IN THE UNITED STATES PATENT OFFICE

Applicant LEO SZILARD
Serial No. 10,500
Filed March 11, 1935.
Div. 56. Room 4725.

APPARATUS FOR NUCLEAR TRANSMUTATION.

Hon. Commissioner of Patent,
Washington, D.C.

Sir,

In response to the Official Action of the 14th January, 1937, please amend claim 44 as follows:-

Line 4 re-write the last six words to read "to produce fast cathode rays".

Line 6 delete "stream" and substitute "rays".

Also in claim 45, please change "a fast cathode stream" to read "fast cathode rays" in line 4, and in line 6 change "stream" to "rays".

Add new claims 52 to 55 as follows.

52. A method of generating a radio-active element from elements which transmute in the process into their own radio-active isotopes, consisting in irradiating a compound of the element which will not dissociate to give ions of the free element, and separating the element freed from the compound in the process by chemical methods.

53. A radio-active body comprising an element and neutrons combined with the nuclei of said element.

54. A method of generation of radio-active substances comprising the steps of producing a fast electron stream, directing such stream to fall upon an anti-cathode to produce hard X-rays, and allowing such X-rays to fall upon a body of an element having a dissociable neutron.

55. In apparatus for the generation of radio-active bodies by the use of X-rays, means for producing the X-rays comprising a tube for generating fast cathode rays and an anti-cathode exterior to said tube and arranged to intercept the cathode rays therefrom to produce said X-rays.

R E M A R K S.

The contents of the Official Action under reply have been carefully studied, and also the pertinent parts of the

that a process should be carried out, which process is possibly already known. But Applicant has done more than this, because a carrying out of that process gives an unexpected result which in the normal course of events would not be observed at all, and which only with the aid of the Applicant's teaching is ever suspected. In Applicant's submission the only publication of the production of radio-activity by his method (as viewed in its broadest aspect defined by claims 24 to 26, for example), is that which was made by Prof. Fermi, in Ricerca Scientifica 1934, (referred to subsequently in a book published by Franco Rasetti). Fermi independently made the same invention as Applicant after the date of Applicant's earliest English Patent Application. It will be seen in Rasetti's book entitled "Elements of Nuclear Physics" (1937) published in the Prentice-Hall Physic Series, and by Blackie & Son Limited, that Applicant's own publications in "Nature" are referred to by Rasetti. It is submitted that to persons versed in this art, the discovery that radio-activity could be produced by neutron radiation, was something totally unexpected, and hitherto unsuspected.

For the reasons advanced above, it is submitted that Applicant's broad claims 24 to 27 inclusive should be allowed.

It has been stated above that the earlier observers if they ever did produce radio-activity could hardly have been expected to observe it as such. This statement is made for the following reason. When a nucleus transmutes by bombardment with a neutron, the nucleus undergoes transmutation by splitting, by splitting with capture of the neutrons, or by radio-active capture of the neutron (i.e. without splitting.).

If transmutation is effected by splitting, then the radioactivity produced is of negligable importance from a practical point of view and would be extremely difficult to observe. On the other hand if transmutation takes place by radiative capture, then the production of radioactive elements is much enhanced. It is contended that earlier observers used fast neutrons so that they could in fact only have obtained transmutation by complete splitting or at most, splitting with capture. In Applicant's claim 28 the neutron radiation is defined as being obtained by accelerating diplogen ions in the form of positive rays and allowing the rays to fall upon diplogen. Neutron radiation produced in this manner will not in general be concerned with neutrons of sufficient speed to cause only splitting. In fact the major part of the action would be due to radiative capture of the neutron. For this reason alone it is submitted that claim 28 in any case differs patentably from the known art.

Claim 29 defines broadly a novel method of producing neutron radiation and it is, therefore, submitted that this claim is for patentable subject-matter. The cited publication in Bell System Technical Journal does not refer to the method of producing neutron radiation in which the nuclei of an element are caused to mutually collide. Claims 30 and 31 similarly define new methods of producing neutron radiation, and are likewise submitted to be for patentable subject-matter.

Claim 32 refers to a method for the production of neutron radiation which can only produce neutrons of a character too slow for anything but radiative capture. Furthermore it is submitted that the use of hard X-rays in

Signed at 500 Riverside Drive, New York City in the County of New York and State of New York this 11th day of March A. D. 1935

Leo Szilard

O A T H

State of New York)
) ss.:
County of New York)

Leo Szilard

the above-named petitioner, being duly sworn, depose and say that he is citizen of Germany and Hungary and resident of 500 Riverside Drive, New York City and that he verily believes ..... to be the original, first, and sole inventor of the improvement in apparatus for nuclear transmutation described and claimed in the annexed specification; that he does not know and does not believe that the same was ever known or used before his invention or discovery thereof; or patented or described in any printed publication in any country before his invention or discovery thereof or more than two years prior to this application; or in public use or on sale in the United States for more than two years prior to this application; that said invention has not been patented in any country foreign to the United States on an application filed by him or his legal representatives or assigns more than twelve months prior to this application and that no application for patent on said improvement has been filed by him or his representatives or assigns in any country foreign to the United States, except as follows:

England; March 12, May 9, June 14, June 28, July 4, Sept. 20 and Sept. 25, 1934.

Leo Szilard

Sworn to and subscribed before me, this 11th day of March A.D. 1935

Henry M. E. Thormann
Notary Public, Kings Co. No. 14, Reg.No. 6016
Cert. filed in N.Y.Co. No. 48, Reg.No.6126
Commission expires March 30, 1936

(SEAL)

TRANSMUTATION OF CHEMICAL ELEMENTS

The invention concerns methods and apparatus for the production of nuclear transmutation leading to the generation of radio-active bodies, to the storage of energy by means of the generation of radio-active bodies and the utilisation of the energy which has thus been stored for the production of heat and power, further to the liberation of nuclear energy and the utilisation of the liberated energy.

1) Generation of radio-active bodies. It is possible to produce with good efficiency radio-active bodies from various elements, if such elements are exposed to the penetrating radiation, the active agent of which are neutrons, that can be produced in various ways by means of electrical discharges. One way of generating such a neutron radiation consists in causing a nuclear reaction of hydrogen of the atomic weight 2 (diplogen)* with itself or other light elements

Fig. 1 shows an example of a suitable arrangement. 11 is an electrical discharge tube ejecting a beam 12 of fast diplogen ions.** The ions fall on a substance 13 consisting of for instance of gaseous diplogen or a diplogen compound or lithium, causing transmutation, i.e. a nuclear reaction of the diplogen ion with an atom of the target. The substance 13 is surrounded by a layer 14 containing the element which we wish to transmute into a radio-active element. In order to have a good efficiency, the thickness of the layer 14 has to be sufficiently large, compared with the mean free path of the neutron, for this transmutation.

Fig. 2 shows the electrical discharge tube referred to in fig. 1. It is a high voltage positive ray tube. There is an auxiliary positive ray tube on top of the high voltage tube. 11 is the anode, 15 the cathode of this auxiliary tube. Diplogen is admitted through the tube 13 and pumped away through

Sub. new Specification & Claims as per C1 & C2

Other suitable arrangements are based on a different principle. The nuclear reaction of diplogen with itself for instance can be enforced by "heating up" diplogen through an electrical discharge for a fraction of a second. We can, for instance, store electrical energy by charging a condenser and then suddenly discharge the condenser through diplogen. We thus obtain a neutron radiation which can be used for the generation of radio-active bodies as above. ~~Such devices for "heating up" will be described further below.~~

LS x *also called deuterium

LS x **also called diplons or deutons

Such an arrangement is shown in Fig. 3. The discharge tube 41, 44 which contains diplogen is connected through a spark gap 51 to the condenser 52 which is intermittantly discharged through the diplogen. The condenser 52 is connected with a high voltage supply (D.C.) through the chokes 53, 54.

In order to ~~xxxxxxxx~~ have a good efficiency the discharge tube has to be devised so as to introduce in a very short period of time a very large energy concentration in a small space filled with diplogen. One possibility of achieving this is by means of accelerating charged particles in a vacuum discharge tube and allowing them to go through the small space filled with diplogen.

Fig. 4 shows an illustration of the method. 41 is a discharge tube. 42 an electrode in this discharge tube. 43 a thin metal window hermetically sealing the vacuum in the discharge tube and allowing the passage of charged particles from the discharge tube into the interior of the vessel 44. A number of other discharge tubes similar to tube 41 can be placed around the vessel 44 in a position similar to that of 41, and all these tubes can be operated simultaneously. Each tube may have a separate set of electrical condensers and all these condensers may be discharged across the corresponding discharge tube simultaneously by using an electric impulse to bridge all the spark gaps simultaneously. The corpuscular rays of all the discharge tubes are focused on a small area 45 the "transmutation area" the volume of which is only a small fraction, ~~e.g. of xxx xxxxx of~~ of the volume of the vessel 44. The vacuum tube~~s~~ 41 may be operated as cathode ray tubes. Vacuum can be maintained in the interior of the vessel 44.

Up till now we have described the generation of radioactive bodies from elements which are transmuted by neutrons into radioactive bodies, by methods in which neutrons were

liberated in a nuclear reaction between light elements. The nuclear reactions between the light elements were brought about either by the bombardment of a target containing light elements with a beam of fast light atoms or by heating up a small space containing a light element. Now two further methods will be described for the liberation of the neutrons leading to the generation of radioactive bodies. One of these is based on the fact that neutrons can be liberated from certain elements, for instance beryllium, by X-rays.

Figure 5 shows an arrangement suitable for the production of hard X-rays. 1 is the primary of a transformer, the secondary 2 of which is connected to the points 3 and 4. 3 is connected to the cathode 8 of the rectifier tube 5 and to the anode 7 of the rectifier tube 6. Point 4 is connected to the cathode 9 of the rectifier tube 10 and to the anode 11 of the rectifier tube 12. The cathodes 13 and 14 are connected to each other and to the earth. The anodes 15 and 16 are connected to point 17, and this point is connected to the pole 18 of the impulse generator 20, the pole 19 of which is connected to earth. The impulse generator 20 is built of condensers 21, resistances 22 and spark gaps 23.

This impulse generator is adapted to produce intermittant voltage up to 10 million volts, transmitted to the discharge tube 24 through the spark gap 25. 26 is the cathode of the discharge tube, the anode 27 of which is connected to the earth. The fast electrons emerge through the metal window 27 (which is the anode as well) and are hitting a body 28. This body is used as an anticathode and yields hard X-rays with very good efficiency if it is built of Bi, Pb or some other heavy element.

In Figure 6, 27 is the window of the high voltage tube through which the fast electrons are ejected. The electrons hit the rotating anticathode 30 which is covered with lead or tungsten (W) 31. This anticathode is water-cooled, the water entering the rotating body through the axis 35. 32 is a beryllium block in which a space has been left for the rotating anticathode and for the path of the cathode rays 33 between the window 27 and the anticathode. This beryllium block may for instance have a size of 25 cm. x 25 cm. The voltage used to operate the electron tube may be three million volt. The beryllium block is surrounded by a block 34 of the element which we wish to transmute into a radio-active element. For instance, iodine or arsenic or any other element that is suitable. While it is advisable to use metalic beryllium in the block 32 the element in the block 34 may be present in the form of an organic compound in order to make an isotopic separation possible after irradiation. The dimensions of block 34 may, for instance, be 50 cm. x 50 cm.

Fast electrons have a similar action on beryllium as hard x-rays, a fraction of this action may be due to the direct action of the fast electrons on the beryllium. In view of the fact that hard x-rays generate fast electrons in the beryllium, part of their action can be due to fast electrons. In any case, we do not wish to differentiate here between the action of fast electrons and hard x-rays, and while we think it likely that the direction action of hard x-rays on the beryllium plays the major part in the liberation of neutrons, we wish to envisage the following modification of our method: The electrons of the discharge tube fall instead of lead on beryllium which can be put into the place of the lead coating 31 of the rotating anticathode 30 in Figure 6.

Many elements transmute when bombarded by slow neutrons into their own radio-active isotope and it requires a special method chemically to separate the radio-active element from its irradiated isotope. We can achieve such a separation by irradiating a suitable chemical compound of the said element. Those atoms of our element which transmute into a radioactive atom are thrown out of the compound and xxxxxx will subsequently be called "free" If we choose a compound which in the circumstances does not interchange the atoms of our element bound within the compound with the "free" atoms, which are their isotopes, we can chemically separate the "free" atoms from the compound and thereby separate the radioactive isotope from the irradiated element. Compounds in which the element in which we are interested are bound direct to carbon are very often suitable. For instance, in the case of iodine compounds like iodoform or ethyl iodide can be irradiated and after irradiation the radioactive isotope can be concentrated by separating the "free" iodine from the iodoform or the ethyl iodide. In order to protect radioactive iodine a small amount of ordinary iodine can be dissolved in the organic iodine compound before irradiation or after irradiation but before separation.

In the following we shall deal with methods and apparatus for the production of energy and generation of LS X radio-active bodies by means of chain re-action. In order to maintain such a chain an initial radiation of neutrons is generated by one of the methods described further above. If the neutrons enter a space which has the proper shape and size and which is filled with a proper combination of LS x elements their energy or their number, or both, can be increased through their interaction with the substance which fills the chain reaction space. The interaction of a neutron with matter can lead to the liberation of further neutrons - these newly liberated neutrons liberate again in their turn further neutrons so that we can have a chain reaction in which a large number of neutrons are liberated, the total number of which is determined by the geometry of the arrangement.

Figure 7 and 8 show such a chain reaction apparatus. A neutron radiation, the initial radiation, is generated by the high voltage canal ray tube 1 (shown in greater detail in figure 2.) This tube generates fast deutons which strike the target 28 which contains deuterium. The neutron radiation emerging from 28 acts on the matter 3 which fills the spherical transmutation space. The composition of this matter 3 will be discussed further below and is such that a chain reaction is released by the neutrons. The pumps 120, 121 and 122 pump a liquid for instance water or mercury LS x through the pipe systems 107, 110, 111 thereby cooling the transmutation area 3 and driving the heated liquid through the boiler 126. The boiler supplies steam to a power plant. The neutrons emerging from the sphere 3 act on a layer 9 which is composed of an element xx that will transLS x mute into a radio-active body (which is suitable for the storage of energy.)

LS x An essentially different way of introducing the initial radiation into the chain reaction chamber is the

arrangement shown in Figure 9. 401 is the cathode ray tube described in Figure 1. 402 is a sheet of a heavy element for instance Pb, or U in which penetrating radiation (hard X-rays) is generated with an extremely good
LS X efficiency if the electrons have a voltage ~~about-or~~ over
LS X one million volt. This efficiency increases very rapidly with the voltage, and is much higher than it could be expected from the experience based on ordinary x-ray work. The thickness of the sheet 402 is such as to enable the generated penetrating radiation to penetrate through this sheet and act on the transmutation chamber 106 (in Figure 8). Nevertheless the sheet can be sufficiently thick to utilise more than half of the energy of the cathode rays. The X-rays emerging from sheet 402 penetrate the
LS X layer 3 and can liberate ~~efficient-particles~~ neutrons either from the layer 3 or from a substance 407 placed in the interior of the layer 3.) For instance, if we have
LS X ~~diplogen~~ beryllium present in 4o3 or in 3 neutrons will be ~~xxxxxx~~ liberated by X-rays. These neutrons can then maintain a chain reaction as discussed further above and further below.

The advantage of using X-rays as an initial radiation is the following: The x-rays penetrate through a perfectly closed layer 3 into the interior of the layer and therefore a leak of neutrons from the interior can be avoided. This is speciallz important if we have to deal with a neutron chain in which no multiplicator action is involved. In such cases x-rays may beused with advantage as initial radiation especially in view of the unexpectedly large efficiency of the x-ray production by means of fast electrons acting on heavy elements.

In the simpliest case, when neutrons alone form the links of the chain, we shall demonstrate in the following the importance of the shape and the size of the transmutation space. If we have a closed spherical layer of material in which the chain reaction takes place the inner radius (r_i) of which is large compared with the

mean free paths / of the ~~efficient particles which~~ neutrons which maintain the chain, the density (s) of the neutrons will with good approximation be given as a function of the radius (r) by the following equation:

$$D\, d^2(rs) / dr^2 + A\,(rs) = 0$$

D and A are determined by: the mean free path of the neutrons a; the mean velocity of the neutrons w; the factor of the multiplicating action f which says how many collisions of a neutron LS X ~~electron~~ are needed in the average in order to produce one neutron LS X new ~~electron~~. $A = w / af$; $D = aw / 3$: $\sqrt{\frac{D}{A}} = \frac{a\sqrt{f}}{\sqrt{3}}$

We are interested in the critical thickness ℓ_0 of the spherical layer for which the gradient of the density s vanishes. If the thickness $(r_2 - r_1)$ approaches ℓ_0 we can maintain with a very weak source of initial radiation in the interior of the inner surface of the spherical layer a very strong chain reaction and we can easily get one thousand or more times more neutrons emerging from the chain reaction layer than the number of the neutrons forming the initial radiation. If the outer surface ($r = r_2$) of the spherical layer were to stand free in space the density s would be zero for that surface and the critical value l_0 would be given by $l_0 = \pi / 2\sqrt{D / A}$. If the outer surface is covered by some material, for instance if the transmutation layer is immersed into water or covered by lead the critical value l_0 is reduced. This is due to the back scattering by water or lead and also to the fact that the neutrons are slowed down in the water and their mean free path is thereby reduced.

It is important to prevent neutrons from escaping out of the interior of the inner surface of the spherical layer and also from being absorbed in the interior. If the initial radiation is generated by apparatus placed into the interior of the sphere the material used should be so selected as to lead to a minimum of absorption.

If the thickness is larger than the critical value l_0 we can produce an explosion.

We shall now discuss the composition of the matter in which the chain reaction is to be maintained. We wish to distinguish three main types of chains.

(a) Pure neutron chains, in which the links of the chain are formed by neutrons of the mass number 1 alone. Such chains are only possible in the presence of a metastable element. A metastable element is an element the mass of which (packing fraction) is sufficiently high to allow its disintergration into its parts under liberation of energy. Elements
LS X like uranium and thorium are examples of such metastable elements; these two elements reveal their metastable nature by emitting alpha particles. Other elements may be metastable without revealing their nature in this way. Whether an element is metastable or not can be determined by means of the mass spectrograph. If, for instance, the value obtained by Bainbridge for beryllium by means of the mass spectrograph, which appears to be generally accepted at present, is really valid, we have to conclude that beryllium is a metastable element and can disintergrate into parts with the liberation of energy, one of the parts set free in its disintergration being a neutron.

Per C

If we have an element which is metastable but the disintergration of which is inhibited and if this inhibition can be lifted in a collision with a neutron we shall call such an element an inhibited metastable element. If an inhibited metastable element "A" is exposed to neutrons, we may have the following reaction.

"A" + n = "B" + n + Energy

LS X The element "A" transmutes into an element "B" which has the same atomic number and mass number and energy is transmitted to the neutron. The element "B" may break up into an element "C" and a neutron, the element "C" having the same atomic number as "B". The element "C" may or may not break up into further parts. If the interaction of a neutron with the element "A" leads in this way to an increase in the number of neutrons (the newly created neutrons would together with the original neutrons continue to interact with the elements "A" thereby forming
LS X the links of a chain reaction.) We shall call element "A" a metastable multiplicator.

All particles which have a mass approximately equal to the mass of the proton or a multiple thereof can play a similar role as the neutrons provided they carry no charge or a negative charge and we shall call all these particles heavy non-positive particles. Protons, deutons and other positive particles can not be used as links of chain reactions. All pure chains in which one and the same heavy non-positive particles forms the links of the chain must necessarily make use of inhibited metastable elements. The simplest non-positive heavy particles apart from the neutron are the neutron with the mass number 2 and the negative proton.

(b) Chains in which two different types of heavy non-positive particles alternate. Such chains need not necesarily make use of metastable elements. For instance, an element "D" may be so chosen that when interacting with a neutron (of mass number 1) a double-neutron (a particle with the atomic number 0 and the mass number 2) should arise and when interacting with a double-neutron a neutron should arise, and that these reactions should have a positive energy balance. If such a chain could be maintained in deuterium each link would liberate between 4 to 5 m.e.v.

$$\left.\begin{aligned} H\,(2) + n\,(1) &= n\,(2) + H\,(1) \\ H\,(2) + n\,(2) &= H\,(3) + n\,(1) \end{aligned}\right\} \quad 4.5\,\text{m.e.v.}$$

Per C

Such a chain can also be maintained in mixtures of two different elements "E" and "F" which show the reactions:

$$\text{"F (m)"} + n\,(1) = n\,(2) + \text{"G (m - 1)"}$$

$$\text{"E (k)"} + n\,(2) = \text{"I (k+1)"} + n\,(1)$$

We shall call an element "F" which reacts with a heavy non-positive particle and transmutes into an element the mass number of which is one less, a converter element. An element "E" which reacts with a heavy non-positive particle and transmutes into an element the mass number of which is increased by one, reducer element. Most elements which yield protons when bombarded by deutons can be used as reducer elements. Beryllium can act as a converter element. In order to have a chain action in which the number of neutrons increases we must have apart from the converter and the reducer a multiplicator element which either splits up double-neutrons into two neutrons or from which neutrons are liberated in a process in which the interacting non-positive heavy particle is not captured.

"C"- Chain reactions in which a heavy non-positive particle, for instance, a neutron, and a sygma quantum alternate.

