior of $\sigma_f(37)$ and $\sigma_f(11)$ as a function of neutron energy. This similarity has raised the question as to whether 37 may be the source of fissions in the 11 sample or vice versa.

As stated above, not more than 0.2 μgm of 11 could be present in the 37 sample if all its alpha activity were due to protoactinium alone. Furthermore, the chemistry is such as to eliminate to a large extent any of the small amount of element 91 which might have existed in the large amount of uranium present in the original material.

On the other hand the existence of the transuranic element 93 in natural samples of protoactinium seems unreasonable. However, the last sample of 11 investigated was prepared by members of Dodson's group in such a way as to purify it of 37. To the original solution of 11 a sample of 39 tracer was added and its β activity was followed through the chemical purification steps. These steps eliminated the tracer to within the experimental limits of detection, 0.3%.

It therefore seems highly probable that $\sigma_f(37)$ and $\sigma_f(11)$ vary in a very similar way with neutron energy and furthermore have cross sections of the same order of magnitude.

The preparation of the 37 sample used in these experiments was the responsibility of A. Wahl. The samples of 11 were prepared by members of Dodson's group. We are indebted to Wahl and Dodson for stimulating discussion and assistance with the problem stated above. The instrumentation and observations on $\sigma_f(37)$ were performed by D. Frisch and K. Greisen.

MEASUREMENTS ON $\sigma_f(00)$

A sample of ionium was made available to us through the kindness of Segrè. This material was extracted from uranium ores by Fontana at Berkeley and was given to Segrè by J. Hamilton. The quantity of ionium present in this

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extracted thorium was determined by measuring the alpha activity of a known aliquot and it was found to contain 22% ionium.

A foil containing 54 μgm of 00 and 184 μgm of 02 was prepared for us by members of Dodson's group. It was examined for fission in a manner similar to that described above. No fissions were found for a neutron energy of 1 Mev and at 1.3 Mev the number of fissions observed was roughly the number expected from the known fission cross section of thorium and the mass of 02 present in the foil.

One can therefore conclude that ionium has approximately zero cross section for fission at neutron energies below the thorium, 02, threshold.

DETERMINATION OF $\sigma_f(02)$

For the sake of completeness the cross section of thorium has been recalculated from the data reported by Taschek in LA-39. These measurements could be expressed in terms of $\sigma(02)/\sigma(28)$. Since the time the above report was written our knowledge of $\sigma(28)$ has improved to the extent shown in Fig. 8. The fission cross section of thorium expressed in barns as a function of neutron energy is shown in Fig. 12. The magnitude of the uncertainty arising from observational error to be attributed to the data on the ratio can be judged by referring to the figures of LA-39. Experience with thorium as a threshold detector has led us to believe that the threshold for thorium fission is not nearly as sharp as one would expect from a simple extrapolation to lower energies of the curve shown in Fig. 12. There is good evidence that thorium exhibits fission under bombardment with neutrons of energy less than 1 Mev.

MEASUREMENTS ON THE CROSS SECTION FOR $B^{10}(n,\alpha)LA^7$ REACTION

In LA-46 Bailey and Hanson reported our measurements on the cross section of boron for alpha emission, relative to $\sigma_f(25)$, as a function of the energy of the incident neutrons in the interval .15 to 1.5 Mev. Since that time the technique of manufacturing thin films of boron has been developed and

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measurements with thermal neutrons have been reported by Bailey and Blair in LA-90. These films of boron have been used to extend our measurements on the B(n,α)Li cross section over the range of energy from 5 Kev to 500 Kev and so to overlap the results reported in LA-46.

The technique of the measurements is the same as that given for the determination of other cross sections reported above, i.e., a B foil and a 25 foil of known masses are mounted back to back in a comparison chamber and are irradiated with the same flux of known-energy neutrons. The relative counting rates of disintegration particles and fission fragments are observed. Care must be taken in using the above technique with thick films of B and other light elements by turning the ionization chamber through 180° to average the relative counting rates for the two orientations, one with the light fragments ejected in the direction of the incident neutron beam and one with the fragments emitted in a direction opposite to the direction from which the neutrons are coming. This precaution is necessary to average out angular asymmetries expected in the nuclear reactions with light elements. It should be emphasized that in our observations, which were all with thin films, both alpha particles and lithium nuclei are observed in the boron disintegration so that there is approximately 100 percent efficiency for detection of either the B or 25 "fission" process.

The relative counting rates are transformed into $\sigma(B)$ through a knowledge of the masses of B and 25 on the foils and $\sigma_f(25)$ as a function of neutron energy. The results are shown in Fig. 13, where the cross section of boron of normal isotopic constitution is given as a function of neutron energy. The accuracy of these data is essentially limited by the uncertainty in the 25-fission cross section and the masses of the foils used. The effective masses of the foils were determined by assuming the "fission" cross sections of 700 and 550 barns for B and 25 respectively for thermal neutrons and comparing the relative fission rates when the foils were placed in a thermal flux. The cross

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sections as given are thought to be accurate to approximately five percent with respect to the 25 cross section. On an absolute basis the uncertainty is increased by the amounts stated on page 20 of this report. It is gratifying to report that three completely independent sets of data [LA 46 and present data with two comparison chambers] which overlap in energy interval covered are in agreement to within 5 percent.

MEASUREMENTS ON THE CROSS SECTION OF THE $Li^6(n,\alpha)H^3$ REACTION

One of the most desirable properties that a nuclear disintegration resulting from neutron bombardment could possess is that the cross section times the neutron velocity should be constant. Although this is the case for several reactions in the thermal-energy region it has not been found to be true for neutrons of higher energy. When it was established that boron did not follow the 1/v law an investigation of lithium was initiated in the hope that it would prove to be unique. Although this hope proved to be unfounded and the complete investigation was interrupted, sufficient data were acquired to give the approximate form of the cross section between 30 and 700 Kev.

As in the case of boron, thin films of Li were compared to 25 to determine the relative "fission" rate. The masses of these films were determined by the thermal-neutron "weighing" technique, assuming the cross sections of 69.5 and 550 barns respectively.

Two independent sets of data were obtained and are shown in Fig. 14. The higher-energy data were acquired with neutrons whose energy was less well-defined than for the case of the lower-energy data. The results shown are admittedly preliminary and incomplete but do indicate quite clearly that a marked resonance in the cross section for this process occurs in the neighborhood of 280 Kev. The magnitude and width of this resonance are not well-established as witnessed by the discrepancy between the two sets of data taken with different resolving powers.

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SUMMARY

The cross sections of all isotopes except 25 reported in this paper are dependent upon the knowledge of $\sigma_f(25)$. A study of Fig. 5 and a consideration of the validity of our assumptions as to the energy independence of the long counter as well as the tests with the compensated ionization chambers lead us to make the following statements about the uncertainty of $\sigma_f(25)$.

First, all our cross sections are based on the value $\sigma_f(25) = 1.35$ barns for neutrons of 1 Mev. The estimated uncertainty in this value given by Hall, Koontz, and Rossi is $\pm$ 5 percent. The cross sections here reported are linear functions of this normalization value. The absolute values shown in Fig. 5 are in fair agreement with this standard and make it seem unlikely that any major change in this value will be adopted in the future. Other methods of determining $\sigma_f(25)$ on an absolute basis are being pursued by members of this group.

Second, the agreement between the compensated-ionization-chamber and long-counter measurements of flux in the energy interval 50 to 500 Kev, the region in which the dependence of the long-counter sensitivity to energy is least subject to experimental proof, increases our confidence in the long-counter measurements. The agreement between our long-counter observations and those of other observers with quite different instruments, in the energy region from 400 to 2000 Kev, is also very gratifying. Below 200 Kev the experiments with a degraded Y-Be source substantiate our assumption in no uncertain manner. In view of the above we feel that the uncertainty arising from the imperfection of our assumption as to the characteristics of the long counter can hardly exceed 5 percent.

Third, the uncertainty in the neutron energy associated with a certain cross section is to be considered. A statement as to the spread in neutron energy employed in the various parts of the neutron spectrum has been given on

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page 5 of this report. The average energy for a particular observation is therefor defined to a higher accuracy. It is only in the energy region below 50 Kev that one needs to consider the energy uncertainty. However, in view of the fact that the cross section is increasing rapidly in this region the measured cross sections up to 20 Kev may be too large by an amount which is difficult to estimate, possibly as great as 5 to 10 percent.

Fourth, the assumption that the Li(p,n) reaction is a source of monoenergetic neutrons under ideal conditions has been questioned at various times. Earlier evidence eliminated the possibility that two groups of neutrons whose energy differed by more than 200 Kev could be present. The fact that the 2-PG and long-counter measurements are in essential agreement from 50 to 500 Kev indicates that if two groups are present their energy difference cannot exceed 50 Kev. This argument is based on the fact that the hydrogen-recoil ionization chamber and long counter have distinctly different energy response. The hydrogen chamber receiving neutrons of say 60 Kev would record the flux from the presumed lower-energy group of 10 Kev with practically zero efficiency, whereas the long counter would record all the flux. One would expect the hydrogen-chamber measurements of cross section to exceed those of the long counter and to show a sharp change at that neutron energy which is equal to the difference in energy between any two different energy groups which might be present from the Li(p,n) source.

It therefore seems safe to assume that the source of neutrons used is essentially monoenergetic to within the practical limits imposed by intensity considerations and proton voltage control.

Summarizing these uncertainties it is estimated that absolute values of $\sigma_f(25)$ are reliable to within 20 percent from 5 to 15 Kev, to within 15 percent from 20 to 50 Kev, to within 10 percent from 50 to 2000 Kev.

