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FISSION SPECTRUM

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ABSTRACT

Measurements of the spectrum of the fission neutrons of 25 are described, in which the energy of the neutrons is determined from the ionization produced by individual hydrogen recoils. The slow neutrons producing fission are obtained by slowing down the fast neutrons from the Be-D reaction of the Stanford cyclotron. In order to distinguish between fission neutrons and the remaining fast cyclotron neutrons both the cyclotron current and the pulse amplifier are modulated. A hollow neutron container, in which slow neutrons have a lifetime of about 2 milliseconds, avoids the use of large distances. This method results in much higher intensities than the usual modulation arrangement. The results show a continuous distribution of neutrons with a rather wide maximum at about 0.8 MV falling off to half of its maximum value at 2.0 MV. The total number of neutrons is determined by comparison with the number of fission fragments. The result seems to indicate that only about 30% of the neutrons have energies below .8 MV. Various tests are described which were performed in order to rule out modification of the spectrum by inelastic scattering.

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FISSION SPECTRUM

1. PROBLEM AND METHOD

The neutrons emitted in consequence of the fission of U_{25} have been studied by various investigators. Zinn and Szilard1) have recorded the proton and α recoils in an ionization chamber. Proton recoils from fission neutrons have also been observed by Chadwick2) in a photographic emulsion and by Bennett and Richards3) in a Wilson cloud chamber. A rough determination of their energy has furthermore been obtained by Christy and Manley4) from the absorption coefficient in water. The results of Chadwick give a distribution with the maximum at 2 MV and a half width of about 1.3 MV. The absorption data yield an "effective" energy of 2.2 MV and the tracks observed in the cloud chamber originally seemed to indicate a considerable number of neutrons even above 4.5 MV.

The object of the present investigation was to redetermine the energy distribution of the fission neutrons of U_{25}, making use of the cyclotron as an abundant source of primary neutrons. This has the obvious advantage over the methods previously applied to obtain good statistics within short running times and to avoid the cumbersome geometrical sacrifices necessitated by low intensities. On the other hand, because of the great number of primary neutrons from the cyclotron target with energies in the same range as those of the secondary fission neutrons to be observed, a rather intricate arrangement and method of recording had to be devised.

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1) Phys. Rev. <u>56</u>, 619, 1939.
2) Report B-86
3) CP-325
4) CP-209

The method of detection is essentially the same as that used by Zinn and Szilard1). The fission neutrons, emerging from a disk of tuballoy, produce proton recoils in a hydrogen-filled ionization chamber. The ionization pulses of these recoils are amplified and those lying between an energy E and $E+\Delta E$ are selected and recorded. Assuming for the moment that the range of the recoils is small compared to the linear dimensions of the chamber, so that its wall effects can be neglected, and letting R(E) be the number of recoils in the chamber per unit energy and time, we find the number N(E) of fission neutrons per unit energy and time emerging from the disk to be

$$N(E) = - \frac{E}{SDh\ (\rho)} \frac{dR}{dE} \tag{1}$$

where S is the effective fraction of solid angle under which the recording volume of the chamber is seen from the disk, D its effective depth, and h the number of hydrogen atoms per unit volume, (ρ) is the scattering cross section of the proton for a neutron of energy E. It is furthermore assumed in (1) that, over the investigated range of energy, the neutron-proton scattering is isotopic in a reference system moving with the center of gravity of the two particles. This cross section is sufficiently well known, both from experiment and theory5), and with all the other quantities in (1) given, the problem reduces to the determination of the recoil distribution R(E).

The source of primary neutrons was a Be target, bombarded with a beam of 2.6 MV deuterons from the Stanford cyclotron. In order to eliminate in R(E) all those recoils due to primaries, the neutrons from

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5) See paragraph 10 of the Handbook, L. A. 11, and the more detailed discussion of an unnumbered Berkeley report by Bohm and Richman, Dec. 21, 1942, catalogued in the L. A. library as UCRL-320.

the target were slowed down in paraffin and by the well known method of delayed modulation of source and detector$^{6)}$ only those effects due to purely thermal neutrons were observed. Since thermal neutrons cannot induce fission of the isotope U_{28}, our investigation of the fission spectrum refers to U_{25} alone.

Before entering into a more detailed description of our method it is necessary to discuss the essential determining factors. Since it was to be foreseen that the spectrum would extend well above 2 MV, it was important that the gas in the ionization chamber should have the relatively high stopping power of abour 8 times that of air. This requires a considerable pressure of the gas which, with a feasible electrode spacing and collection voltage, leads to collection times of the ions in the neighborhood of one millisecond. It is true that the collection time could be considerably shortened by collecting unattached electrons; since, however, the induced voltage pulse in the chamber is proportional to the average distance from the collecting electrode to the region where the electrons are liberated, recoils of the same energy would give pulses of different size, depending upon their position relative to the next positive electrodes. This would spoil the resolution to such an extent, that electron collection must be deliberately avoided and care must be taken that not only the positive but also the negative charges collected are attached to heavy ions which have approximately the same collection time.

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6) L. W. Alvarez, Phys. Rev. 54, 609, 1938.
C. P. Baker and R. F. Bacher, Phys. Rev. 59, 332, 1941.

With the comparatively poor resolution which one gets with a collection time of one millisecond it becomes necessary to work with the considerable time lag of several milliseconds between the moment at which the source ceases and that at which the detector starts to operate. It was found that the primary fast neutrons together with the capture γ-rays give during the "on" period of the source an accumulated pulse of the order of 100 MV; although this pulse was largely neutralized by a feed-back circuit, it still was necessary to wait about 6 milliseconds after "turning off" the source before it ceased to interfere with the recording of the comparatively few and small recoils from fission neutrons. During this time a neutron of 1/30 V energy would travel 15 meters; to work at such distances from the target would cause an excessive loss of intensity and we had to use a different arrangement to maintain good intensity in spite of the necessary time lag.

This arrangement consists essentially of a hollow container with walls having an albedo as close to unity as possible into which slow neutrons enter from the cyclotron. Let ν be the average number of times a neutron of velocity v can be reflected from the wall without being captured and let the linear dimensions of the container be L; then it is obvious that after a time $\theta \approx \frac{L\nu}{v}$ from their entering, the density of slow neutrons inside the container will still be of the original order of magnitude. ν is connected with the mean number N of free paths which a neutron traverses in the reflecting substance before capture by

$$\nu \approx \frac{\sqrt{N}}{2} . \tag{2}$$

For paraffin it is $N \cong 150$, $\nu \cong 6$ so that with $L = 100$ cm, $v = 2.5 \times 10^5$ cm/sec one should expect a delay time $\theta \cong 2 \times 10^{-3}$ sec; if instead graphite with $N \cong 1000$ is used, the delay time can for the same dimensions be increased by a factor 2.5.

A more quantitative theory of the container can be given by solving the diffusion equation

$$\dot{\rho} = \frac{lv}{3}\nabla^2\rho - \frac{v}{Nl}\rho \tag{3}$$

for the density ρ of neutrons with velocity v and mean free path l. Assuming all radii of curvature of the wall to be large compared to ℓ and its thickness large compared to $\sqrt{N}\ell$, one can easily see that while no neutrons enter the container the density inside will be uniform, and as a function of time will decrease according to

$$\rho = \rho_0 e^{-\frac{vt}{\nu L}} \tag{4}$$

where

$$L = \frac{2\sqrt{3}V}{A} \tag{5}$$

with V and A standing for the inside volume and wall area of the container respectively.

For a container with walls of uniform material the quantity ν in (4) is given by (2). In our case the wall material was not uniform but consisted of oil in tin cans (this having the same albedo as paraffin) lined on the inside with 12 cm of graphite. This lining did not cause an excessive use of graphite and yet helped considerably to increase the albedo. One obtains in this case of a lined wall, instead of (2),

$$(6)\qquad \nu = (N_2^{\frac{1}{2}}/2)\,\frac{1+(N_1/N_2)^{\frac{1}{2}}\tanh\left((3/N_1)^{\frac{1}{2}}\Delta/\ell\right)}{1+(N_2/N_1)^{\frac{1}{2}}\tanh\left((3/N_1)^{\frac{1}{2}}\Delta/\ell\right)}$$

where in our case N_1 and N_2 stand for the number of free paths before capture in graphite and oil respectively, ℓ is the mean free path in graphite and Δ the thickness of lining. Taking $\ell = 2$ cm, one obtains $\Delta = 12$ cm, $\nu = 9.5$, i.e. increase of the delay time $\frac{L\nu}{v}$ over that without lining by about a factor $1\frac{1}{2}$.

For the discussion of the most suitable modulation scheme and dimensions of the container it is best to note the ratio of slow neutrons striking a body of surface S per unit time (averaged over a full modulation period) to those entering the container per unit time while the source is in operation. It is given by

$$(7)\qquad r = \frac{\sqrt{3}}{2}\,\frac{S}{A}\,\frac{L\nu^2}{vt}\,e^{-vt_2/\nu L}\left(1-e^{-vt_1/\nu L}\right)\left(1-e^{-vt_3/\nu L}\right)$$

where t is the period of the modulation cycle, t_1 and t_3 are the times during which source and detector respectively are in operation and t_2 is the time lag between them. In this formula t_2 can be considered as given by the method of recording, ν by the material of the walls. The other quantities remain to be chosen in the most convenient manner. Our container was cubical with an inside edge of 120 cm; this gives $A = 8.64\text{x}10^4\text{cm}^2$, $L = 69$ cm and, with $v = 2.5\text{x}10^5$cm/sec and $\nu = 9.5$, the characteristic time of the container becomes

$$(8)\qquad \Theta = \frac{L\nu}{v} = 2.6\text{x}10^{-3}\ \text{sec.}$$

In our final measurements the modulation was made with 60 cycle A.C., giving for its period $t = 1/60$ sec $= 16.67\text{x}10^{-3}$ sec; we had further $t_2 = 5.85\text{x}10^{-3}$ sec. $t_1 = 1.73\text{x}10^{-3}$ sec, and $t_3 = 8.02\text{x}10^{-3}$ sec.

The decay of the neutron density in the container was checked experimentally by varying the time lag t_2 between the end of the source and the start of the detector operation. As indicators for slow neutrons we used the α-particles from the B_{10} reaction in a BF_3 chamber, the fission fragments of U_{25} from a thin enriched target in a fission chamber and finally the fission neutrons, observed by the recoils in the hydrogen-containing ionization chamber. The exponential decay was verified in all three cases with the best experimental determination of θ giving

$$(9) \qquad \theta_{obs} = 1.8\text{x}10^{-3} \text{ sec.}$$

The reason for this value being about 30 per cent less than the calculated value (8) has to be sought mainly in the corners of the container which have been neglected in the calculation and act as neutron traps; particularly the paraffin-walled entrance channel represents a rather deep cavity and will tend to decrease the effective albedo of the container wall.

The experimental arrangement is shown in Fig. 1. The deuteron-Be neutrons, emerging from the target T of the cyclotron are slowed down in the paraffin howitzer H; from here they pass through an entrance channel E, like wise of paraffin, which joins to an opening O in the container. This opening is 120 cm high. The channel E isframed in wood and can be pulled up to allow access into the container. The ionization chamber I with the first stage amplifier F is hung on springs at the center of the container with the tuballoy disk, 12 cm in diameter and 1.3 cm thick, suspended in front of the chamber. This disk can be pulled from outside to the top of the container in order to take background counts. The distance from the center of the disk to that of the collecting volume in the ionization chamber is 16.3 cm. With the center of the chamber having 60 cm as the nearest distance to the wall of the container, a conservative estimate of the relative probability for a fission neutron to pass through the chamber after being reflected by the wall, compared to that of direct passage, would be given by $\left(\frac{16.3}{60}\right)^2 = 7$ per cent. It was therefore safe to assume that with this geometry the distortion of the fission spectrum, due to inelastic scattering at the walls would not be appreciable; as will be seen later this fact was also experimentally verified.

2. APPARATUS

Ionization chamber.

The considerations of paragraph 1 show that, in the construction of the linear amplifier and ionization chamber used for the recording of the recoils produced by the tuballoy neutrons in the gas of the chamber, it is of greatest importance to have the highest possible resolution; this requires a minimum of characteristic time and therefore a minimum collection time. On the other hand, the gas pressure in the chamber should be high in order to insure high stopping power which minimizes the wall effects of the chamber. Obviously the three requirements contradict each other and one has to choose a reasonable compromise, unless one uses extremely high collecting voltages in the chamber. Previous experiments(7) of this nature have shown that voltages up to about 10 KV can be sufficiently well filtered at reasonable expense and that the insulation problem is not insurmountable. For the dimensions of the chamber we chose very closely the ones of Barschall and Kanner(8) since it was felt

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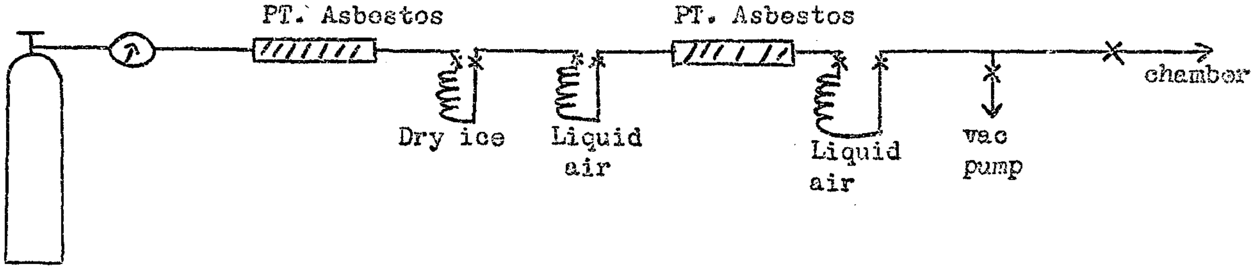
7) E. Baldinger, P. Huber and H. Staub, Helv. Phys. Acta 9, 245, 1938.
also: P. Huber, Helv. Phys. Acta 14, 163, 1941.

8) H. H. Barschall and M. H. Kanner, Phys. Rev. 58, 590, 1940

that here experience on stability and microphonics would be the predominant factors. Thus the counting volume was fixed to be a cylinder of 8.5 cm diameter and 8.5 cm height. This volume was divided into 6 sections by means of transparent electrodes (Fig. 2). The electrodes connected to the high voltage are simple brass rings supporting a woven mesh of vacuum-heat-annealed copper wire of 8 mils diameter, the mesh-width being 1/8". The transparency of every grid is thus about 87 per cent. Top and bottom high-voltage electrodes were solid plates. The collecting electrodes are of the guard ring type. A thin brass ring 1/8" wide and 1/16" thick supports a wire mesh similar to the one of the voltage electrodes. This system in turn is supported by a wider brass ring, the guard ring, through two small amber beads so that there is a distance of 1/16" between collecting electrode and guard ring. At a third point of the collecting electrode a brass strip protrudes through a slot of the guard ring into a grounded shielded tubing containing the common lead for all the collecting electrodes. In the course of the experiments two steel containers for this ionization chamber structure were used. The first, which is able to stand pressures up to about 60 atmospheres, has a base plate 1 1/8" thick and a half-spherical dome 1/4" thick and a cylindrical part 1/4" thick, 7" in diameter, and 3" high. Its total weight is 61 lbs. The second container is for about 20 atm. and has a base plate of 3/8" and a 1/3 spherical dome 1/8" thick. Its cylinder of 1/8" wall thickness is otherwise similar to the first one (Fig. 3). The weight of this container is 19 lbs. Since our first experiments obtained with the 61 lb. container showed that the average energy of the tuballoy neutrons is considerably lower than expected it was decided to use less stopping power and consequently reduced pressure, which enabled us to use the much lighter container, thus reducing the danger of inelastic scattering in its walls. (See paragraph 4).

The gas filling of the chamber at the high pressure required some particular precautions. Direct fillings of the hydrogen from the tank showed that the gas was too impure, containing probably high amounts of oxygen and maybe condensible materials in the form of small drops, and also dust particles. We therefore cleaned the gases very thoroughly by burning the oxygen in hydrogen over hot Pt asbestos, which also served as a mechanical filter, and by subsequent cooling with liquid air. This purification was done very slowly at about a rate of one litre atmospheric pressure per minute. The same procedure was followed for the deuterium filling. The argon used, among others, in our last experiment was very pure and therefore passed only through a dry-ice-cooled copper spiral. A schematic diagram of the purification train is given below.



This purification was actually so effective that we succeeded in collecting free electrons. A careful consideration of the collection process in an ionization chamber shows that such a feature is quite undesirable, resulting in extreme differences in pulse size according to the location of the charge as described in paragraph 1. A minute amount of oxygen was therefore admitted to the chamber allowing the attachment of free electrons and still giving high mobilities. This oxygen contamination was of the order of 1 part in 10^5.

Recording circuits.

It is obvious that the construction of the chamber results in an unusually high capacity which together with the grid capacity of the first tube amounts to 62$\mu\mu$F.; this of course tends to produce a very unfavorable ratio of electric noise to signal (this ratio being proportional to $\sqrt{C}$). This can only be counteracted by a careful selection of tube type and operation condition of the first stage, and the grid-leak resistor. The use of such a resistor was felt to be necessary in order to prevent fluctuations of considerable duration of the working point of the tube due to inevitable fluctuations of the ionization chamber high voltage supply. The resistance was chosen as large as possible, viz., $10^9\Omega$ resulting in a time constant of the first stage of 60 milliseconds. In the first part of the experiment we had to use a type 38 tube for the first stage since any special type was not available. In this case the noise level of about 18μ volts was largely due to the tube. We were later able to secure a type 1603 (special tube for low noise, microphonics, hum), reducing the noise level to about 8μ volts which was probably about equally due to tube and resistance noise. The filament supply was 6.3 volts D.C.

From the first stage which is directly attached to the chamber the pulses are fed (see Fig. 4A) to a conventional 3 stage voltage amplifier whose first tube is a low microphonic type 1620, the other two 6J7. Great care was taken to operate the tubes strictly within the linear part of the characteristics. After the first 6J7 the amplification channel splits into two branches, the first leading to the last 6J7, the other to a separate voltage amplifier using a type 6SJ7. The output of the latter is fed through a discriminating circuit and over a diode rectifier back to the cathode bias of the first tube thus representing a feedback with a feedback factor 30. This feedback is only in operation during the "off" period of the selector, shown in Fig. 4B. It was necessary to incorporate this feed back circuit since the charge collected in the ionization chamber from the fast-neutron burst is so big that even after many characteristic amplifier-times there would still be an appreciable disturbance present giving rise to an unsteady intensity-dependent level over which the useful fission pulses are super-imposed. However, with the feedback in operation the voltage between grid and cathode of the first tube is kept at a small fraction of its original height. Obviously the feedback can only work if the feedback voltage pulse is a true image of the original pulse. Since the amplifier does not transmit any D. C., whereas the original pulse certainly contains a D. C. component, it is obvious that a non-linear distortion has to be introduced. This is achieved by applying the feedback pulse to a condenser, C_{21}, whence the charge leaks off through a variable resistance. This latter has to be adjusted until the time constant is the same as that of the original pulse. In order to avoid oscillations it was necessary to make all the time constants quite large.

The modulation of the feedback is accomplished in the following way. A type 6SJ7 tube, V_4, is connected across the output of the last 6SJ7 voltage-amplifier tube, V_3. At zero grid voltage this tube acts as an effective short circuit of approximately 2000 Ω impedance across the output, reducing the output voltage to a fraction of a volt compared to the original voltage of about 30 volts which is present if the shorting tube is at cut-off (approximately -10 V grid voltage).

The advantage of this type of discrimination over the conventional screen or suppressor grid modulation is the absence of square-wave modulation of the plate current of the modulated tube. In the present arrangement we get only a very weak modulation voltage (approximately 0.1 volt compared to 30 volt pulse size) developed across the output of the

6SJ7 voltage amplifier, whereas with the usual modulation it would be of the order of the pulse size itself.

The output of the voltage amplifier, which is set to give pulses of approximately 10 to 50 volts, is fed to a discriminator modulated in the same way but opposite in phase to the one just described. This discriminator suppresses the remainder of the fast-neutron pulse. At the same time the pulses are shortened to a time constant of $2 \cdot 10^{-3}$ sec. After passing through an additional amplifier stage (necessary since the discrimination cannot be performed at the grids of the recording thyratrons) the channel again branches and leads to two separate inverter tubes which restore the pulses to their original height and positive sign. One channel leads to a single thyratron and recording device, recording all the pulses above a certain height, depending on the bias setting of the thyratron. This integral counter served as an additional monitor since its bias is left constant during a measurement.