Many elements which capture a neutron emit a radiation which carries away the energy liberated in the capture process. While the nature of this radiation is not yet established beyond doubt (a large fraction of it may consist in a gamma radiation) it can be shown from the laws of thermo-dynamic equilibrium that this radiation, which we shall call sygma radiation, can liberate neutrons from elements and the cross section of this process (which is the inverse process of the capture) can be calculated. Some elements emit two sygma quanta if they capture a neutron and can act therefore as multiplicators in a chain reaction. If we have a mixture of elements (even pure elements have to be considered as mixtures of their isotopes) we can choose the components of the mixture so that one of the components "K" captures neutrons and emits two sygma quanta of the energies E_1 and E_2; another component "L" absorbs the quanta of energy E_1 and emits neutrons which are again captured by "K" and lead again to the emission of sygma quanta; a third component "M" absorbs the quanta of energy E_2 and also emits neutrons which too will be captured by "K".

Per C In order to have a large absorption coefficient for the sygma quanta we ought to choose such elements "L" and "M" which have a resonance for quanta of the energies E_1 and E_2 respectively. Similarly "K" may have resonance for the capture of the neutrons liberated by the sygma radiations from the other components or else the neutrons may be slowed down for instance by elastic collisions in hydrogen and "K" may have resonance for the neutrons which have been slowed down to its resonance level (which may be at zero energy).

LS X One possible combination of the resonance levels is that "K", "L" and "M" have all resonances at zero energy of the neutron ("K" for capture, "L" and "M" for liberation of neutrons) and that E_1 and E_2 are slightly above the binding energies of the neutron in "L" and "M" respectively.

Examples for elements which have a resonance for the capture of neutrons at zero energy are cadmium, mercury et cetera. Other such elements, like for instance - rhodium transmute into a radioactive element if they capture a neutron. If a radioactive element is formed one of the two sygma (gamma) quanta may be emitted with a considerable time lag, corresponding to the half life period of the radioactive element.

By maintaining a chain re-action in combination with means for leading away and utilizing the heat set free in the transmutation process energy can be produced and utilized for power production. In the same way, by heating up deuterium by means of an electrical discharge as described in that part of this specification which relates to Figures 3 and 4 in combination with means for leading away and utilizing the heat set free in the transmutation process energy can be produced and utilized for power production.

(1) In an apparatus for the production of radioactive elements I claim the combination of a device adapted to produce neutrons and a body (containing an element which transmutes into radioactive elements when interacting with neutrons) exposed to the neutrons generated by the said device.

(2) In an apparatus for the production of radioactive bodies, according to Claim One, I claim the said device being the combination of a high voltage canal ray tube adapted for the generation of fast deutons or other light ions and deuterium or other light elements exposed to the said canal rays.

(3) In an apparatus for the production of radioactive bodies, according to Claim One, I claim the said device being the combination of a high voltage x-ray tube and an element from which neutrons are liberated by x-rays, for instance, beryllium exposed to the x-rays generated by the said tube.

Ger C (4) In an apparatus for the production of radioactive bodies, according to Claim One, I claim the said device being the combination of a high voltage electron tube and an element from which neutrons are liberated by fast electrons exposed to the cathode rays generated by the said tube.

(5) In an apparatus for the production of radioactive elements, according to Claim One, I claim the said body which is exposed to the ~~radix~~ neutrons generated by the said device containing a chemical compound (of an element which transmutes into radioactive elements when inter-acting with neutrons) adapted for the chemical separation of the generated radioactive element from its non-radioactive isotope.

(6) In an apparatus for the production of radioactive elements, according to Claim One, I claim in the said device the combination of means for storing electrical energy, an electrical discharge tube adapted to produce a high energy concentration in a small space if the electrical energy stored by the said means is suddenly discharged ~~through~~ through it, deuterium or mixtures of deuterium or helium and other light elements in the said small space, means for discharging suddenly ~~the~~ the stored energy through the said discharge tube.

(7) In an apparatus for the production of energy, I claim the combination of means for storing electrical energy, an electrical discharge tube adapted to produce a high energy concentration in a small

space if the electrical energy stored by the said means is suddenly discharged through it, deuterium or mixtures of deuterium or hydrogen with other light elements in the said small space, means for discharging suddenly the stored energy through the said discharge tube, means for leading away and utilizing the heat liberated in the transmutation process.

(8) In an apparatus for the production of radioactive elements or energy, I claim the combination of a device adapted to generate an initial radiation, for instance a neutron radiation, exposed to this radiation a body so composed that a chain reaction of neutrons be maintained.

(9) In an apparatus for the production of radioactive elements or energy, according to Claim 8, I claim the exposure of an element, which is transmuted into a radioactive element by neutrons, to the neutron radiation generated in the said body.

(10) In an apparatus for the production of radioactive elements or energy, according to Claim 8, I claim means for leading away the heat generated in the transmutation process, means for utilizing the generated heat for power production.

(11) In an apparatus for the production of radioactive elements or energy, according to Claim 8, I claim the said body being so composed that a chain of heavy non-positive particles is maintained.

(12) In an apparatus for the production of radioactive elements or energy, according to Claim 11, I claim that the said body contains a metastable multiplicator.

(13) In an apparatus for the production of radioactive elements or energy, according to Claim 11, I claim that the said body contains a converter element, a reducer element, and a multiplicator.

(14) In an apparatus for the production of radioactive elements or energy, according to Claim 8, I claim that the said body contains beryllium.

(15) In an apparatus for the production of radioactive elements or energy, according to Claim 8, I claim that the said body be so composed that the chain in which neutrons and sygma particles alternate be maintained.

(16) In an apparatus for the production of radioactive elements or energy, according to Claim 15, I claim that said body contains an ele-

ment "K" which emits more than one sygma quanta for each captured neutron and one or more elements "L", "M" . . . which absorb strongly the sygma quanta emitted by "K" and eject neutrons in doing so.

U. S. DEPARTMENT OF COMMERCE

UNITED STATES PATENT OFFICE

August 9, 1968
(Date)

THIS IS TO CERTIFY that the annexed is a true copy from the records of this office of Pages 8 and 9, as originally filed, forming part of the Application of Leo Szilard, filed March 11, 1935, Serial Number 10,500, for Apparatus for Nuclear Transmutation.

By authority of the
COMMISSIONER OF PATENTS

R. C. Talliner

Certifying Officer.

USCOMM-DC 26805-P62

also from being absorbed in the interior. If the initial radiation is generated by apparatus placed into the interior of the sphere the material used should be so selected as to lead to a minimum of absorption.

If the thickness is larger than the critical value l, we can produce an explosion.

mean free paths a of the ~~xxxxxxxxxxxxxxxxxxxxxxxx~~ neutrons which maintain the chain, the density (s) of the neutrons will with good approximation be given as a function of the radius (r) by the following equation:

$D\, d(rs) / dr + A(rs) = 0$

D and A are determined by: the main free path of the neutrons a; the mean velocity of the neutrons w; the factor of the multiplicating action f which says how many collisions of an ~~electron~~ neutron are needed in the average in order to produce one new ~~electron~~ neutron. $A = w / af$; $D = aw / 3$; $\sqrt{\frac{D}{A}} = \frac{a\sqrt{f}}{\sqrt{3}}$

We are interested in the critical thickness l_0 of the spherical layer for which the gradient of the density s vanishes. If the thickness $(r_2 - r_1)$ approaches l_0 we can maintain with a very weak source of initial radiation in the interior of the inner surface of the spherical layer a very strong chain reaction and we can easily get one thousand or more times more neutrons emerging from the chain reaction layer than the number of the neutrons forming the initial radiation. If the outer surface $(r = r_2)$ of the spherical layer were to stand free in space the density s would be zero for that surface and the critical value l_0 would be given by $l_0 = \pi/2 \sqrt{D / A}$. If the outer surface is covered by some material, for instance if the transmutation layer is immersed into water or covered by lead the critical value l_0 is reduced. This is due to the back scattering by water or lead and also to the fact that the neutrons are slowed down in the water and their mean free path is thereby reduced.

It is important to prevent neutrons from escaping out of the interior of the inner surface of the spherical layer and also from being absorbed in the interior. If the initial radiation is generated by apparatus placed into the interior of the sphere the material used should be so selected as to lead to a minimum of absorption.

If the thickness is larger than the critical value l_0 we can produce an explosion.

We shall now discuss the composition of the matter in which the chain reaction is to be maintained. We wish to distinguish three main types of chains.

(A) Pure neutron chains, in which the links of the chain are formed by neutrons of the mass number 1. alone. Such chains are only possible in the presence of a metastable element. A metastable element is an element the mass of which (packing fraction) is sufficiently high to allow its disintergration into its parts under liberation of energy. Elements like uranium and thorium are examples of such metastable elements; these two elements reveal their metastable nature by emitting alpha particles. Other elements may be metastable without revealing their nature in this way. Whether an element is metastable or not can be determined by means of the mass spectrograph. If, for instance, the value obtained by Bainbridge for beryllium by means of the mass spectrograph, which appears to be generally accepted at present, is really valid, we have to conclude that beryllium is a metastable element and can disintergrate into parts with the liberation of energy, one of the parts set free in its disintergration being a neutron.

If we have an element which is metastable but the disintergration of which is inhibited and if this inhibition can be lifted in a collision with a neutron we shall call such an element an inhibited metastable element. If an inhibited metastable element "A" is exposed to neutrons, we may have the following reaction.

"A" + n = "B" + n + Energy

The element "A" transmutes into an element "B" which has the same atomic number and mass number and energy is transmitted to the neutron. The element "B" may break up into an element "C" and a neutron, the element "C" having the same atomic number as "B". The element "C" may or may not break up into further parts. If the interaction of a neutron with the element "A" leads in this way to an increase in the number of neutrons (the newly created neutrons would together with the original neutrons continue to interact with the elements "A" thereby forming the links of a chain reaction), we shall call element "A" a metastable multiplicator.

Undated Notes

Drawings and specifications mainly concerned With Nuclear Transmutation

P E T I T I O N

TO THE COMMISSIONER OF PATENTS:

YOUR PETITIONER Leo Szilard
citizen of ~~the United States~~ Germany & Hungary and residing at 500 Riverside Drive, New York City. in the County of New York and State of New York and whose Post Office address C/O B. Liebowitz - 420 Riverside Drive, New York City.

prays that Letters Patent may be granted to him for the improvement in apparatus for nuclear transmutation set forth in the annexed specification; and he hereby appoint

~~State of~~ of attorney with full power of substitution and revocation, to prosecute this application, to make alterations and amendments therein, to receive the patent, and to transact all business in the Patent Office connected therewith.

Leo Szilard

S P E C I F I C A T I O N

TO ALL WHOM IT MAY CONCERN:

Be it known that I Leo Szilard
citizen of ~~the United States~~ Germany and Hungary and resident of New York City in the County of New York and State of New York have invented certain new and useful Apparatus for nuclear transmutation of which the following is a specification

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KENNETH H. MURRAY
HARRY E. DOWNER
CARL E. RING

E1512

Washington, D.C.
January 25, 1939

Mr. Leo Szilard
Kings Crown Hotel
420 West 116th Street
New York City, N.Y.

Dear Mr. Szilard:

At the request of Mr. R.M. Adams I am enclosing a photostatic copy of Figures 7, 8 and 9 of the drawings as originally filed in your application, Serial No. 10,500.

Very truly yours,

CMF:dr
att.

Asst. Dept. Corp.

13

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C-7

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KENNETH H. MURRAY
HARRY E. DOWNER
CARL E. RING

February 27, 1939.

E-1512

Dr. Leo Szilard,
Kings Crown Hotel,
420 West 116th Street,
New York City, N. Y.

Dear Dr. Szilard:

In accordance with your request I am returning herewith the three photostats of Figs. 7, 8, and 9 of your U. S. Application Ser. No. 10,500. I have had these photostats copied and have given the copies to the draftsman to use in making new drawings for your divisional application.

As you requested, the cost of these drawings will be charged to your personal account.

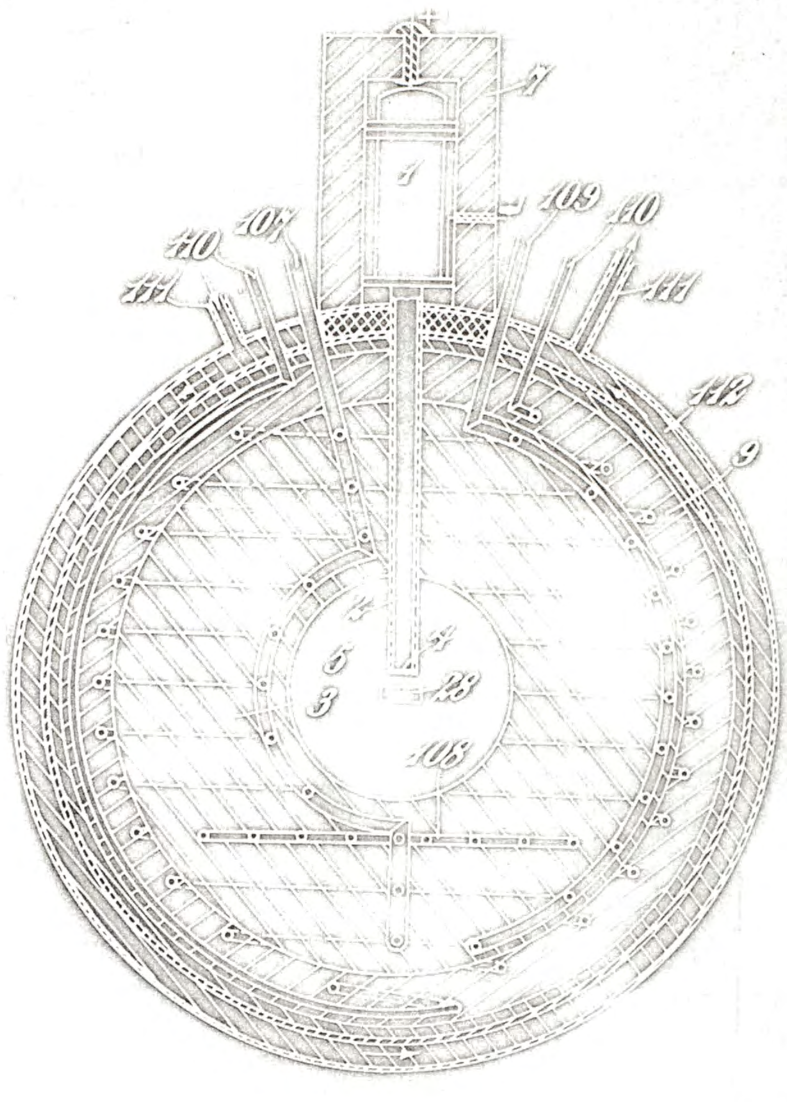
Very truly yours,

Encs.

SPECIAL DELIVERY

PWS C-7

10500



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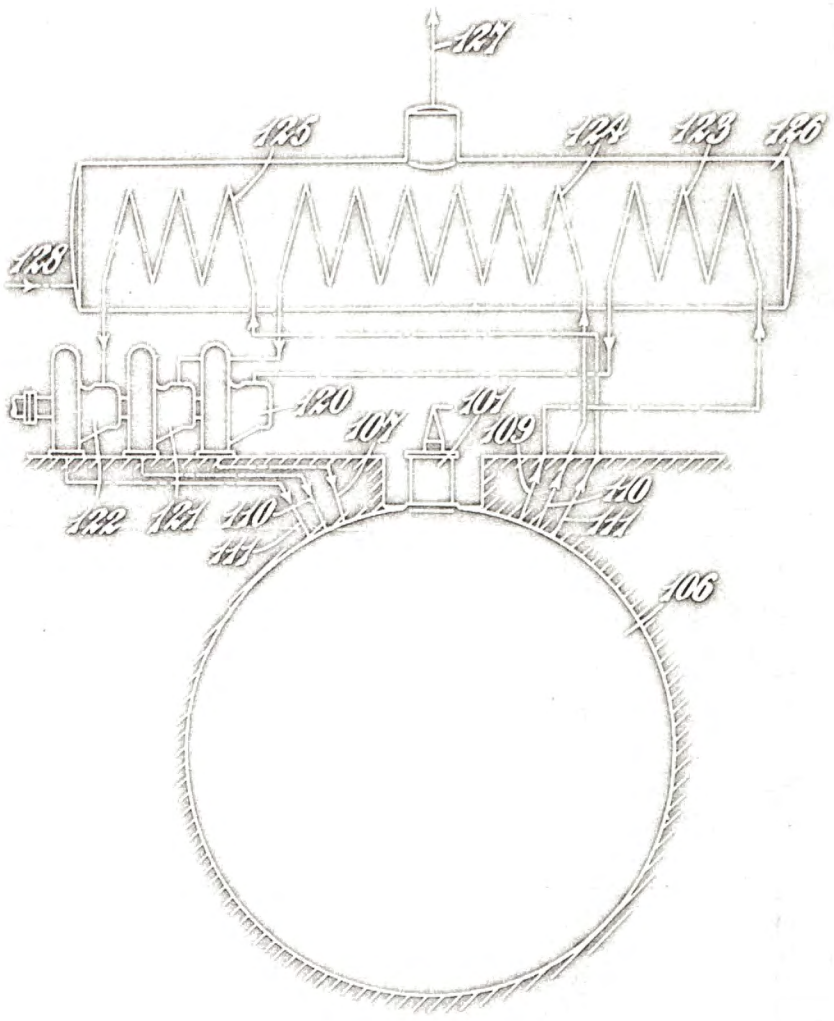
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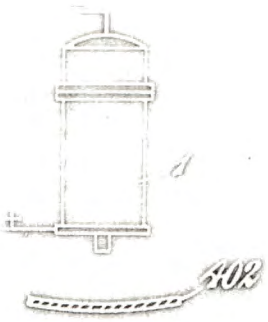
Fig. 8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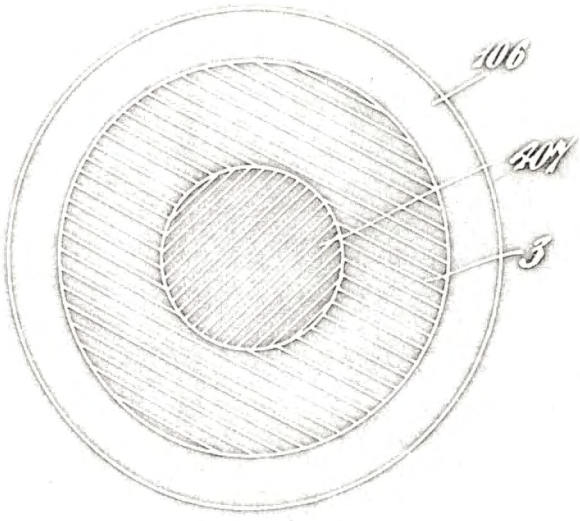
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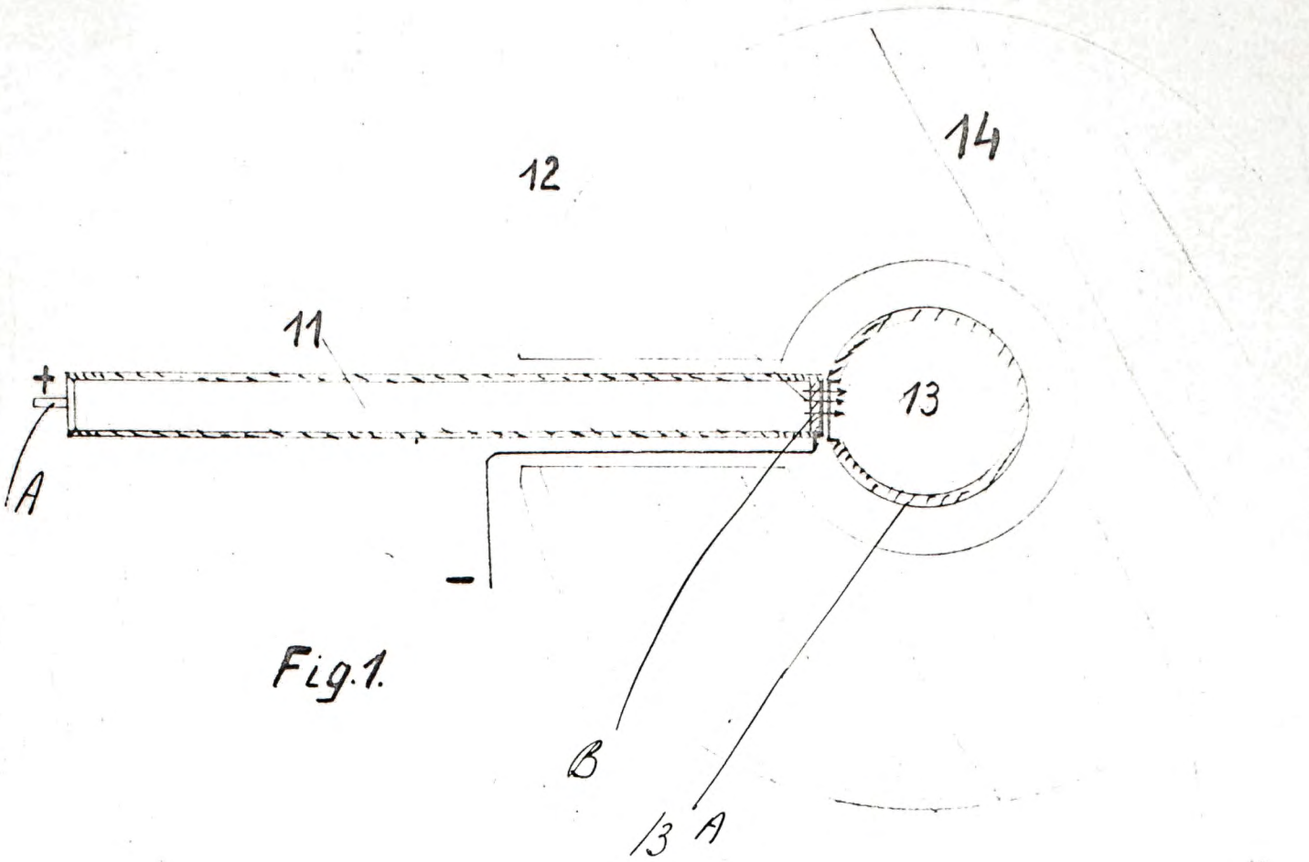
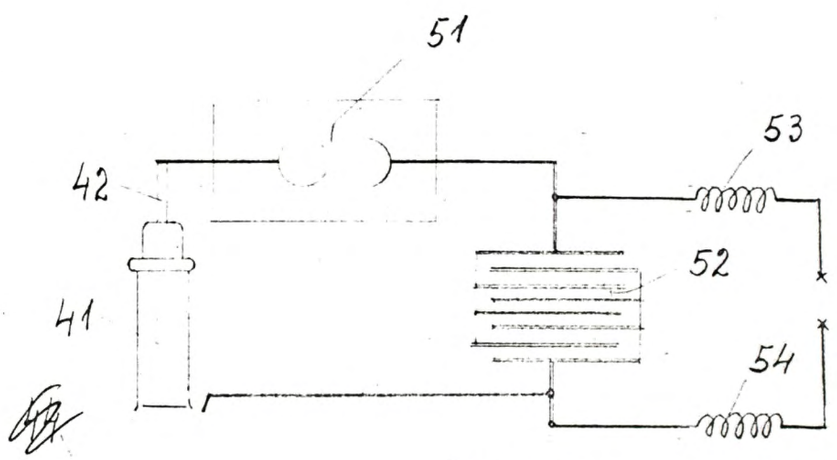


Fig. 1.