[redacted]

[redacted] [redacted]

At one time in the history of the theory of nuclear physics it was thought that the cross sections of neutron-capture processes leading to "fission" which were energetically possible would follow a $1/v$ law up to energies of the order of 1 Mev. Although the experimental evidence contradicts this expectation, plotting $\sigma \cdot v$ as a function of neutron energy, has proved to be a convenient and illuminating method of presenting data. Such a plot is shown in Fig. 15 with the unit of velocity that which corresponds to 1 Kev.

The only general feature of these curves is that in the energy interval from 1 to approximately 30 Kev the value of $\sigma \cdot v$ increases for 25, 49, B and Li. This common behavior might be blamed on an erroneous increase in 25 cross section in this region since all the other cross sections must reflect the 25 in view of the method of measurement. Although this may be in some measure a true argument it can scarcely account for all the increase since it seems unlikely in view of the discussion above that our measurements of $\sigma(25)$ could be sufficiently uncertain. Furthermore, the percentage increase in $\sigma \cdot v$ in going from 1 to 30 Kev is for 25, 49, B and Li equal to 231, 235, 180 and 167. In going from 1 to 10 Kev the ratios are 169, 149 and 150 for 25, 49, and B, respectively. There seems to be nothing in common about these numbers. The values given in this report for $\sigma \cdot v$ at 1 Kev are in general due to McDaniel, et al. The fact that our measurements at 5 Kev and greater energies extrapolate in a reasonable fashion to the values at 1 Kev obtained by modulated-neutron-beam techniques gives increased confidence in the values reported for the energy interval from 5 to 30 Kev.

The arguments given above have been stressed because it is difficult to account for the form of the cross section of boron as a function of neutron energy on the basis of existing nuclear theory. We are indebted to V. Weisskopf for stimulating discussion on this point.

In considering the reliability of the cross sections of isotopes other

[redacted]

[redacted]

than 25 it is evident that the uncertainty in their values will exceed the uncertainty given above for 25. This additional ambiguity will arise from such causes as errors in mass determination, usually less than 2 percent, and statistical errors in the limited number of "fissions" observed. This latter uncertainty is in general indicated on the figures and in those cases not shown is considered to be less than 3 percent.

[redacted]

[redacted]

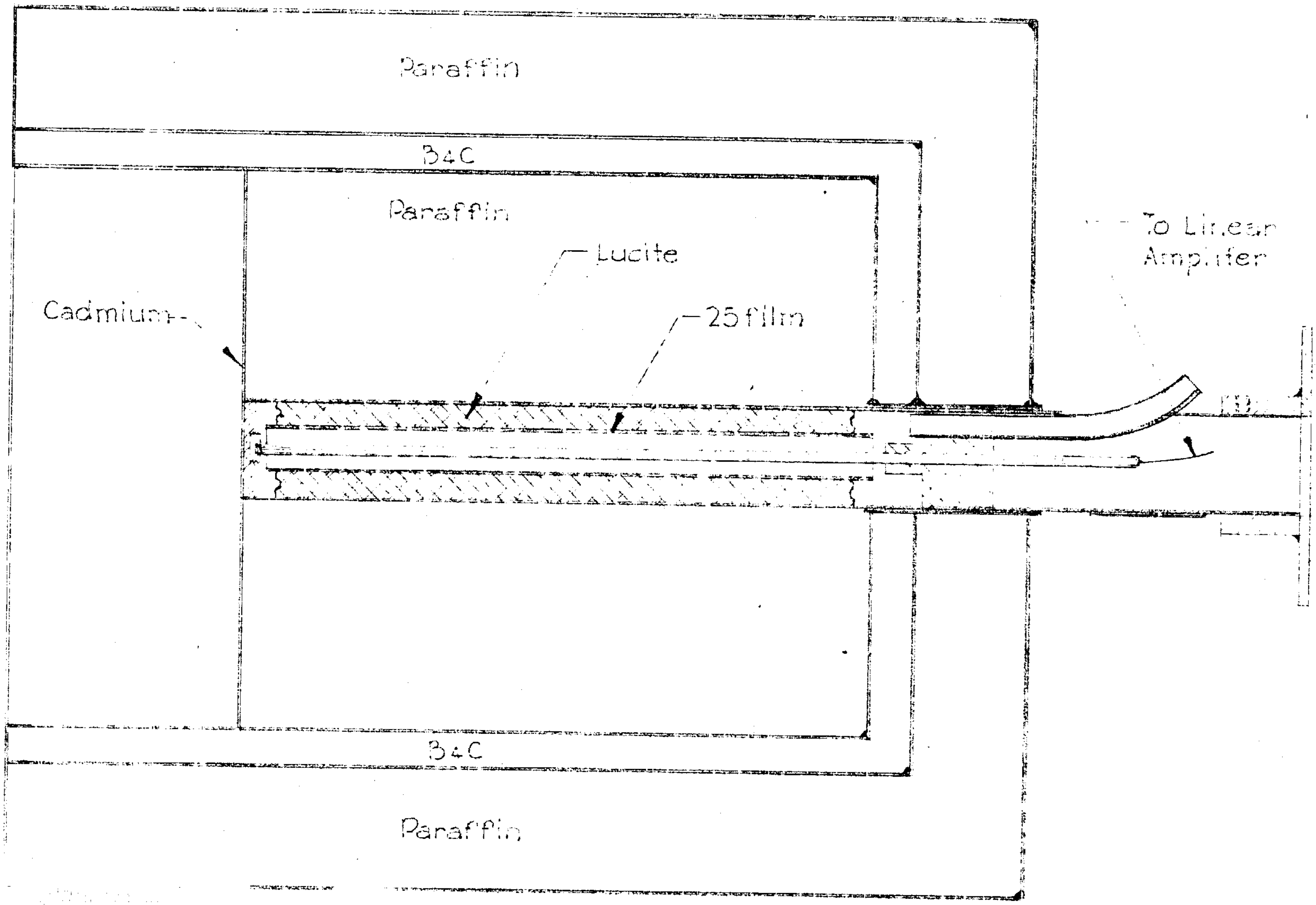
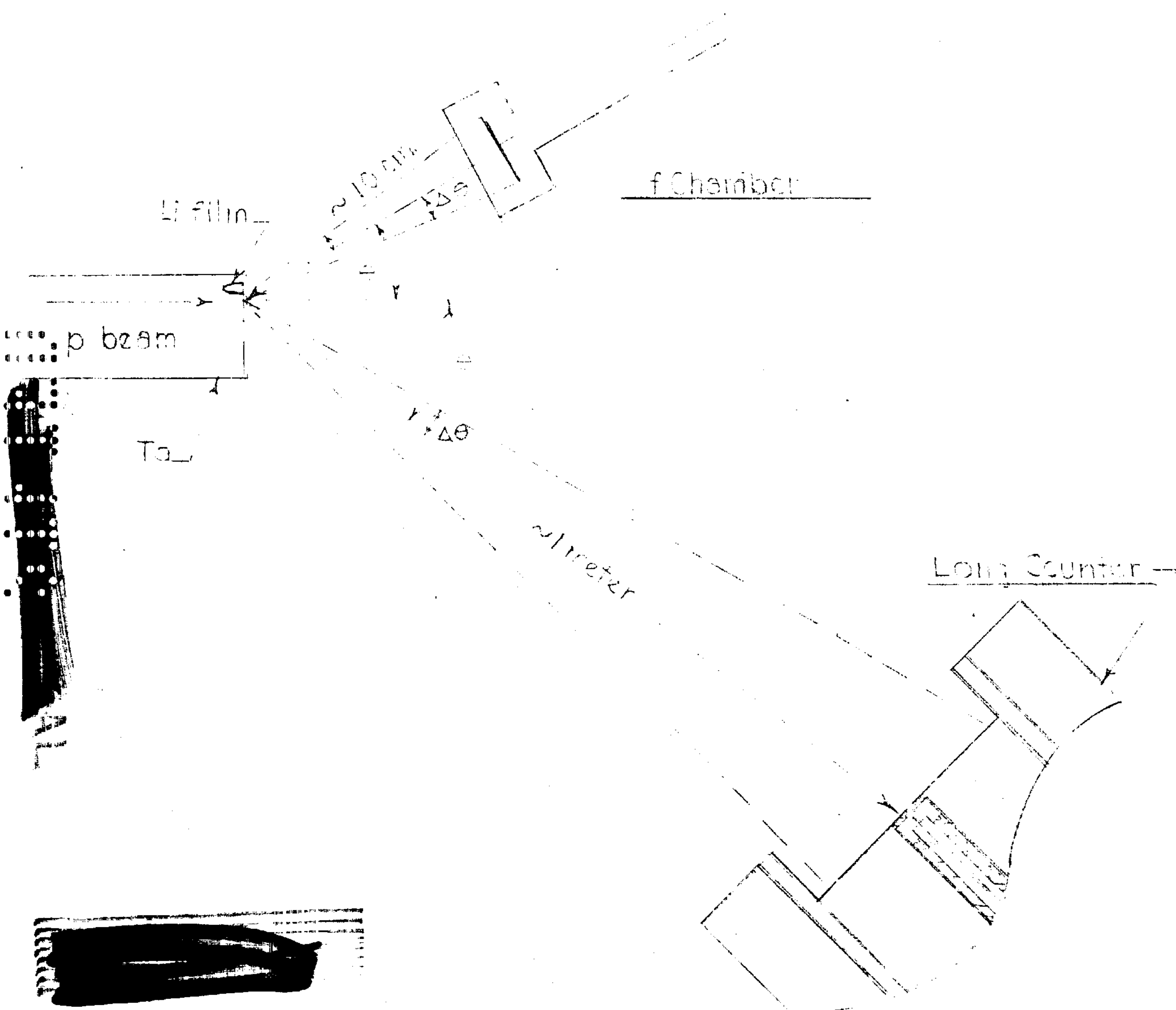