The other channel leads to a so-called selector, similar in construction to the one described by Roberts[9]. The selector consists of a pair of slightly differently biased thyratrons; their bias can be varied without changing this difference. Pulses actuating none or both thyratrons are not recorded; only those are recorded which actuate only the thyratron with the lower bias. This is accomplished by feeding the output pulses of the self-quenching thyratrons to the primaries of two transformers whose secondaries are connected in series but opposite in phase. If both thyratrons are actuated the difference of the two pulses appears across the two secondaries. This difference can be quite high but is of very short duration since, due to the finite ascending time of

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9) Arthur Roberts, Rev. Sci. Instruments <u>11</u>, 44, 1940

the pulses on the grids, the thyratrons fired at different times (a fraction of a collection time, i.e., approximately 10^{-4} sec). However, by making the time constants of the transformer circuits quite long it is possible to reduce the difference pulse to a sufficiently small value without affecting the height of the single pulse.

If the output of the two transformers were recorded a serious error in the size distribution of the pulses would be encountered. If a recoil proton should be produced shortly before the measuring interval of the amplifier starts, it would happen that only a fraction of the charge of that recoil would be measured since collection would have started before the measuring period. Apparently this would lead to too many short pulses. The same effect of course takes place at the end of the measuring interval. The number N of such distorted pulses can easily be estimated.

$$N \sim \int_{t_0-T}^{t_0} I(t)dt + \int_{t_0+t_3-T}^{t_0+t_3} I(t)dt \qquad (10)$$

The total number of recorded pulses however is

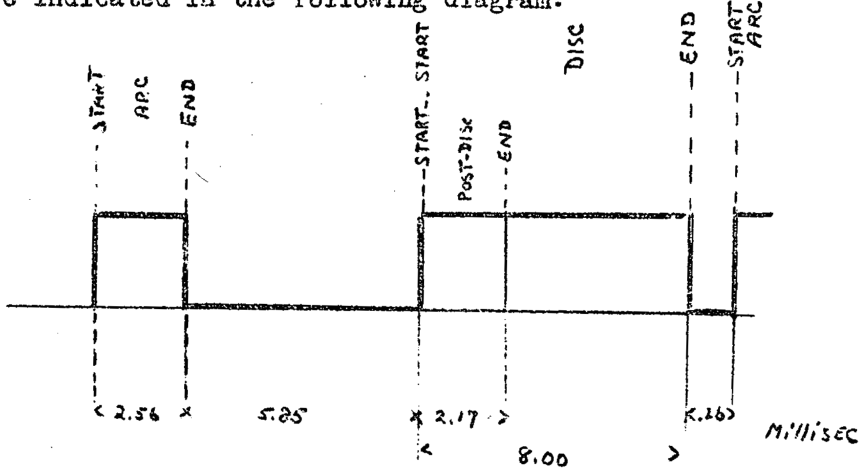
$$N_0 \sim \int_{t_0-T}^{t_0+t_3} I(t)dt \qquad (11)$$

where I is the slow neutron intensity at the time t; T the collection time, t_0 the time of start of the recording interval and t_3 its duration. According to paragraph 1, $I(t) \sim e^{-t/\theta}$ where θ is the characteristic time of the neutron container. Since T is about 1/6 and θ about 1/4 of t_3 it is apparent that the second term in (10) is negligible ($<1\%$) whereas the first one is about 50% of the total number of counts.

This effect however can be avoided (as far as the start of the measuring interval is concerned) by preventing the recorder from recording pulses which fire the thyratrons within a collection time after the start of the recording interval. This "post discrimination" is done in the following way. The comparatively long pulses of the differential selector are first sharpened to a pure exponential pulse of about $2 \cdot 10^{-5}$ sec duration. Then they are fed to the grid of a thyratron whose bias is modulated by a negative square wave starting right at the beginning of the measuring interval and lasting for a time of the order of one collection time. The negative modulation is so high as to prevent the pulses of the sharpener, which are all of equal height regardless of the height of the pulse originally actuating the selector to operate the thyratron. If the sharpener were actuated during this time of post discrimination the sharpener pulse would already have decayed appreciably at the time at which the negative modulation of the thyratron has stopped. It will therefore not actuate this thyratron, which, without the modulation, is biased so that sharpener pulses just actuate it at the moment when they reach their full height. On the other hand sharpener pulses originating after the start of the measuring interval reach their maximum height only after the modulation has ceased and will therefore be recorded. The accurate duration of the post discrimination interval can be determined experimentally. The procedure will be described in paragraph 3. Finally the output of the post discriminator thyratron is fed in the same way as the output of the integral thyratron to a 6L6 power tube and recorded by a relay-operated Cenco counter. All the power supplies for the amplifier and the high voltage of the ionization chamber were fed from a 500-watt, constant-voltage transformer.

The square-wave generators for the modulation of the feedback, discriminator and post discriminator are represented in Fig. 5. Feedback and discriminator are modulated by the same generator, but are made opposite in phase by taking the modulating voltage off at B and C, respectively, Fig. 5A. The modulation frequency is 60 cycles; hence a cycle is equal to about 9 neutron lifetimes in the container (see section 1). The square wave is produced by the multivibrator circuit shown in Fig. 5A. The start of the square wave is controlled by means of a phase-shifting network, whereas its end is determined by the time constant of the coupling circuit between the plate of one and the grid of the other thyratron. This arrangement has proved to give much less distortion of the square wave than the usual circuit using two independent phase-shifting networks.

The timing of the square wave and the related events of the cycle are indicated in the following diagram:



The capital letters refer to Fig. 5A.

The square wave of the post discriminator has to start at the latest at the termination of the discriminator interval and has then to last for a time to be determined experimentally. Again two thyratrons are arranged in a multivibrator circuit. The start is accomplished by distorting the discriminator end by means of capacitive coupling into a sharp pulse fed to the grid of the thyratron which is usually "off". The duration of the pulse again is controlled by the RC value of the circuit coupling the two thyratrons. Since the timing of both generators obviously depends essentially on grid and plate voltage, both supplies are stabilized by voltage-regulator tubes.

Modulation of cyclotron.

In the construction of the modulation of the cyclotron arc considerable care was taken again to make the pulses as square as possible. For this reason a low-power square-wave generator, identical in construction with the one used for the discrimination, controls the arc current through a set of 6L6 beam power pentodes. This avoids the use of high power thyratrons and results in better square waves. With the moderate load of the thyratrons their plate current varies only very slightly with the grid voltage, and, furthermore, the phase setting is practically independent of load fluctuations, which in the case of an arc source are inevitable.

Monitor.

The integral counter described above serves as a monitor, allowing one to refer a certain number of pulses observed at a given setting of the differential selector to a standard number of fissions. Nevertheless it was felt that an additional independent monitor system would appreciably increase the reliability of the apparatus and also serve to locate possible spurious response. As an additional monitor we used an integrating BF_3 ionization chamber with switching mechanism described previously10).

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10) E.M. Fryer and H. Staub, Rev. Sci. Instruments 13, 187, 1942

In this arrangement, a condenser charged to a standard voltage is allowed to discharge through the BF_3 chamber. Its time constant was set so that with the usual modulated target current of 2 microamperes the discharge time was about two minutes. The monitor chamber was located in a paraffin block close to the target at the entrance of the neutron container. After every discharge the monitor interrupted the counter system of both integral and differential counter for a few seconds in order to give time for reading the number of counts. It shall be mentioned here that the BF_3 chamber would not act as an entirely reliable monitor since it records only the total number of neutrons produced at the target. However their time of emission during the "on period" of the arc also affects the number of recorded fission pulses and it was actually observed that the shape of the target current pulse fluctuated irregularly. Obviously the performance of the integral counter as a monitor is independent of such fluctuations.

Timing of modulation.

Although the setting of the instances of the various modulator events as such is not very critical it is obviously of greatest importance to keep a certain setting constant over a whole measurement unless one refers only to the integral counter as monitor. In order to check continuously these settings a null method was developed since it was found that the simple measurements of the distances of the various square waves on a cathode-ray oscillograph screen was too inaccurate partly due to the strong non-linearity of the oscillograph sweep. For every event (start and end of target current, start and end of discrimination, end of post discrimination) to be measured, a separate phase-shifting network consisting of precision condensers and resistance boxes was inserted into a sinusoidal 60-cycle horizontal sweep of the cathode-ray oscillograph. The phase of this sweep was calculated from the values of R and C required to make the event to be measured occur at the instantaneous zero sweep voltage, i.e., on the screen at the place of the undeflected beam. Such a setting is independent of the oscillograph characteristics (amplification and non-linearity) except for the position of the undeflected beam which, before the measurements were taken, was always set to a cross hair by means of a permanent magnet. Phase checking was very frequently done during a measurement. In order to be independent of possible spurious time lags between arc and target current, the phase of the latter was checked by feeding the voltage drop produced by the target current across a resistance of several tenths of a megohm.

The various suitable time values of the events were determined experimentally. Particularly the most important time difference between end of target current and start of measuring interval was set so as to give only very small γ-ray background without having to sacrifice too much intensity (see section 1). The length of the post discriminator interval however had to be determined experimentally rather accurately, since the exact value of the collection time was not known, and also because an additional lag was introduced by the long time constant of the differential selector output. This determination was performed in the following way. At a certain setting of the differential selector bias the counting rate was taken while the setting of start and end of arc, end of post discriminater and end of discriminator interval were kept constant and the start of the discriminator interval was moved towards the arc. If the collection time were zero the counting rate should stay constant, since all the extra pulses starting during the post discrimination are not recorded. With a finite collection time however the counting rate should increase or decrease monotonically depending on the nature of the pulse-distribution curve, as the post discriminator start moves towards the arc.

This is simply due to the fact that during the post discriminator interval the length of the pulses is cut, thereby adding to and subtracting from the true number of any particular length. Since in our case the number-of-recoils-versus-length curve drops very strongly, more pulses are thrown out of an interval than are thrown in. We therefore expect the counting rate to increase as one lengthens the post discriminator interval until the interval becomes longer than a collection time. From then on the rate should be constant since all the extra pulses are rejected by the post discrimination. This behavior has indeed been observed. For the high pressure chamber the counting rate increased from post-discrimination time zero to 2 milliseconds by a factor 3 and then stayed practically constant. Measurements were taken up to 3 milliseconds. The length of the post discriminator interval was therefore set to 2.17 milliseconds.

Testing of amplifier performance.

In order to measure the amplification and the linearity of the amplifier an artificial pulse generator was built generating reproducible pulses of well determined size. Previous experiments involving similar measurements7) had shown that mechanical switches for this purpose are not reliable since they frequently lead to oscillating breaks or closings of the contact. Therefore a thyratron was used for closing the circuit which, once fired, stays conducting. The breaking of the current was performed by a relay but no use was made of this pulse. Fig. 6 shows the arrangement of the pulse generator. Suppose the thyratron is conducting whereas the capacity feeding the 75-volt neon tube is below its flash voltage. After sufficient time the voltage rises to the flash point, the neon tube flashes, thereby operating the relay and interrupting the plate current of the thyratron. At the same time the grid of the thyratron becomes charged negatively due to the capacitive coupling between plate and grid circuit.

Then this charge leaks off and when the grid has attained a sufficiently low voltage the thyratron flashes again since in the meantime the relay has been closed. This process repeats itself at a rate of 40 or 75 pulses per minute according to the two possible settings of the time constant. Across the cathode resistor a voltage is therefore developed consisting of essentially square pulses, whose ascent is well determined whereas the descent may be oscillatory. Their height is well determined by the current and the known resistance. For the measurement of the amplification the high-voltage electrode of the ionization chamber is connected over a suitable voltage divider to the cathode resistor. Due to the capacity of the chamber the grid of the first amplifier tube receives alternately positive and negative pulses, the negative ones being of no interest. It is to be noticed that the decay constant of the pulses in the amplifier is necessarily the same as that of the recoil pulses. The only difference consists in the rise of the pulse. For relative check measurements on the differential selector however the pulses can be made to rise slowly by inserting a resistance-capacity network into the output of the generator as shown in Fig. 6.

It is essential for the measurements that the level on which the recoil pulses appear at the selector is free of any 60 cycle or its higher harmonic ripples since the recoil pulses are synchronized with this frequency. Furthermore, the pulses are superposed on a γ-ray background which is also synchronized. In order to make sure that no appreciable synchronized level change of the amplifier was present, pulses of a certain size were fed into the fourth stage of the amplifier and their length measured by the selector as a function of the phase setting. The synchronization was obtained by coupling capacitively the breakoff of the modulating voltage of the post discriminator to a scale of 16 circuit which reduced the number of pulses to 3.75 per sec. These pulses were superimposed upon the negative voltage leaking off the grid of the pulse generator thyratron thereby synchronizing the pulses of the latter. Their phase could be changed by changing the phase of the post discriminator pulse generator. No phase systematic deviation of the level comparable to the statistical noise level could be detected over the interval of phase investigated.

The stabilized D. C. output voltage of the pulse generator can also be fed to a potentiometer circuit, which when connected to a large precision voltmeter, enabled us to measure and check the bias setting and flash voltages of the selector and integral thyratrons. At a plate voltage of 105 volts the grid flash voltage was about 12 volts and varied over half a year not more than ± .2 volts. The same variation was observed for the bias settings. This was felt to be constant enough since the smallest pulses measured were about 13 volts at the grids of the selector thyratrons.

3. MEASUREMENTS AND CALIBRATION

Experimental procedure.

Three different measurements of the fission spectrum of 25 were performed. In the first one the heavy container, filled with purified hydrogen of 39 Atm., was used. In this case the stopping power was 8.6; thus a proton recoiling forward from a 2.5 Mev neutron had a range of 1.2 cm. The second set of data was obtained with the heavy container filled with 26 Atm. of hydrogen, reducing the stopping power to 5.7. The third set was taken with the light container filled with a mixture of 13.8 Atm. hydrogen and 2.7 Atm. of argon. This mixture has the same stopping power as pure hydrogen of 26 Atm.

The three measurements were taken in the following way. After the amplifier and monitor had been turned on for at least one hour, the phases of the various events of the modulation and discrimination were set as described in Section 2. The bias of the integral thyratron was set to a standard value at about 1.2 MV neutron energy. At every bias setting of the differential selector recordings were made over five discharge intervals of the BF_3 monitor with the tuballoy close to the chamber and immediately following five runs with the tuballoy removed to the ceiling of the neutron container. The change in the bias setting of the differential selector was deliberately made in a quite unsystematic way usually by letting a high bias setting follow a low one. The setting of the bias on the scale of its dial could be reproduced to about 0.2 volt compared to 13 volt of the smallest pulses measured. Every bias setting was then repeated in the above way in the course of the measurement about four times. The number of recoils observed at one particular bias setting was then computed as the ratio of the difference of the two values of the differential selector, with alloy in and out, to the difference of the corresponding values of the integral counter. Most of the runs except those at the very lowest energies were taken at an average cyclotron target current of 2.0 microamps. At this intensity the BF_3 monitor interval lasts about 2 minutes. During this time the integral counter records about 100 counts of which about 20 are background as measured with the alloy removed. For the differential counter we observed, at around 1 Mev, about 50 counts of which about 10 were background. This background of about 20% was rather constant for energies above 0.8 Mev whereas it varied a great deal below 0.8 Mev being sometimes as low as 20% and sometimes as high as 60% of that total number observed with the differential selector.

Considerable care was taken to ascertain that the observed number of pulses, particularly at the low energies, was unaffected by coincidences arising from the high intensity of the primary neutrons. These coincidences could result from superposition of electrons from the strong γ-ray background or of the fission neutrons themselves. For energies below 1 MV this necessitated a reduction of the target current to a value as low as 0.5 microamps in certain cases.

The consistency of the data taken were in general not as good as might be expected from purely statistical reasons, this being true for the integral counter as well as for the differential selector which sometimes showed fluctuations about twice as large as the values calculated from statistics. We have taken this fact into account by calculating the actual mean-square deviation as well as the statistical. The errors given in the results are either the observed or calculated ones, whichever turned out to be bigger. During the course of the measurements several checks of the amplification were made by applying pulses of a given size produced by the pulse generator described in Section 2 to the ionization chamber and measuring the corresponding integral and selector response. In our first run (heavy steel container 39 atm of H_2) we observed erratic variations of the amplification of about 15% making the final calibration of our measurements rather uncertain. For the subsequent runs (low pressure and hydrogen argon mixture) the variations stayed within 2% after the amplifier had been thoroughly checked over and several deficiencies had been corrected.

Calibration.

The conversion of bias setting into recoil energy for each of the three measurements was done in the following way. Before the actual measurements were taken a careful calibration showed that for the amplifier an almost perfectly linear relation exists between input voltage at the grid of the first tube and bias setting of the differential selector. (Fig. 7) Only at the very largest input voltages we observed a very slight deviation of a few per cent from linearity. This amount is so small that a correction for energy and interval width could be neglected, particularly since the number of counts observed at these energies was extremely small.

Before and after every set of measurements of the fission spectrum the amplifier and ionization chamber were moved to a source of monochromatic neutrons from the D-D reaction in order to establish the relation between bias setting and recoil energy. The D-D reaction tube used for this purpose was of a similar design to the one described by Baldinger, Huber and Staub⁷⁾. It was operated at 30 to 40 KV acceleration voltage, and about 15 KV source voltage. The target of heavy ice was everywhere at least 3 ft away from any large amount of materials, and the chamber was placed at the same distance from the target as the alloy disc in the fission measurements. Due to the fact that the tube was operated at such low voltage the energy spread caused by the finite solid angle subtended by the chamber is negligibly small. With this arrangement the number of recoils at the various settings of the differential selector was recorded. Since the BF_3 monitor is too insensitive for this type of measurement the integral counter served as the only monitor. The results given are the ratio of the difference of the readings of the differential selector with the ion source on and off to the corresponding difference of the integral counter. During these measurements again several amplification checks were usually made in the way described above. No changes of the amplification were observed for the low-pressure hydrogen and hydrogen-argon mixture runs, whereas for the high pressure run again changes of about 15% were noticed. In order to establish finally the energy-bias relation the point of maximum in the neutron distribution of the measured D-D spectrum obtained by the analysis described in Section 4 was taken to be equal to 2150 MV neutron energy.

In addition to the calibration measurements the following series of tests were also performed with the D-D source using the heavy container and 39 Atm. of H_2. 1) Test for inelastic scattering by the iron of the container of the ionization chamber by slipping an iron ring of approximately the same weight as the heavy container over the latter and measuring the D-D spectrum in the way described below in section 4, 1d. 2) Test for the inelastic scattering due to the walls of graphite and oil of the neutron container (Section 4, 1c). This test could only be done approximately with the D-D source by surrounding the latter from four sides with an oil and graphite wall of the same thickness as used for the neutron container at a distance equal to that existing between the tuballoy sample and the walls of the neutron container. 3) Test for inelastic scattering in the tuballoy sample itself by interposing the sample between D-D target and ionization chamber. In this last case no noticeable distortion was observed, indicating that the influence of inelastic scattering of neutrons of 2.5 MV in the alloy is negligible. The main objection against these tests is due to the fact that they give only information on the inelastic scattering for neutrons of 2.5 MV energy. It is of course fully realized that the inelastic scattering may be quite different for other energies. However it was felt that, due to the smallness of the effect, our results on the fission spectrum should not be greatly affected by inelastic scattering even at smaller and higher energies. The results of these various tests are given and discussed in Section 4.

Experiment with deuterium.