FIG. 3.



-10,500 - SZILARD -

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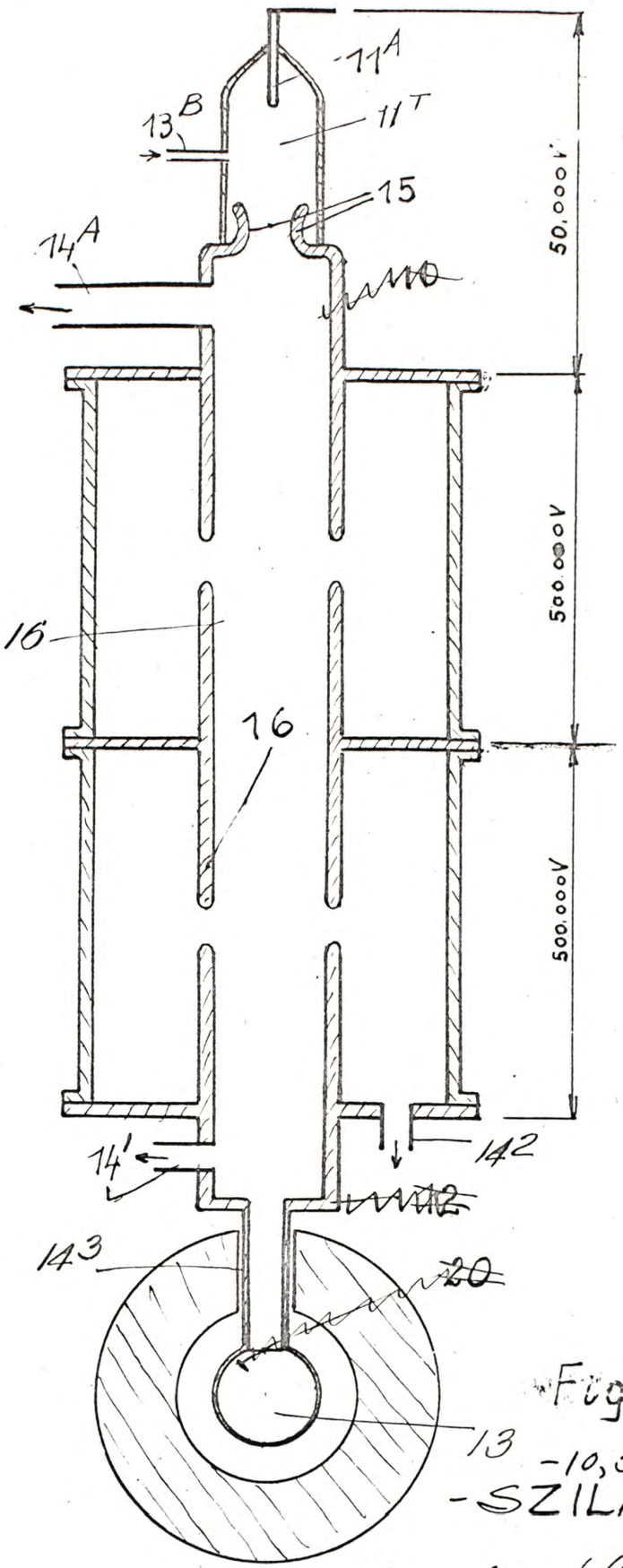

Fig 2.

-10,500-

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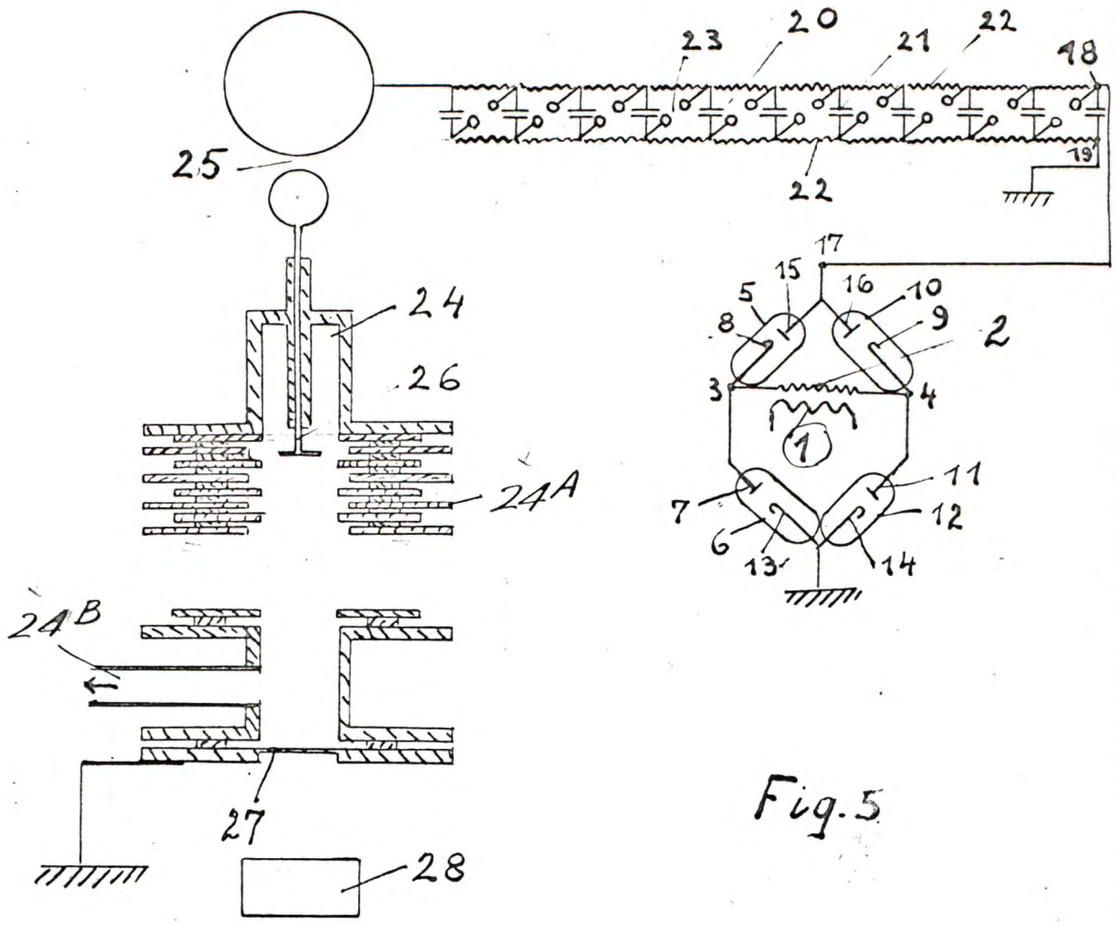

Fig. 5

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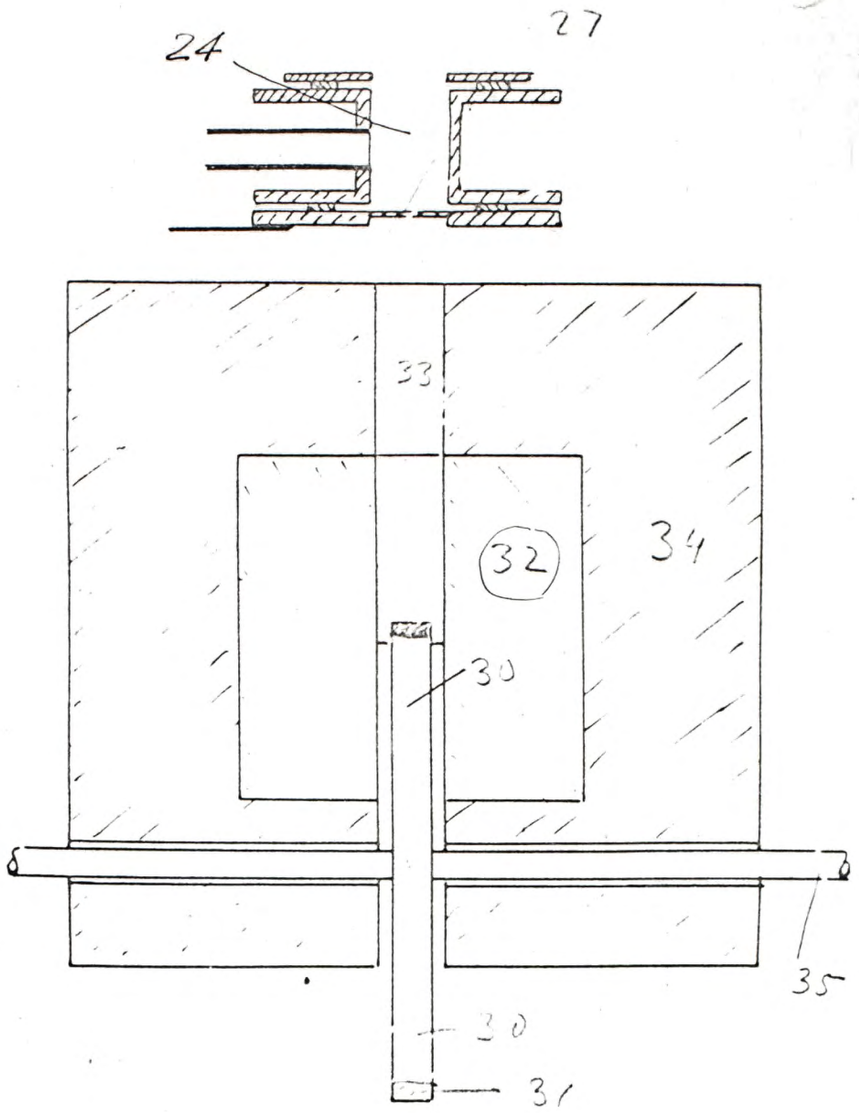

Fig. 6.

-10,500-
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subsequently to be called neutron chain reactors ~~which I shall call~~

~~Method~~ process and apparatus for

This invention concerns the large scale production of radioactive elements, ~~which~~ by means of certain types of nuclear reactions may lead to an efficient system of energy storage. ~~and~~ the production of heat which may be used for the production of electric power by means of a nuclear chain reaction. The links of the chain are neutrons which have no charge and have a mass approximately equal to the proton mass (or in certain cases possibly a multiple thereof). If a neutron of a certain velocity is brought to react with the nucleus of an element "A", and if as a result of this reaction on the average more than one neutron is emitted in place of the original neutron which disappears, we have then conditions in which a chain reaction of neutrons may be maintained. Naturally, the average number of neutrons emitted in the reaction need not be a whole number, it may be a number like, f.i. 1.3; this may mean f.i. that for one reaction in which two neutrons are emitted there are two reactions in which only one neutron is emitted. In order to be able to maintain a chain reaction ~~it is further~~ necessary that the velocity of the neutrons which are emitted ~~in the reaction should be~~ larger than the velocity which the neutron must necessarily have in order to cause this reaction, and the requirement that the average number of neutrons emitted should be larger than 1 refers to neutrons the velocity of which fulfills this requirement. If we have to deal with a reaction in a heavy element which can more efficiently be brought about by slower neutrons than by faster neutrons, arrangements can be used in which a neutron, which arises out of the breaking up of the heavy element, suffers collisions with nuclei of a light element such as for instance hydrogene or deuterium, and is thus slowed down before it bfeaks up another nucleus of a heavy element. If a chain reaction is maintained which obeys these general functional requirements, and if arrangements are

for instance

$$\text{"}A\text{"} + n = \text{"}B\text{"} + \alpha + n$$

$$A'' + n = \text{"}C\text{"} + n$$

$$\text{"}A\text{"} + n = \text{"}D\text{"}$$

The neutrons

used which obey some other geometrical requirements which will be discussed later, it is possible to maintain chains which comprise 1000, or even more, nuclear reactions each. It is then possible f.i. to obtain a neutron output which is more than thousand times larger than the neutron input. Large amounts of radioactive substances may be generated, both directly from the heavy element which is broken up and also by the large neutron output itself. Heat is generated by the breaking up of the heavy element, and if means are used to lead away and utilise this heat, the chain reaction may be used for power production.

Fig. 1 illustrates certain aspects of the invention. In Fig 1, 1 is a neutron source placed in a hollow sphere in the center of a closed spherical layer containing a heavy element U which is broken up by neutrons according to the reaction. n + U equal element 1 + element 2 + 2 n.

If a body containing element "A", ~~having the proper shape and proportions~~, is bombarded by neutrons, these neutrons will react with element "A" and liberate neutrons in numbers exceeding their own. These liberated neutrons will again react with element "A" and will again liberate an increased number of neutrons, so that finally the number of neutrons emerging from the body may far exceed the neutron input. We have to deal with a chain reaction. Naturally, the average number of neutrons emitted when a neutron reacts with element "A" need not be a whole number, since we may have a number of competing reactions. For instance we may have the reactions:

In these equations "A" is the carrier of the chain reaction, "B", "C" and "D" stand for one or more elements which are either stable or which tranform into stable elements by emission of charged particles but without the emission of a neutron. The average number of neutrons liberated by these reactions depends on the relative probability of the three reactions. If these probabilities are w_1, w_2 and w_3 respectively, it is necessary that w_1 should be larger than w_3 in order to have the reaction lead to an increase of neutrons, i.e. the liberation of an average number of nuetrons larger than 1 for the disappearance of a neutron. The relative probabilities of these reactions may be to some extent dependent on the velocity of the neutron which enters into reaction with element "A"; the dimensions of the body in which a chain reaction is maintained may be reduced by arrangements by which a neutron arising out of the breaking up of element "A" suffers collisions with nuclei of a light element, such as for instance in hydrogene or deuterium, and is thus slowed down. The slow neutron thus produced will

then react with another nucleus of the element "A", and the neutrons liberated are again slowed down, and so on.

In order to be able to utilize a nuclear reaction in which an excess number of neutrons is liberated by neutrons for the maintenance of a chain reaction, it is not sufficient to measure the cross-section and other constants of the reaction, but it is also necessary to be aware of the laws which govern the neutron output of such reactions in function of the geometrical conditions. Once the general laws, the type of behaviour is known, the exact dimensions can be easily determined in each particular case by actually measuring the neutron output. Such experimental adjustments can, however, only be made if the general type of behaviour is known.

In order to describe this general behaviour we consider in figure 1 a closed spherical layer (1) containing the carrier of the chain reaction "A" and a neutron source (2) in the center of the hollow sphere (3) inside the closed spherical layer (1). The inner radius of the closed spherical layer is r_1, the outer radius is r_2, and we wish to consider a case where the mean free path of the neutron a is small compared with r_1. a is the average distance which the neutron travels in the spherical layer (1) between two collisions in which the neutron changes its direction by ~~spherical~~ scattering. ~~But~~ It may take a number of such collisions before a nuclear reaction occurs in which two neutrons are emitted. The average number of collisions needed for this we designate by f. With these assumptions there will be at a point inside the spherical layer generated per cc. and sec. As neutrons where s is the neutron density at the point and A is given by

$$A =$$

In such a spherical symmetrical case the number of neutrons diffusing from the inside toward the outside along a radius per sec. and square cm is given by $D\frac{ds}{dr}$. In this expression D corresponds to the diffusion constant, and it is

D =

Whether or not a stationary solution is possible depends on the constants A, D and the boundary conditions and the values of r_1, r_2. If $(r_2 - r_1)$ is not too large ~~for a given set of constants~~, stationary solutions are possible, and for stationary solutions the number of neutrons per cc obeys the following equation:

$$\frac{d^2(rs)}{dr^2}$$ or for longer r and writing x in place of r

The solution of this equation has the form of

$rs = C_1 \sin kr + C_2 \cos kr$ where $k =$ or for longer r and writing x in place of r

If the outer surface of the spherical layer stands free in space so that we can put the density s at the outer surface $(r = r_2)$ equal zero, and we can write

$$rs = +C \sin k(r_2 - r) \quad \text{or} \quad s = \frac{C}{r}\sin(r_2 - r)$$

If we have no absorption of neutrons in the hollow sphere (3) inside the chain reaction layer 1 the neutron density s will fall within the chain reaction layer from its maximum value at $r = r_1$ to zero at $r = r_2$. ~~If there is no absorption the number of the neutron input (the number of neutrons left at the neutrons~~ There is a critical radius r_1 for which $\frac{ds}{dr} = 0$ If r_2 has a fixed value, and the chain reaction layer is made thicker and thicker by making r_1 smaller and smaller while the number of neutrons N emitted by source 2 is maintained

~~$\frac{ds}{dr}_{r_1} = N$~~

constant

$$\frac{d}{dr}\frac{\sin(r_2 - r)}{r} = 0$$

Assuming that the outer surface of the spherical layer stands free in space, we can put the density s at the outer surface ($r=r_2$) equal zero. For any given density of neutrons s on the inside surface ($r=r_1$), the neutron density will fall within the spherical layer with increasing r.

If a body containing element "A", having the proper shape and proportions, is bombarded by neutrons, these neutrons will react with element "A" and liberate neutrons in numbers exceeding their own. These liberated neutrons will again react with element "A" and will again liberate an increased number of neutrons, so that finally the number of neutrons emerging from the body may far exceed the neutron input. We have to deal with a chain reaction. Naturally, the average number of neutrons emitted when a neutron reacts with element "A" need not be a whole number, since we may have a number of competing reactions. For instance we may have the reactions:

In these equations "A" is the carrier of the chain reaction, "B", "C" and "D" stand for one or more elements which are either stable or which tranform into stable elements by emission of charged particles but without the emission of a neutron. The average number of neutrons liberated by these reactions depends on the relative probability of the three reactions. If these probabilities are w_1, w_2 and w_3 respectively, it is necessary that w_1 should be larger than w_3 in order to have the reaction lead to an increase of neutrons, i.e. the liberation of an average number of nuetrons larger than 1 for the disappearance of a neutron. The relative probabilities of these reactions may be to some extent dependent on the velocity of the neutron which enters into reaction with element "A"; the dimensions of the body in which a chain reaction is maintained may be reduced by arrangements by which a neutron arising out of the breaking up of element "A" suffers collisions with nuclei of a light element,such as for instance in hydrogene or deuterium, and is thus slowed down. The slow neutron thus produced will

then react with another nucleus of the element "A", and the neutrons liberated are again slowed down, and so on.

In order to utilize a nuclear reaction in which an excess number of neutrons is liberated by neutrons for the maintenance of a chain reaction, it is not sufficient to measure the cross-section and other constants of the reaction, but it is also necessary to be aware of the laws which govern the neutron output of such reactions in function of the geometrical conditions. Once the general laws, the type of behaviour is known, the exact dimensions can be easily determined in each particular case by actually measuring the neutron output. Such experimental adjustments can, however, only be made if the general type of behaviour is known.

In order to describe this general behaviour we consider in figure 1 a closed spherical layer containing the carrier of the chain reaction "A" and a neutron source in the center of the hollow sphere inside the closed spherical layer. The inner radius of the closed spherical layer is r_1, the outer radius is r_2, and we wish to consider a case where the mean free path of the neutron a is small compared with r_1. a is the average distance which the neutron travels in the spherical layer between two collisions in which the neutron changes its direction by spherical scattering. But it may take a number of such collisions before a nuclear reaction occurs in which two neutrons are emitted. The average number of collisions needed for this we designate by f. With these assumptions there will be at a point inside the spherical layer generated per cc. and sec. As neutrons where s is the neutron density at the point and A is given by

In such a spherical symmetrical case the number of neutrons diffusing from the inside toward the outside along a radius per sec. and square cm given by $D \frac{ds}{dr}$. In this expression D corresponds to the diffusion constant, and it is

D =

Whether or not a stationary solution is possible depends on the constants AD and the values of r_1, r_2. If $r_2 - r_1$ is not too large for a given set of constants, stationary solutions are possible, and for stationary solutions the number of neutrons per square cm s obeys the following equation:

The solution of this equation has the form of

If the outer surface of the spherical layer stands free in space so that we can put the density s at the outer surface ($r = r_2$) equal zero, and we can write

If we have no absorption of neutrons in the hollow sphere inside the chain reaction layer 1 the neutron density s will fall from its maximum value at $r = r_1$ to zero at $r = r_2$.