FIG. 1
DETECTOR 2
Scale: $\frac{1}{2}$" = 1"

[redacted]

FIG 2



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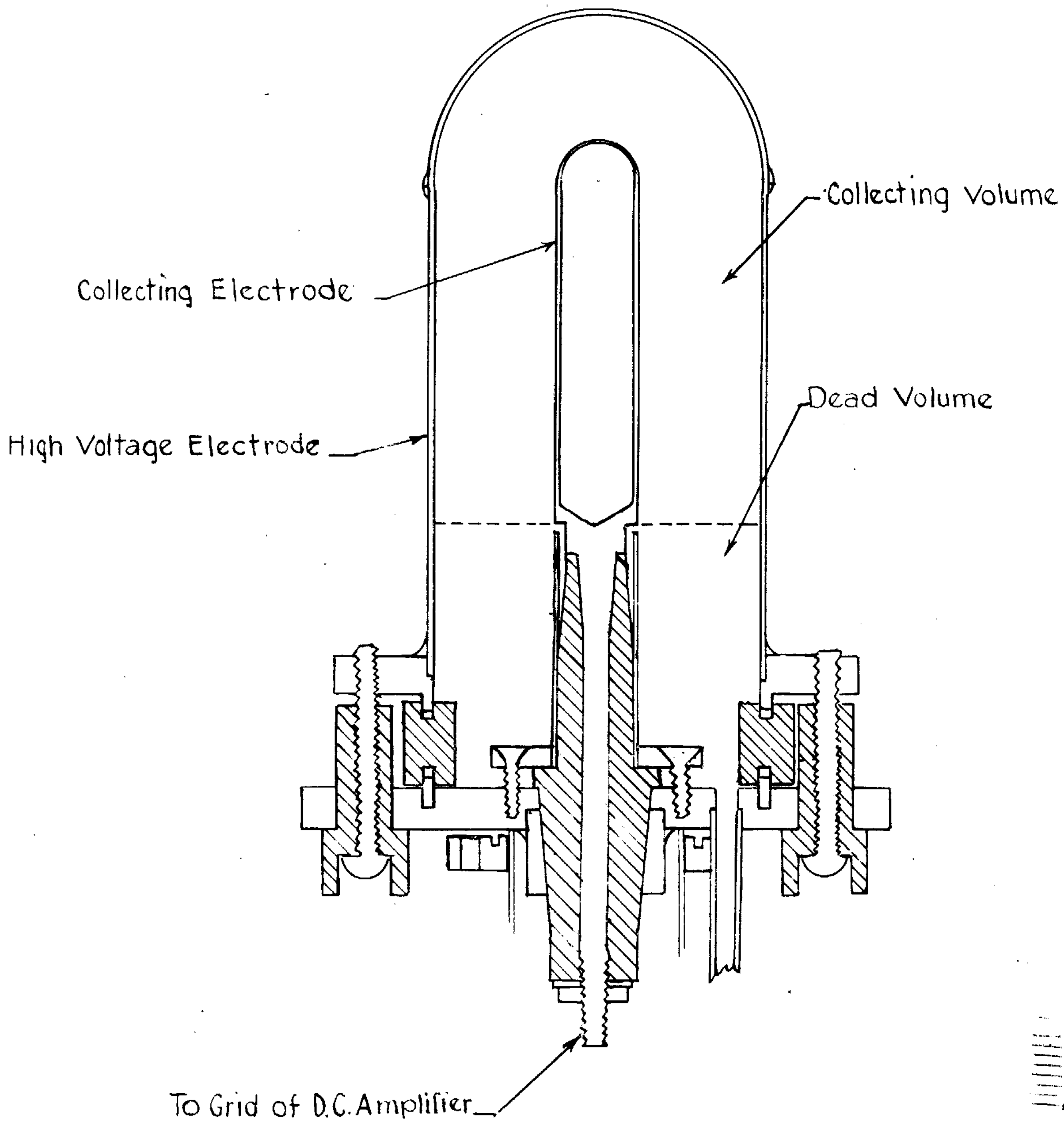

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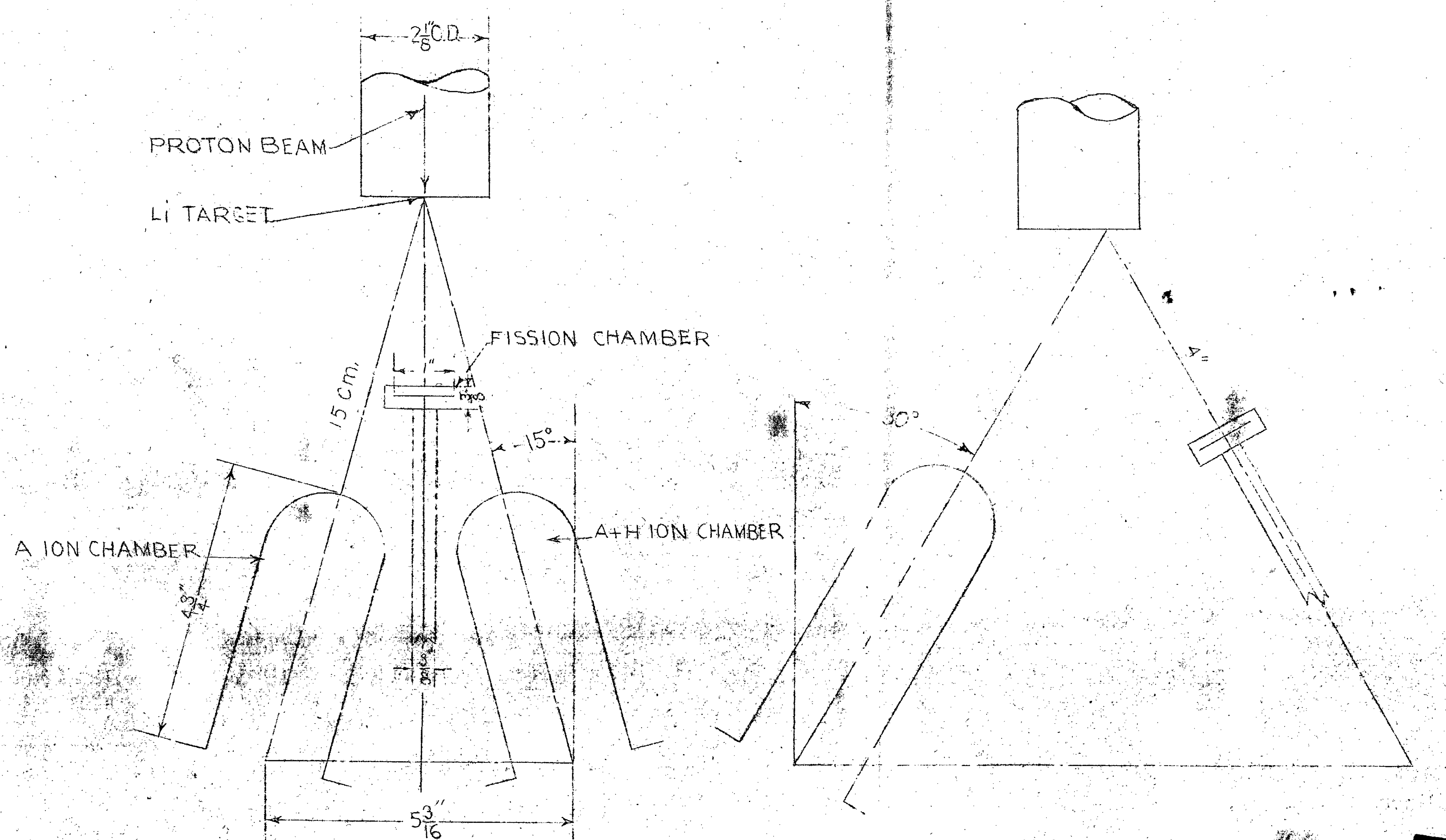
FIG. 3

[redacted]