It was planned also to make a measurement of the fission spectrum by using deuterium recoils instead of protons. For this purpose the light container was filled with 16.3 atmospheres of deuterium purified in the same way as the hydrogen. At this pressure the range of a forward deuterium recoil due to a 2.5 MV neutron is exactly the same as a forward proton recoil due to a neutron of the same energy in hydrogen of 26 atm. pressure, thus giving the same wall effect as in the second measurement. By irradiating the chamber with the neutrons from the D-D source, with the same arrangement as in the case of hydrogen, we found that the recoil distribution shows a very marked deviation from that which one would expect for isotropic scattering. At high energies, the curve shows (see Section 4) a distinct maximum. In order to test the proper functioning of the apparatus and whether the anisotropy of scattering depends on the neutron energy, the latter was changed by turning the chamber from the position at right angles to a position along the direction of the incident deuterons. Although the bombarding energy is quite small this arrangement nevertheless changes the neutron energy from about 2.5 to 2.7 Mev energy. The distribution however indicates still a considerable anisotropy, possibly somewhat different from that at 2.5 Mev. A discussion of these results is also given in Section 4. The anisotropy found in these measurements led us to abandon the measurements of the fission spectrum with deuteron recoils.

Total yield.

Since our measurements give results only for energies of the neutrons above 0.8 Mev it was felt desirable to measure also the total number of neutrons emitted by the tuballoy under the given condition. By this measurement we were enabled to compute approximately the number of neutrons with energies below 0.8 Mev. This was done by measuring the total number of fissions produced in a well known sample of enriched 25 inside the neutron container during a discharge period of the BF_3 monitor. As shown in Section 4 one can then compute the total number of neutrons to be expected per monitor interval. Immediately following the fission measurement we determined the number of neutrons above a certain energy (approximately 1 Mev) by measuring the total number of recoils having energies in excess of this amount. This was done simply by removing the one thyratron of the selector system with the higher bias setting. Fission and recoil measurements were done with the fission sample and the tuballoy in the same position inside the neutron container. It is pointed out in Section 4, paragraph 5, that the difference of the collection times in the hydrogen and the fission chamber causes an error in determining the total number of neutrons. This error could have been corrected by finding a new setting of the post discrimination appropriate to the collection time in the fission chamber by measuring the fission rate as a function of the length of the post discriminator interval as described in Section 2. Unfortunately this measurement is not very accurate and furthermore the construction of the modulator for the post discrimination does not allow settings between zero and one millisecond. The curve obtained shows however that, due to the shorter collection time in the fission chamber, the proper length of the post discriminator interval should be shorter than for the recoil chamber, viz. less than 1 millisecond.

Next, with a post discrimination interval of 1.2 milliseconds, we measured the number of fissions observed above a certain energy versus this energy. This again was done by removing the thyratron with the higher bias of the selector. Over almost the full range of possible bias settings this curve is practically horizontal. The curve allows easy extrapolation of the integral number of fissions to zero energy. This shows that in this region we measure the total number of fissions, independent of the bias setting.

These two measurements were done at settings of the modulation scheme different from the one used with the neutron chamber. In order to get a counting rate increased by about a factor 6, these two measurements were taken with the end of the arc time much closer to the measuring interval. Finally, the total number of fission was measured with exactly the same phase settings as in the case of the neutron recoils. This means that the post discrimination of 2.2 milliseconds is in both cases sufficient, i.e., no cut pulses will be recorded. The way the results are then corrected is described in Section 4. The bias of the single thyratron of the selector system was set at a quite low value and the number of fissions recorded, giving 1.2 counts during a monitor interval of about 2 minutes duration. It may be mentioned that in the case of the fission measurements the amplification had of course to be reduced very strongly. The background measured with the arc current off was, at the very lowest bias (about 12 Mev pulse size), less than 3%. Above approximately 20 Mev no background counts were recorded during the whole measurement of the bias curve.

4. RESULTS

By the method described in the preceding paragraphs a great number of recoil distributions was recorded, with variation of the gas filling of the ionization chamber, the surrounding materials, etc., and with many test runs to find the most suitable conditions for recording and to ascertain the reliability of the results. To each set of runs of the fission recoils there belongs an auxiliary run of the recoils produced by the neutrons from a low-voltage D-D source in which the chamber, its filling and the recording apparatus were identical to those used at the cyclotron. Knowing the neutrons to be monoenergetic at 2.5 Mev, these D-D runs were important not only to test the apparatus as a whole and the analysis of the data, but also as a calibration for the translation of pulse size into energy of the recoil. We shall afterwards report the essential runs singly, taken both with D-D and fission neutrons, and discuss them separately.

Method of analysis.

First, however, we shall describe the method of analysis upon which our final conclusions are based. Although, as discussed in Sections 1 and 2, proper care was taken to avoid excessive wall effects, corrections had to be made for them; for the highest energies observed in the fission spectrum these corrections amounted to as much as 50%, for the lowest about 15%. The wall corrections were based upon careful calculations of Hammermesh and Weinstock, the former using a numerical, the latter, as an independent test, an entirely different analytical method. The only simplifying assumption in these calculations was that of perfect coaxial collimation of all neutrons, passing the chamber; due to the finite extension and distance of the alloy disk, the neutrons emerging from it actually entered the chamber with an average deviation from coaxiality of 14 degrees. Both the smallness of this angle and an empirical test for collimation made with D-D neutrons make us feel confident that the error introduced by the simplification is negligible. A conservative estimate of the percentage error of the wall corrections is 10% of which several percent is due to the inaccurate knowledge of the ranges. The calculations were carried out for the geometry of our chamber and a gas of a stopping power equal to that of 39 atm. of H_2.

The result of these calculations and the form in which they have been used can be stated as follows: Consider a mono-energetic neutron group of energy E_0 under the conditions of validity of equation (1) Section 1, these neutrons would give a uniform recoil distribution and we shall assume it to be, in arbitrary units,

$$R(E,E_0) = \begin{cases} 1 & \text{for} \quad E < E_0 \\ 0 & \text{for} \quad E > E_0 \end{cases} \tag{12}$$

Instead of this uniform distribution the calculations give a monotonically decreasing one, which in sufficiently close approximation, can be represented over the whole range of energy up to 4 Mev by a linear law; in the same units one obtains instead of (12)

$$R(E,E_0) = \begin{cases} \alpha(E_0)\left[1 + u(E_0)\,(E_0-E)\right] & \text{for } E < E_0 \\ 0 & \text{for } E > E_0 \end{cases} \tag{13}$$

It can be shown that, with a law of the form (13) instead of (12), equation (1) of Section 1 has to be replaced by

$$N(E) = -\frac{E}{SDh\,\sigma(E)\alpha(E)}\left[\frac{dR}{dE} - e^{v(E)}\int_E^\infty \frac{dR(E')}{dE'}\,e^{-v(E')}\,u(E')dE'\right] \tag{14}$$

with

$$v(E) = \int^E u(E')dE' \tag{15}$$

The function $\alpha(E)$ has been tabulated; its values up to 5 Mev are represented in Fig. 8. For the other function $u(E)$ entering in (13) it was found that the analytical representation

$$u(E) = .23\,(E - 0.6) \tag{16}$$

holds well down to $E = 0.6$, where the energy E is measured in Mev. Below that energy the wall corrections are so small that one can take $u = 0$, $\alpha = 1$, i.e., use (1) instead of (12).

Besides the runs taken with a gas filling of 39 atm H_2, to which the above data apply directly, other runs were taken with 26 atm H_2 and with a hydrogen-argon mixture of the same stopping power. Fortunately it is not necessary to recompute rigorously the wall corrections for this new stopping power, since within 3% the ranges for this small stopping power can be stated to be the same as those for the bigger one if here all energies are multiplied by a factor 1.29. Thus without appreciable loss of accuracy the same functions $\alpha(E)$ and $u(E)$ could be used as before by mere substitution of the argument by 1.29 E.

In the analysis of the following runs we have throughout used the procedure of first representing the observed recoil distributions $R(E)$ by a smooth curve and taking for $\frac{dR}{dE}$ its derivative rather than using the "experimental derivative" as the difference of two consecutive measured values. It is clear that because of their statistical fluctuations this latter way of determination would lead to far greater fluctuations in the analyzed spectra and that these fluctuations would not give a fair representation of the actual statistical uncertainty since they would become the greater the closer the measured points are spaced. In the measured recoil distributions themselves no greater fluctuations were found than those to be expected experimentally and it seems therefore that the representation of the data by a smooth curve is justified. An evaluation of the statistical errors must then be based upon the uncertainty with which a smooth curve can be fitted, and this can best be obtained by inspection.

It is also pertinent to the following analysis that we have used for the function $\sigma(E)$ in (14) the simple square-well result for the neutron-proton cross section of Bohm and Richman[4)].

We shall now report and discuss the data obtained:

1) Chamber filled with 39 atm H_2:

a) D-D spectrum: The observed recoil distribution R(E) and the neutron distribution N(E) derived from it on the basis of equation (14) are plotted in Fig. 9. The latter clearly shows the line of the D-D neutrons with an instrumental half-width of 0.6 MV. The strong broadening of the line is not so much caused by noise as by the incomplete and unequal collection due to the high gas pressure. The size of the pulses corresponding to the maximum at 2.5 MV indicates that only 60% of the ions are collected; the loss of 40% is to about equal parts due to recombination and to the considerable ratio of collection time to characteristic time of the amplifier. The tail on the low-energy side is probably partly instrumental and partly caused by inelastic scattering, due to the neutrons in the chamber and the surrounding materials; its area is about 15% of that of the line.

b) Fission spectrum: With the same chamber and gas filling with which the previous D-D run was made, the recoils from fission neutrons were recorded, and R(E) and the deduced fission spectrum N(E) are plotted in Fig. 10. The smooth curve used for the representation of R(E) is proportional to $e^{-E/.725}$ where the energy E is measured in Mev. We have found also in the subsequent runs that such an exponential law gives a good fit to the observed recoil distribution which, in fact, in our energy scale, has been extended up to 4.5 Mev. Unfortunately the energy scale in this run is rather uncertain: while from the position of the maximum of N(E) in the previous D-D run we would estimate the error in our calibration to be about 10%, erratic changes of the amplification larger than that have been observed during this run (see Section 3). Since the curve N(E) can be brought to agreement with the more reliable ones obtained later by a mere scale change in the energy by a factor 1.35, we consider it most likely that here actually an error of about 30% in our calibration has slipped in. One more point of the recoil distribution has been measured, which in Fig. 10 would come at E = .96 MV with a value more than twice that of the first one plotted at 1.23 MV. This point was measured above a considerable and strongly varying background, caused mostly by capture γ-rays; this, together with the fact that it would represent almost a discontinuity in the recoil distribution and with other considerations, to be presented later, makes it most unlikely that a real significance can be ascribed to it.

c) Test for inelastic scattering in graphite and oil: Since the distribution curve N(E) of Fig. 10 even if we omit the probable reduction of the energy scale indicates considerably lower energies of the fission neutrons than those given by other observers, it was felt important to demonstrate that this discrepancy was not caused by excessive inelastic scattering. We want to mention that, in order to explain it by this cause, one would have to assume the number of inelastically scattered neutrons to constitute more than half of all neutrons observed, which, with our arrangement, is from the start most unlikely. To obtain an idea for the inelastic scattering from the walls of the container, discussed in Section 1, graphite and oil was arranged around the D-D source (see Section 3). The result is plotted in Fig. 11, and on it the curves of Fig. 9 are indicated by dashed lines. As was to be expected only about 5% of the content of the line is added to the low energy tail. While it is true that this test holds only for neutrons of 2.5 MV, it does not seem very probably that the inelastic scattering should be much bigger for other energies in the fission spectrum. It seems therefore safe to assume that any distortions of the spectrum from the walls of the container are entirely negligible.

d) Test for inelastic scattering from iron: Since the chamber with which these high-pressure runs were taken contains about 61 lbs of Fe, this big mass close to the counting volume also had to be considered as a possible source of inelastic scattering. A ring of iron with the same weight as the chamber was slipped over it, being on the average even closer to the counting volume than was the main mass of the chamber. The result with the D-D neutrons is given in Fig. 12. There is a noticeable increase of the low-energy tail below 1.5 Mev, which brings the area of the tail from 15% to about 30% of that of the line. Although even such an amount of inelastic scattering would not be excessive, this measurement indicated that the iron of the chamber had to be considered as one of the main disturbing factors of our experiment. Not until we verified later that another chamber with only 13 lbs of Fe gave the same result as our old chamber, did we feel confident that also this source of inelastic scattering was negligible.

2) Chamber filled with 26 atm H_2:

After the first preliminary run of the fission spectrum reported in paragraph 1b it was clear that its energies were low, and therefore that the ranges of the recoils were small enough to allow a reduction of the stopping power and a consequent gain in the collection of the ions by reduced pressure. This highly desirable feature made it seem worthwhile to repeat the runs taken with 39 atm, using the same chamber but a gas pressure reduced to 2/3 of its original value.

a) D-D spectrum: The results are plotted in Fig. 13. Here the size of the pulses corresponding to 2.5 Mev indicates a collection of 72% of the ions, compared to the 60% obtained with the higher pressure. The better collection manifests itself also in the greater sharpness of the line; its half-width is here only 0.4 MV compared to the 0.6 MV previously obtained. The low energy tail however remains the same as before, its cause being evidently not connected with the collection of the ions.

b) Fission spectrum: (See Fig. 14) The recoil distribution R(E) was represented here by the curve (const.)$\cdot e^{-E/.55}$ rather than $e^{-E/.725}$ as represented in Fig. 10. The difference in the fission spectrum N(E) can be described by a contraction of the energy scale by a factor 1.35. This measurement and those of the D-D spectrum taken before and after its performance were made within less than a week, and frequent tests showed no changes in the amplification by more than 2% over this period. Since also the D-D line reported in 2a was considerably sharper than the one obtained with the high pressure in the chamber, the calibration of this run is far more reliable and can safely be estimated to be correct within 10%. Although the lowest point at .72 MV lies again somewhat high it does not exhibit as much of a discontinuity as the lowest point obtained with the high pressure. Due to the lower pressure, the electrons released from capture γ-rays caused here a smaller background than before, which may account for the absence of the anomaly of the lowest point observed with the higher pressure.

3) Light chamber filled with Deuterium:

All the measurements reported so far were taken with the heavy 61-lb iron container of the ionization chamber. As mentioned in paragraph 1d, this great mass of iron had to be suspected as a considerable cause for inelastic scattering and a repetition with a much lighter chamber was felt necessary as a check on this point. In order to obtain such a check, a new chamber weighing 19 lbs of Fe and filled with 16.3 atm of D_2 was used, as discussed in Section 3. While all recoil distributions obtained with hydrogen were monotonic, in this case with deuterium we obtained clearly a maximum from the neutrons of the D-D source. This can be explained by a non-isotropic scattering of neutrons on deuterons in a system moving with the center of gravity of the two systems. In order to investigate just this anisotropy, Barschall and Kanner$^{8)}$ have also observed the recoils of deuterons by D-D neutrons; their results show only a faint indication of such an anisotropy. At the same time, however, their distribution shows a much less steep decrease on the high energy end, indicating that their resolution was not as good as ours and tending to obscure the features caused by anisotropic scattering. As a check on this rather surprising result the recoil distribution was taken, observations once being made of the neutrons emerging perpendicularly to the deuteron beam, once in its direction, i.e., with monoenergetic neutrons of 2.47 MV and 2.73 MV respectively. Both recoil distributions are plotted versus their energy in Fig. 15 and show the proper displacement. Since in the case of He a resonance P-scattering is known to exist$^{11)}$ it was thought possible that a similar resonance would exist here with a sufficient sharpness to show a marked difference in the anisotropy for the two energies. While this cannot be deduced from our results it yet seems most unlikely that the appearance of the maximum is an instrumental effect. Before a thorough investigation of the angular dependence of the scattering of neutrons on deuterons is made over a sufficient range of energy, it seems, in any event, that deuterium is not suitable for the investigation of the fission spectrum since in the

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11) H. Staub and W.E. Stephens, Phys. Rev. 55, 131, 1939.

absence of sufficient data the latter could not be derived in an unambiguous manner. No fission measurements were therefore taken with the deuterium-filled chamber.

4) Light chamber filled with a mixture of H_2 and Argon:

As another gas replacing the deuterium mentioned above and having the same stopping power as the 26 atm H_2, we decided to use a suitable mixture of argon and hydrogen. In order to have a pressure low enough to be safe in our lighter steel container, we chose a mixture of 13.8 atm H_2 and 2.73 atm A.

a) D-D spectrum: (see Fig. 16) The collection was here even better than in the run described in paragraph 2a, with the chamber filled with 26 atm H_2, for here 78% of the ions were collected. This again was accompanied by increased sharpness of the line, which here has a half-width of only .14 MV. In this case the broadening can be entirely accounted for by the normal width of the background without any further instrumental broadening.

b) Fission spectrum: (see Fig. 17) A good representation of R(E) was found here to be proportional to $e^{-E/.57}$, compared to $e^{-E/.55}$ which was used for fitting in 2b. Since the stopping power and therefore the wall corrections were equal, the fission spectrum resulting from these two runs is substantially the same. This agreement serves as a good check upon the calibration since this run was taken both with better collection and higher amplification than the one reported in paragraph 2b, which increased the voltage pulses from recoils of the same energy by a factor 1.3. At the same time it shows that the iron of the chamber causes no appreciable distortion of the fission spectrum, since the recoil distribution is not noticeably affected by changing the iron mass of the container by a factor three.

The lowest point which we consider significant in this run lies at E = .89 Mev. Actually measurements were taken for two lower points, one at E = .72, the other at E = .56 MV. They represent a discontinuity of the same type as discussed in paragraph 1b, the former lying almost three times, the latter more than seven times, as high as the point at .89 MV. Since in run 2b taken with 26 atm hydrogen no such anomaly was noticed at E = .72 MV, it seems likely that the anomaly observed here is due to the disturbing effect of the capture γ-rays. It was indeed noticed that for the same intensity the background from γ-rays was considerably bigger than in 2b, probably due to the presence of argon which would cause a greater detour factor for the Compton electrons and thus increase the ionization per electron made in the collection volume. Unfortunately no crucial experiment could be made to demonstrate beyond doubt that the observed anomaly is actually caused by the disturbance from γ-rays and the rejection of the two lowest points here and of the lowest in paragraph 1b is based upon purely circumstantial evidence.

5. Determination of the total number of neutrons:

In all the runs previously discussed our measurements allowed us barely to reach below the maximum of the fission spectrum which in 2b and 4b was found to occur at .82 MV. Since it did not seem impossible, particularly in view of the anomaly discussed above that a considerable fraction of the fission neutrons might have even less energy, it was felt important to devise a method by which the fraction of neutrons below the lower end of the explored region could be determined. For this determination it is necessary in the first place to establish the effective number of fissions produced in the alloy disk. As an indicator for this number we used an enriched sample, thin both for thermal neutrons and for fission fragments and containing 116 μg. of U_{25}*), the fission fragments being counted in a small ionization chamber from which the pulses were recorded with the same apparatus and the same modulation as those from the proton recoils from fission neutrons. Per interval of our monitor 1.2 ± .1 fissions were observed to occur on the average. If also our alloy disk were thin for slow neutrons, the number of fissions produced in it should be as much greater than in the enriched sample as the amount of U_{25} contained in it exceeds that of the enriched sample. Our alloy contained 2930 g. of the alloy and therefore $\frac{2930}{139} = 21.1$ g. of U_{25}. In order to compute, from the masses of U_{25} in the thin sample and in the tuballoy disk, respectively, the number of fissions produced in the latter, one has to correct for the self-absorption of thermal neutrons in the alloy disk. For the self-absorption in the tuballoy the following cross section values for thermal neutrons were used:

Capture cross section $\sigma_c = (3.0 \pm .3) \times 10^{-24}\ \mathrm{cm}^2$

Fission cross section $\sigma_f = (4.3 \pm .4) \times 10^{-24}\ \mathrm{cm}^2$

Scattering cross section $\sigma_{sc} = (12 \pm 2.5) \times 10^{-24}\ \mathrm{cm}^2$

The thickness of the disk was 1.3 cm which is of the same order of magnitude as the mean free path of a neutron and makes a rigorous calculation of the self-absorption quite difficult. Instead we have computed the self-absorption under three different assumptions:

a) Neglecting the scattering. This leads to a reduction factor of .58 compared to a situation in which the self-absorption in the disk would be negligible.