Assuming that the outer surface of the spherical layer stands free in space, we can put the density s at the outer surface ($r=r_2$) equal zero. For any given density of neutrons s on the inside surface ($r=r_1$), the neutron density will fall within the spherical layer with increasing r.

The device in Fig... is suitable to automatically regulate the radiation (?) to a certain value within narrow maximum and minimum limits. The spherical shell 1 encloses ..... It is closed by the plug 2 fitting into the opening 3. The plug 2 is attached to the stem 4 which is slidably guided by the guides 5 and 6 and may move up and down, the plug 2 thereby uncovering more or less the opening 3 and by ..... lowering or raising respectively the radiation. The stem 4 carries the rack 7 engaging the pinion 8. The shaft 9 of the pinion 8 also carries the gear 10 which engages the worm 11 on the shaft 12 of the motor 13. This is a three phase motor the sense of rotation of which will be reversed by interchanging the connections of any two of its main terminals to the respective outlets of a three phase current supply. In the figure the terminal 14 is always connected to the outlet 31 and the terminals 15 and 16 are connected to the contact points 24, 30 and 25, 29 of the relays 21 and 26 respectively. The relay 21 has contact springs 22 and 23 and the relay 26 has contact springs 27 and 28. The contact springs 22 and 27 are connected to the outlet 33 and the contact springs 23 and 28 are connected to the outlet 32. The position of the contact springs shown in the drawing is the one which will leave the motor without current i.e. corresponding to the balanced state of the device. The radiation affects the ionisation chamber 17 connected to the amplifier 18. The amplifier is also connected to the outlets 19 and 20 of a suitable electric source. The relays 21 and 26 are connected in series across the output terminals of the amplifier 18. The ionisation chamber 17 the amplifier 18 and the relays 21 and 26 are so adjusted that the current in the relays will be enough to

keep the contact springs 22 and 23 in the "break" position and not enough for bringing the contact springs 27 and 28 in the "make" position as long as the radiation is within the aforesaid narrow limiits and thereby ionisation in the chamber 17 is within corresponding limits. When, however, radiation falls below the lower limit allowed the contact springs 22 and 23 will make and the motor 13 will rotate in one sense so as to lower the plug2 whereby radiation will be increased as long as relay 21 will be energised enough to break. This latter intensity of current will be higher than that at which the contact springs 22 and 23 will make as there is always some inherent friction in the relay. Means not shown in the drawing as for instance a friction spring may be provided for to increase and adjust the margin between the current intensities required for making and breaking respectively.

In a similar way when radiation exceeds the upper limit allowed the contact springs 27 and 28 will make and the motor 13 now with two of its terminals connected crosswise to the two corresponding outlets will rotate in a sense reversed to that before indicated so as to lift the plug will drop the radiation as long as relay 26 will be de-energised enough to breake. This latter intensity of current will be lower than that at which relay 26 will make and means as explained in respect of relay 21 may be provided for to increase this margin.

These said margins or in other words the lag in the operations of the relays 21 and 26 is useful to prevent oscillations of the system. In Fig..... the current i in the relays is plotted against the stroke a of the plug 2. i_1 is the current at which relay 21 will make and i_2 that at which it will break; i_4 is the current at which re-

lay 26 will make and i_3 that at which it will break. Due to the .....(Traegheit) of the mechanical part of the system as for instance momentum of the motor, clearance in the gears etc. the plug will travel somewhat over the limits indicated by a_1 and a_4 and its lowermost and uppermost positions are indicated by ~~xx~~ a_{min} and a_{max} respectively and the corresponding values of the current in the relays by i_{max} and i_{min} respectively.

In Fig..... another device is shown for automatic regulation. The spherical shell 40 is partly filled by a liquid .... which communicates through openings or channels 41 to the ~~tube~~ pipe 42 and thereby to the ~~xxxxxx~~ tank 43 the upper portion of which is filled with air or gas. The spherical shell 40 has also an opening 45 for admitting and exhausting air or gas and this opening 45 communicates to the pipe 46. 47 is an exhaust valve and 48 is an admission valve. To the tank 49 ~~is~~ air or gas is supplied by a compressor 50 and means known to the art and not shown in the drawing are provided for to influence the operation of the compressor by the pressure in the tank 49 so as to keep this pressure ~~xxx~~ within limits. When valve 48 is opened and air or gas is admitted to the interior of the sphere 40 liquid is pressed out through the openings 41 to the tank 43 thereby compressing the air or gas in the space 44. When the valve 47 is opened air or gas will escape from the sphere and liquid will return to the sphere by expanding action of the air or gas in the space 44. Radiation will be ....

The ionisation chamber 54 the amplifier 55 with connections 56 and 57 to a suitable electric source and the relays 58 and 61 are made and adjusted in a similar manner to the corresponding parts in Fig... Relay 58 has a contact spring 59 and a break contact 60 and relay 61

has a contact spring 62 and a make contact 63. The valves 47 and 48 are opened by solenoids with coils 50 and 51 and iron armatures 64 and 65 are outlets of a source suitable to operate the valves. 52 and 53 respectively./The position of the contact springs shown in the drawing is the one which leaves both valves closed i. e. corresponding to the balanced state of the device. The elements of the device are so adjusted as to keep this state as long as the radiation is within the limits required.

When radiation falls below the lower limit allowed valve 48 is opened and air or gas is admitted to the sphere and the level of the liquid is lowered whereby ..... and the radiation is intensified as long as relay 58 will break; on the other hand when radiation exceeds the upper limit allowed valve 47 is opened whereby liquid returns to the sphere and radiation drops as long as relay 61 breaks. Fig... indicates the operation of the device when a is used to indicate the hight of level of the liquid in the sphere. What was said of the lag in the operation of the relays and of the uppermost and lowermost positions of the plug 2 in reference to the Fig.... holds good also for this embodiment according to Fig.... the role of the liquid level replacing the position of the plug. The extremes of a are determined by the momentums of the valves and iron cores and the liquid.

Appendix Notes
enclosed in May 1946

~~APPENDIX TO INTRODUCTION~~

#20 The following text, taken from a patent application filed in the name of the author in the United States Patent Office in March 1935, may be of interest ~~in this connection~~ since it seems to be the first public available text discussing a neutron carried chain reaction and contains the first calculation of the critical radius of a spherical chain reactor.

See also
S b c 20
Anal 10, 5-00

// If we have a closed spherical layer of material in which the chain reaction takes place the inner radius (r) of which is large compared with the mean free path of the neutrons which maintain the chain, the density (s) of the neutrons will with good approximation be given as a function of the radius (r) by the following equation:

$$D \frac{d^2(rs)}{dr^2} + A(rs) = 0$$

D and A are determined by: the mean free path of the neutrons a; the mean velocity of the neutrons w; the factor of the multiplicating action f which says how many collisions of neutron are needed in the average in order to produce one new neutron.

$$A = w/af \; ; \; D = aw/3 \; ; \; \sqrt{\frac{D}{A}} = \frac{a\sqrt{f}}{\sqrt{3}}$$

// We are interested in the critical thickness of the spherical layer for which the gradient of the density s vanishes. If the thickness $(r_2 - r_1)$ approaches ℓ we can maintain with a very weak source of initial radiation in the interior of the inner surface of the spherical layer a very strong chain reaction and we can easily get one thousand or more times more neutrons emerging from the chain reaction layer than the number of the neutrons forming the initial radiation. If the outer surface $(r = r_2)$ of the spherical layer were to stand free in space the density s would be zero for that surface and the critical value l would be given by $l = \pi/2 \sqrt{D/A}$. If the outer surface is covered by some material, for instance if the transmutation layer is immersed into water or covered by lead, the critical value l is reduced. This is due to the back scattering by water or lead and also to the fact that the neutrons are slowed down in the water and their mean free path is thereby reduced.

// It is important to prevent neutrons from escaping out of the interior of the inner surface of the spherical layer and also from being absorbed in the interior. If the initial radiation is generated by apparatus placed into the interior of the sphere the material used should be so selected as to lead to a minimum of absorption.

// If the thickness is larger than the critical value l we can produce an explosion.

We shall now discuss the composition of the matter in which the chain reaction is to be maintained. We wish to distinguish three main types of chains.

(a) Pure neutron chains, in which the links of the chain are formed by neutrons

of the mass number 1 alone. Such chains are only possible in the presence of a metastable element. A metastable element is an element the mass of which (packing fraction) is sufficiently high to allow its disintergration into its parts under liberation of energy. Elements like uranium and thorium are examples of such metastable elements; these two elements reveal their metastable nature by emitting alpha particles. Other elements may be metastable without revealing their nature in this way. Whether an element is metastable or not can be determined by means of the mass spectrograph. If, for instance, the value obtained by Bainbridge for beryllium by means of the mass spectrograph, which appears to be generally accepted at present, is really valid, we have to conclude that beryllium is a metastable element and can disintergrate into parts with the liberation of energy, one of the parts set free in its disintergration being a neutron.

If we have an element which is metastable but the disintergration of which is inhibited and if this inhibition can be lifted in a collision with a neutron we shall call such an element an inhibited metastable element.

If an inhibited metastable element "A" is exposed to neutrons, we may have the following reaction.

"A" + n = "B" + n + Energy.

The element "A" transmutes into an element "B" which has the same atomic number and mass number and energy is transmitted to the neutron. The element "B" may break up into an element "C" and a neutron, the element "C" having the same atomic number as "B". The element "C" may or may not break up into further parts. If the interaction of a neutron with the element "A" leads in this way to an increase in the number of neutrons (the newly created neutrons would together with the original neutrons continue to interact with the elements "A" thereby forming the links of a chain reaction.) We c

APPENDIX ~~to Page 1~~ ~~X-21~~

~~The reader may be reminded~~ It ought to be remembered at this point that in natural uranium essentially only thermal neutrons which are absorbed lead to fission and thus to neutron emission. Neutrons which are absorbed at higher energies are "absorbed at resonance" without leading to neutron emission, and are lost from the point of view of a chain reaction. Thus a fast neutron emitted in a uranium-carbon system is ~~thus~~ slowed down, a certain fraction is absorbed at resonance and the rest reaches the thermal region. Of the neutrons which ~~leave~~ reach the thermal region, some are absorbed as thermal neutrons by the carbon and the rest is absorbed as thermal neutrons by uranium, leading to neutron emission. The paper assumed that no neutrons other than thermal neutrons are absorbed by carbon.

APPENDIX ~~Note 1 to Page 12~~ 22

This would be a conservative assumption for a single absorption line which obeys the Breit-Wigner formula. For such an absorption line the absorption falls off with 1/v in the thermal region and reaches a minimum at $0.2_{o}E$ where E_o is the resonance energy. Beyond the resonance energy the absorption falls rapidly and becomes negligible for $2E_o$ if E_o is not too close to the thermal region. If E_o is higher than five volts and if the temperature of the thermal neutrons does not exceed 1/10 of a volt than the absorbing cross-section beyond 2 E_o is less than 1/10 of the absorbing cross-section for the thermal neutrons.

~~Added in 1946:~~ By postulating $E_2 = 10\ E_1$ we have made a seemingly arbitrary pessimistic assumption with respect to the magnitude and the character of the resonance absorption. As far as magnitude is concerned the choice was justified by the following consideration: Results obtained by Joliot, Halban, Kowarski, and Perrin's paper,[13] indicate that a water-uranium systems comes close to be chain reacting but certainly does not go much beyond being at best just about chain reacting. If we replace H with C it takes 6.5 collisions with carbon to slow down as much as by one collision by H, and since the scattering cross-section of carbon is 4 as compared with 18 for H, therefore we have to replace 1 H atom by 30 carbon atoms, if we wish to have the same resonance absorption in both systems. The absorption of H for thermal neutrons is about.3, and therefore, if the absorption of carbon for thermal neutrons is 30 times smaller, i.e., if $\sigma_c(C) = 0.01$ ~~captured carbon is .01~~, the loss of thermal neutrons by absorption

will also be the same for the carbon as for the H system. In calculating the uranium-carbon system we had to use a number of constants which were only very inaccurately known but we chose a set of values in such a manner as to make the carbon-uranium systemjust about chain reacting (under the most favorable conditions) for the value of = .01. For the set of constants used this condition was fullfilled by postulating that neutrons between energies E_1 and E_2 are absorbed at resonance if they come into contact with uranium and by setting $E_2 = 10\ E_1$.

As to the character of the resonance absorption which we thus assumed to be pure surface absorption, this was of course a misleading assumption. It was partly made because it introduced only one perimeter and led to very simple formulae, and partly because the author overestimated the importance of the resonance absorption in the lowest resonance line as compared to the absorption in the higher resonance lines. Subsequent calculations made by others which were inmany respects more accurate, still maintained this simple assumption with respect to resonance absorption until the late Fall of 1941, when on the basis of new experimental evidence procured to a large extent at his initiative, E. P. Wigner presented the first correct treatment of the resonance absorption which took into account the contribution of the high resonance lines.

* 23

APPENDIX ~~to Page 7~~

Optimum conditions for a chain reaction will be seen later, if ε is as large as possible and the best value of R is therefore the value which makes expression 20 a maximum.

for

~~# 24~~

APPENDIX ~~to Page 8a.~~

The approximation is good only for small spheres about R = 5 cm, or less. It has the advantage of leading to very simple formulae but if these formulae were used for large spheres (such as would have to be considered if we went over from uranium-metal to uranium-oxide spheres), the error would become too large, leading to an over-estimate of the thermal neutron absorption in carbon. For small spheres however, there would have been no advantage in using the correct value for the thermal neutron absorption in carbon which leads to very much more complicated formulae, as long as the resonance absorption ~~is~~ was treated exclusively as surface absorption, the way it was done in this paper. ~~For small spheres,~~ only when the correct treatment of the resonance absorption is introduced, is it of value for small spheres to treat the thermal absorption also correctly. The use of the simple formulae in the case of smaller spheres is even of some advantage, inasmuch as the error introduced in the value of thermal absorption shifts the optimum towards smaller spheres, thereby partly counteracting the effect of having neglected the volume resonance absorption which tends to shift the optimum towards larger spheres.

APPENDIX to Page 9

* (25)

Equation 25 means that we have optimum conditions when half of the fast neutrons which are emitted but not absorbed by the uranium thermal region are absorbed by the carbon. That means that the other half must be absorbed by uranium at resonance so that we may interpret equation 25 as saying that we have optimum conditions when an equal fraction of the neutrons is lost through resonance absorption in uranium and through thermal absorption in carbon.

Equation 26 shows that we get optimum conditions by having ε as large as possible.

*(26) Korr

APPENDIX ~~Footnote to Page 17.~~

We may in place of calculating μ, rather calculate the multiplication factor μq. Where q represents the fraction of the neutrons which is absorbed in the thermal region by uranium. Obviously we have

$$q = (1-p)\frac{\sigma_a(U)}{\sigma_a(U) + n\sigma_c(C)}$$

~~and~~

Thus using for μ

~~Substituting into this equation for~~ its value from equation 38, we find

$$\mu q = 1 - \frac{1}{s}\,\frac{1 - I_{ext}/I_0}{I_{int}/I_0}\,(1-p)\,\frac{1}{\frac{\sigma_a(U)}{n\sigma_c(H)} + 1}$$

This gives for $n = 3$, $p = 0.5$ and $\frac{\sigma_a(U)}{n\sigma_c(H)} \sim 5$: $\mu q = 0.85$

For $\mu q = 1$ we could just maintain a chain reaction in the system. By comparing the experimental results obtained for n = 1, n = 2, and n = 3, we can extrapolate the larger values of n and thus can see that q goes even closer to 1, if we increase n beyond 3.

The situation would not appear quite so favorable if we assumed that p did not have the value of .5, but were smaller, for instance, had the value of .3. But even in that case, we still would find for n = 3, q= .79.

It may thus be seen that in spite of the uncertainty of the value p, the experiment shows that a homogeneous water-uranium system can come very close to be chain reacting.

The value of μ of course is very sensitive to the value of p and for $p = 0.3$ we would have $\mu = 1.42$ in place of $\mu = 2$

APPENDIX ~~to Page 19.~~ ★ (27)

1. We find more favorable conditions if we take into account the temperature of the uranium spheres and the surrounding graphite is lower than the temperature of the bulk of the graphite, since in that case, due to a sort of Knudsen effect, the density of thermal neutrons is increased in the cold graphite which surrounds the uranium spheres.

★ (28)

2. The value of $\underset{\sim}{R}$ = 8 cm. was chosen because it makes the value of ε in equation 20 a maximum. However, to use our simple formulae for such a large radius is rather stretching them beyond their validity.

APPENDIX ~~to Page 21~~ ✱(29)

Since this R = 5 cm is at room temperature close to the ~~floor~~, which makes the expression for ε given in 20 a a maximum, for $\sigma_c(\epsilon)$ = .005, The value q = .6 also corresponds to the same carbon absorption cross section. The value for $\frac{4\pi R^3}{3}\frac{1}{\lambda} = 0.0336$ corresponding to 30 tons of uranium is a numerical error. The correct value is .022, corresponding to about 21 tons of uranium.

*30

hor

APPENDIX to Measurements

The description of a measurement proposed in the original paper has been omitted here ~~for the sake of brevity~~.

If uranium is bombarded with neutrons which have been slowed down by paraffine wax ~~in the usual way~~ to a few volts, it emits neutrons which ~~are faster than the neutrons with which it is being bombarded. Not more than a fraction of the~~ have a few million volts energy. ~~1/6~~ neutrons thus emitted is sufficiently fast to disintegrate beryllium in such a way that the beryllium breaks up according to the reaction

$$Be^{9} + n = [Be^{8}] + n + n$$

Therefore, if a mixture of berrylium and uranium, containing a large excess of beryllium is bombarded by slow neutrons in a sufficiently thick layer, one neutron of medium velocity shot into this layer will produce on the average more than one neutrons by the breaking up of one uranium and one beryllium atom. The neutrons thus liberated can go on reacting with the mixture, and it is possible to maintain a chain reaction by observing the requirements as explained in connection with the general equation which holds for stationary chain reactions.

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1) Markle

Biology

Dodé – letter

2.) Ardolets
Cannon

3x) Health

4x) Carnegie Inst.

Pontecorvo:

Cd + Rn+Be = 50 min
fast

C.R. soft β

excited Cd + (internal conv.)
(mark unt?)

Kallmann – letter

$Mo + D \rightarrow Mo^{*} \rightarrow Ma^{*}$

excited gives internal
conv β + Kurodl. + γ

Segrè – Seaborg letter

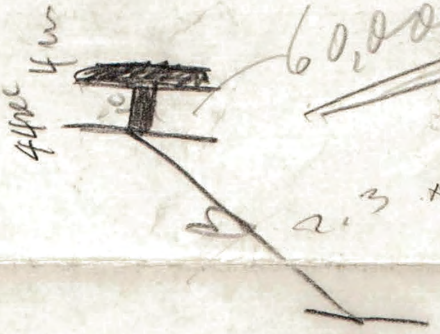
Rh

Goldhaber in ~~[illegible]~~ April
Pontecorvo
Backer

4 min

40 sec.

60,000 V



2.3×10^6 V ; dembordes
spectre

138 Dora Rd
Wimbledon
London SW19

Negro

1 clock

Cowley

the

Influencing of Universities

Goldwater

E. M. White

Dept. of Hosp.

Brandeis

SU-7 8113

68W 82

G. 6.

Immigration Law. —

State Dept.

Labor Dept.