TOP VIEW

SIDE VIEW

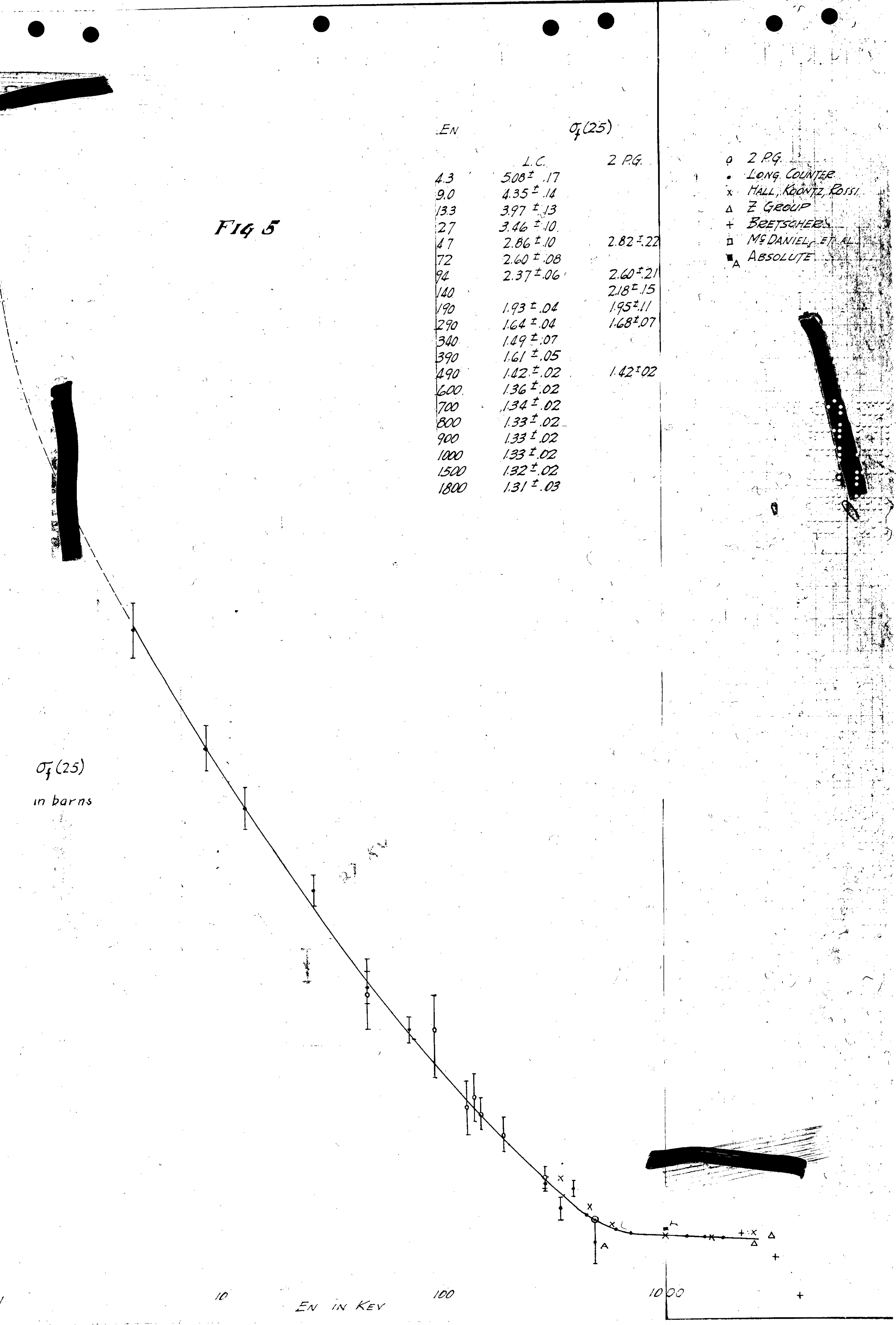
FIG. 4

1/2" = 1"

[redacted]

FIG 5

E_N	$\sigma_f(25)$ L.C.	$\sigma_f(25)$ 2 P.G.
4.3	5.08 ± .17	
9.0	4.35 ± .14	
13.3	3.97 ± .13	
27	3.46 ± .10	
47	2.86 ± .10	2.82 ± .22
72	2.60 ± .08	
94	2.37 ± .06	2.60 ± .21
140		2.18 ± .15
190	1.93 ± .04	1.95 ± .11
290	1.64 ± .04	1.68 ± .07
340	1.49 ± .07	
390	1.61 ± .05	
490	1.42 ± .02	1.42 ± .02
600	1.36 ± .02	
700	1.34 ± .02	
800	1.33 ± .02	
900	1.33 ± .02	
1000	1.33 ± .02	
1500	1.32 ± .02	
1800	1.31 ± .03	



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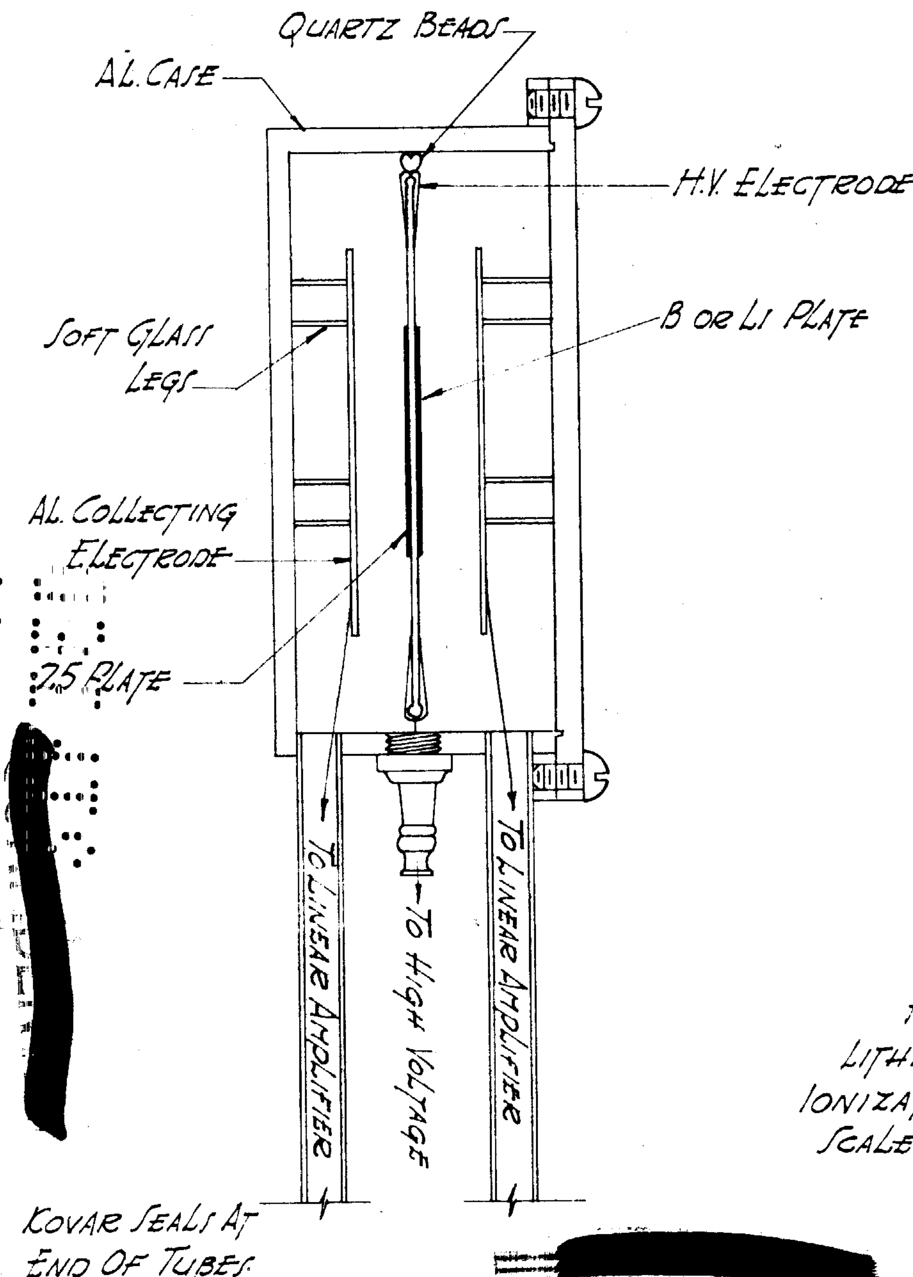