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*) We wish to thank Dr. Segre and his collaborators for kindly preparing and analysing this sample for us.

b) Computing the self-absorption by means of a diffusion theory, modified according to Wigner: Here the correction factor becomes .65; that it is closer to unity than the value obtained under a) is apparently due to the fact that the scattering of neutrons increases their path in the disk.

c) Omitting a correction term $\frac{2}{5}\frac{\sigma_c + \sigma_f}{\sigma_c + \sigma_f + \sigma_{sc}}$ in Wigner's theory, which leads to a correction factor .63: Accepting the average between b) and c), namely .64, as a sufficiently close approximation for the true correction factor, we thus obtain for the number of fissions per monitor interval produced in our alloy disk

$$.64 \times 1.2 \times \frac{21.1}{116 \times 10^{-6}} = 1.4 \times 10^5$$

and, with 2.1 neutrons per fission we get a total of

$$(17) \qquad N = 2.9 \times 10^5$$

neutrons per monitor interval, emerging from the disk during the recording time of our apparatus.

The following data and calculations, connecting this number with the observed number of recoils above our minimum energy, refer to the measurement reported in paragraph 1b with the heavy chamber filled with 39 atm H_2. The calibration, which for this run was unreliable, obviously has no bearing upon this determination and in referring to energies we shall divide the scale by 1.35 which brings this run into agreement with the more reliable ones reported under 2b and 4b.

From (14) we can now compute the total number of neutrons above a certain energy emerging from the disk per monitor interval, using the observed recoil distribution, likewise normalized per monitor interval. The method of normalization by integral counting is described in Section 3. The fraction of solid angle under which the counting volume was seen from the disk was $S = 1.5 \times 10^{-2}$, the depth of the counting volume

$D = 8.5$ cm and the number of hydrogen atoms per unit volume $h = 2.1 \times 10^{24}$. With these data we would obtain for the number of neutrons with an energy above .82 Mev, i.e., above the maximum of our distribution curve, emerging from our disk per monitor interval

$$N' = 3.7 \times 10^5, \tag{18}$$

i.e., even more than the total number 2.9×10^5 given in equation (17).

An important additional consideration has to be made, however, before deriving the really significant number for the fraction of neutrons above .82 Mev. As discussed in Section 3, our measurements were taken with post discrimination which was adjusted such that the collection of ions for each recorded pulse started when the amplifier was already on. Therefore all recoils produced within a full collection time before the end of the post discrimination were recorded as well as all those following it. The fissions which take place follow the exponential decay lay $e^{-t/\theta}$ of our container as discussed in Section 1, and this decay is completed during the on time of the amplifier. This means that, with a finite collection time T, $e^{T/\theta}$ times more pulses are recorded than would be if collection time were zero. The same remark holds of course for the recording of the fission fragments, which was performed with the identical modulation system as that of the proton recoils. If we call T_1, the collection time for ions in the hydrogen chamber, T_2 that for ions in the fission chamber, one obtains for the fraction of neutrons with energy above .82 Mev, not the ratio of the numbers N and N', given in (17) and (18), but that ratio multiplied with $e^{(T_2 - T_1)/\theta}$. A considerable part of the inaccuracy in our determination lies in this exponential factor. Although the decay time θ (see Section 1, formula 9) has been quite well determined to be 1.8×10^{-3} sec., the collection times T_1 and T_2 are not too well known. From the observation of the voltage pulses in the oscillograph we would conclude $T_1 = 1.2 \pm .2$ milliseconds. T_2 is certainly much smaller; assuming it to be so small that it can be neglected in the exponent of $e^{(T_2 - T_1)/\tau}$, we obtain for the fraction f of neutrons above .82 Mev from (17) and (18)

$$f = \frac{3.7}{2.9} e^{-(1.2 \pm .2)/1.8} = 65 \pm 7\%.$$

The finite value of T_2 can only tend to increase this number.

The error introduced in the above-mentioned correction for the self-absorption is estimated to be even somewhat bigger. Besides there are comparatively small errors entering from statistics, in the geometry, the wall corrections, and the neutron-proton cross section. Altogether we estimate f to have a probable error of 25% or the fraction of neutrons above .82 Mev to be no less than

$$f = 65 \pm 15\%. \tag{19}$$

6. Discussion:

In view of our scanty knowledge about the mechanism of emission of the fission neutrons, it is very difficult to judge our results from the theoretical point of view and to make any predictions about the spectrum below the explored energy region. To obtain at least an idea whether the value (19) is at all reasonable we have extrapolated the fission spectrum to $E = 0$, assuming that the neutrons are isotropically emitted from fission fragments, moving with a single velocity v_o. If $E_o = m/2\ v_o^2$ (m = neutron mass) and if the number of neutrons with an energy $E > 9E_o$ is negligible, one can show that the distribution N(E) can be deduced for $E < E_o$, if it is known for $E > E_o$, according to the formula

$$(20) \qquad N(E) = N(4E_0 + E - 4\sqrt{EE_0}) - N(4E_0 + E + 4\sqrt{EE_0})$$

and that the maximum will always occur for $E = E_0$. In Fig. 18 we have represented by the heavy line the fission spectrum to the best of our present knowledge. The extension below the lowest measured energy of $E = .72$ MV has been obtained using (20) and has been indicated by a dotted line. The spectrum resembles very closely that which one would obtain if in a system moving with velocity $v_0 = \sqrt{2E_0/m}$, with $E_0 = .82$ Mev, the neutrons were emitted isotropically in a Maxwellian distribution $\sqrt{E}e^{-E/kT}$ with $kT = .41$ Mev; the spectrum thus computed is indicated in Fig. 18 by circles.

Accepting the spectrum as indicated in Fig. 18 by both the heavy and the dotted line and estimating the fraction of neutrons above the highest measured energy of $E = 3.3$ MV to be 4%, one obtains for the fraction of neutrons above .82 MV

$$(21) \qquad f = 71\%$$

The agreement with the experimental value (19) is well within the probable error, but particularly in view of this error being rather large, it does not of course represent an argument for the assumption that the dotted curve in Fig. 18 represents the true extrapolation at lower energies. It does seem however to strengthen further our suspicion previously expressed that the sharp rise observed at lower energies is due to instrumental rather than real effects. This is further confirmed by the results of Zinn and Szilard[1)] who, with a much smaller chamber than ours, have actually measured the recoil distribution down to $E = 0.55$ Mev without observing such a sharp rise. It is true that in their arrangement both wall effects and inelastic scattering would cause a far greater distortion so that their results cannot be directly compared with ours. The comparison of their recoil distribution with ours shows as expected that these distortions favor the smaller recoils compared to the bigger ones and it does not seem likely that they could make a sharp rise at lower energies disappear.

APPENDIX. DESCRIPTION OF PARTS IN ELECTRONIC CIRCUITS.

AMPLIFIER, FIG. 4A & B.

Tubes

	V
1.	1603
2.	1620
3.	6J7
4.	6J7
5.	6SJ7
6.	6SJ7
7.	6H6
8.	6H6
9.	6SJ7
10.	6SJ7
11.	6H6GT
12.	6SJ7
13.	6SJ7
14.	885
15.	885
16.	885
17.	6L6
18.	6L6
19.	2V3G
20.	2V3G
21.	5Y3GT/G
22.	VR105
23.	VR105
24.	VR105
25.	83
26.	83
27.	5Z3
28.	VR105
29.	VR105
30.	VR105
31.	5V4G
32.	5V4G
33.	VR105
34.	5Z4
35.	VR105
36.	5Z4
37.	VR105
38.	885
39.	885
40.	5Z4

Capacities

	C μF		C μF
1.	4.0 μF	33.	0.1 μF
2.	1.0	34	10.0
3.	4.0	35.	0.1
4.	1.0	36.	1.0
5.	50.0 { elect.	37.	0.1
	25 V.	38.	0.1
6.	5.5	39.	.02
7.	20.0	40.	1.0
8.	1.0	41.	1.0
9.	50.0 { elect.	42.	10.0
	25 V.	43.	.2
10.	2.75	44.	.2
11.	10.0	45.	0.5
12.	0.50	46.	0.5
13.	50.0 { elect.	47.	1.0
	25 V.	48.	1.0
14.	2.75	49.	1.0
15.	1.0	50.	1.0
16.	1.0	51.	8.0 { elect.
17.	50.0 { elect.	52.	8.0 } 100 V.
	25 V.	53.	80.0 { elect.
18.	1.0		80 V.
19.	.02	54.	10.75
20.	1.0	55.	2-3/4
21.	1.0	56.	2-3/4
22.	.003	57.	16.0 { elect.
23.	50 { elect.		450
	50 V.	58.	16.0 { elect.
24.	1.0		450
25.	1.0	59.	16.0 { elect.
26.	0.5		450
27.	50.0 { elect.	60.	16.0 { elect.
28.	50.0 } 50.		450
29.	0.5	61.	5.0 { elect.
30.	1.0		50 V.
31.	0.1	62.	2.75
32.	0.1	63.	10.75
		64.	4.0

Transformers

	T
1.	Audio Input 1:5
2.	" "
3.	" "
4.	" " 1:4.5
5.	" " 1:4.5
6.	Insulation 1:1 (10,000 V.)
7. 8.	10,000 V. 115:2.5 V
9.	115:7500
10.	115:880 C T, 6. 3, 5
11.	115:118 C T
12.	115:5V
13.	115:880 C T, 6. 3, 5
14.	115:750 C T, 6. 3, 5
15.	115:750 C T, 2. 5, 5
16.	115:650 C T, 2. 5, 5
17.	115:650 C T, 2. 5, 5
18.	115:610 C T, 5
19.	115:2.5V

Inductances

	L
1.	15H
2.	15H
3.	12H
4.	12H
5.	12H
6.	15H
7.	15H
8.	15H
9.	10H
10.	10H

Resistances

	R			R			R	
1.	1×10^9		42.	25000		83.	100	Meg.
2.	20000		43.	4000		84.	100	Meg.
3.	0.6	Meg.	44.	30000		85	100	Meg.
4.	50000		45.	1.0	Meg.	86.	10200	
5.	0.5	Meg.	46.	800		87.	200	
6.	0.5	Meg.	47.	800		88.	0.5	Meg.
7.	0.5	Meg.	48.	1.0	Meg.	89.	0.5	Meg.
8.	1.0	Meg.	49.	0.1	Meg.	90.	0.5	Meg.
9.	1200		50.	81500		91.	10000	
10.	0.5	Meg.	51.	75000		92.	200	
11.	50000		52.	100		93.	100	
12.	50000		53.	0.5	Meg.	94.	25	
13.	1.0	Meg.	54.	0.3	Meg.	95.	25	
14.	1200		55.	0.5	Meg.	96.	25	
15.	0.5	Meg.	56.	0.3	Meg.	97.	25	
16.	10000		57.	5000		98.	0.5	Meg.
17.	10000		58.	10000		99.	0.5	Meg.
18.	10000		59.	2000		100.	0.5	Meg.
19.	10000		60.	10000		101.	5000	
20.	10000		61.	0.1	Meg.	102.	50	
21.	50000		62.	100		103.	20000	
22.	20000		63.	50000		104.	6500	
23.	1.0	Meg.	64.	54500		105.	8000	
24.	1200		65.	50000		106.	17500	
25.	0.5	Meg.	66.	50000		107.	8000	
26.	0.1	Meg.	67.	50000		108.	50000	
27.	10000		68.	10000		109.	800	
28.	0.7	Meg.	69.	5000		110.	55500	
29.	0.3	Meg.	70.	0.3	Meg.	111.	0.3	Meg.
30.	800		71.	300		112.	0.5	Meg.
31.	0.1	Meg.	72.	50000		113.	100	
32.	50000		73.	0.1	Meg.	114.	75000	
33.	1.0	Meg.	74.	0.3	Meg.	115.	65000	
34.	1100		75.	25000		116.	20000	
35.	50000		76.	10000		117.	0.1	Meg.
36.	1.0	Meg.	77.	10000		118.	50000	
37.	0.1	Meg.	78.	300		119.	50000	
38.	5000		79.	0.1	Meg.	120.	30000	
39.	.75	Meg.	80.	20	Meg.	121.	50000	
40.	4000		81.	20	Meg.			
41.	0.25	Meg.	82.	100	Meg.			

ARC SUPPLY, MODULATOR AND DISCRIMINATION SQUARE-WAVE GENERATORS

FIGS. 5 A & B

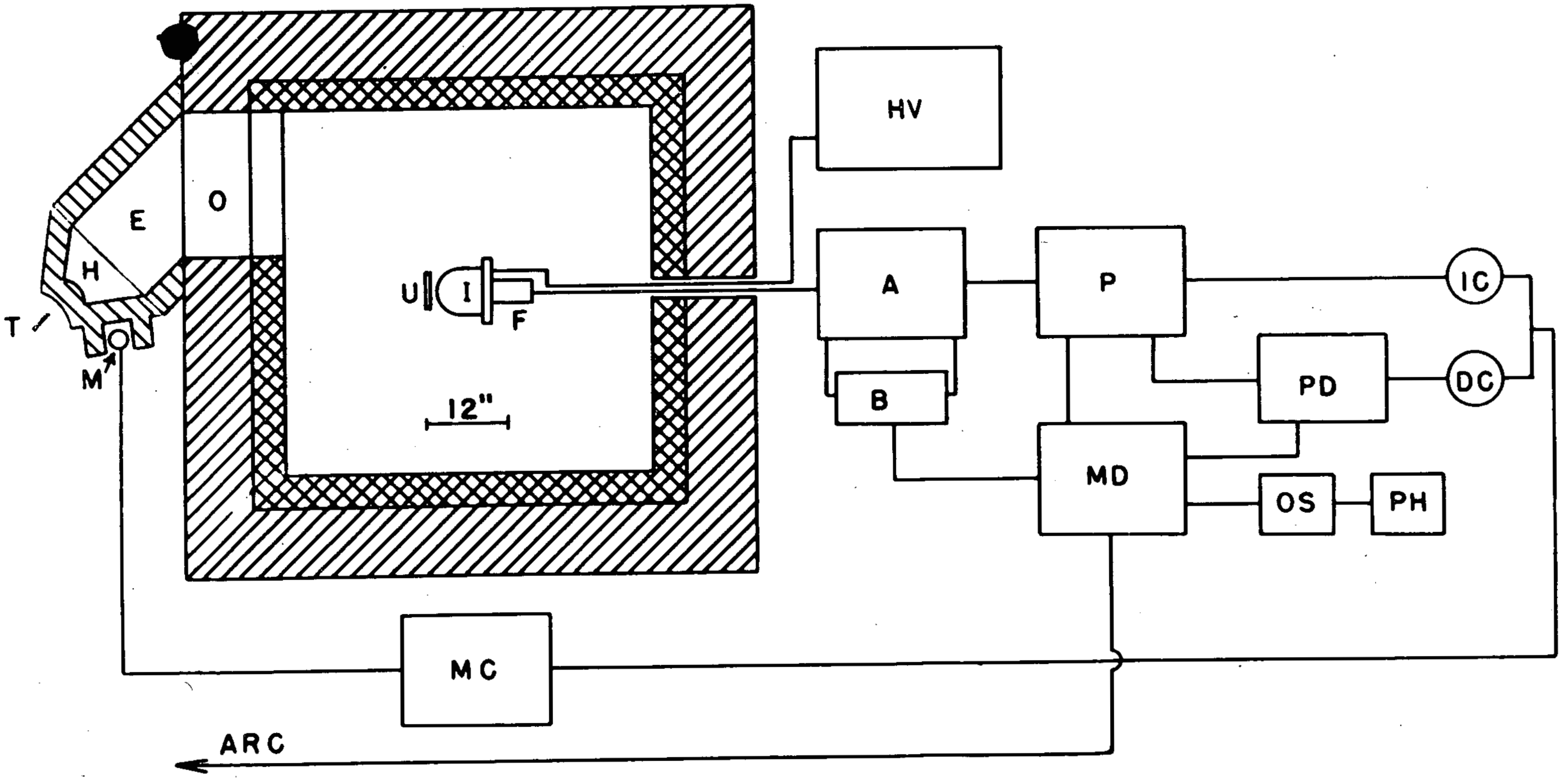
Tubes V	Inductances Ch	Transformers T	Resistances R	Capacities C
1. 866	1. 1H	1. 115:2.5	1. 10	1. 8.0μF
2. 866	2. 1H	2. 115:700CT	2. 10	2. 0.05μF
3. 866	3. 6H	3. 115V.Variance	3. 10	3. 0.02μF
4. 866	4. 10H	4. 115:6.3	4. 10	4. 180 electrolytic
5. 6L6G	5. 15H	5. 115:620C.T5	5. 85000	5. 170 450 V.
6. 80	6. 15H	6. 115:2.5	6. 2000	6. 0.02
7. VR150		7. 115:60	7. 8000	7. 0.01
8. 885		8. 115:750CT,5	8. 1000	8. 0.01
9. 885		9. 115:2.5	9. 1000	9. 12 electrolytic
10. 5V4G		10. 115:73	10. 25000	10. 40
11. VR105		11. 115:750CT,5	11. 1750	11. 1
12. 885		12. 115:2.5	12. 5000	12. 8 "
13. 885			13. 5000	13. 16 " 450
14. 5V4G			14. 0.5 Meg.	14. 0.1
15. VR75			15. 0.1 Meg.	15. 0.01
16. 885			16. 0.1 "	16. 0.02
17. 885			17. 1.0 "	17. 0.01
			18. 10000	18. 12 " 250
			19. 10000	19. 1.0
			20. 5000	20. 0.1
			21. 5700	21. 2.0 " 475
			22. 5000	22. 8 " 450
			23. 1000	23. 0.01
			24. 4000	24. 0.005
			25. 0.1 Meg.	25. 0.001
			26. 0.1 "	26. 10
			27. 1.0 "	
			28. 0.5 "	
			29. 10000	
			30. 10000	
			31. 50000	
			32. 6700	
			33. 2000	
			34. 500	
			35. 1500	
			36. 0.1 Meg.	
			37. 0.5 "	
			38. 0.1 "	
			39. 2000	
			40. 10000	
			41. 0.5 Meg.	