Jan 1st 1930

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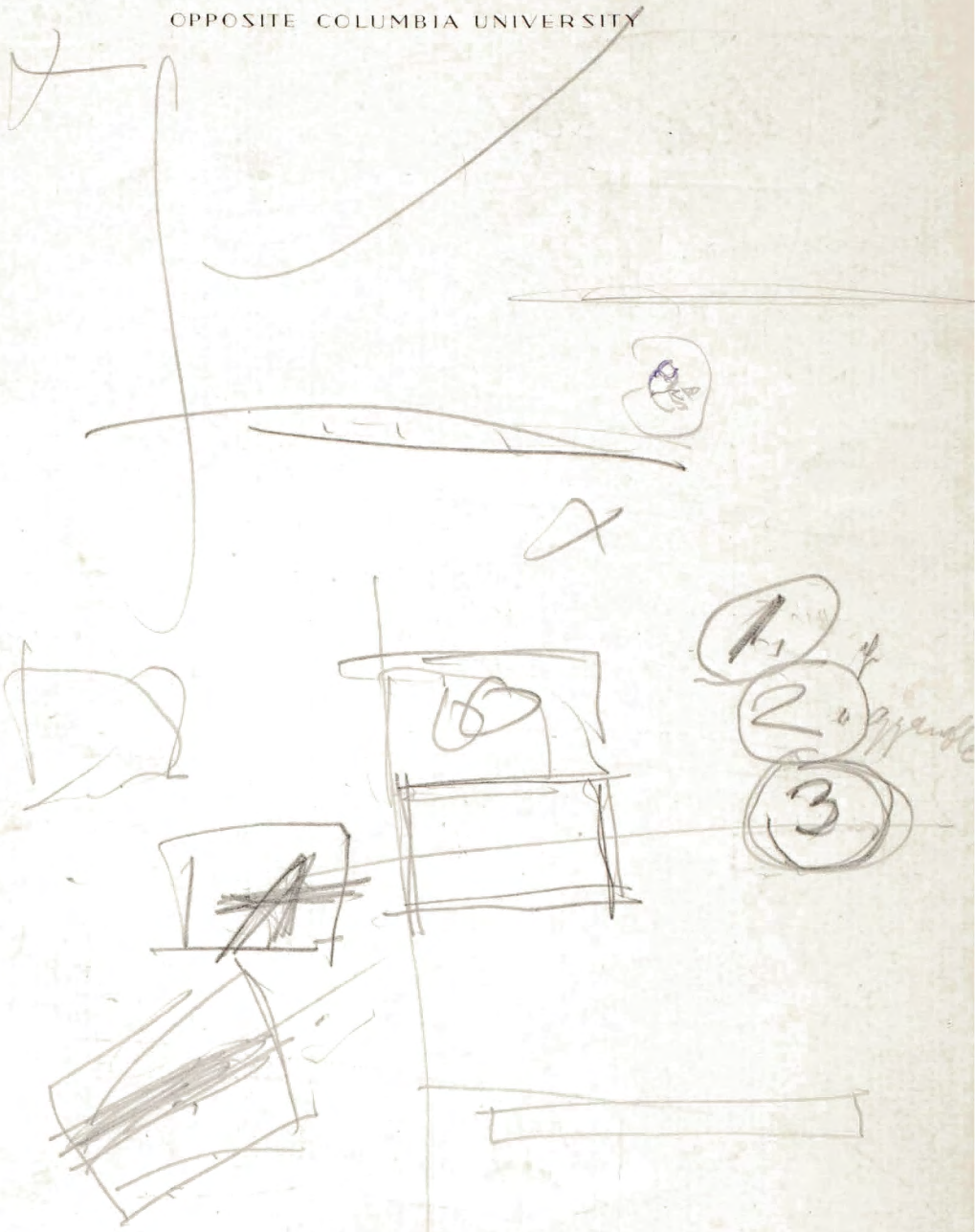


Elevoant
ten

|| Galdhalor || Vingimda 7-6424

Környei

v. Hornbostel Torquisson

Chemdkins

Otto Brodtner

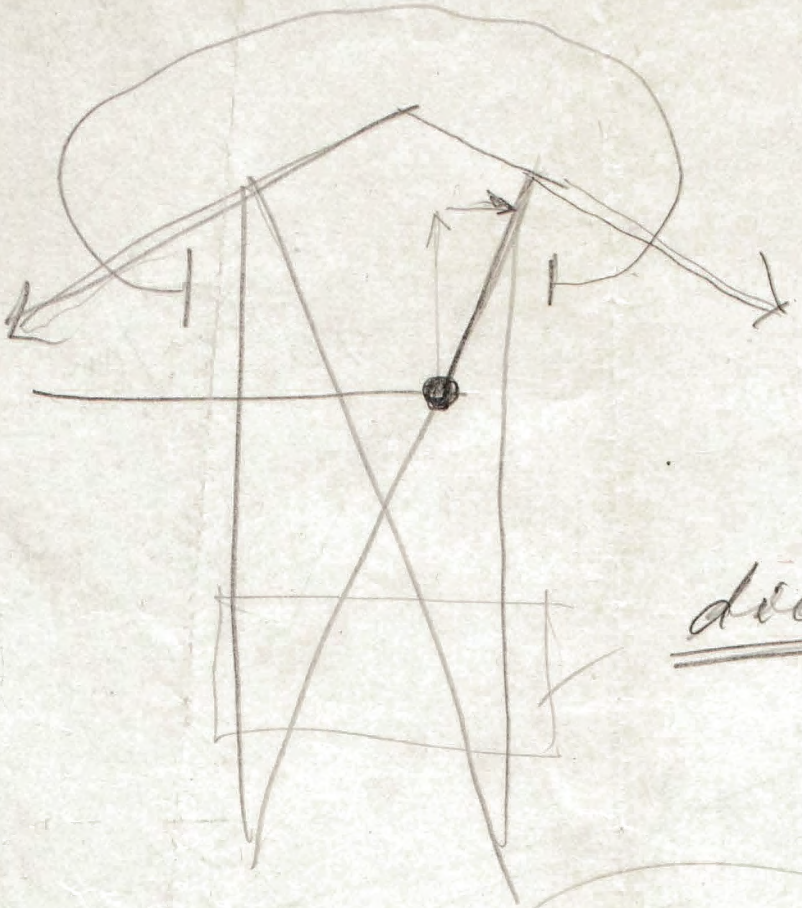
Sfrmua

Ledeak

Balangi

Vallmer ||

10^{-5} m/m



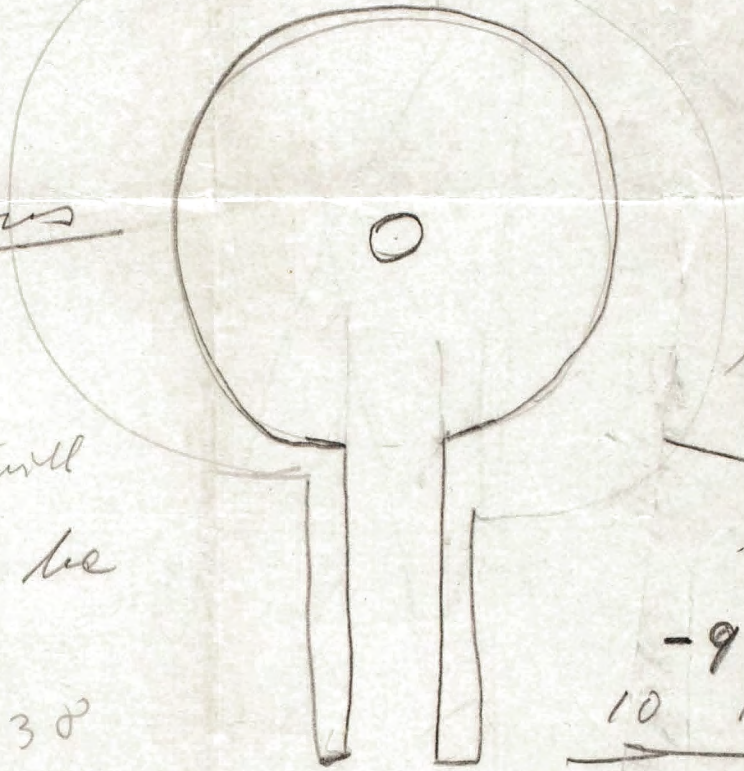
10^{-6} 1/1000

10^{-4} gasc.

dichte 10^{-6} m/m

10^{-6} m/m

double rest



10^{-6} double

1 millivolts

100. 10^{-5} at 235 mill

10^{-4} of 1/2

entering will be
reflected back

10^{-6} of 1/2 238

will be double
scattered

10^{-9} Atm

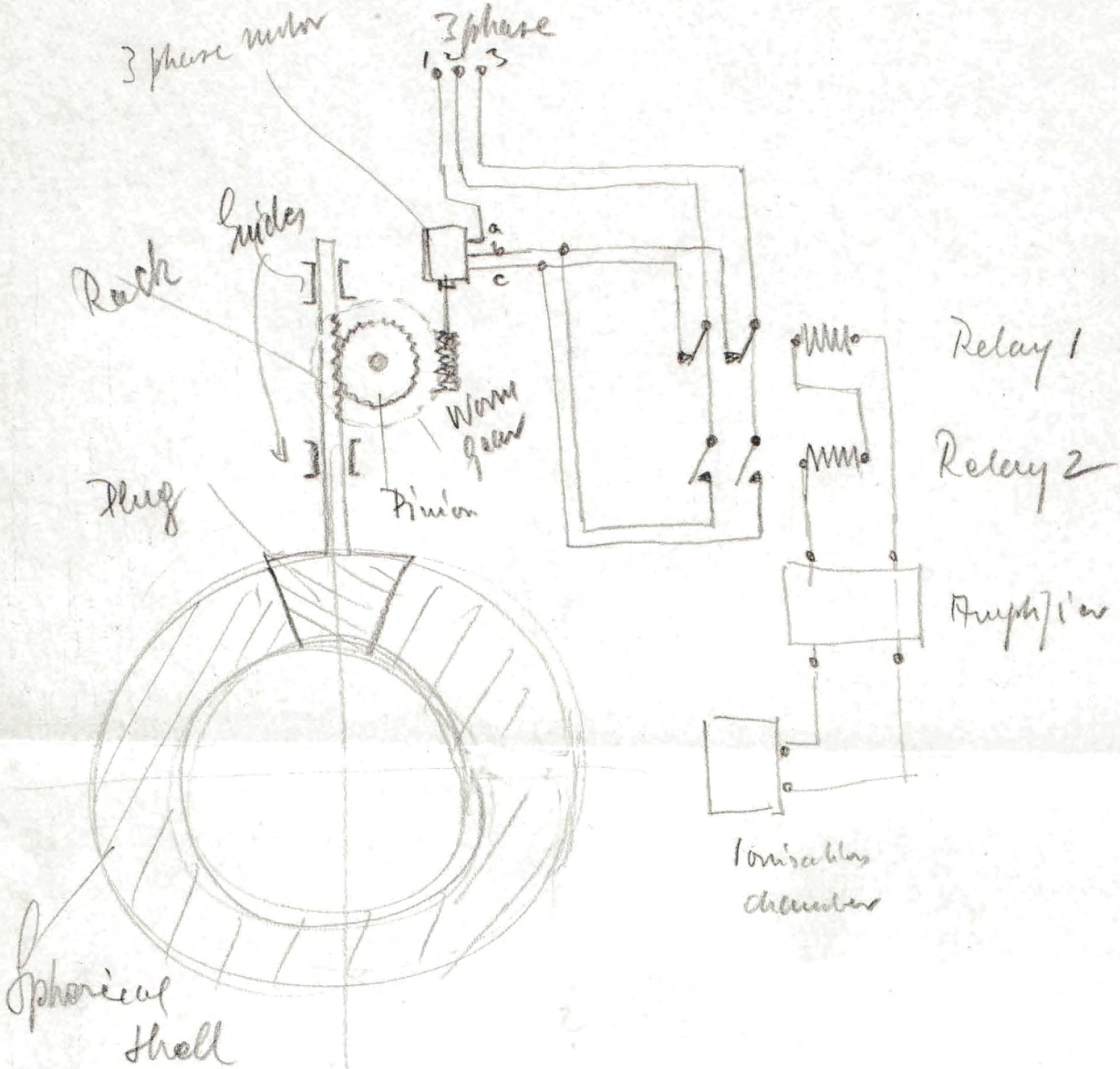
10 cm²

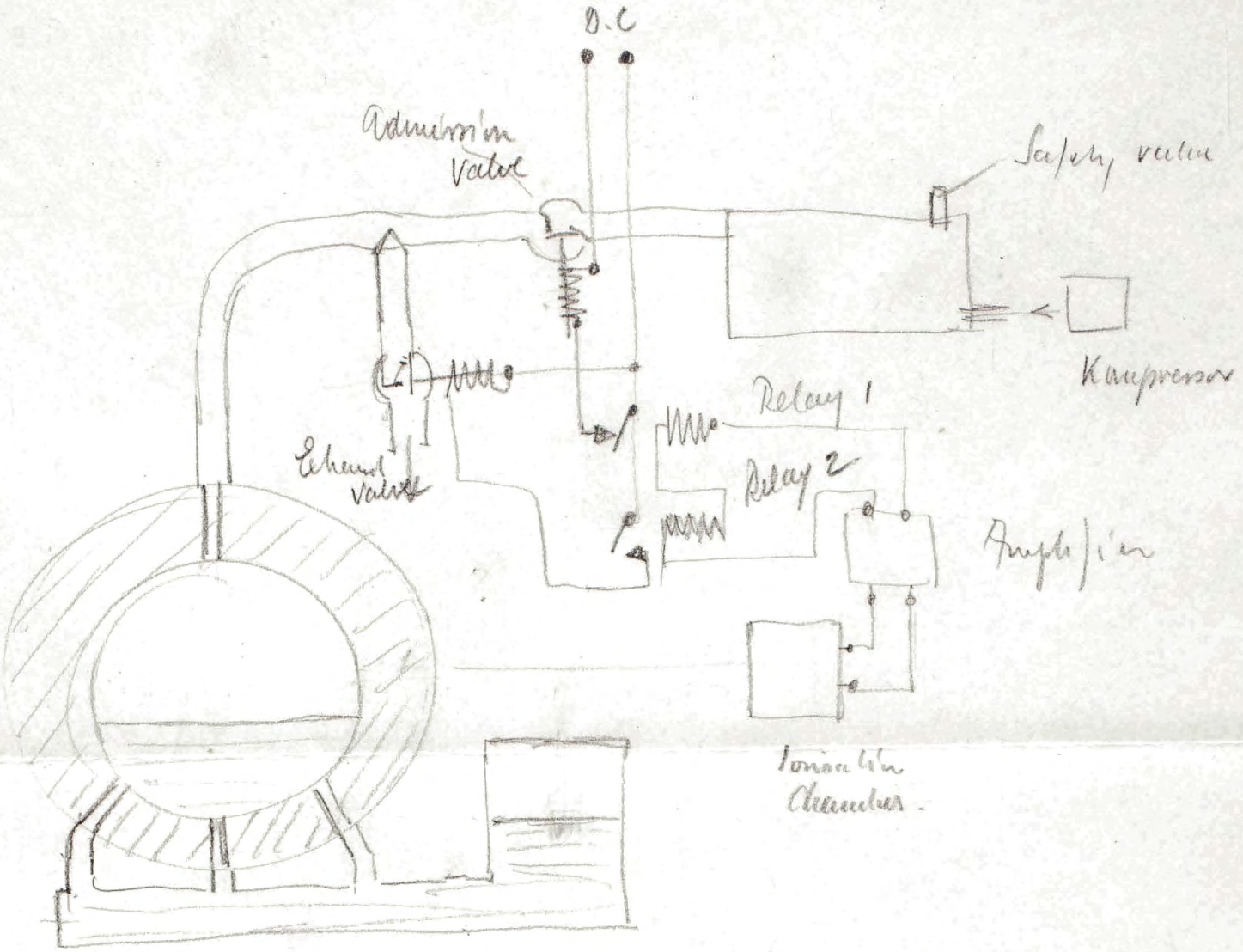
1 cm²

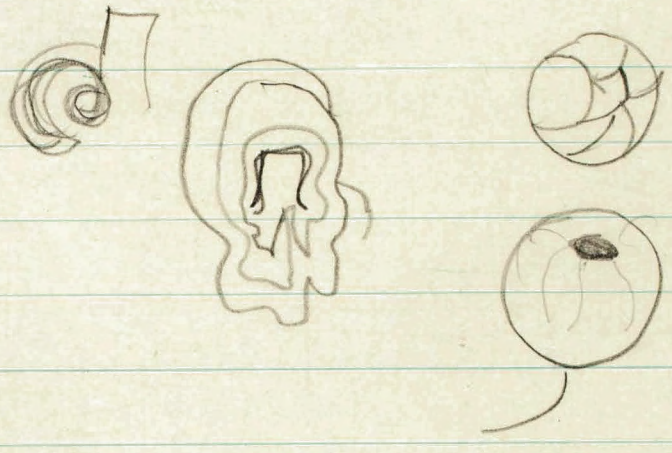
10×10^{-9}, 10^{4} cc of Atm
$= 10^{-4}$ Mcc per sec.

10^{-9} 10^{4} cc/sec

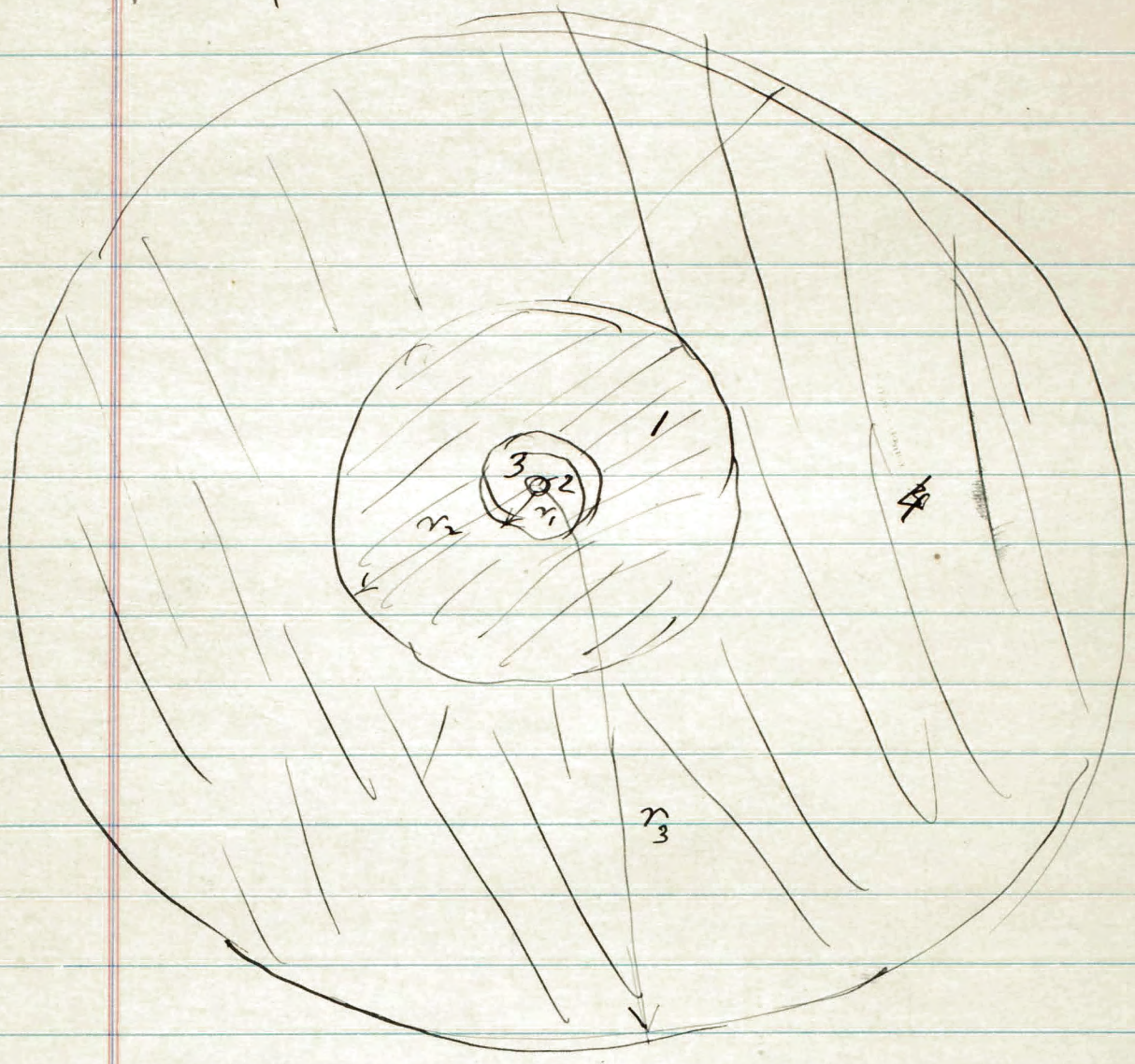
1/1000

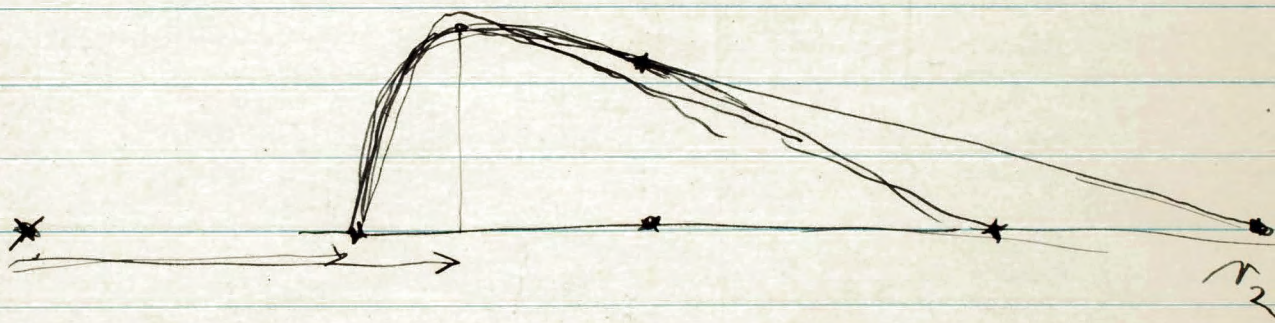

3 phase motor
3 phase
1
2
3
Guides
Rack
a
b
c
Worm gear
Pinion
Plug
Relay 1
Relay 2
Amplifier
Ionisation chamber
Spherical Shell