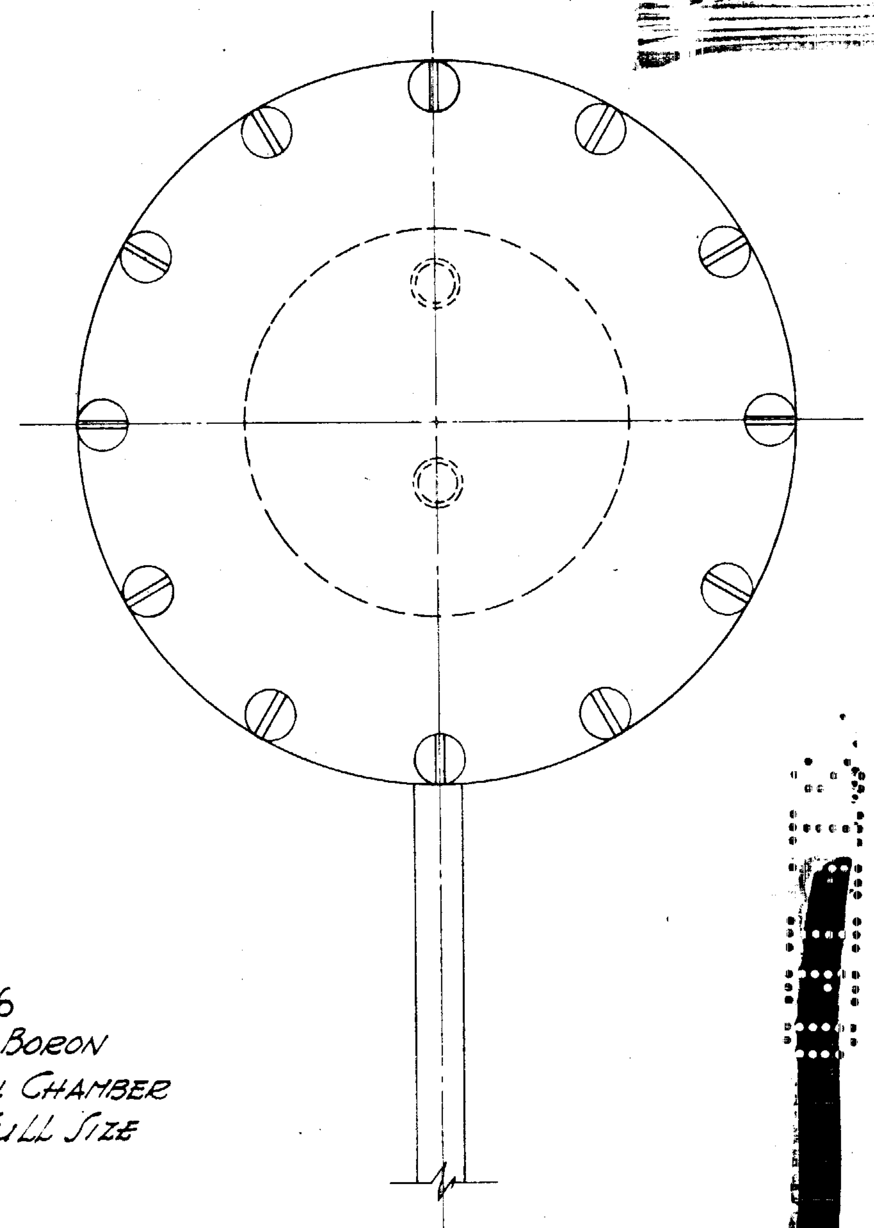


FIG. 6
LITHIUM-BORON
IONIZATION CHAMBER
SCALE - FULL SIZE

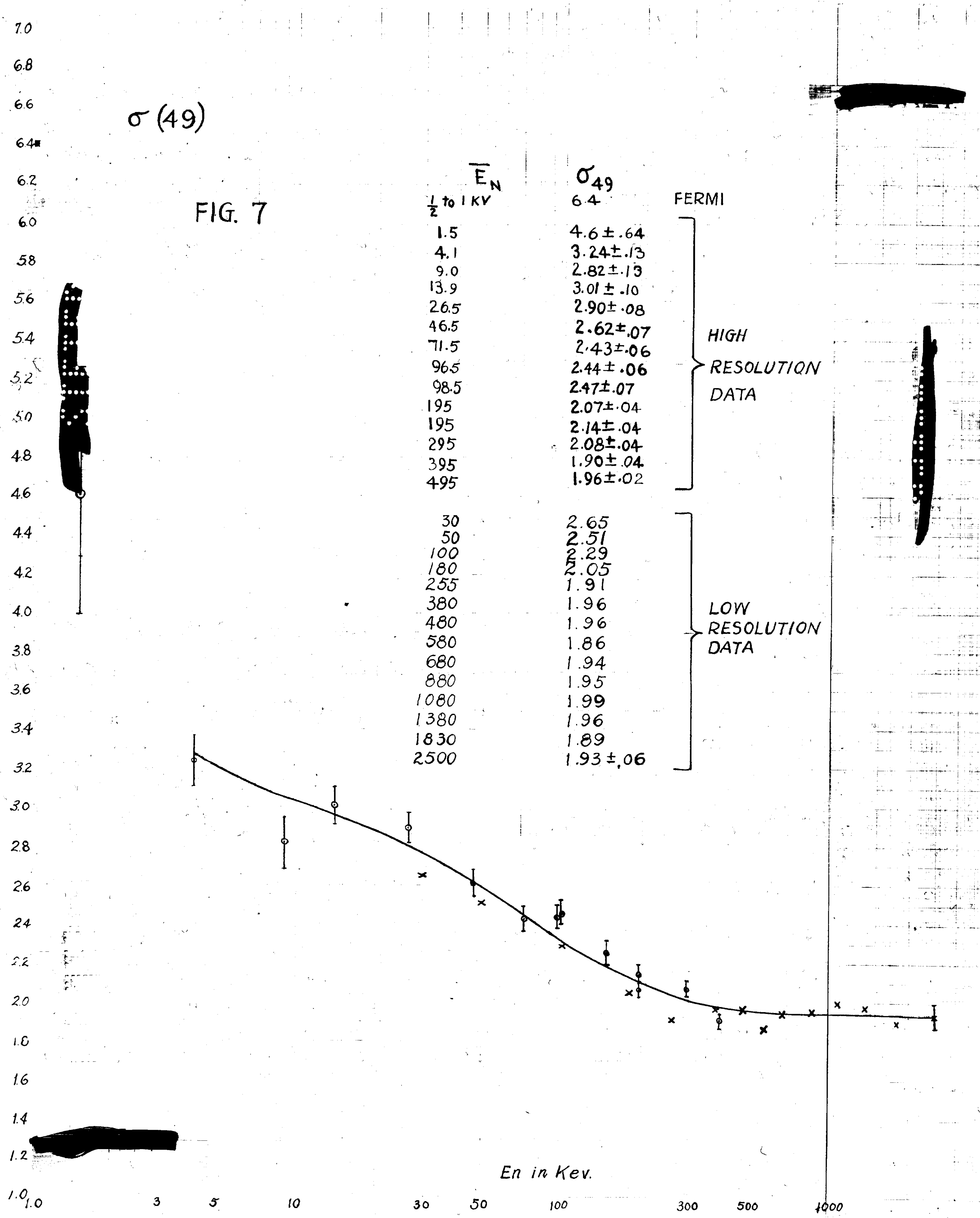
[redacted]

[redacted]

σ (49)

FIG. 7

$\overline{E}_N$	σ_{49}	
½ to 1 KV	6.4	FERMI
1.5	4.6 ± .64	HIGH RESOLUTION DATA
4.1	3.24 ± .13	
9.0	2.82 ± .13	
13.9	3.01 ± .10	
26.5	2.90 ± .08	
46.5	2.62 ± .07	
71.5	2.43 ± .06	
96.5	2.44 ± .06	
98.5	2.47 ± .07	
195	2.07 ± .04	
195	2.14 ± .04	
295	2.08 ± .04	
395	1.90 ± .04	
495	1.96 ± .02	
30	2.65	LOW RESOLUTION DATA
50	2.51	
100	2.29	
180	2.05	
255	1.91	
380	1.96	
480	1.96	
580	1.86	
680	1.94	
880	1.95	
1080	1.99	
1380	1.96	
1830	1.89	
2500	1.93 ± .06	