DESCRIPTION OF PARTS IN FIG. 1

T	Target
H	Paraffin howitzer
M	Monitor Ionizationchamber
E	Entrance Channel
O	Opening in Container
U	Tuballoy disk
I	Ionizationchamber
F	First stage amplifier
HV	High voltage supply for ionization chamber
A	Amplifier
B	Feedback circuit
P	Pulseselector
MD	Modulator
PD	Postdiscriminator
OS	Oscillograph
PH	Phaseshifting network
IC	Integral counter
DC	Differential counter
MC	Monitor circuit

FIG. 1

EXPERIMENTAL ARRANGEMENT



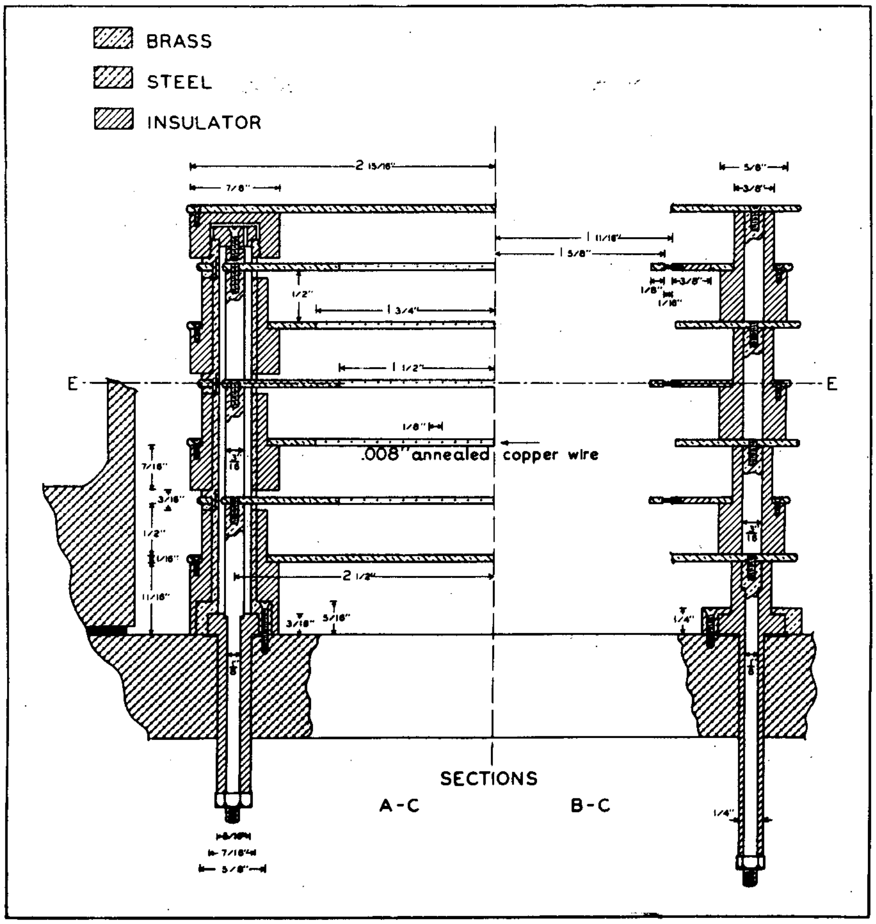

BRASS
STEEL
INSULATOR
2 15/16"
7/8"
5/8"
3/8"
1 11/16"
1 5/8"
1/2"
1 3/4"
1/8"
3/8"
1/16"
1 1/2"
E
E
1/8"
.008" annealed copper wire
7/16"
3/16"
3/16"
1/2"
1/16"
11/16"
2 1/2"
3/16"
3/16"
5/16"
1/4"
1/8"
1/8"
SECTIONS
A-C
B-C
1/4"
5/16"
7/16"
5/8"

FIG. 2A

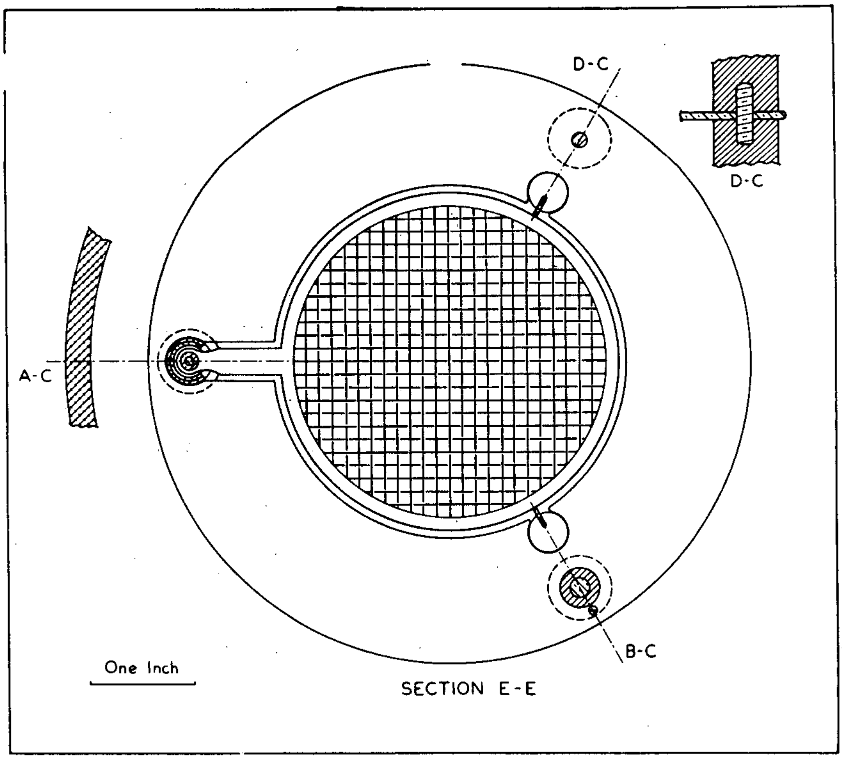

D-C
D-C
A-C
B-C
One Inch
SECTION E-E

FIG. 2B

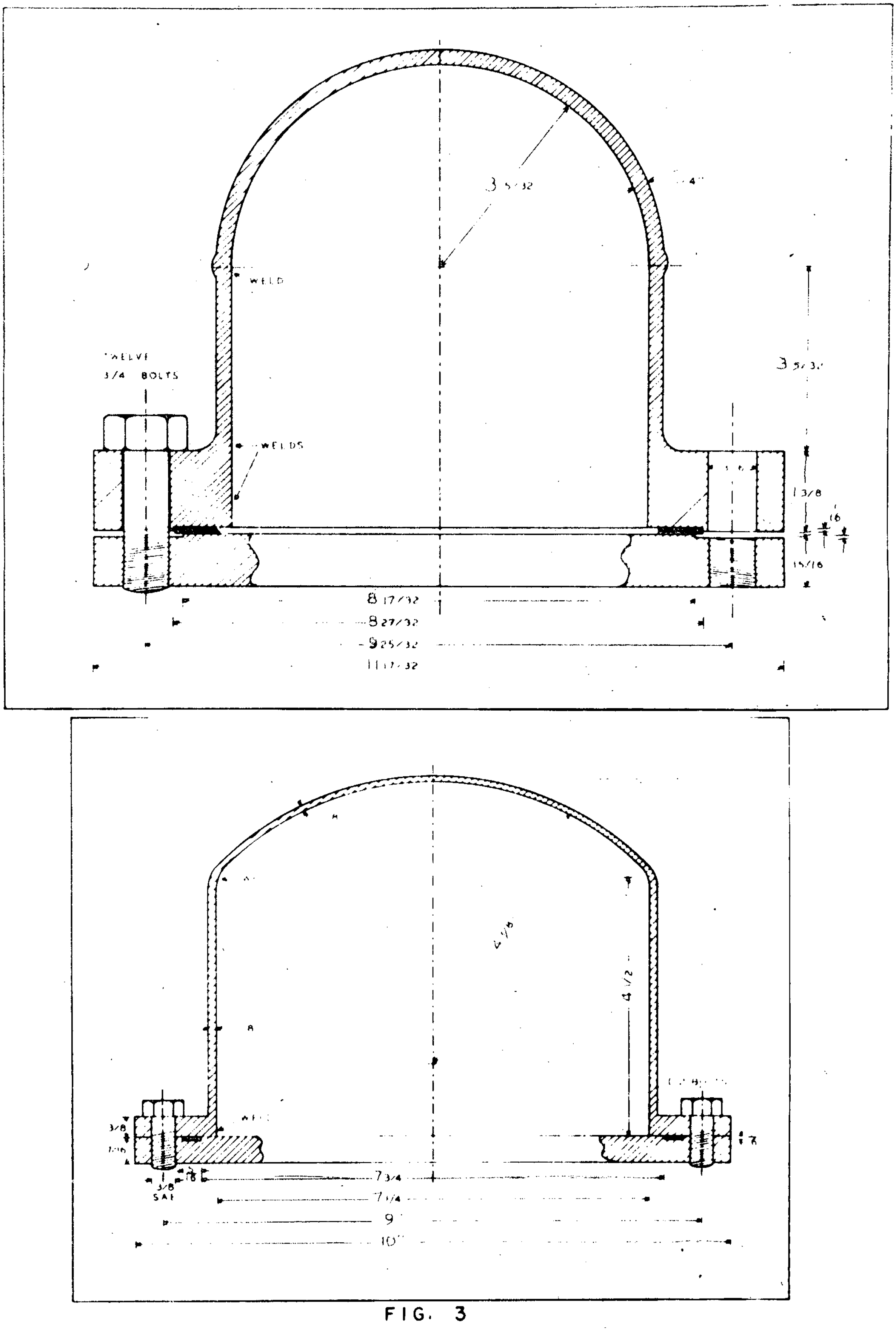
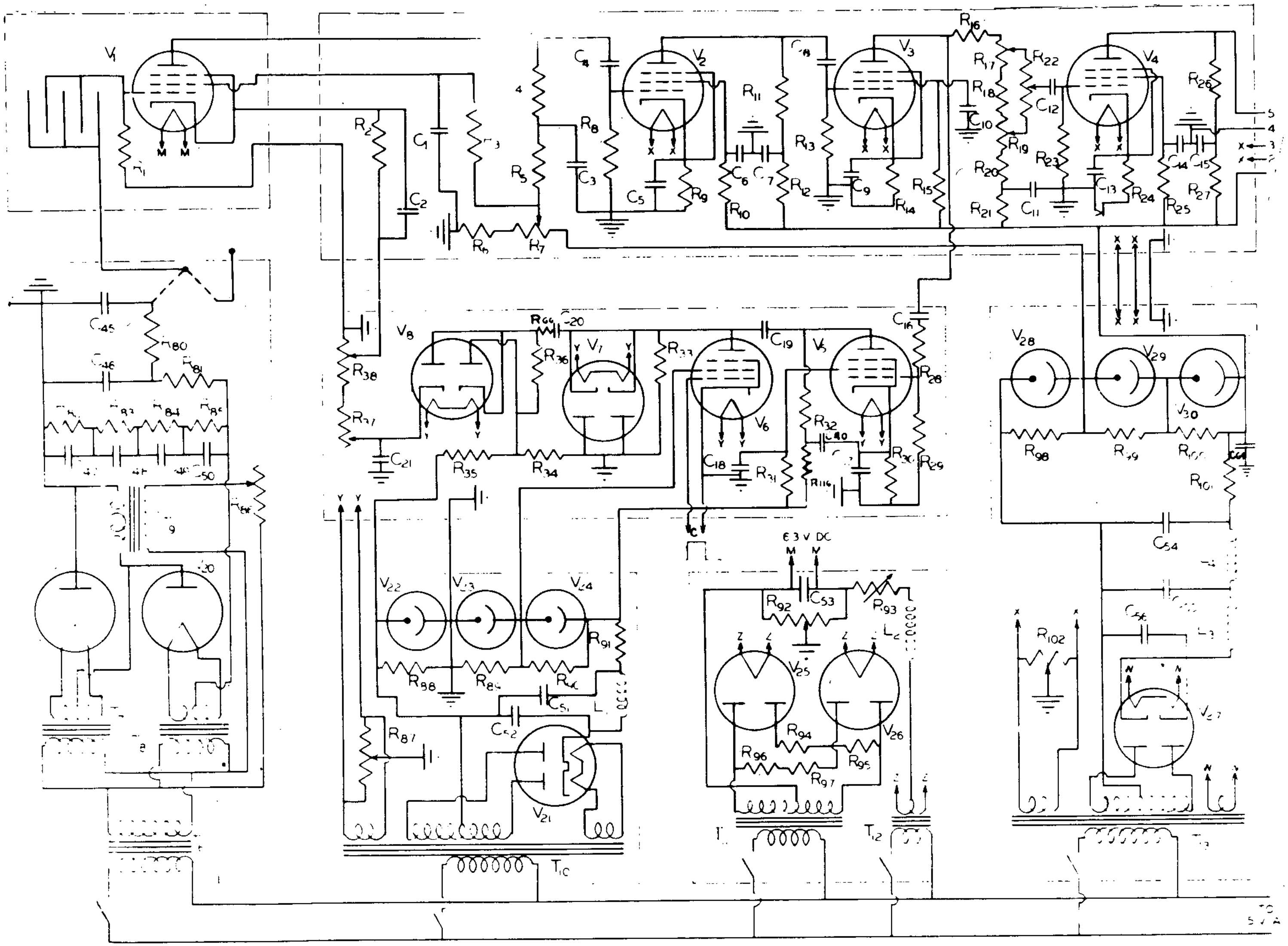
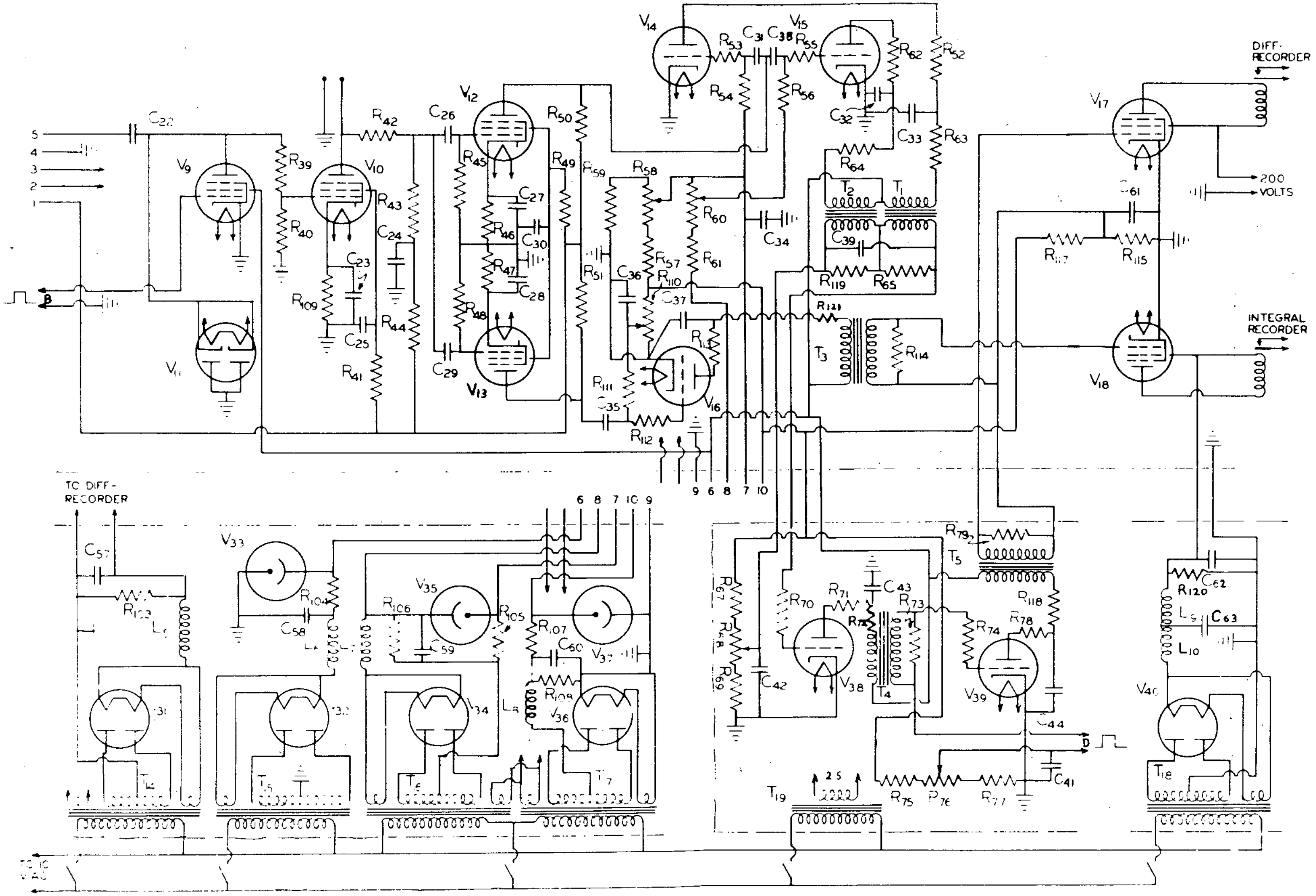

3 5/32
1/4"
WELD
TWELVE
3/4 BOLTS
WELDS
3 5/32
1 3/8
1/16
15/16
8 17/32
8 27/32
9 25/32
11 17/32
4 1/2
WELD
3/8
7/16
3/16
3/8
SAE
7 3/4
7 1/4
9"
10"

FIG. 3



V1
R1
R2
C1
R3
C2
R5
R6
R7
4
R8
C3
C4
V2
C5
R9
R10
C6
C7
R11
R12
R13
C8
V3
C9
R14
R15
R16
R17
R18
C10
R19
R20
R21
C11
R22
C12
R23
C13
V4
R24
R25
R26
R27
C14
C15
5
4
3
2
C45
R80
C46
R81
R83
R84
R85
R86
V8
R38
R37
C21
R64
C20
R36
V7
R33
V6
C19
V5
C16
R28
R29
R30
R31
R32
C18
R116
R35
R34
V22
V23
V24
R91
R88
R89
C51
L1
C52
V21
R87
T10
6.3 V DC
M
M
R92
C53
R93
L2
Z
Z
V25
V26
R94
R95
R96
R97
T11
T12
V28
V29
V30
R98
R99
R100
R101
C54
C56
R102
V27
L3
T13
TO
5 V A
Y
Y
X
X

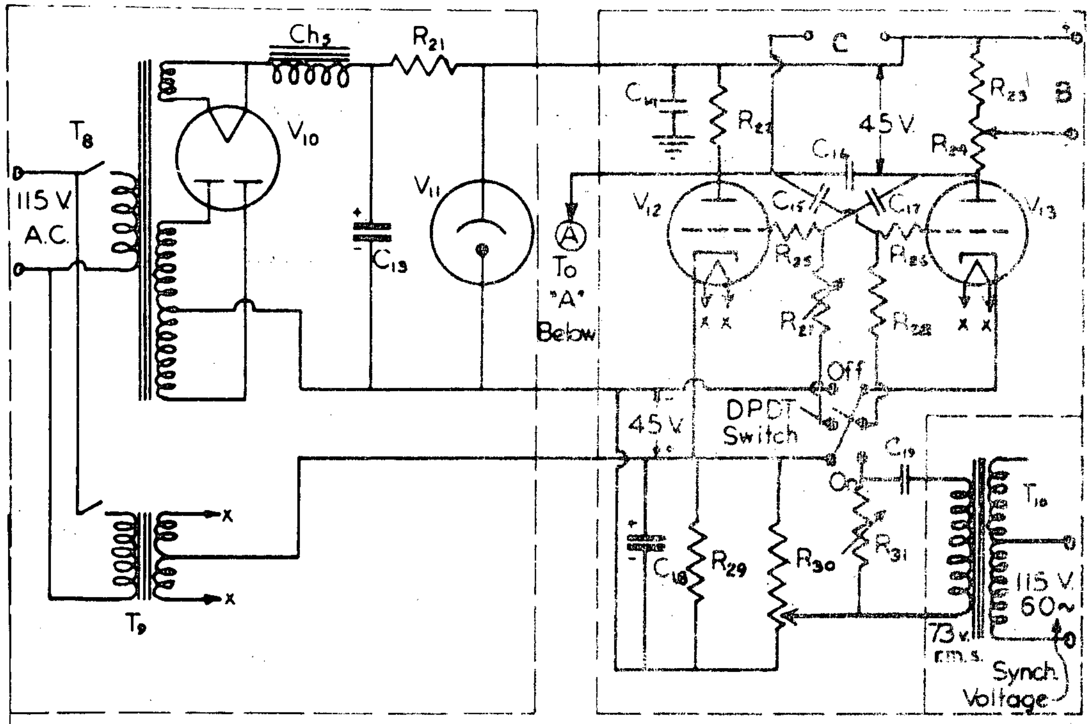
FIG. 4-A



V14
V15
R53
C31
C38
R55
R62
R52
R54
R56
C32
C33
R63
R64
DIFF-RECORDER
V17
200 VOLTS
C61
R117
R115
INTEGRAL RECORDER
V18
V12
C26
R42
C22
5
4
3
2
1
V9
R39
V10
R40
R43
R50
R45
R49
R59
R58
C27
R46
C30
C24
C23
R109
R44
C25
V11
R41
R47
C28
R48
C29
V13
R60
C34
R51
C36
R57
R110
R61
C37
R111
C35
V16
R112
R13
T2
T1
C39
R119
R65
R121
T3
R114
9
6
8
7
10
B
TO DIFF-RECORDER
C57
R103
L7
V31
T14
V33
R104
C58
L6
V32
T15
6
8
7
10
9
V35
R106
C59
R105
V34
T16
R107
C60
V37
R108
L8
V36
T17
R79
T5
R67
R68
R69
C42
R70
R71
C43
R72
R73
V38
T4
R74
R78
R118
V39
C44
D
C41
R75
P76
R77
T19
2.5
C62
R120
L9
C63
L10
V40
T18
TO 10 VAC