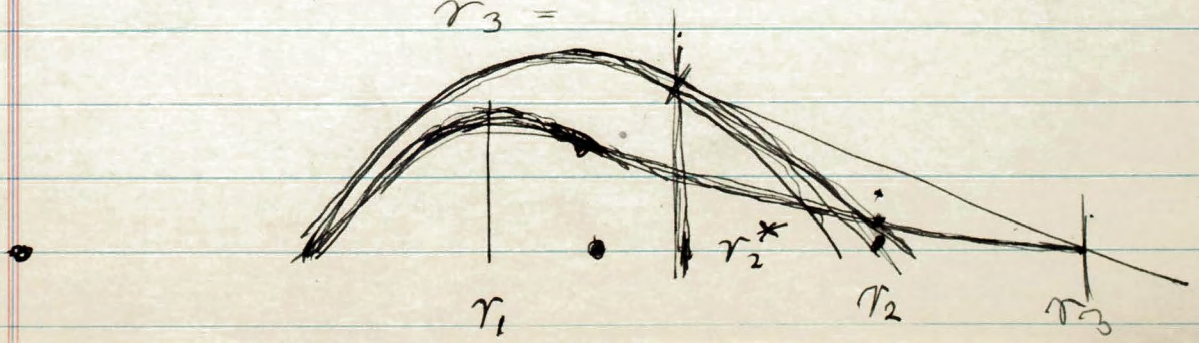

D.C
Admission Valve
Safety valve
Kompressor
Relay 1
Relay 2
Exhaust Valve
Amplifier
Tomachin Accumulator

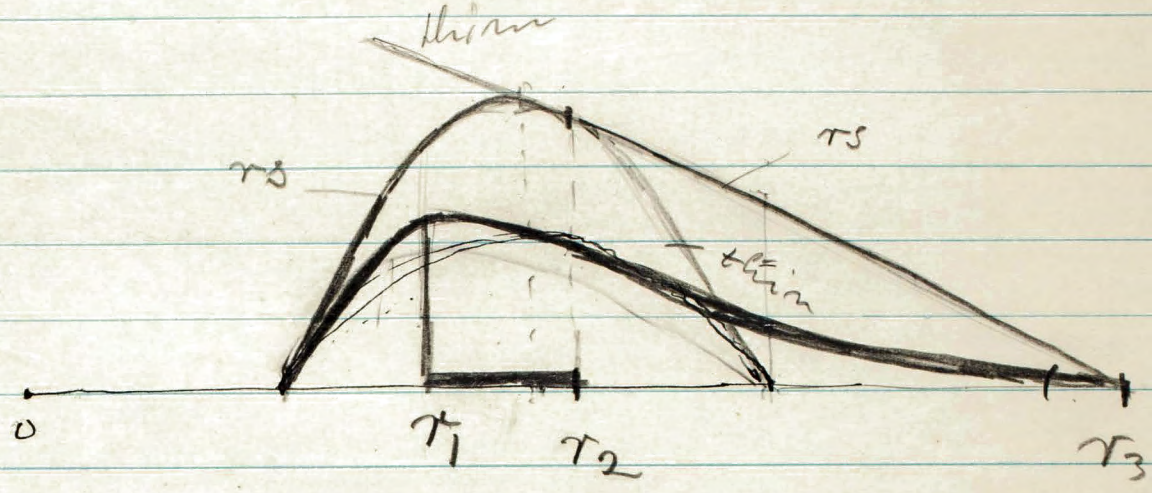


B_i



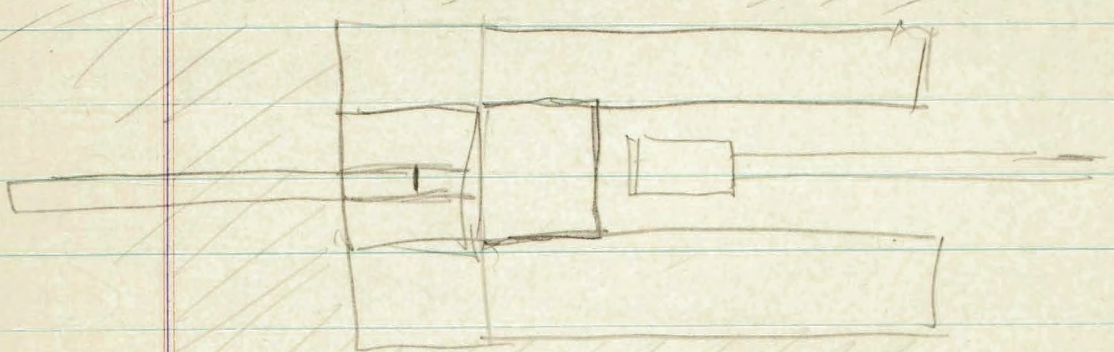





0
r_1
r_2
r_3

the incident neutron ~~is very large, if~~ is larger than one per captured neutron. ~~This is the~~ This ~~fact~~ is the reason for the fact that the "total" critical thickness is only "slightly smaller than the "delayed" critical thickness. —

The ~~ratio~~ of the number of neutron ~~can be~~ emitted ~~measured~~ by the instantaneously ~~emitted~~ to those emitted with delay can be estimated in the following way



This experiment carried out shows that —

16

$\frac{70 \text{ gm}}{16} = 4$

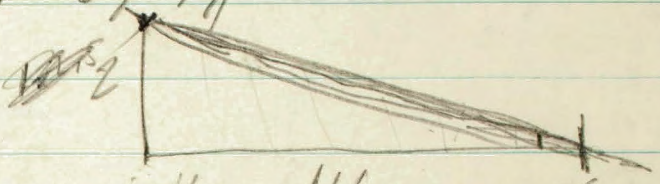
	cc
6	54
1	$\frac{240 \text{ metal}}{18} = \frac{40}{3}$
	13 cc

If 2 are emitted $H = \frac{1}{3} 10^{-24}$

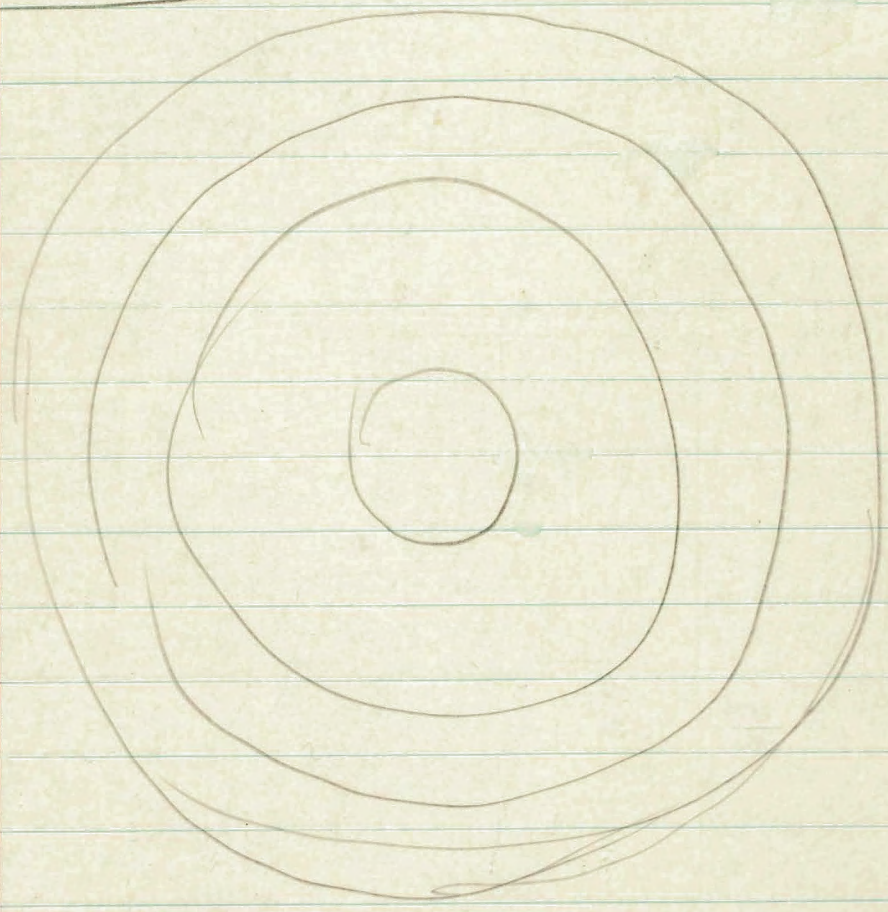
$U = 2 10^{-24}$

6 gr of H auf 240 gm of U

more than 1 gr of H



Bi + U



y

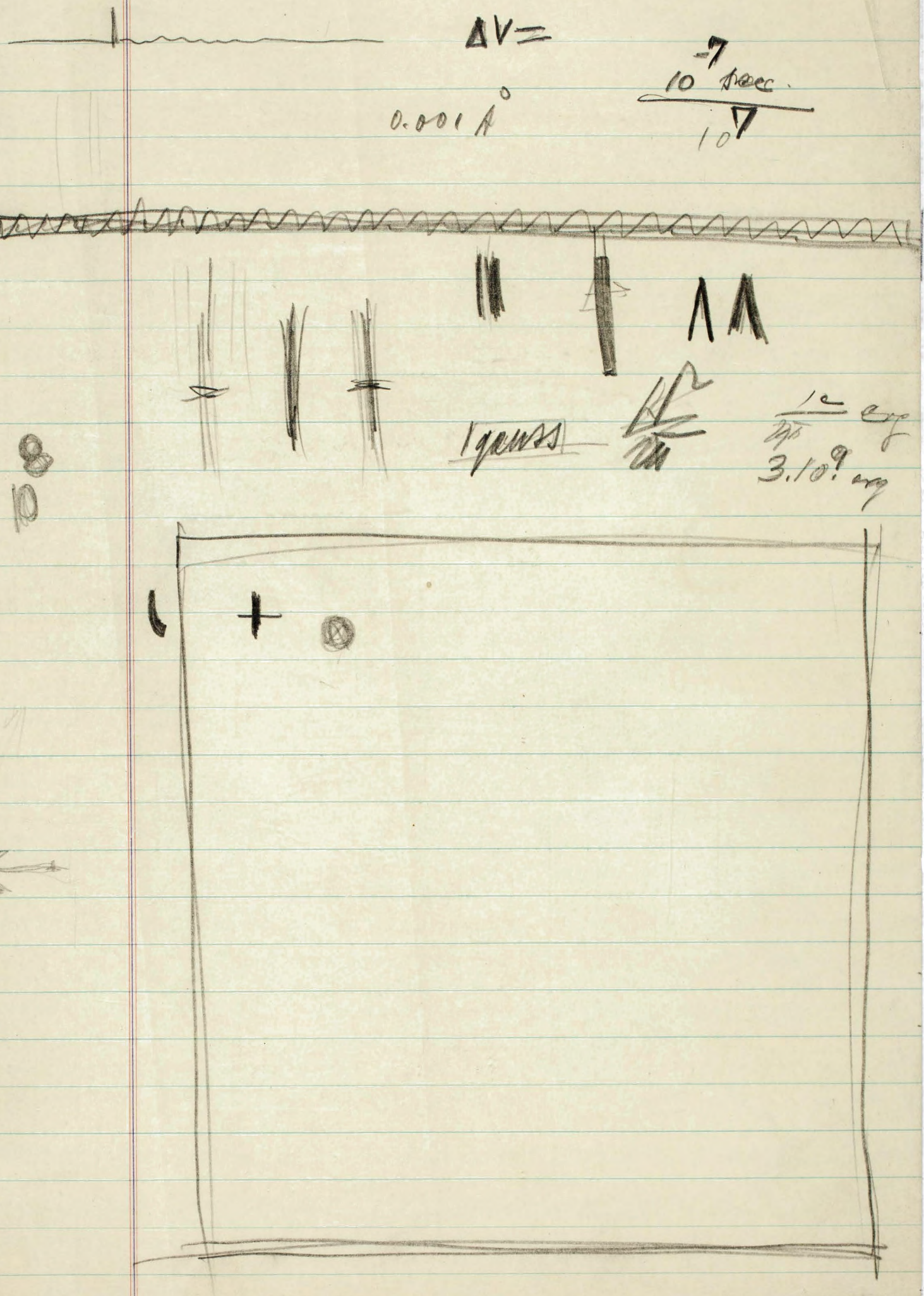
$x \sqrt{y}$

$x \sqrt{\frac{1}{\frac{-2}{6}x+2}}$

sei min

$y = ax + b$

500 000 Volt für berechn


ΔV =
10^{-7} sec.
10^{7}
0.001 Å
1 gauss
$\frac{1}{2\pi}$ erg
3.10^{9} erg

[1.]

~~If U atoms is to bombarded [illegible]~~

If ~~slow neutrons slowed down~~ U is exposed ~~to neutrons, for instance~~ to neutrons (which have been) slowed ~~down by for water or paraffin wax~~ ~~to rooms~~ to a few volts or less are allowed to fall on U, ~~U emits neutrons which are faster than a few volts at the same time~~ ~~by~~ ~~these slow~~

some of these slow neutrons disappear ~~and in their pl~~ (obviously by being captured by U nuclei) and in doing so cause a transmutation of U in which faster neutrons are emitted. — It can be observed that if the ~~slow neutron ex~~ exposure of the U to the slow neutrons is stopped, fast neutrons still continue to come out of U for a few seconds. We may call this delayed neutron emission and denote it by ...

Even when ~~an~~ equilibrium has been reached (i.e. a few minutes after the begin of the exposure of U for) the number of "delayed neutrons" emitted per disappearing ~~slow neutron~~ incident neutron is ~~so~~ still much smaller than one × On the other hand the number of neutrons emitted practically simultaneously (with the capture of (~~with~~ certainly ~~a few~~ less than $\frac{1}{10}$ of a sec after capture)

H	$\frac{4}{3}\ 10^{-24}$	6	54 cc
H	$2,10^{-24}$	1	$\frac{13\text{ cc}}{6^{9}\text{ nickel}}$

~~H~~	H	1	9 cc
H	H	H	$\frac{13\text{ cc}}{22\text{ nickel}}$

$$= \cancel{x}\sqrt{\frac{1}{2-\frac{2}{6}x}}$$

$x=1$

3 ~~$\frac{30}{10}$~~

$\frac{30}{10}$

Note ?? ×× Do you want to change the following:

p2. line 8. "Stationary conditions" should be "conditions stationary"

p3. line 1 omit "not"

lines 29 ~~+ 30~~ not clear - should it be "as a function of - - -"

line 30 should it be "general laws and types" etc

p4 line 10 "neutrons"

p5 1st Symbol in Equation (2) is not clear - Is it "l"?

p7. line 8-9 verb is omitted

line 19 - Fig ?

p11. line 4 - Am 135 + 139 correct ? × (see line 2 p 13)

p14 - (9) is not an equation

(10) is ~~confused~~ not clear

I did not read past p. 16

Sign Petition

10^{-7} $\frac{1}{T}$ $\frac{\nu}{H}$

μ

20 Gauss

$h\nu = \mu H$

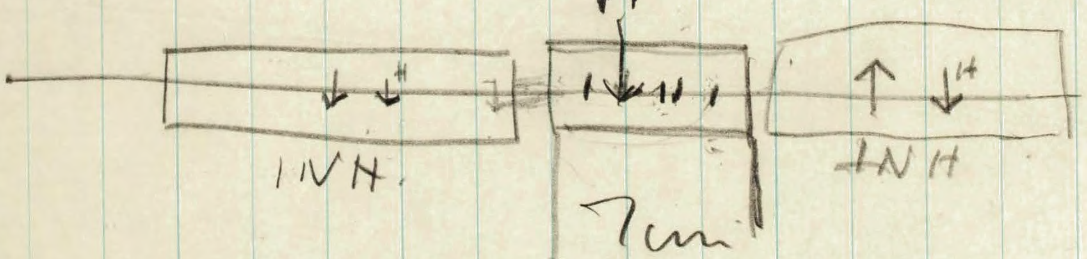
$\Delta\nu \times t \sim 1$

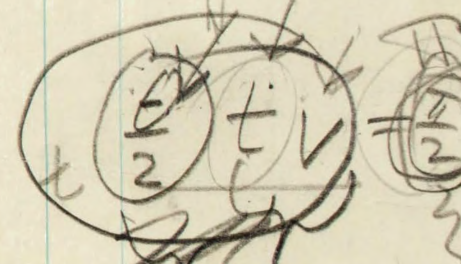
$\Delta E \times \Delta t \sim h$

νt

1000 g → 5000 g

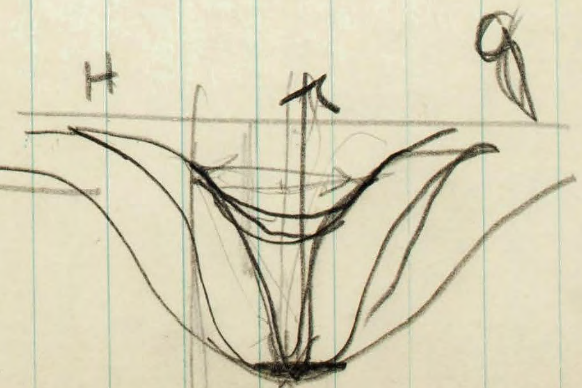
H

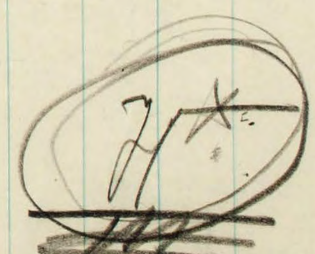




~~10 cm~~

10^{-4} to 10^{-3} sec





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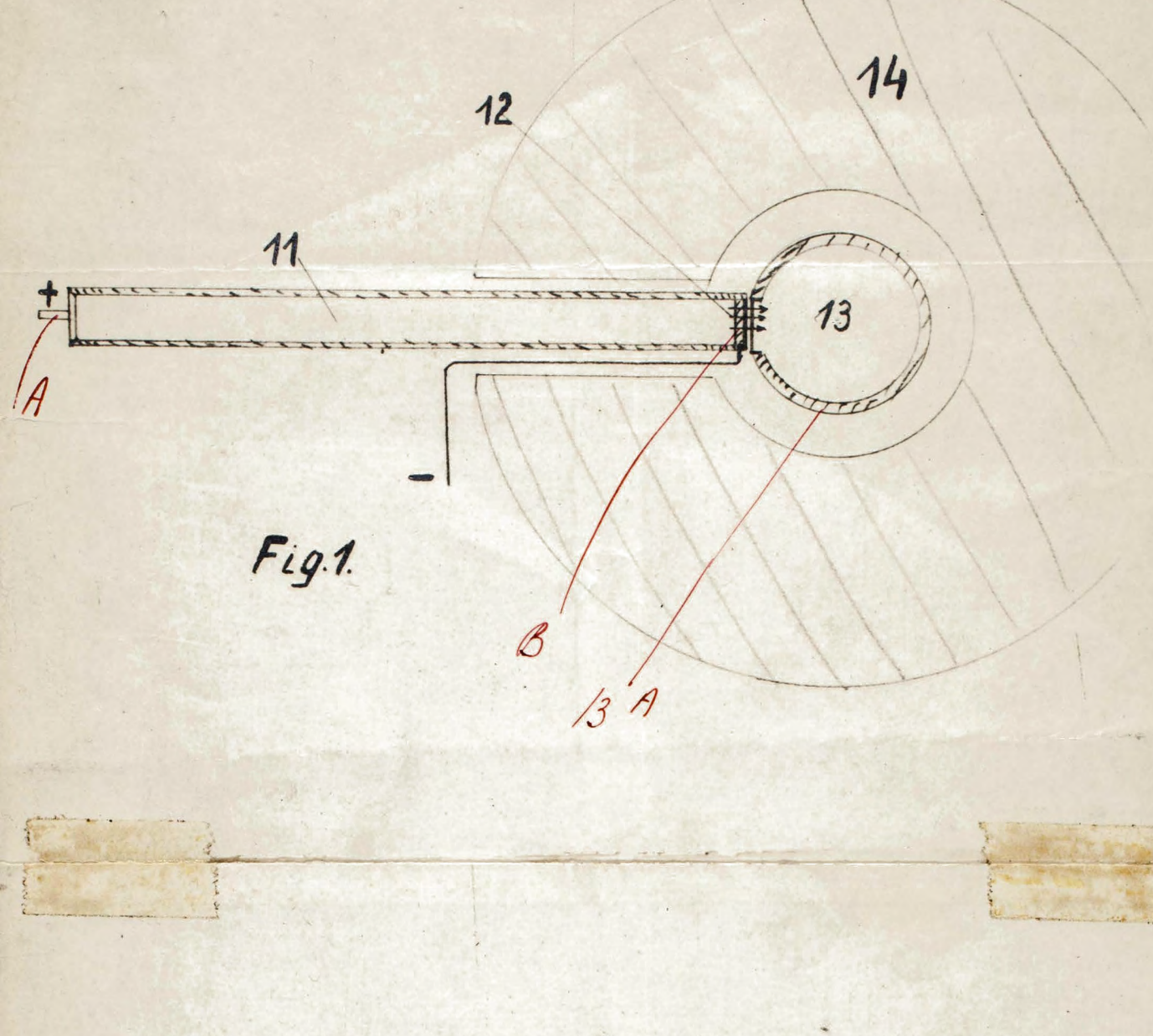
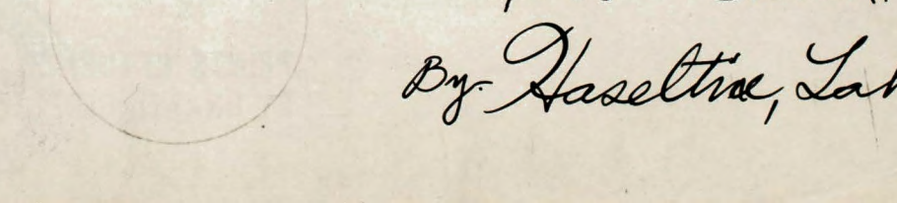


Fig. 1.

FIG. 3.



-10,500 - SZILARD -

By Haseltine, Lake & Co.