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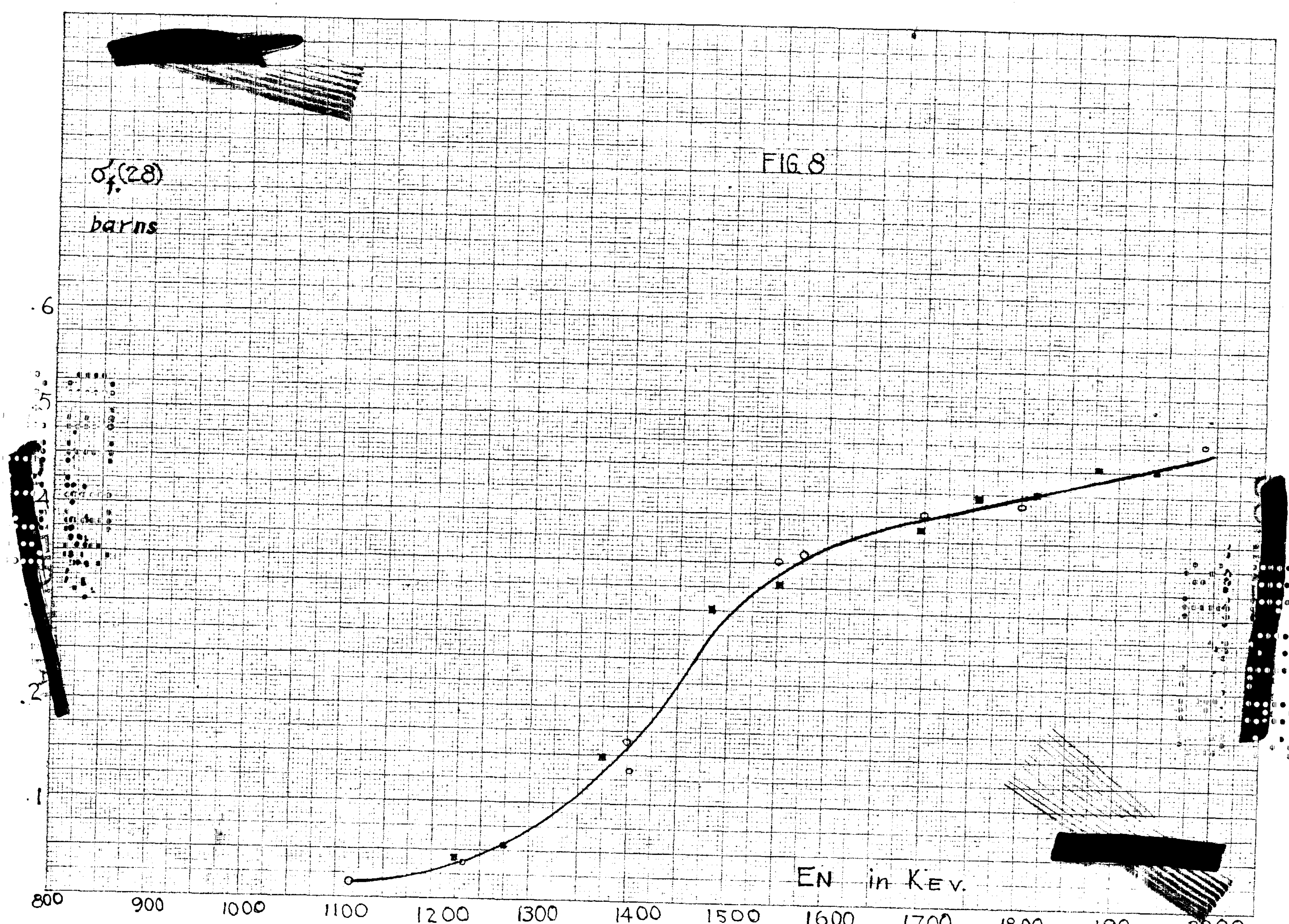
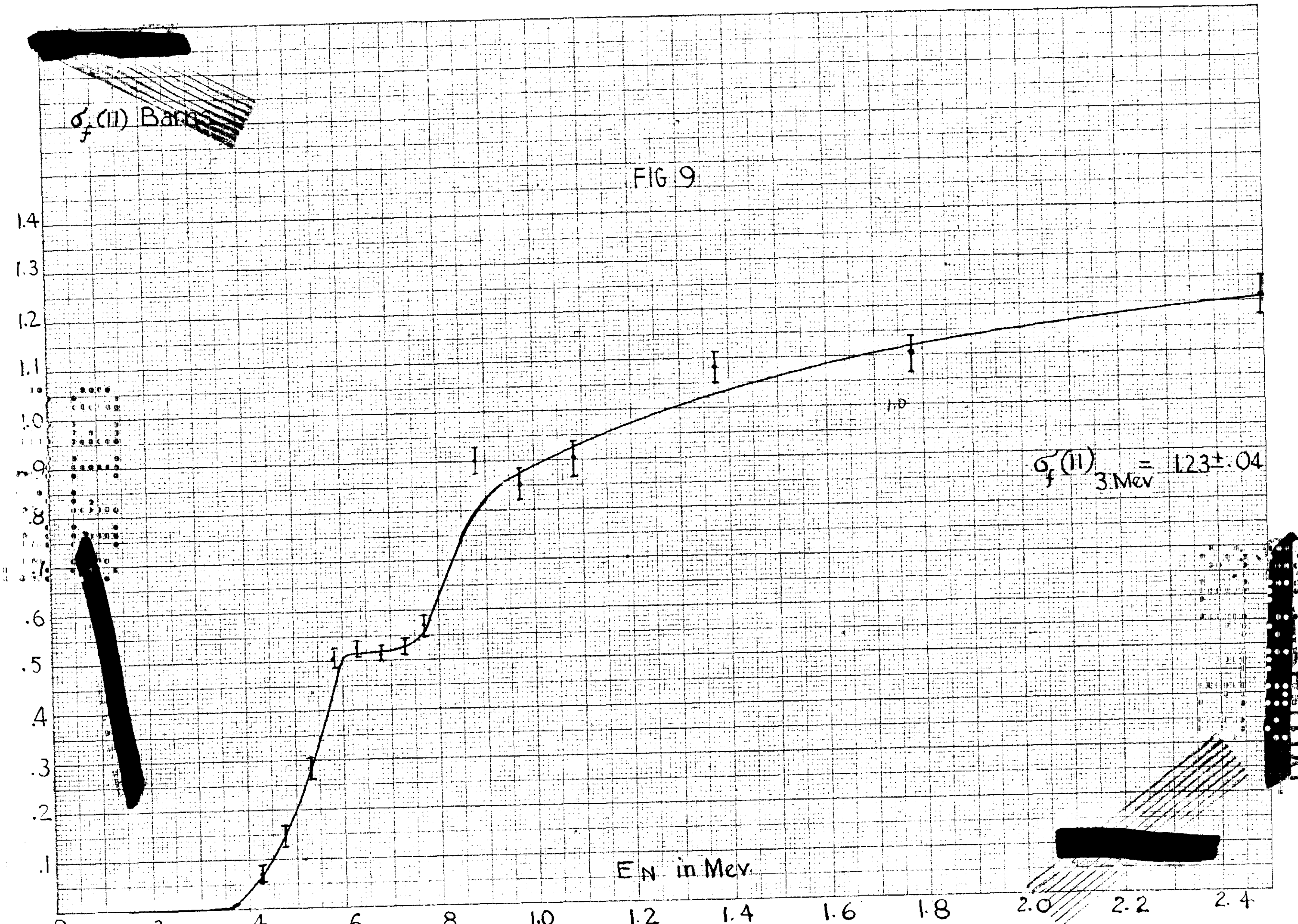


FIG 8
σf (28)
barns
.6
.5
.2
.1
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
190
2000
EN in KEV.


[redacted]
σ_f (II) Barns
FIG 9
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
$\sigma_f(\mathrm{II})_{3\,\mathrm{Mev}} = 1.23 \pm .04$
E_N in Mev
[redacted]
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4