FIG 4- B

Pre-Discriminator Square Wave Generator



Post-Discriminator Square Wave Generator

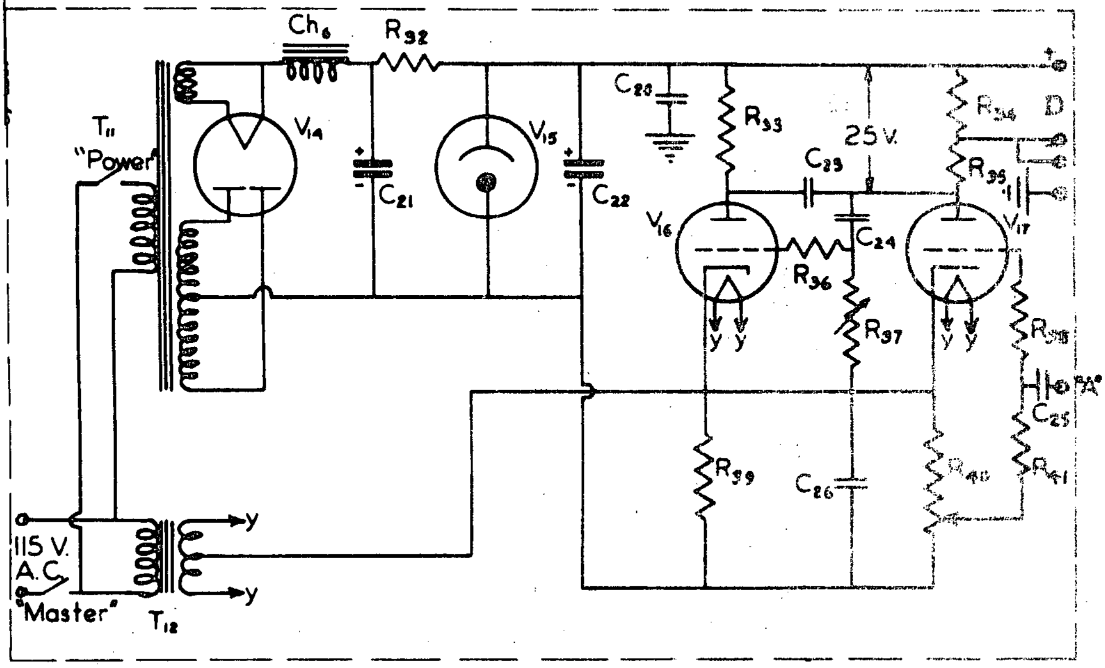


FIG. 5-A

ARC SUPPLY AND MODULATOR

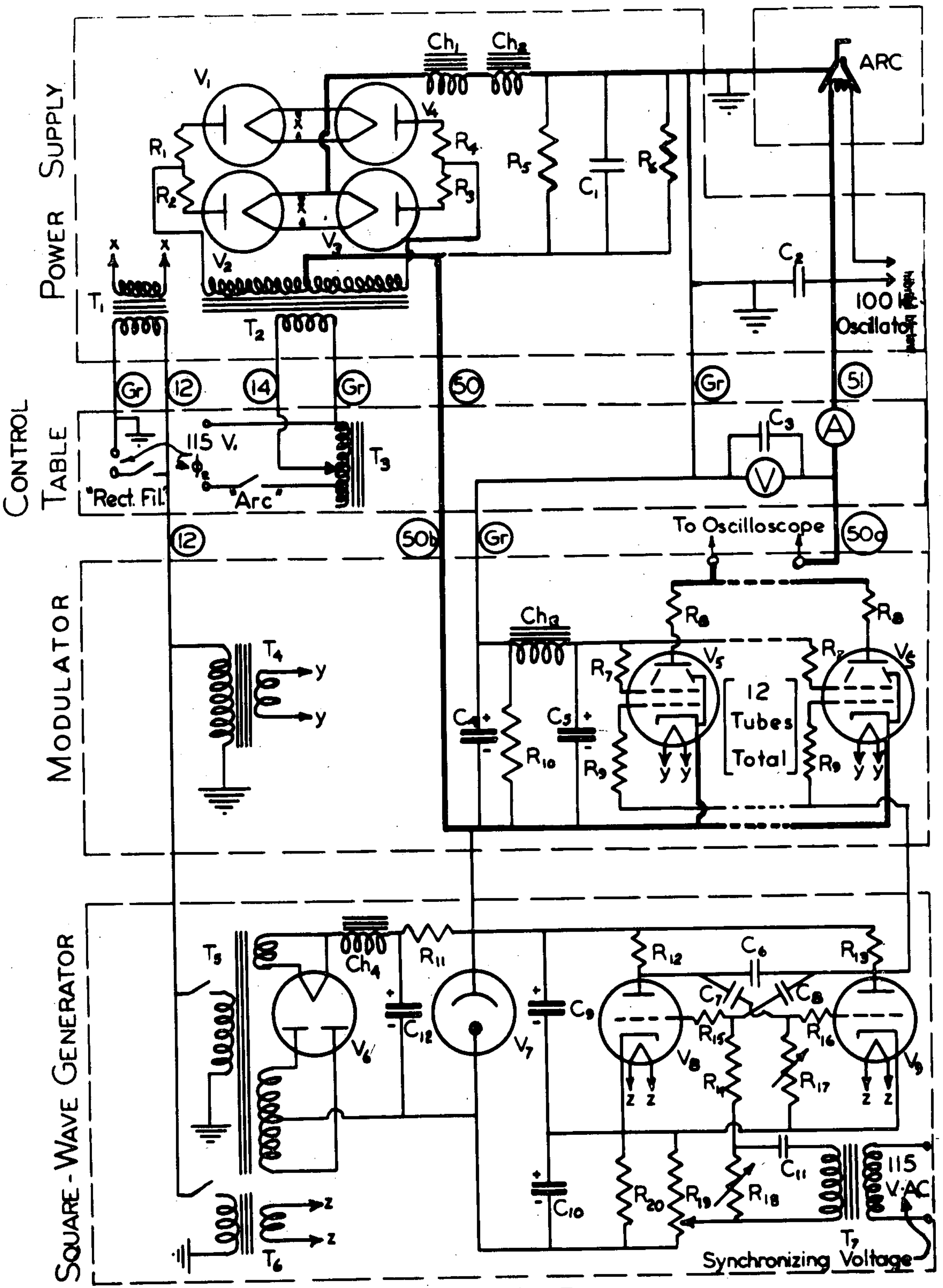


FIG. 5-B

PULSE GENERATOR, POTENTIOMETER, AND SYNCHRONIZATION

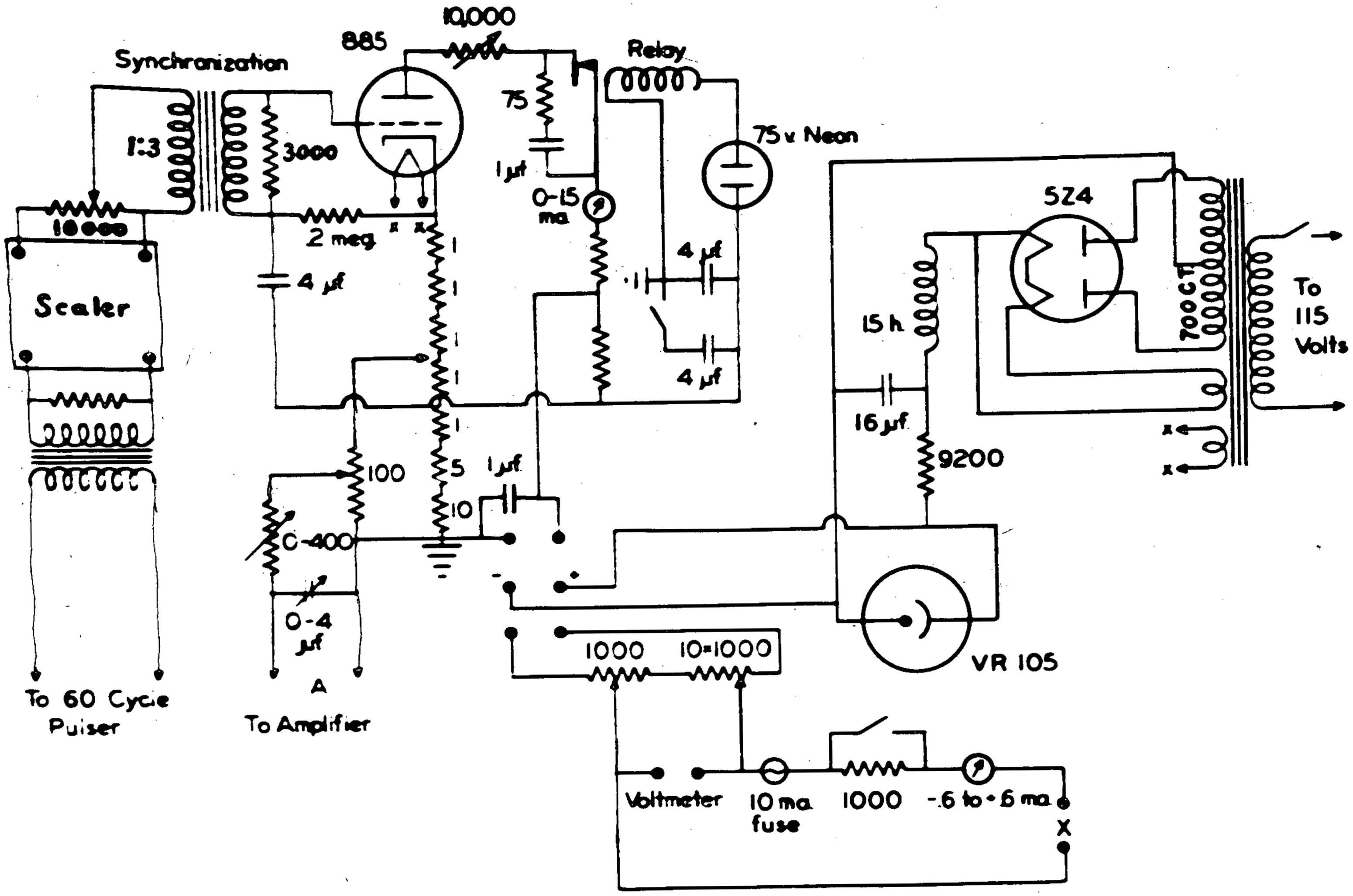


FIG. 6

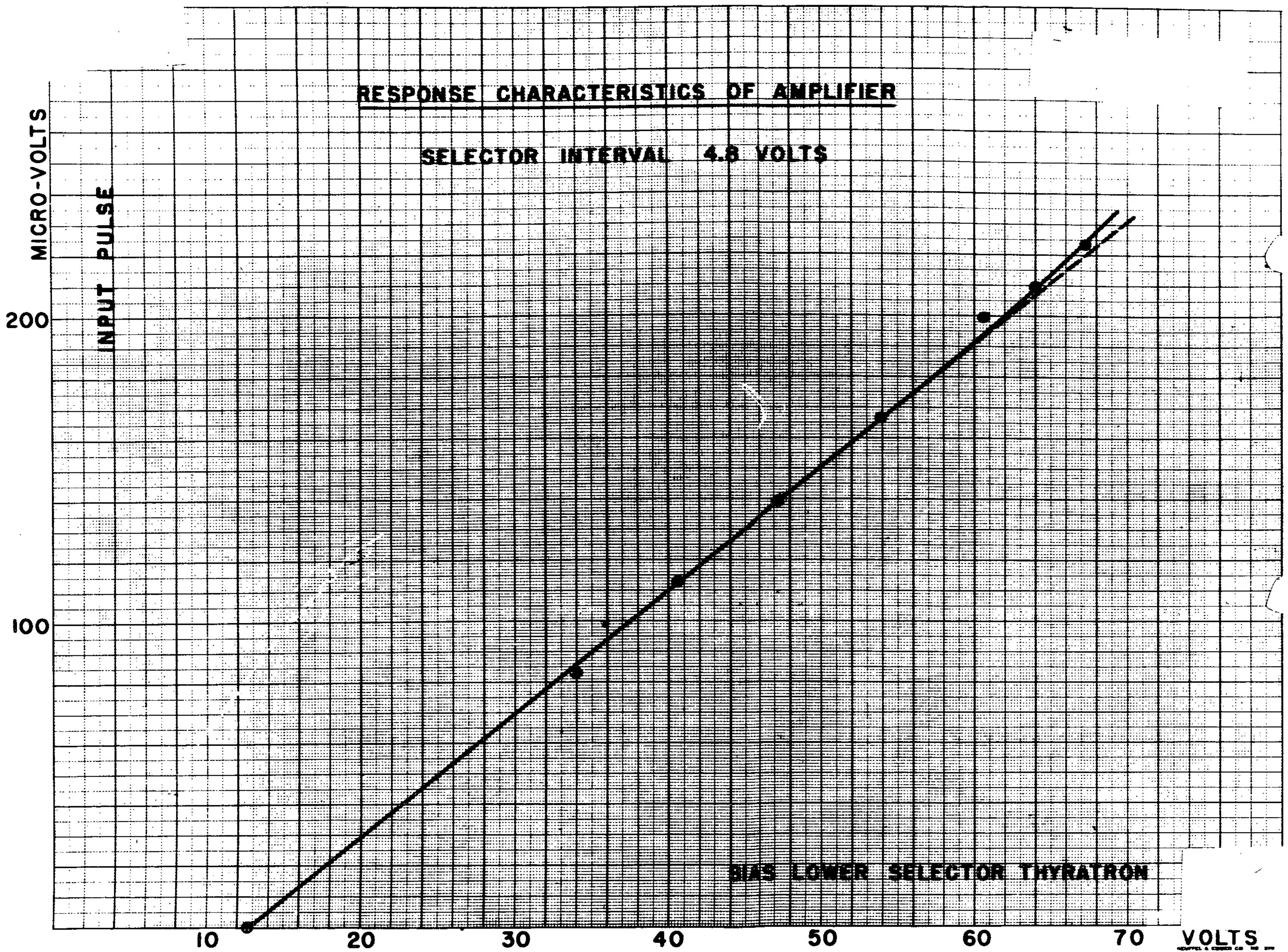

RESPONSE CHARACTERISTICS OF AMPLIFIER
SELECTOR INTERVAL 4.8 VOLTS
MICRO-VOLTS
INPUT PULSE
200
100
BIAS LOWER SELECTOR THYRATRON
10
20
30
40
50
60
70
VOLTS