12 March

1.

C-7

Fig 1 of original 7040- (K.W.)

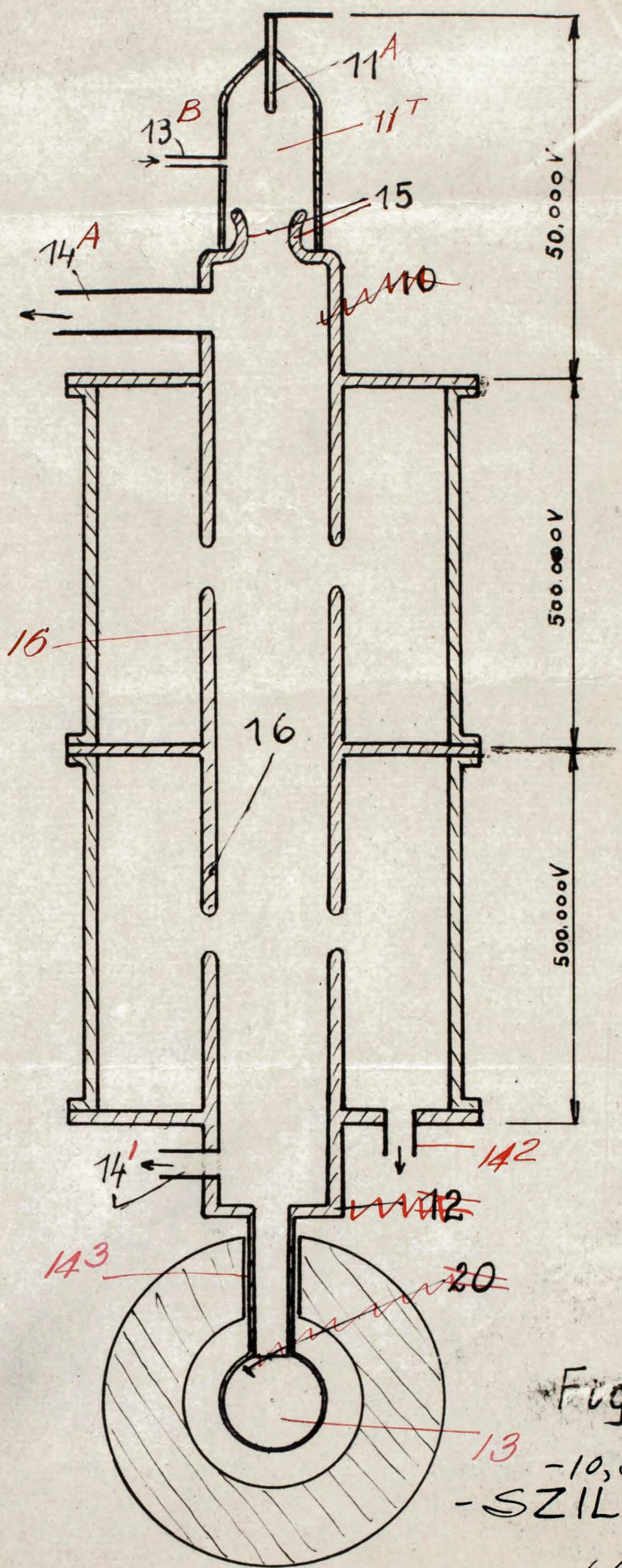


Fig 2.

-10,500-

-SZILARD-

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C-7

Fig 2 of original 7840.
Red corrections added later (K.W.)

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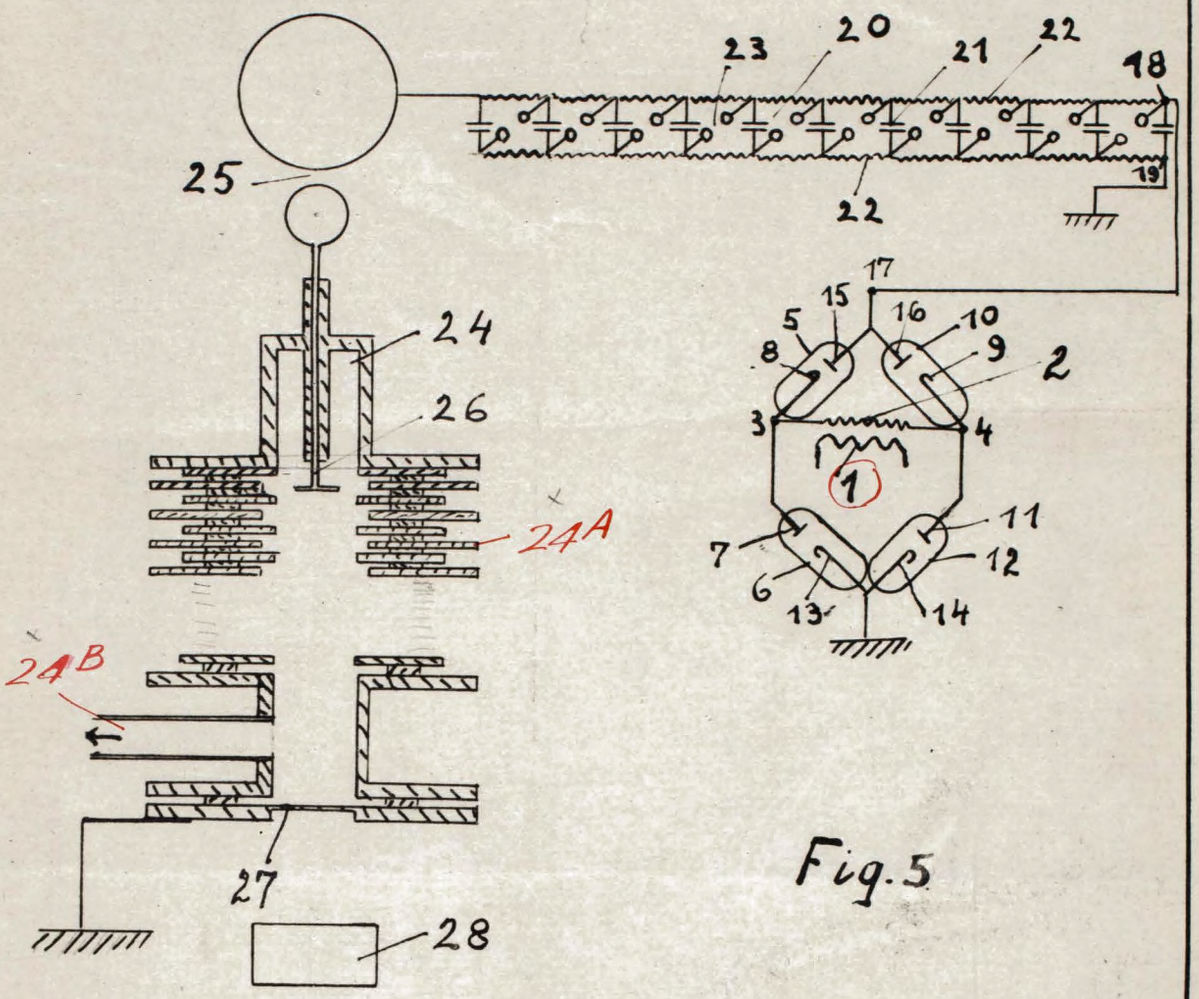

Fig. 5

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C-7

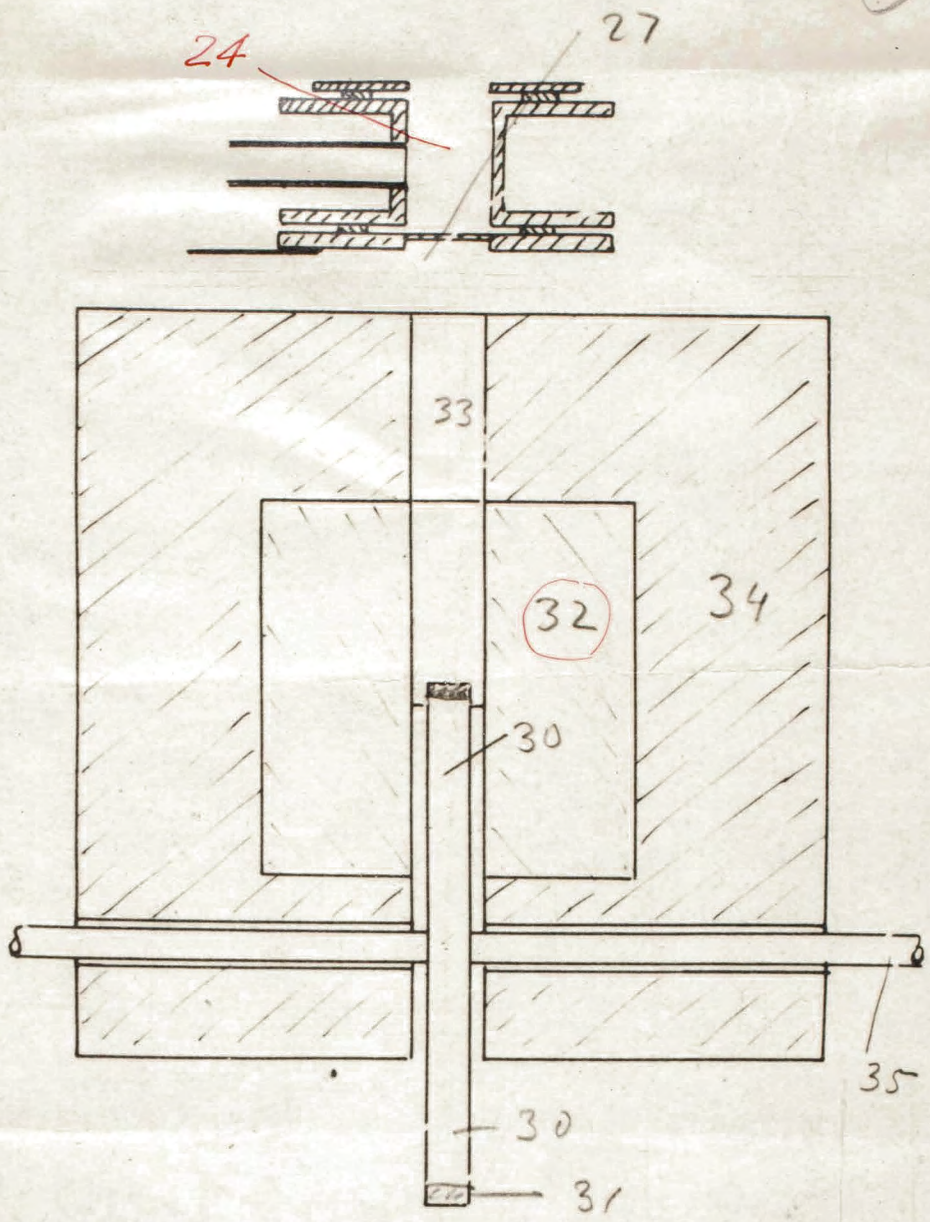

Fig. 6.

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C7

Fig. 6. of original #7840 (K.W.)

Fig. 1.

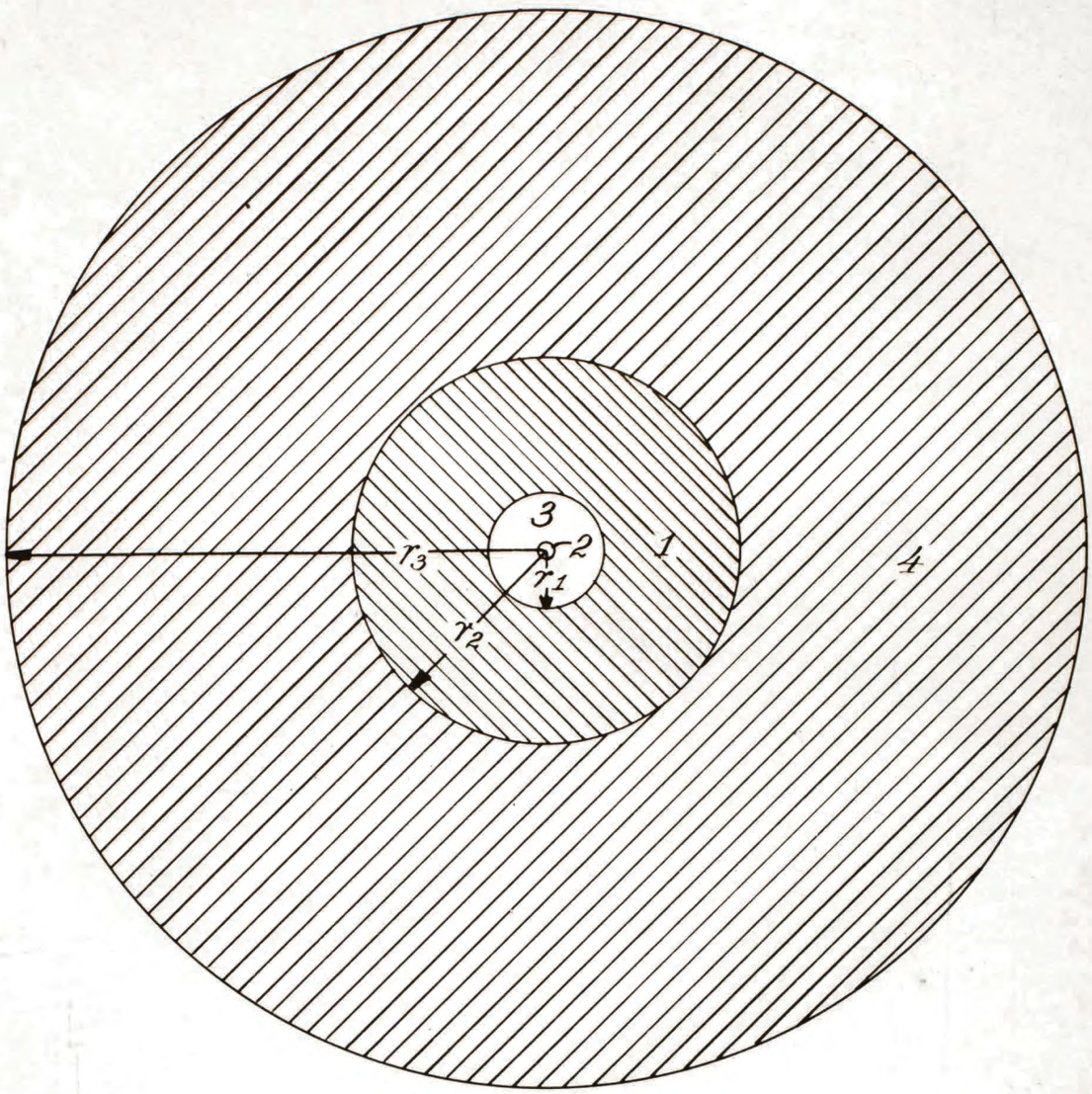

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Fig. 2,

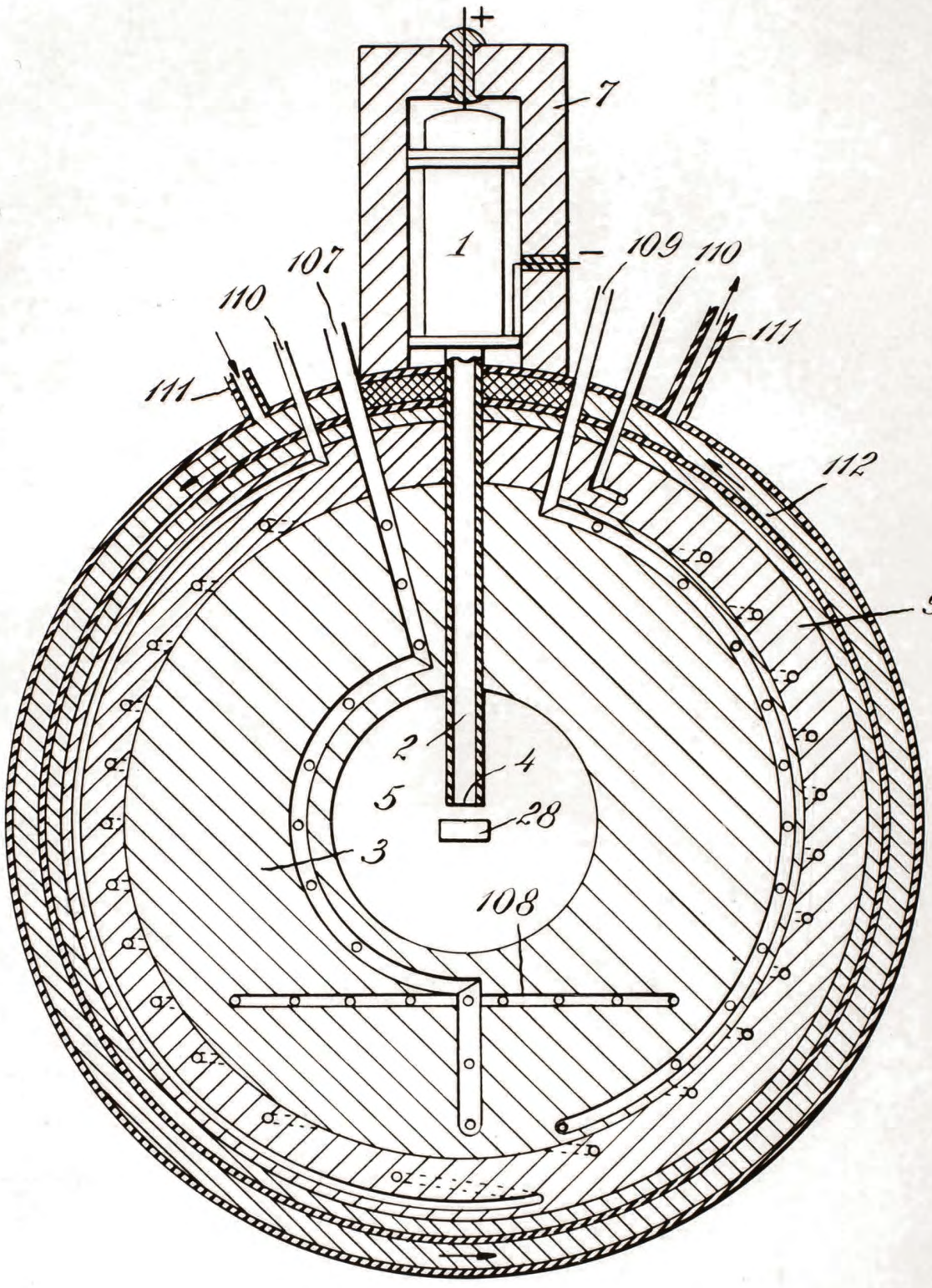

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Fig. 3.

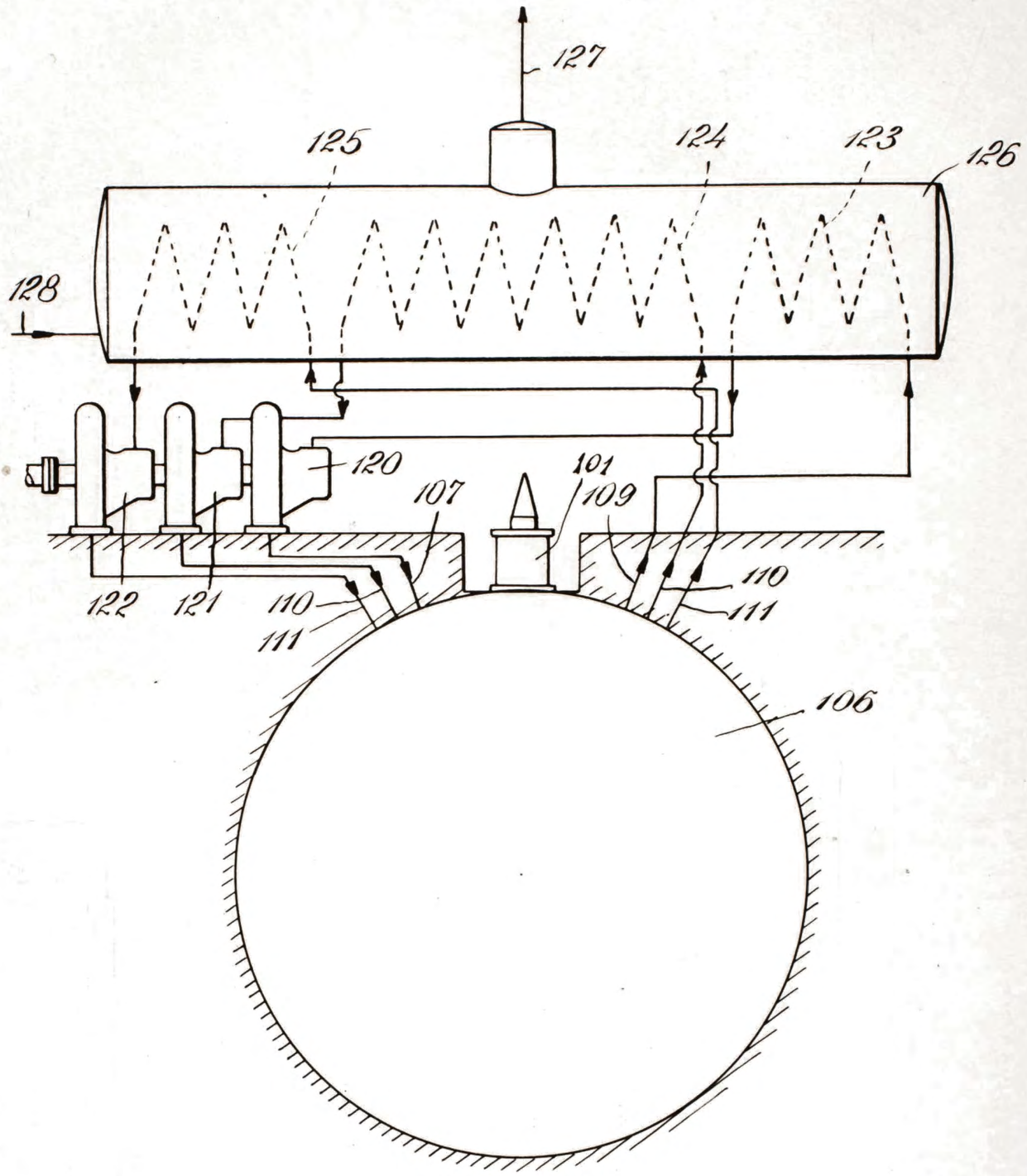

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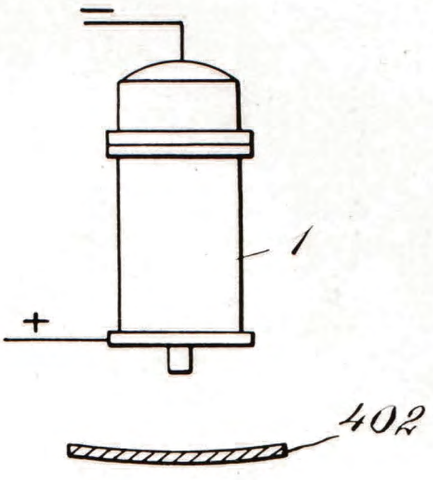
Fig. 4.