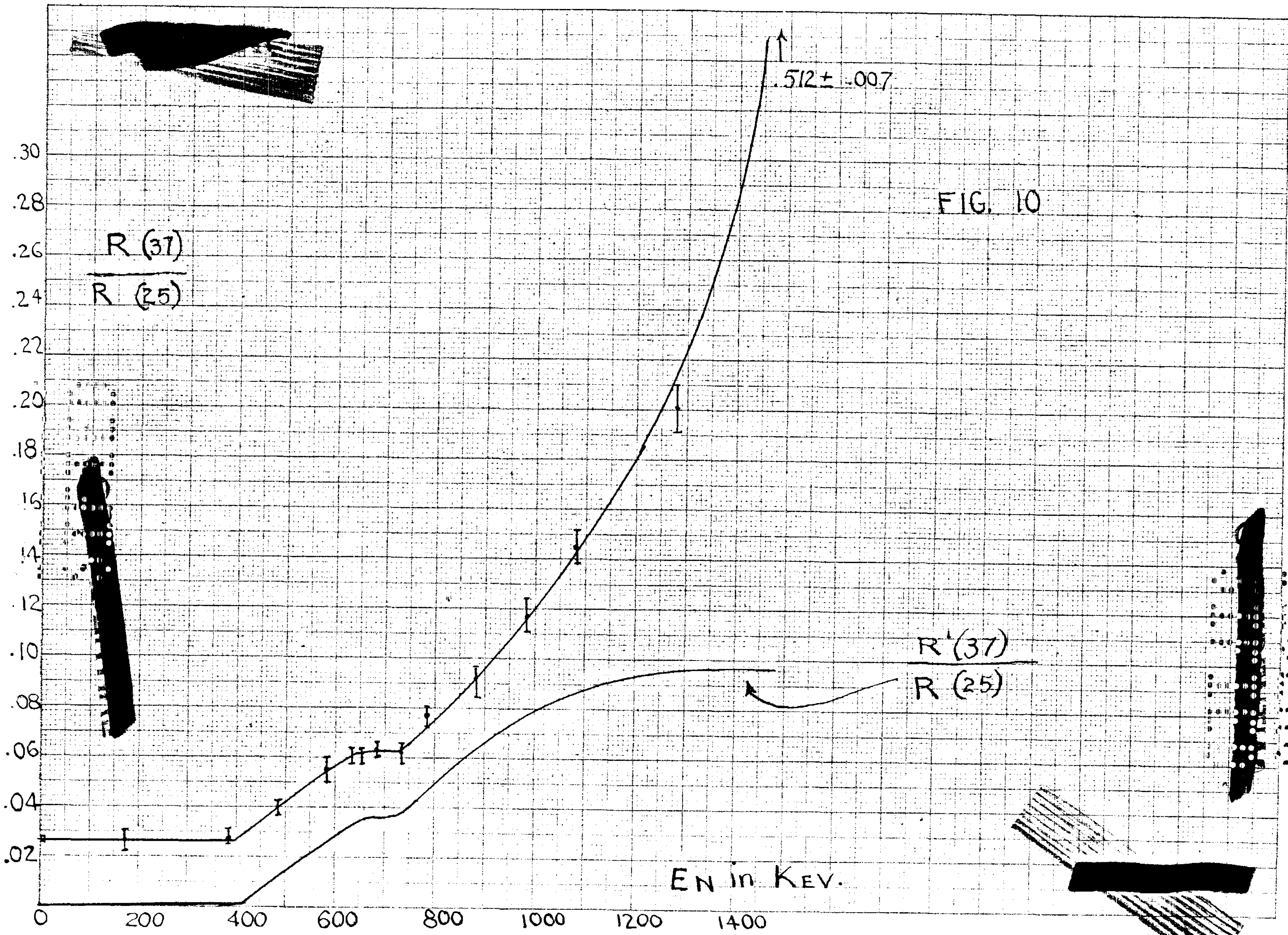
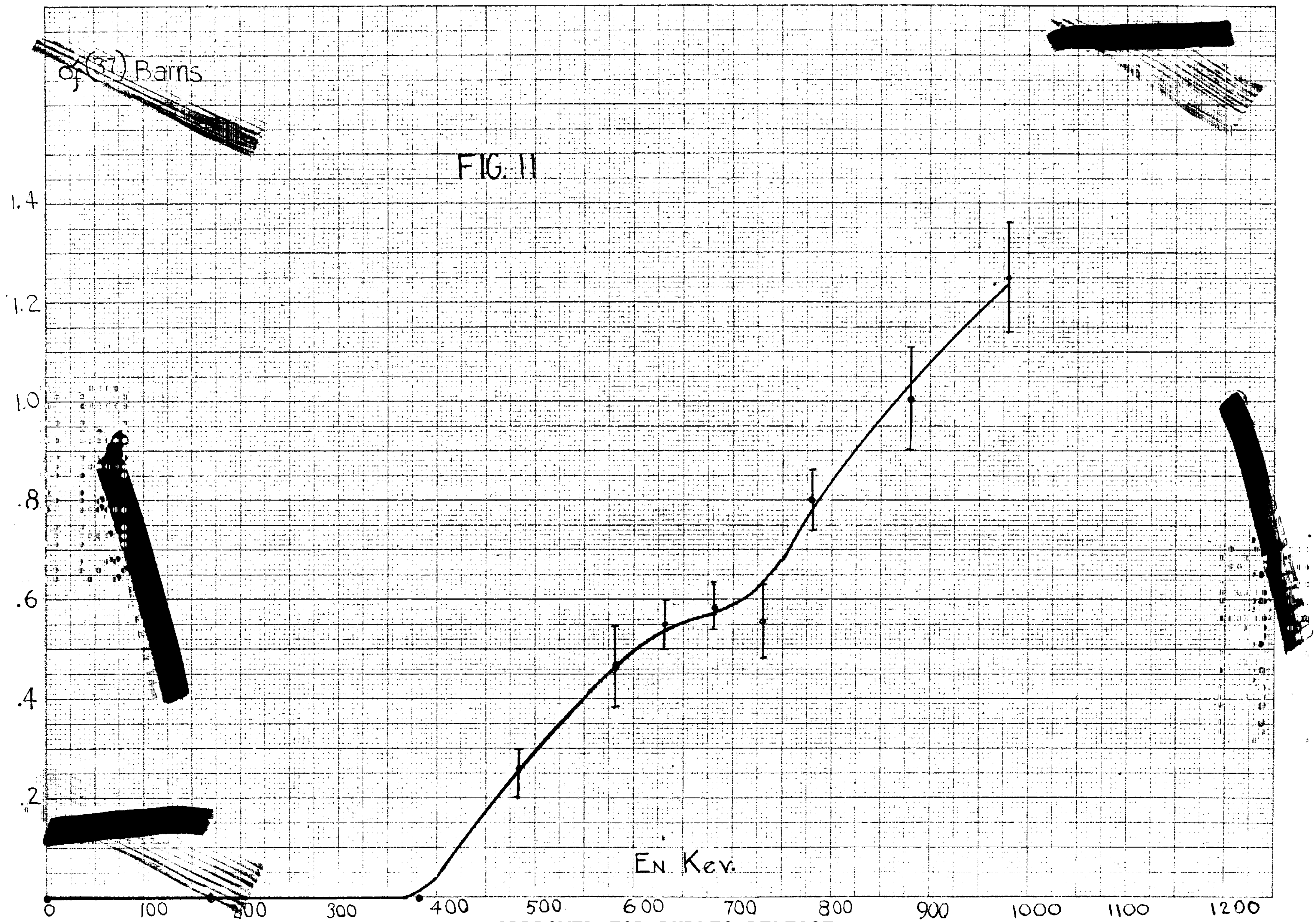
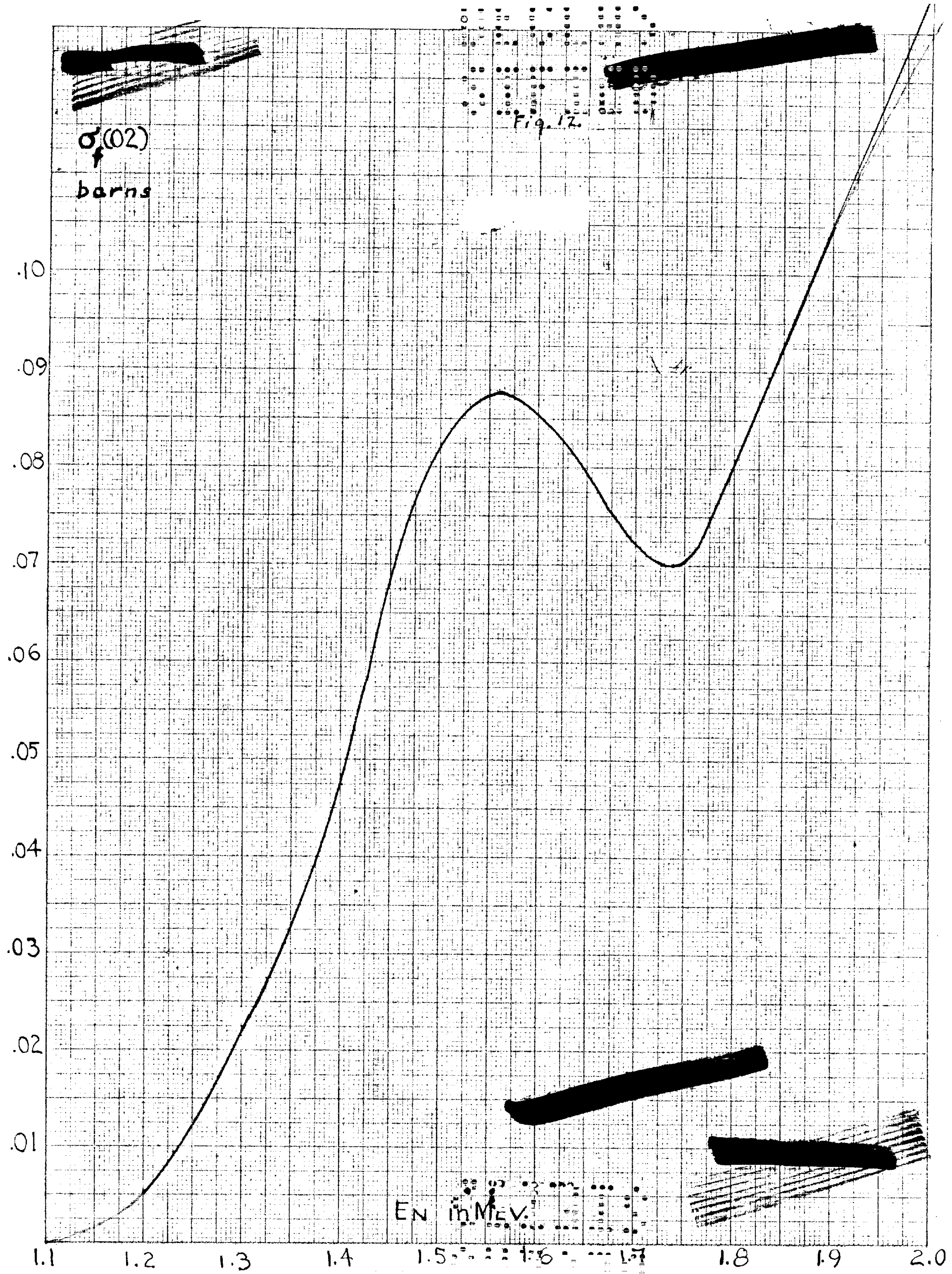

.512 ± .007
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
R (37) / R (25)
R' (37) / R (25)
En in Kev.
0
200
400
600
800
1000
1200
1400

FIG. 10



σf(37) Barns
1.4
1.2
1.0
.8
.6
.4
.2
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
En Kev.

FIG. 11


[redacted]
[redacted]
Fig. 12
σ_f(02)
barns
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
[redacted]
[redacted]
En in MeV.
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0