FIG. 7

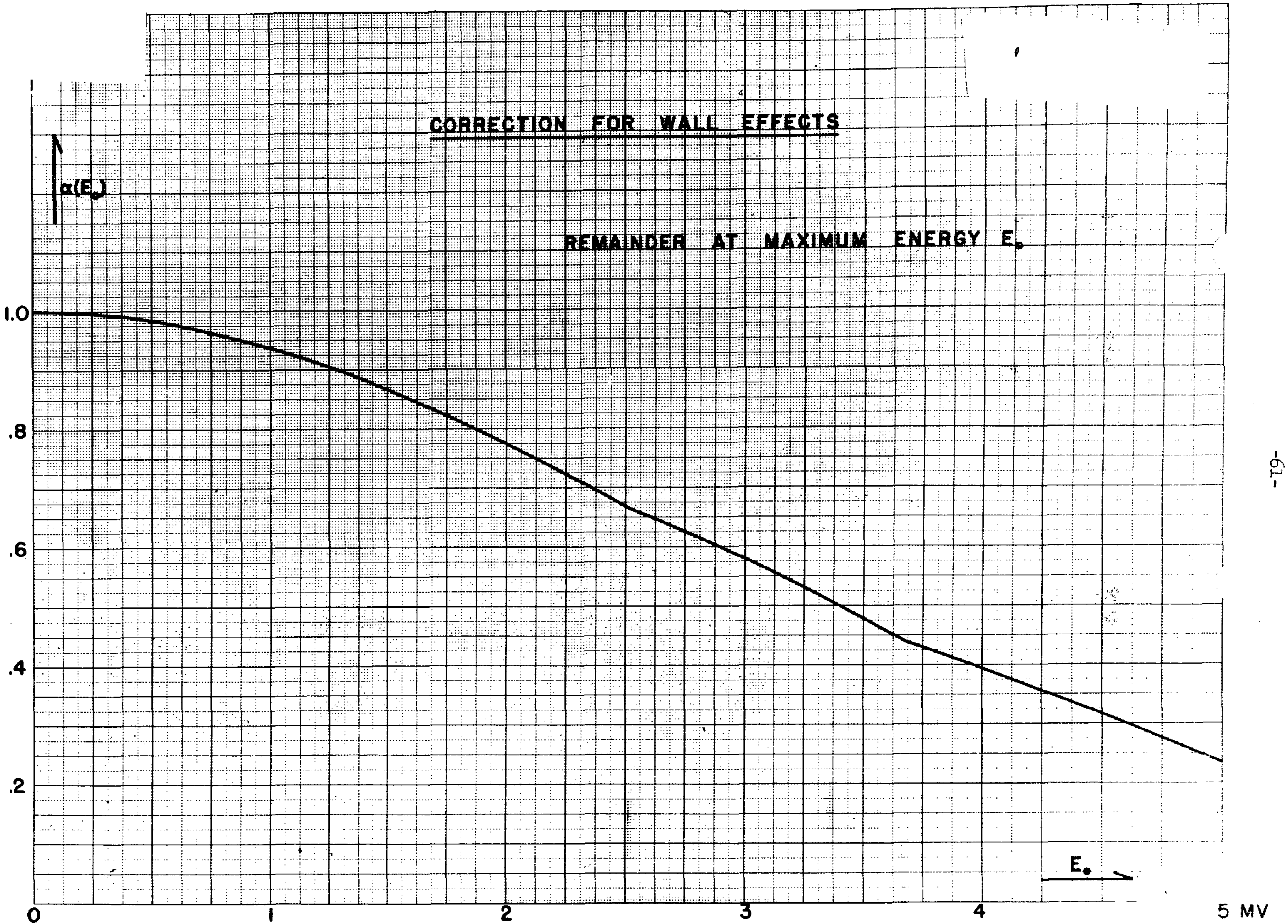

CORRECTION FOR WALL EFFECTS
REMAINDER AT MAXIMUM ENERGY E_0
$\alpha(E_0)$
1.0
.8
.6
.4
.2
0
1
2
3
4
5 MV
E_0

FIG. 8

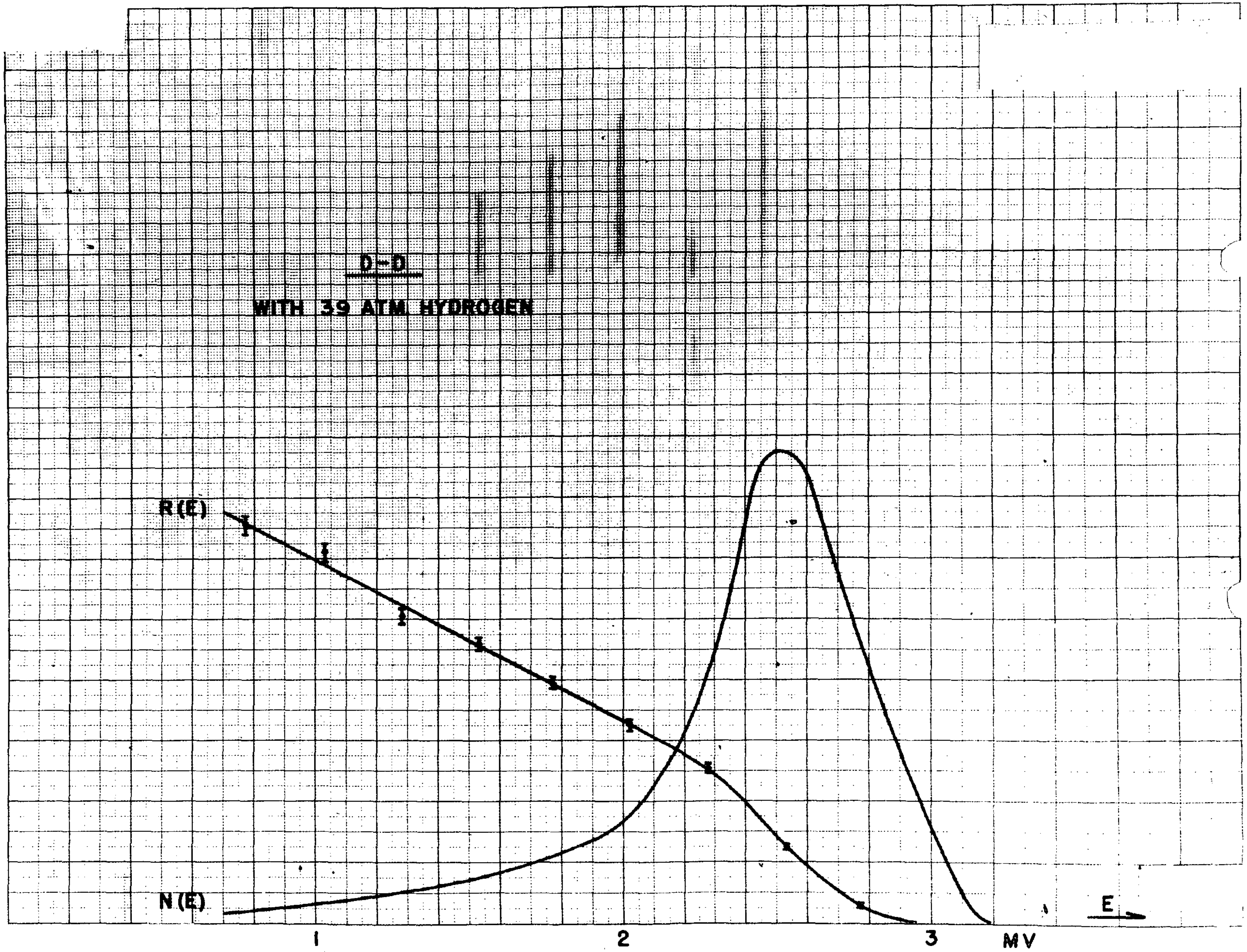


FIG. 9

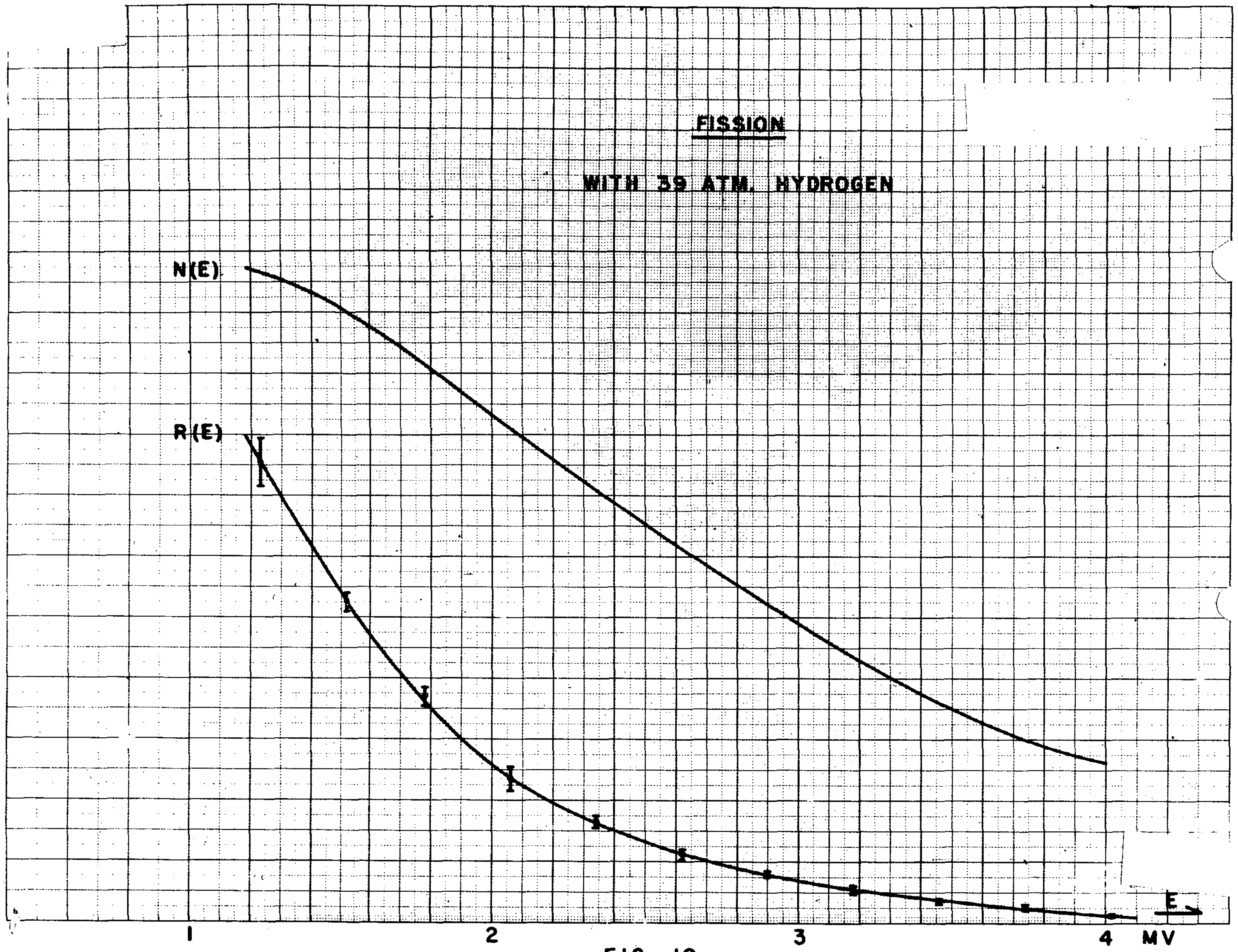


FIG. 10

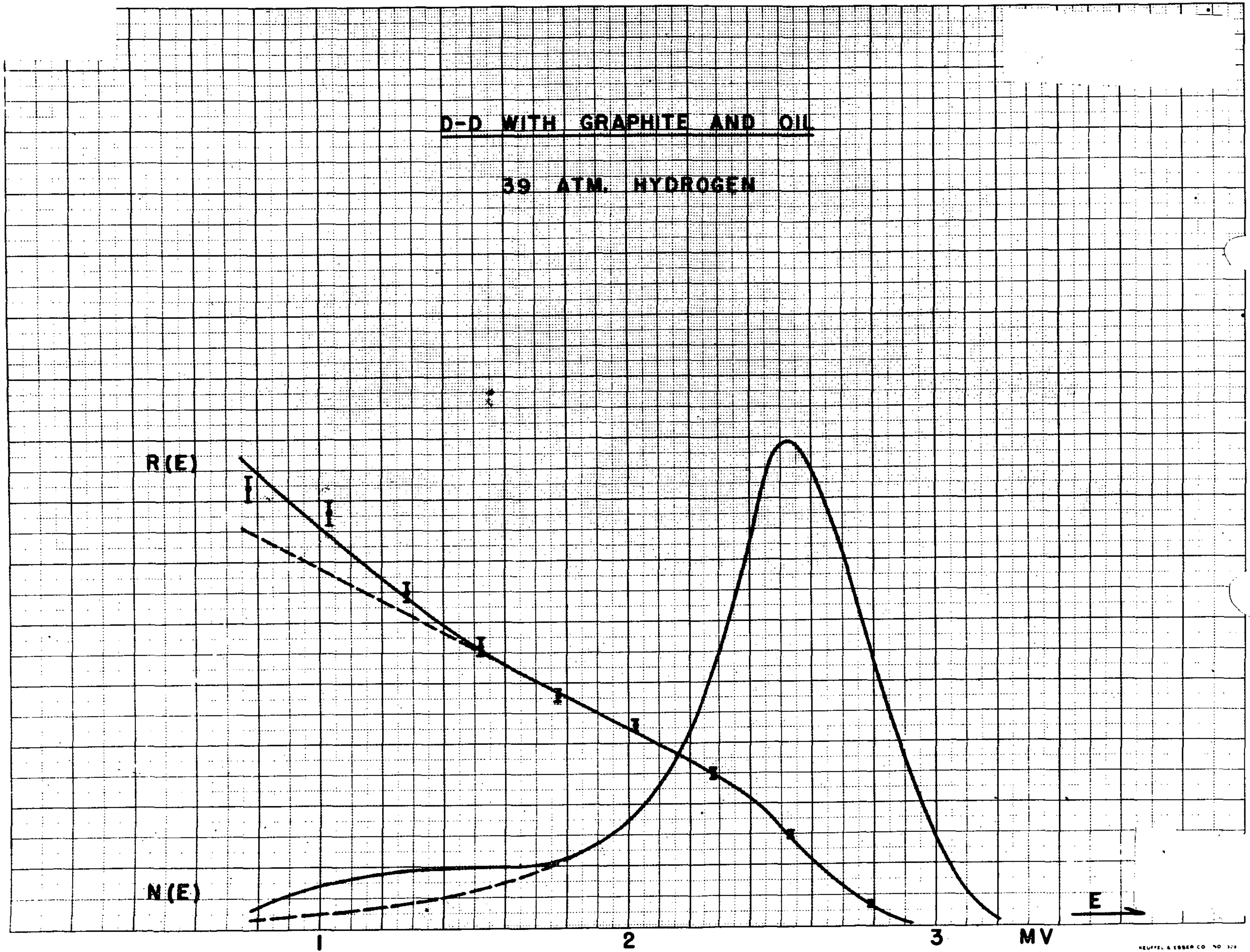


FIG. 11

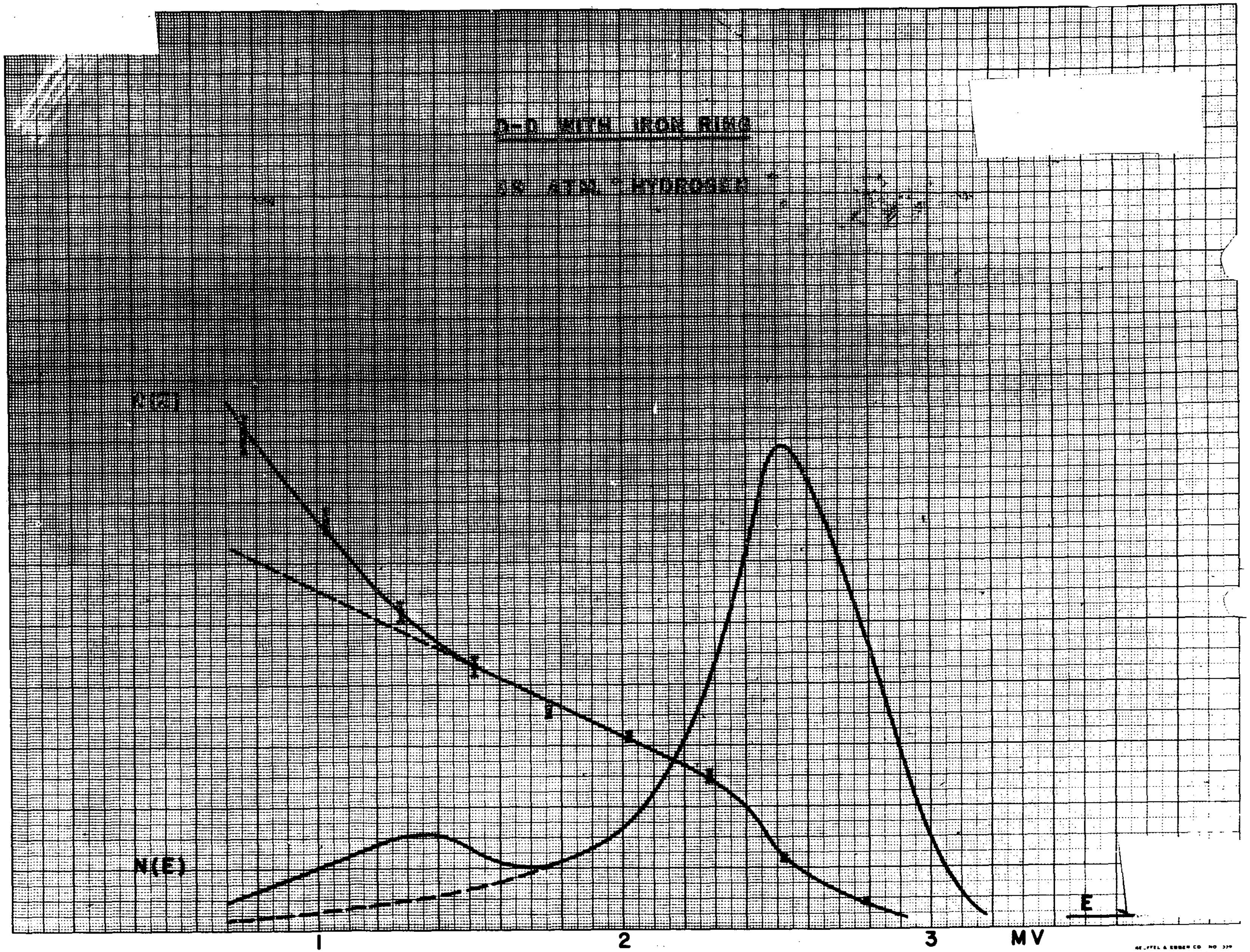


FIG. 12

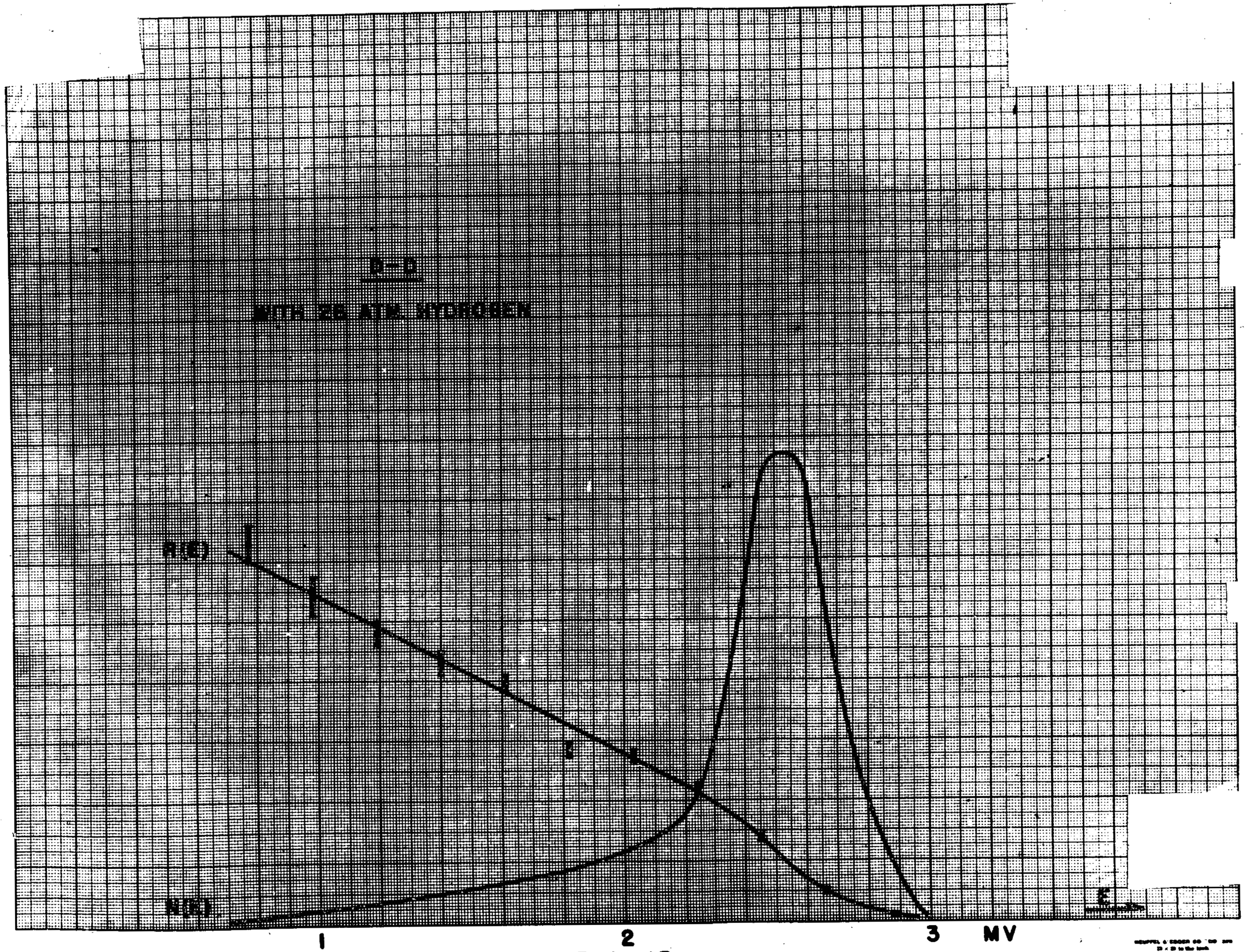


FIG. 13

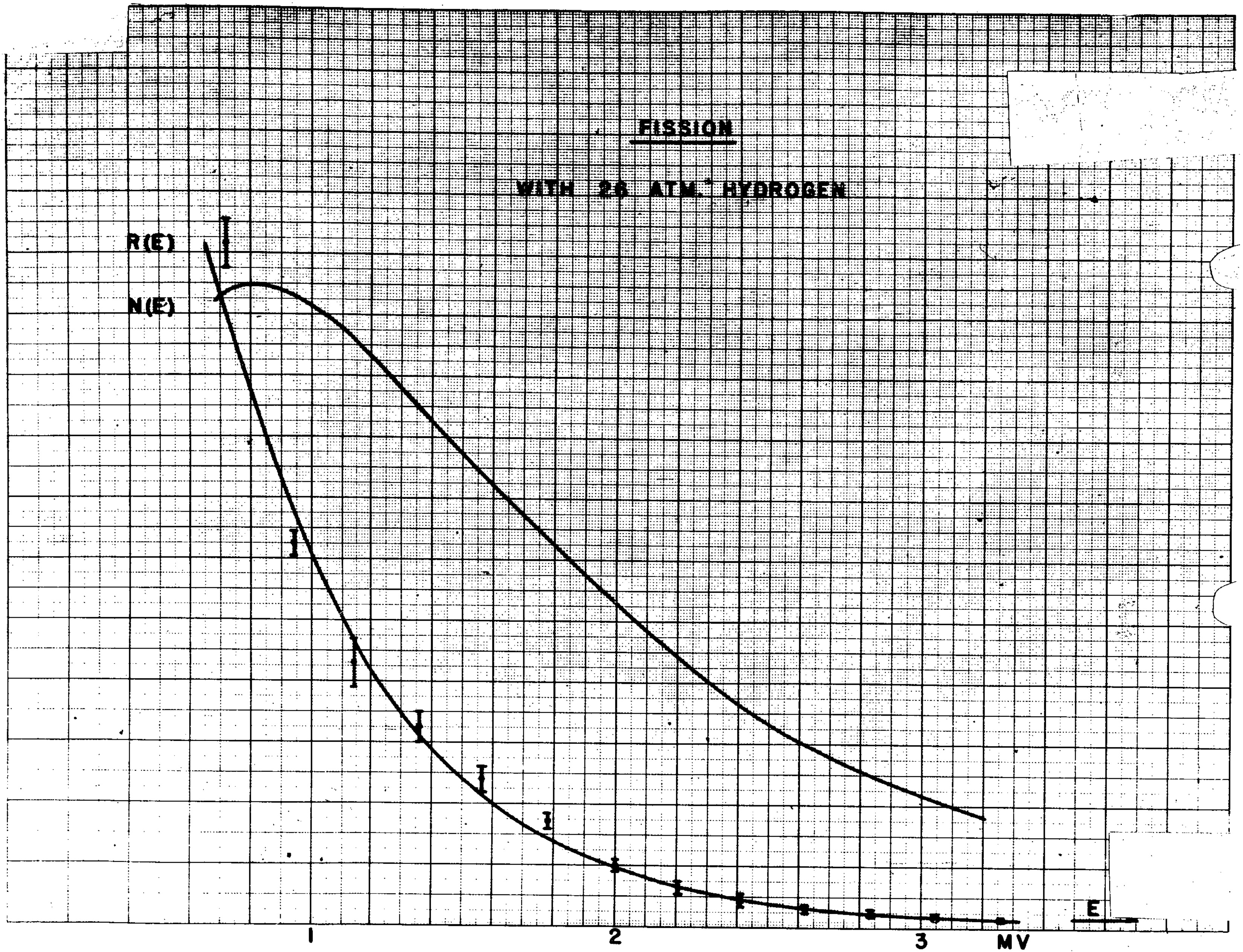


FIG. 14

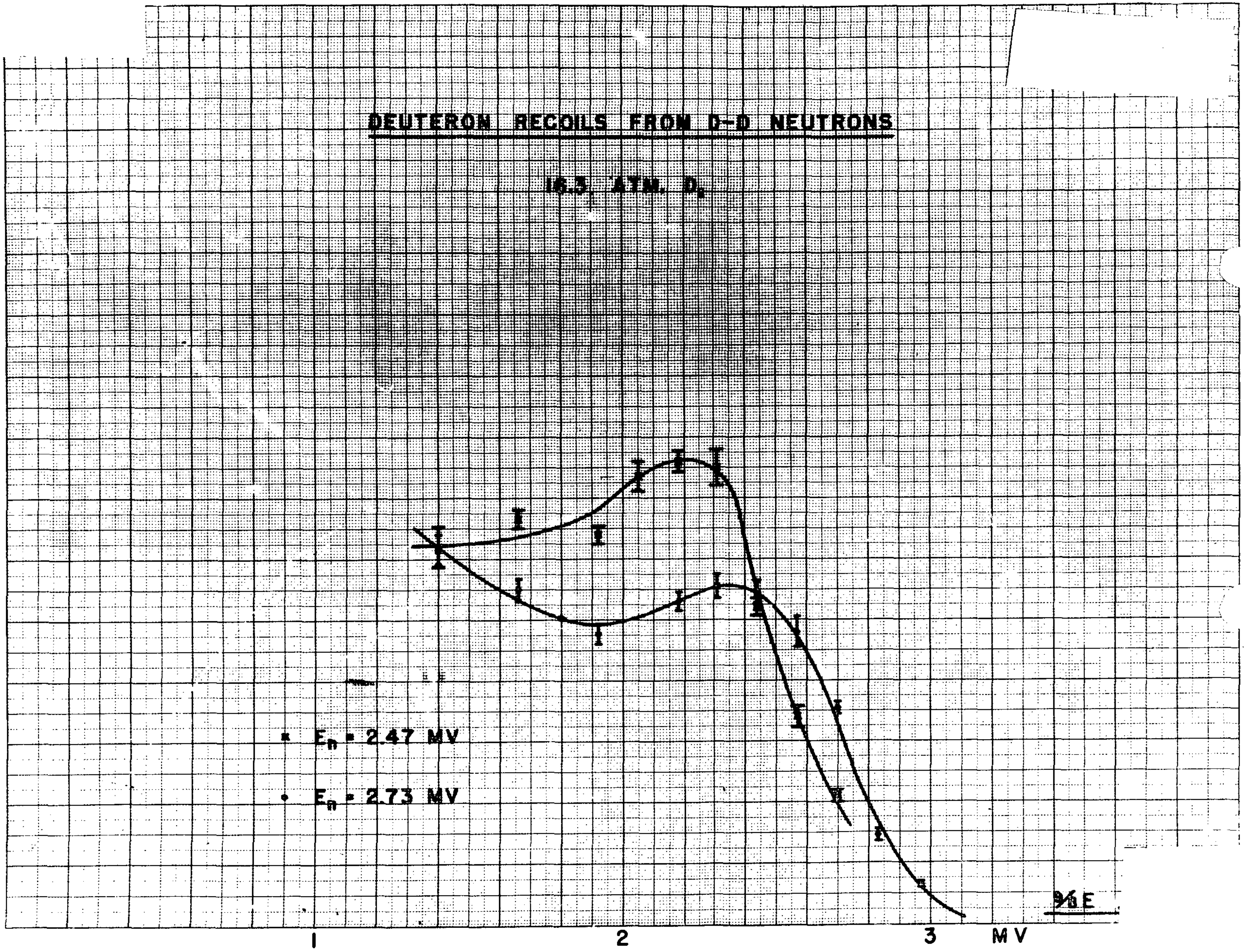

DEUTERON RECOILS FROM D-D NEUTRONS
16.5 ATM. D_2
E_n = 2.47 MV
E_n = 2.73 MV
9/6E
1
2
3
MV

FIG. 15

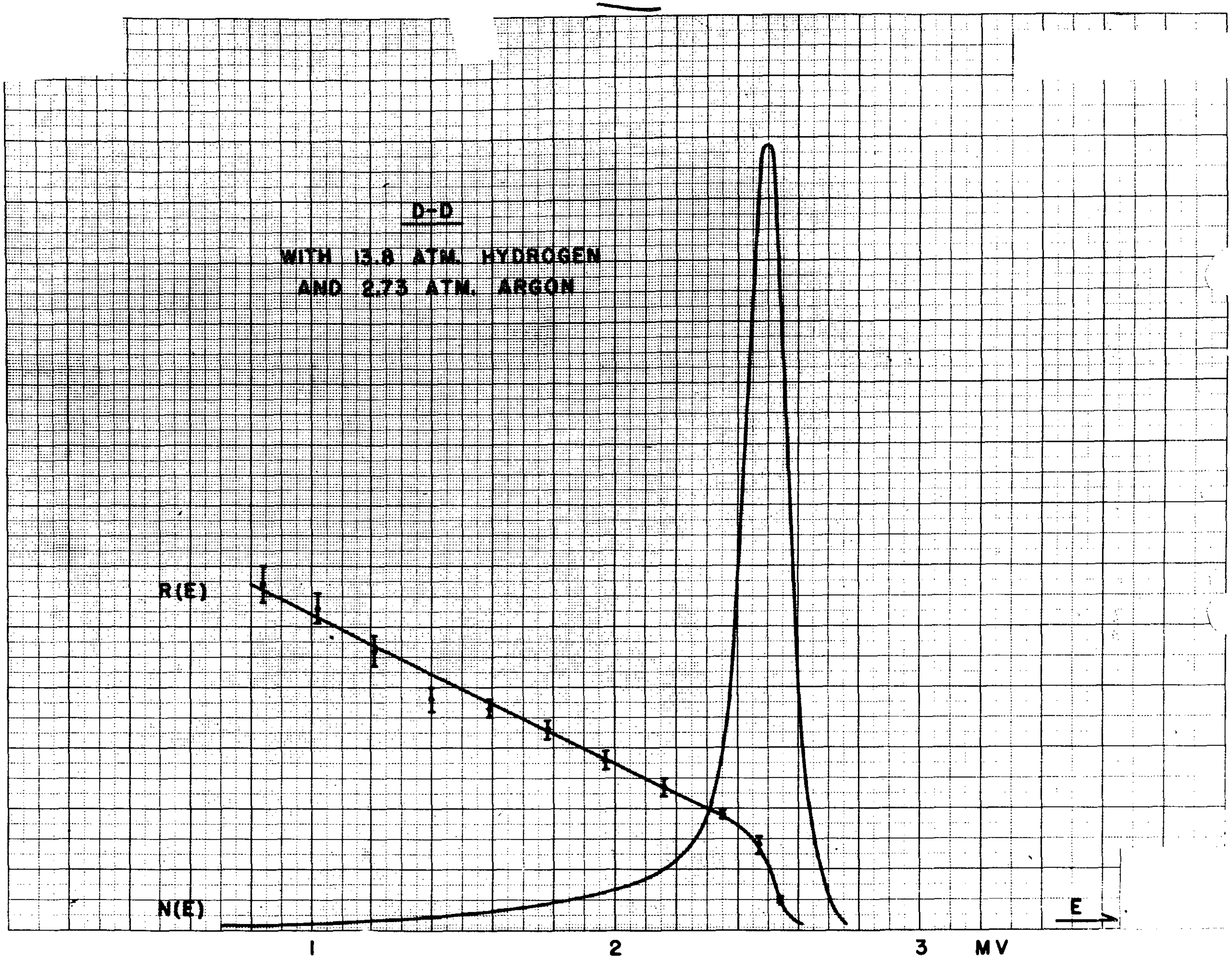


FIG. 16

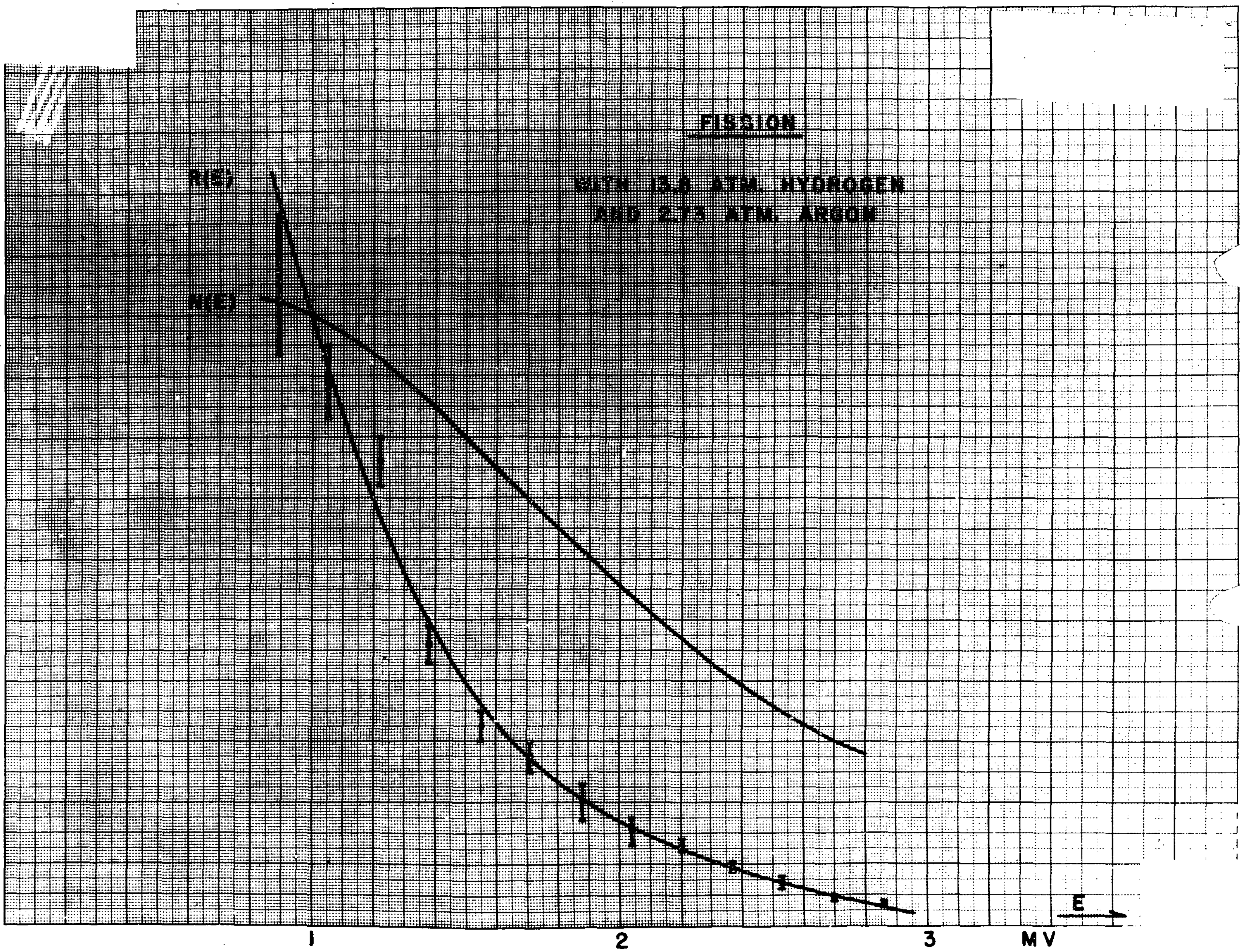


FIG. 17

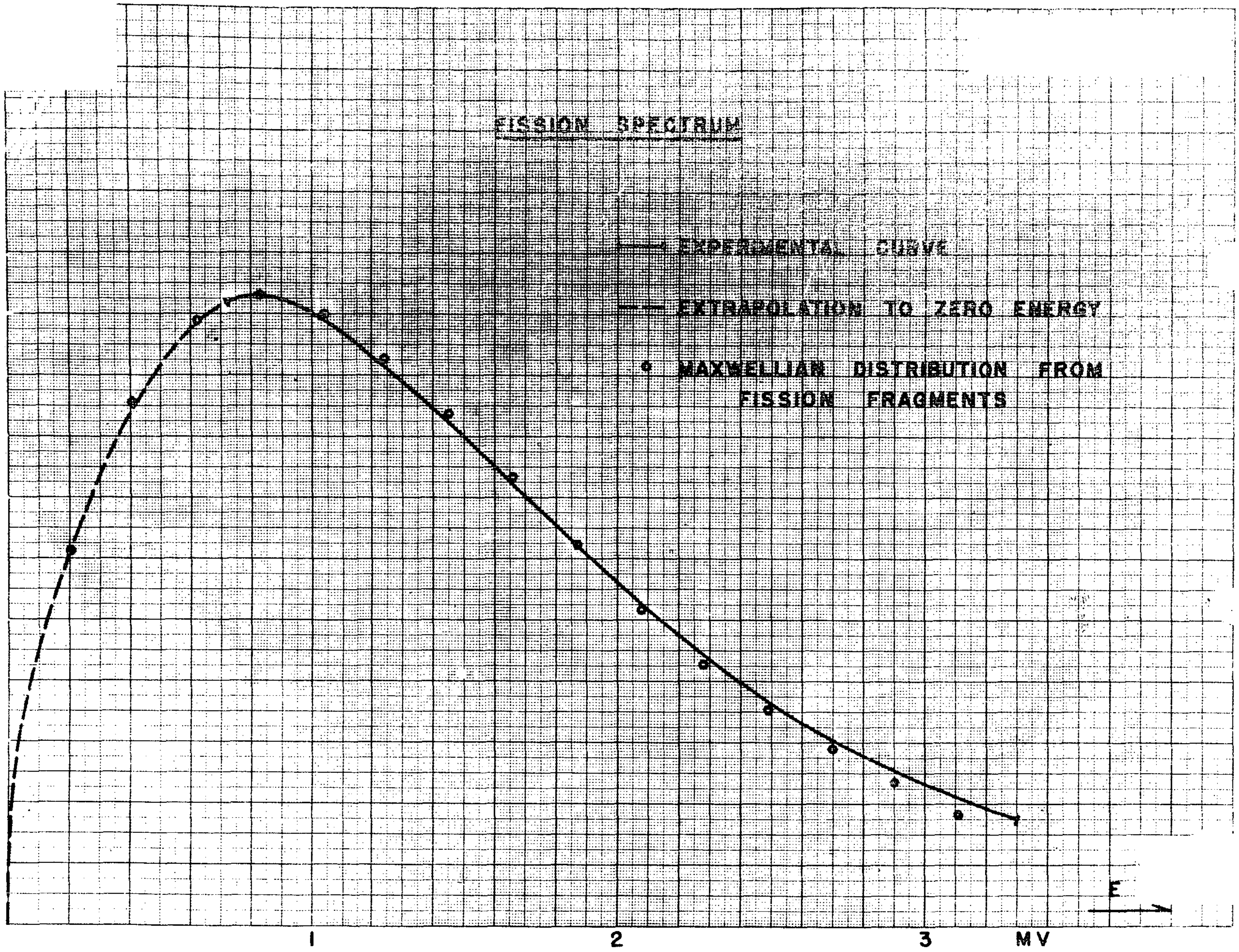

FISSION SPECTRUM
EXPERIMENTAL CURVE
EXTRAPOLATION TO ZERO ENERGY
MAXWELLIAN DISTRIBUTION FROM FISSION FRAGMENTS
E
1
2
3
MV

FIG. 18

FISSION SPECTRUM

Comparison of the data for the fission spectrum, obtained by the pulse height method of Bloch and Staub and photographic emulsion technique of recording recoil tracks by I. H. Perlman and Richards.

Curve 1: Intensity of recorded recoil pulses in arbitrary units versus their energy in MV as obtained by Bloch and Staub. The dots and crosses are the results obtained with two different ionization chambers filled with 26 atm of H_2 and a mixture of 13.6 atm H_2 plus 2.73 atm A respectively.