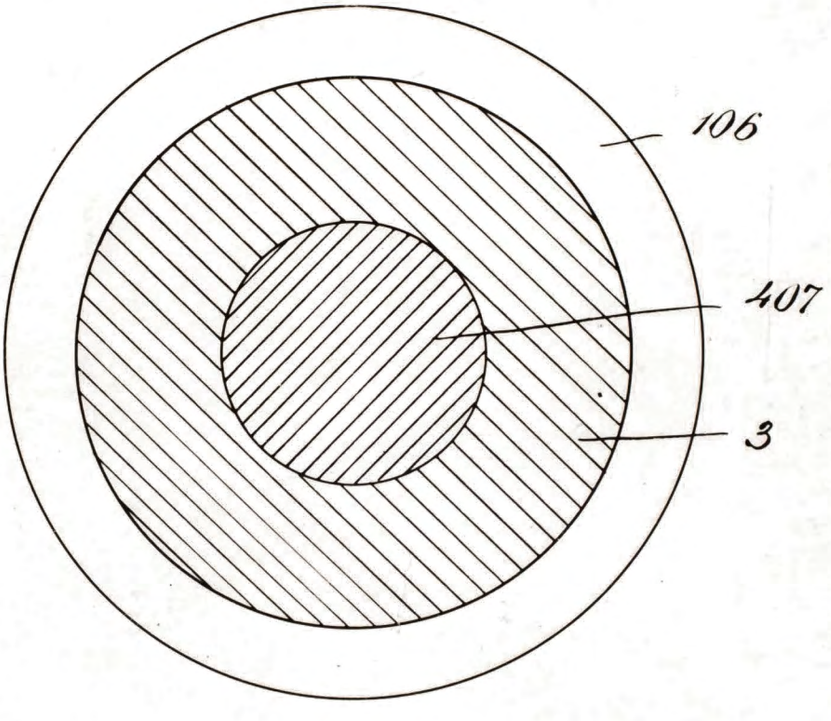


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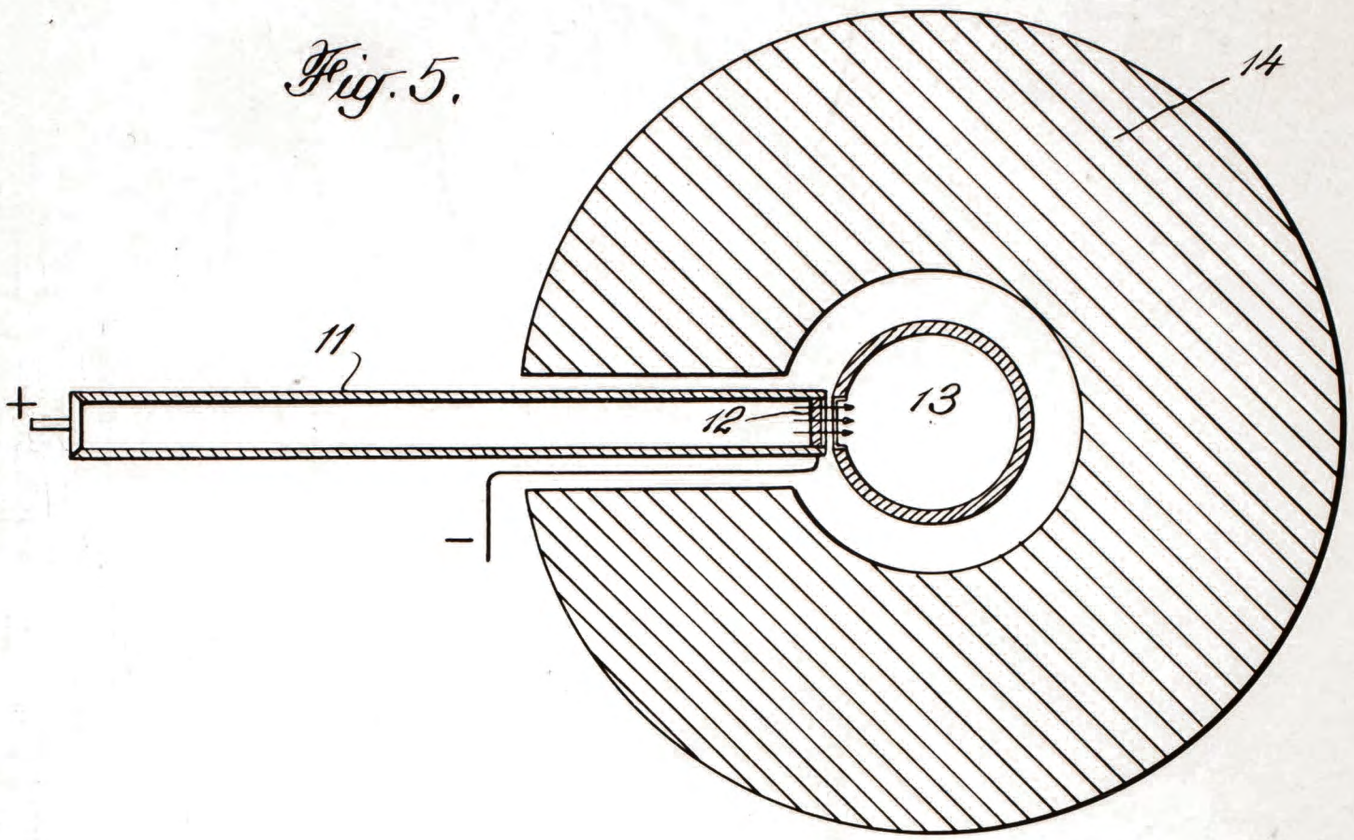
Fig. 5.



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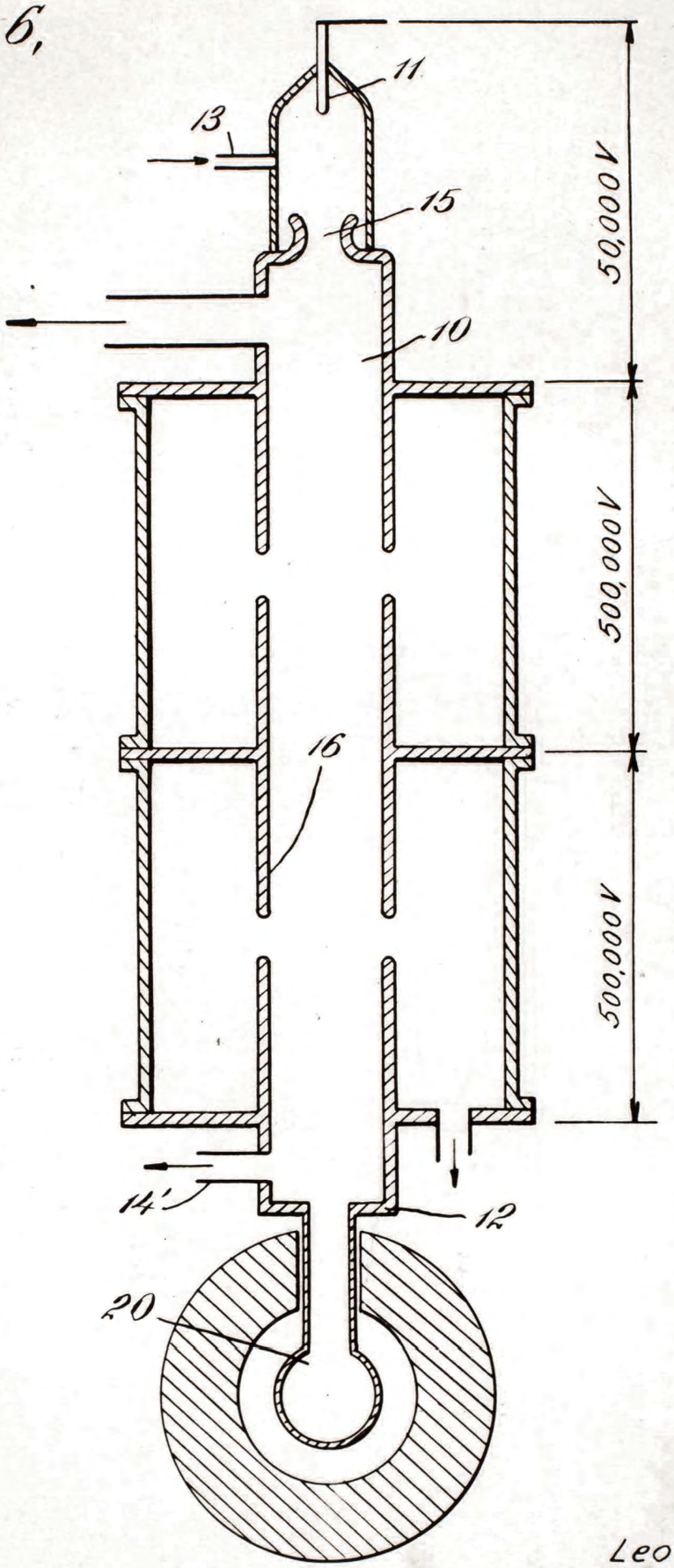
→ Fig

Fig. 6,



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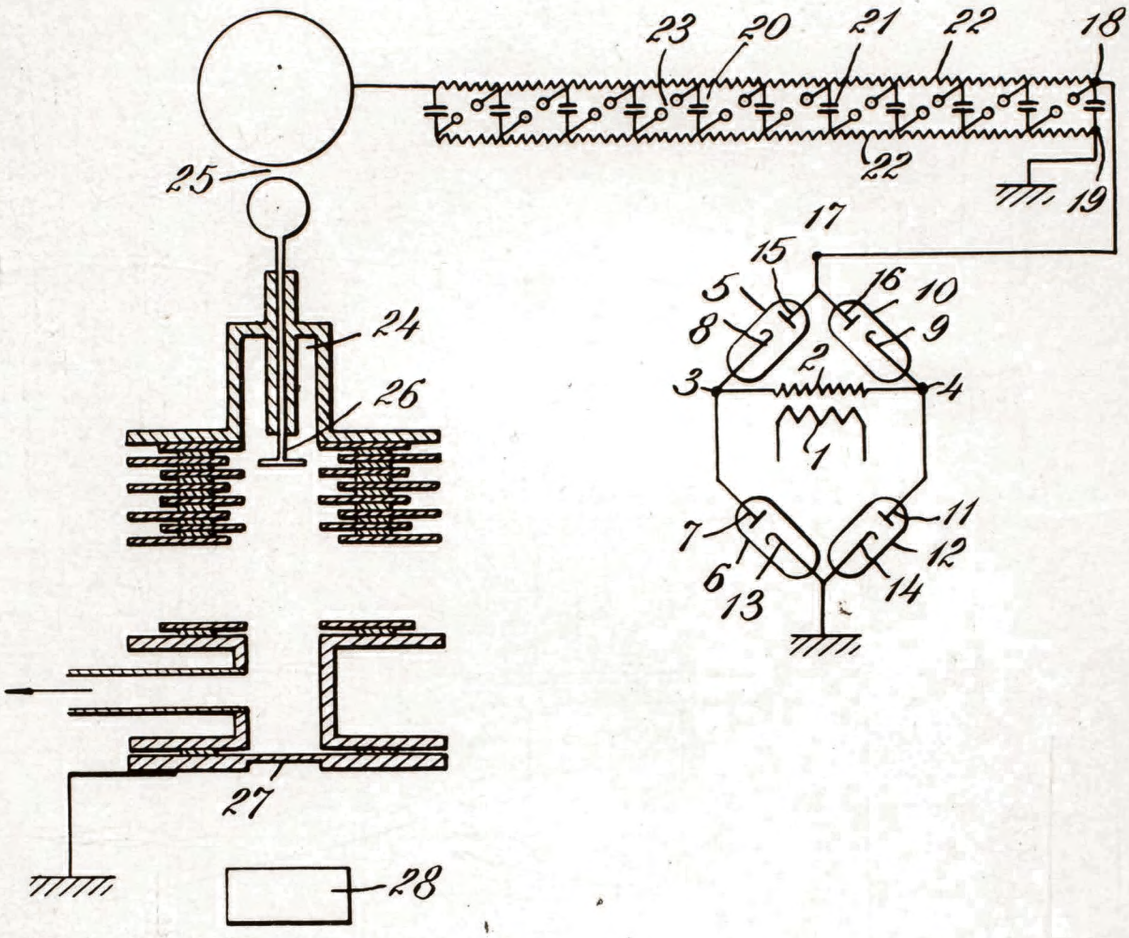
→ Fig 2

Fig. 7.



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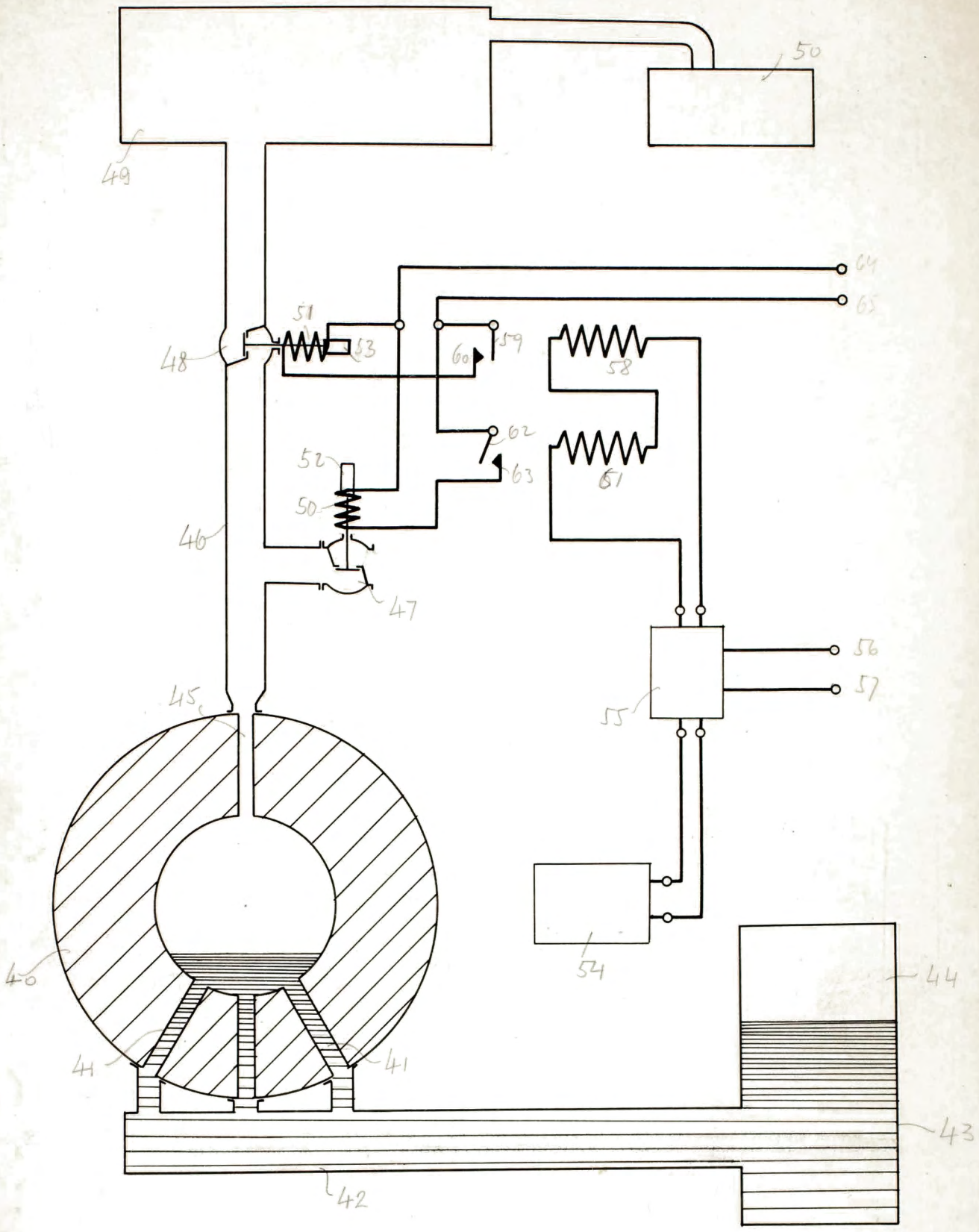
→ Fig 3.



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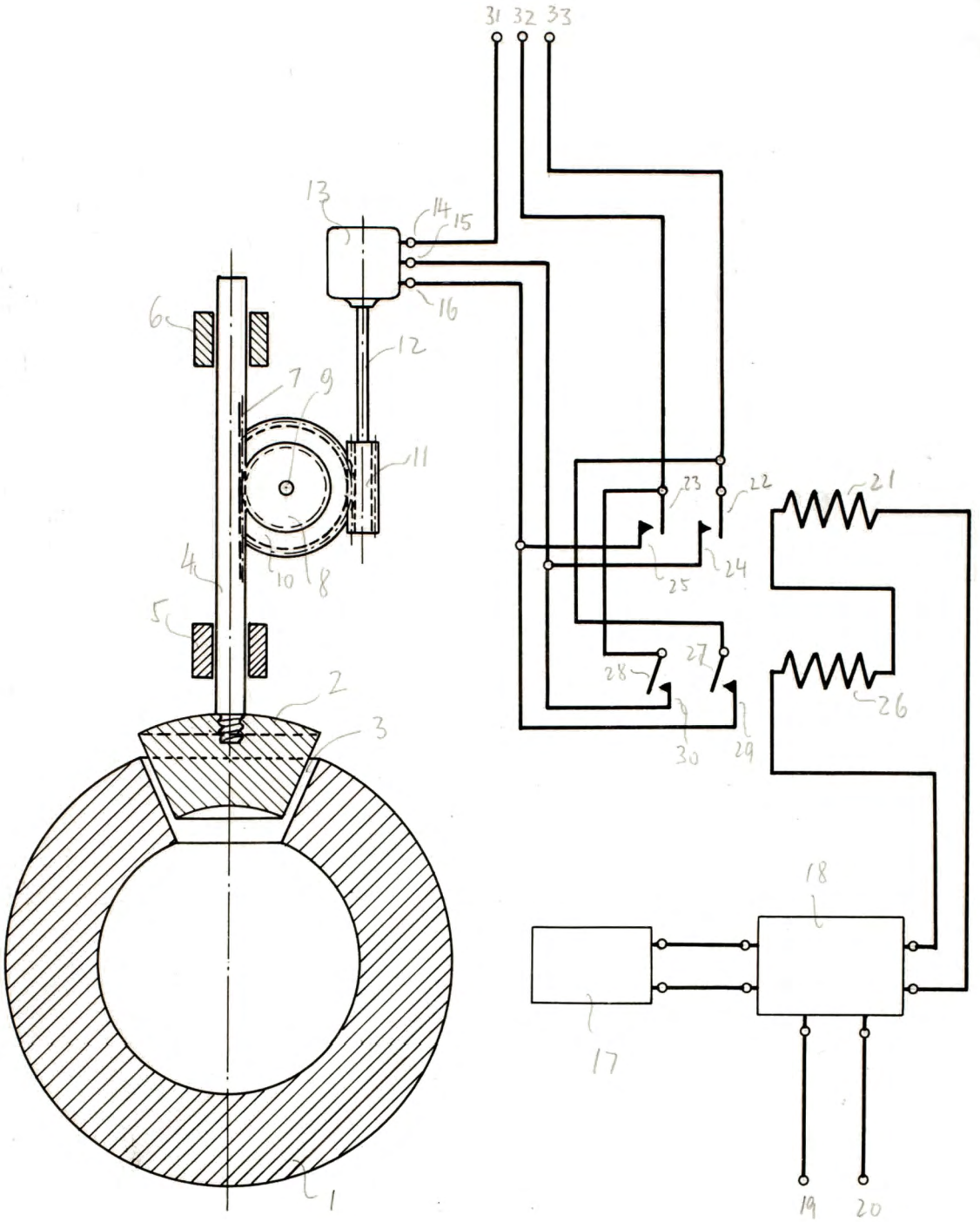

INVENTOR.

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