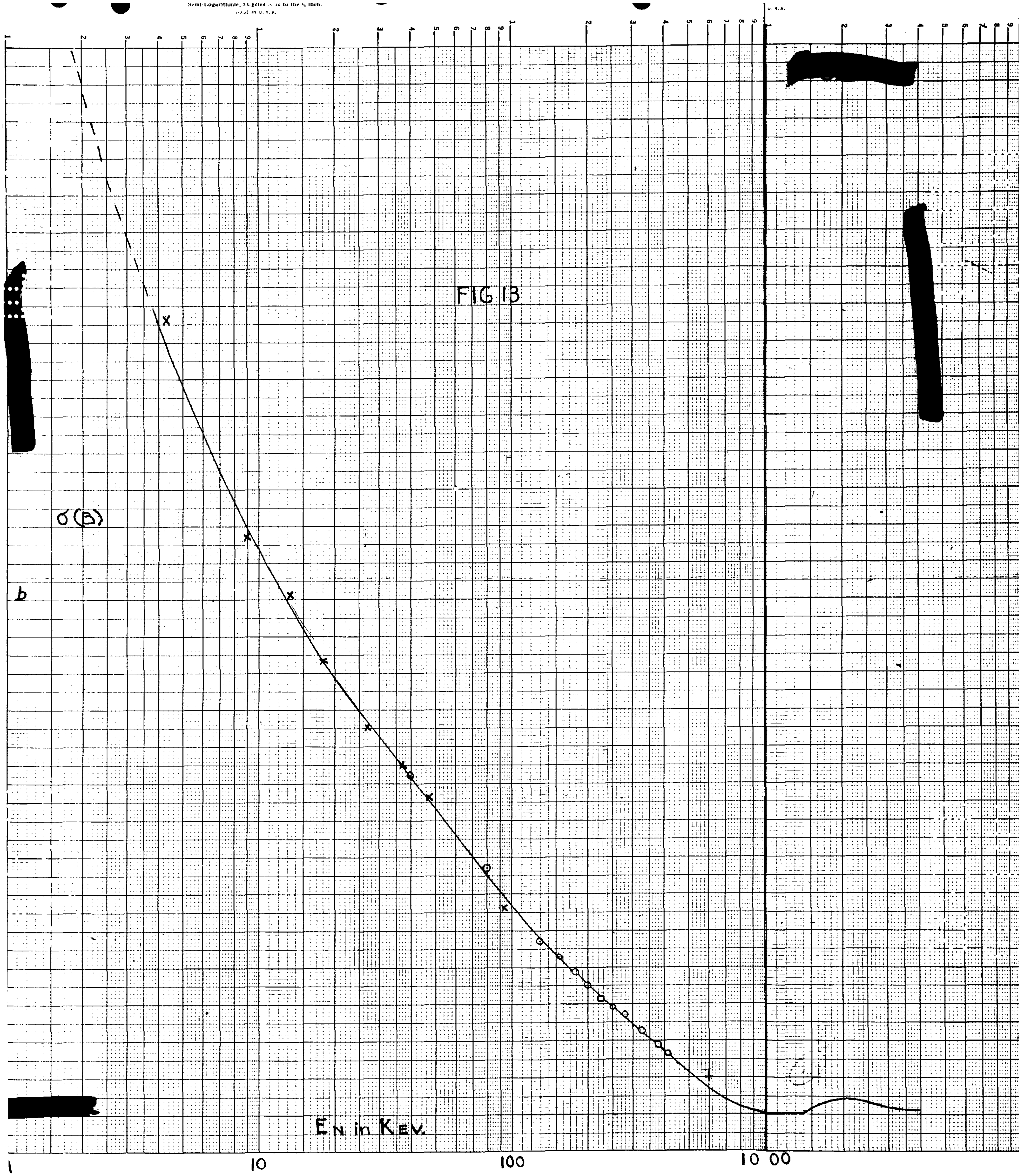
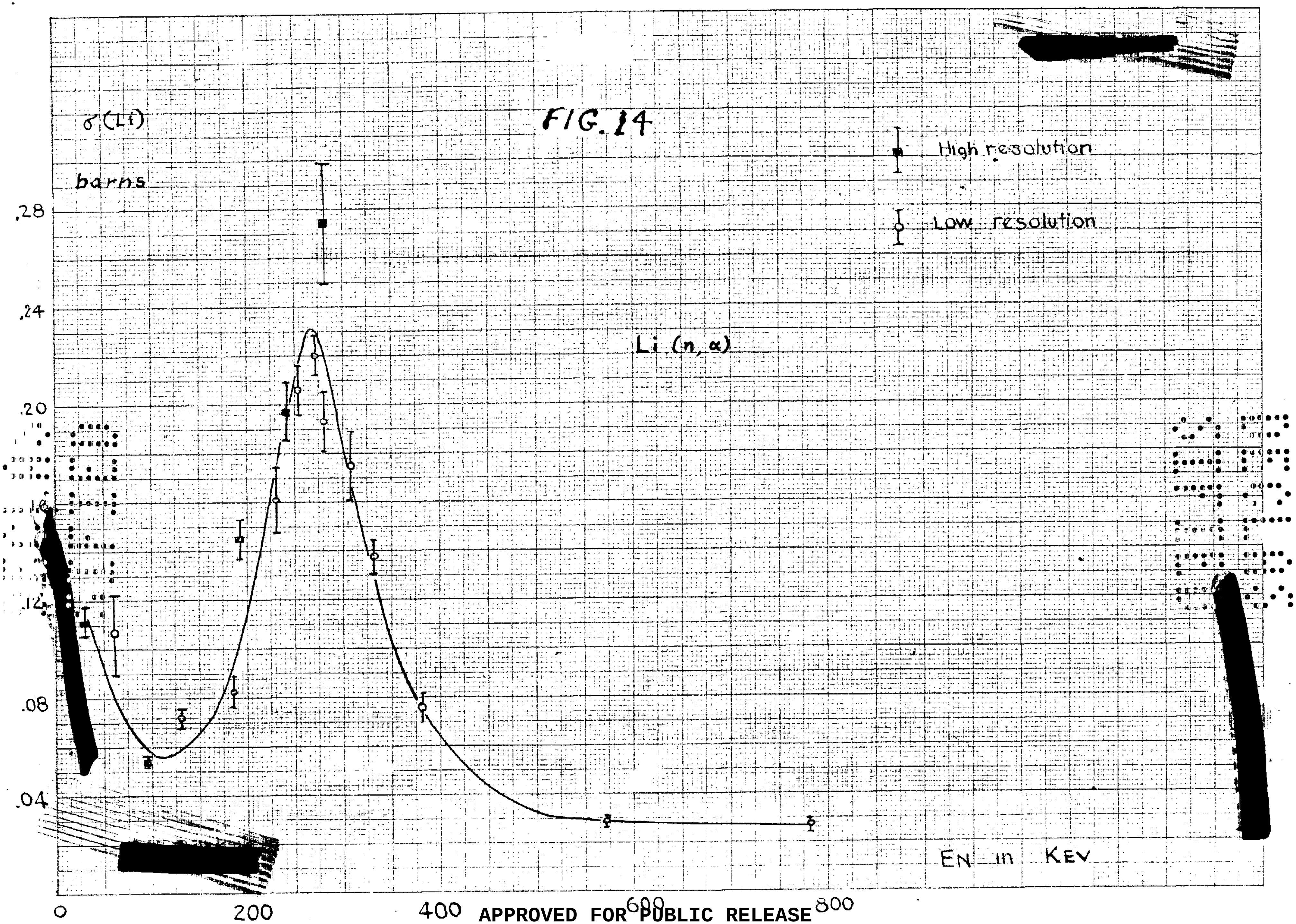


FIG 13
σ(B)
b
E_N in KEV.
1
10
100
10 00



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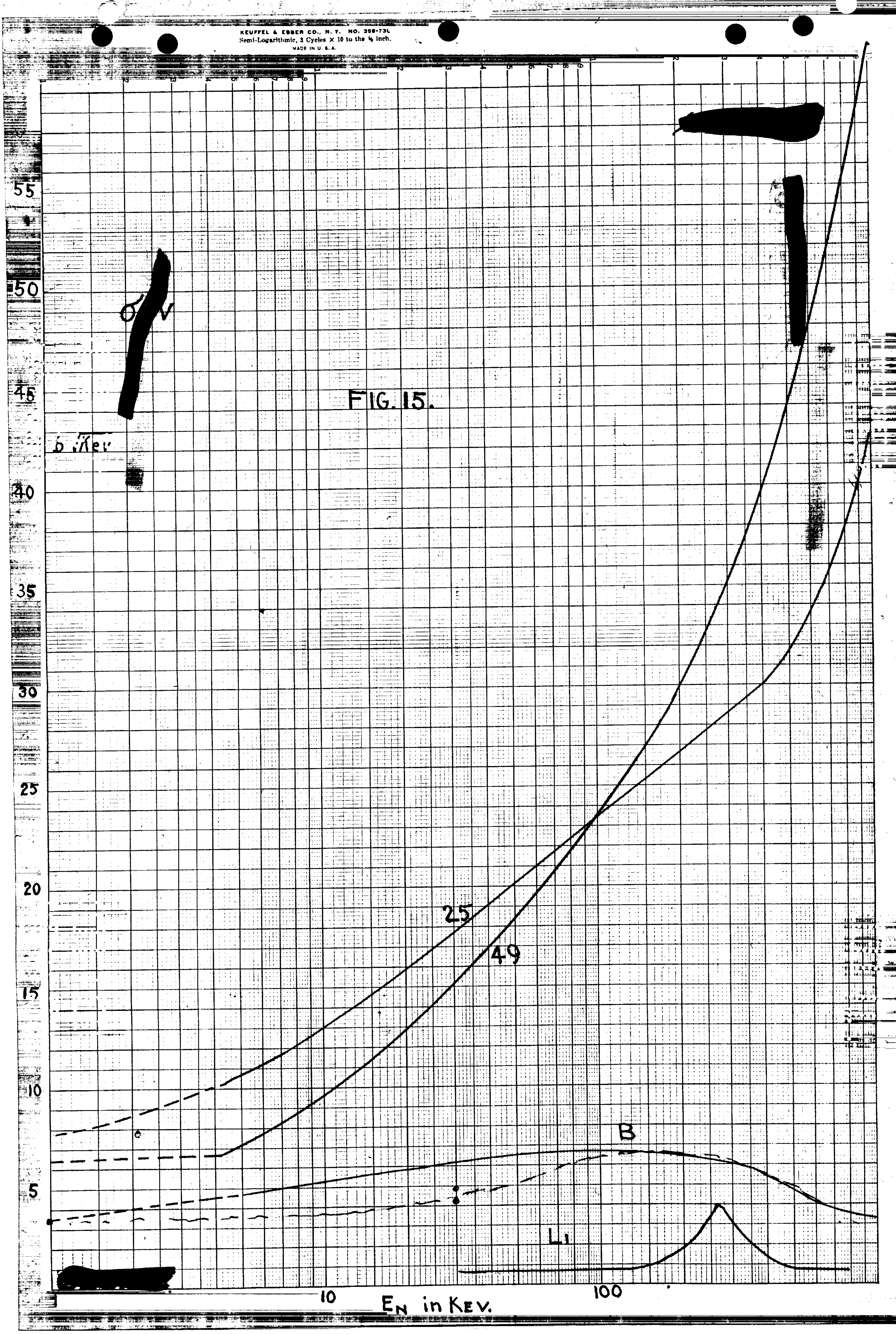
KEUFFEL & ESSER CO., N. Y. NO. 359-73L
Semi-Logarithmic, 3 Cycles × 10 to the ½ inch.
MADE IN U. S. A.
[redacted]
σ [redacted] v
b √Kev
55
50
45
40
35
30
25
20
15
10
5
25
49
B
L1
10
100
EN in KEV.

FIG. 15.