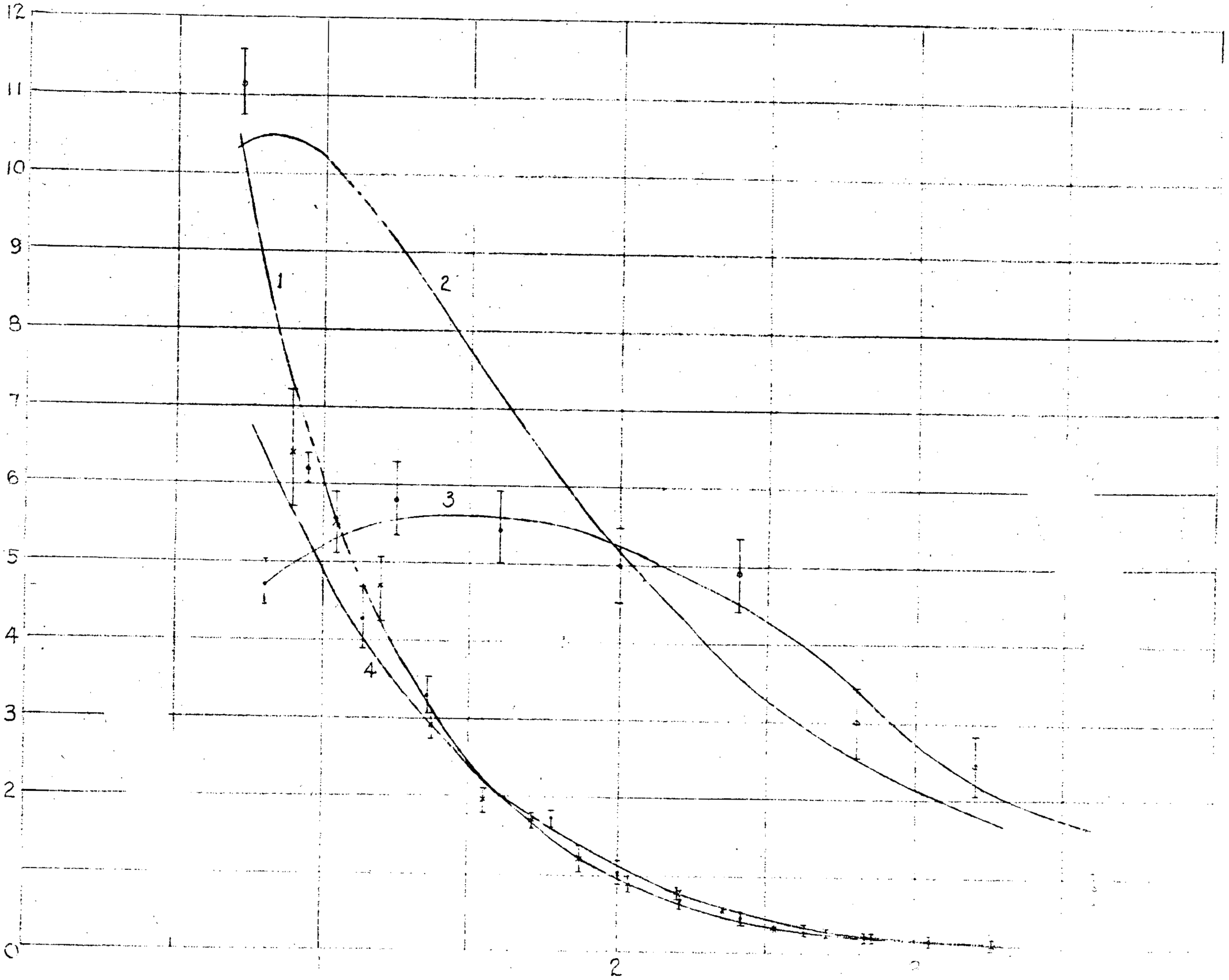
Curve 2: Fission spectrum as derived from curve 1, taking into account the wall effects of the chamber.

Curve 3: Fission spectrum as obtained by I.H. Perlman and Richards. The ordinate scale is chosen so as to make curves 2 and 3 cross at about 2 MV. The circles represent experimental points with their statistical error.

Curve 4: Intensity of recoil pulses versus energy which would be observed in the chambers of Bloch and Staub if the true fission spectrum were given by curve 3.

Remarks: Above 2 MV the fission spectra, obtained by the two methods and represented in curves 2 and 3 agree within the experimental error. Below this energy, curve 2 shows a markedly greater number of low energy fission neutrons with a maximum at about .8 MV instead of 1.5 MV as indicated by curve 3.

The difference of the two results is far less outspoken in the comparison of the integral curves 1 and 4 than of the differential curves 2 and 3 and is not significant above an energy of 1.5 MV. Below this energy there is a significant upward trend of curve 1 compared to curve 4 and the difference at .8 MV is very large compared to the experimental error, indicating either spurious counts in the pulse height method or missing of short recoil tracks in the emulsion technique.



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