On Nuclear Chain Reactions and their Bearing on the Question of Power Production.

Sir,

I wish to draw attention to ~~xhx~~ theoretically possible transmutation processes of a special type and indicate simple experiments which could lead to their detection. The energy liberated in a process of this type may very well be large as compared to the energy input required for the maintenance of the process; if such a process can be realised and is used for the generation of power we may therefore have an active power balance. For instance by radiating a metastable element with neutrons it may prove to be possible to maintain a process in which neutrons cause a metastable element to transmute without being stopped from further remaining active in the process and increasing their average energy and number i.e. we may have a nuclear chain reaction. It is believed

Hist-J R-16

28th July, 1934.

Memorandum of Possible Industrial Applications arising out of a New Branch of Physics.

It is possible to indicate methods which might be successfully applied for the purpose of liberating atomic energy. It is not possible to foretell with certainty that these methods will be successful, but the experiments necessary for ascertaining this are fairly simple and could be carried out on a small scale in the university laboratories. Should such experiments give favourable results, the production of energy and ist use for power production would be possible on such a large scale and probably with so little cost that a sort of industrial revolution could be expected; it appears doubtful, for instance, whether coal mining or oil production could survive after a couple of years.

I have applied for a group of patents in order to obtain patent protection for those methods which seemed to me promising, and it appears that these patents were successful in foreshadowing the latest developments in physics.

They include, for instance, methods for the artificial production of radio-active bodies based on a process which recently has been discovered by Fermi. The production of artificial "radium" for medical purposes based on these processes seems to be a sound commercial proposition, but it would be sidetracking the issue to concentrate on this point.

Facilities are required for two different purposes:-

1.) In order to develop and maintain a group of valid patents £500 are required for the next year, which would also take care of administrative expenses connected with the maintenance of the patents.

2.) If we wish to start the necessary experiments one ought to secure the continuity of work for two to three years. It is not possible to state exactly what facilities will be required as this will depend to a large extent on what facilities will be provided by the university laboratory which would be used as a frame for this work. It would, however, be advisable to have £2,000 available for expenditure that may be incurred.

From the point of view of a financier who could consider contributing to the required facilities the position is this:- the chances that the envisaged experiments will yield a favourable result may be estimated to anything between 1 to 20 and 1 to 5. The value of the return in case of success is, of course, enormous and could hardly be estimated in terms of money, so that from the purely financial point of view it is a sort of lottery with a fairly good chance to win a prize and enormous prizes. Yet it would be highly preferable to get financial support from quarters that would consider the experiments as a research work in the field of science which has a good chance of highly significant industrial applications, and realise that the exploitation of discoveries of this scope must not be organised on a purely commercial basis.

~~But~~ Difficulty will undoubtedly arise from the fact that it is not easy for anybody to form an independant opinion of his own on the merits of the case. A possible way out would be, to get the opinion of some of the professors of the University of London who are working themselves in this field, and with whom I can easily keep in touch on the matter.

Suggested Experiments for the Detection of Nuclear Chain Reactions, and the Liberation of Nuclear Energy.

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I wish to draw attention to theoretically possible transmutation processes of a special type and indicate simple experiments which could lead to their detection. The energy liberated by them ~~may very well~~ would be large as compared to the energy input ~~that~~ which is required for the maintenance of the process.

The simplest type may be obtained by radiating a metastable element with neutrons. Some elements betray their metastable character by being radio-active; others are not radio-active. The mass of Beryllium seems to be sufficient to allow a spontaneous transmutation (for instance into two alpha particles and a neutron) which apparently is inhibited. Such inhibition ~~may~~ might, however, be lifted in a nuclear collision with a neutron; a neutron hitting a Beryllium nucleus would then liberate energy without getting captured and could go on hitting efficiently further Beryllium nuclei, the total number of its efficient collisions, and the total amount of the liberated energy being limited by the geometrical conditions only. We shall call a reaction of this type a "chain".

$$Be + n = "Be" + n + \text{Energy}$$

"Be" would be an isomer of Be, which would or would not break up into parts.

Additional neutrons could be liberated along some such chains, which will then be called "divergent" in this note.

A <u>metastable</u> element must <u>necessarily</u> be involved in a chain in which only <u>one kind</u> of non-positive nucleus, as the neutron, ${}_0n^1$, forms the links of the chain. ~~(singulet chain)~~.

It is theoretically possible to maintain chains in mixtures of <u>stable</u> elements and also in certain pure stable elements if <u>two different kinds</u> of non-positive nuclei form the links of the chain (~~double chains~~). The *detailed* discussion of such chains had better be postponed, pending conclusive evidence which would show that neutrons of the mass number two or negative protons (or other particles which could, together with the neutron, serve as links in such chains) have been actually generated in the laboratory.

<u>Divergent Chains in Stationary Processes.</u>

Some information on the geometrical conditions in which a stationary process can be maintained and on the order of magnitudes involved can be obtained by considering a closed spherical layer in which a divergent chain is maintained by a neutron source placed in the centre of the hollow sphere. In a stationary process the density ρ of the neutrons within the layer is a function of the radius r alone and for our purpose sufficiently well described by the equation

$$d^2(r\rho)/dr^2 + 3f/\lambda^2 \cdot (r\rho) = 0$$

where λ is the mean free path of the neutrons for nuclear collisions in the layer and f is the fraction of the nuclear collisions that yields an additional neutron. This equation holds in the case of spherical symmetry ~~under assumptions which~~ if λ/r and f are both sufficiently small within the layer.

If r_2 is the outer radius of the spherical layer and r_1 its inner radius, stationary solutions are possible if the thickness of the layer $r_2 - r_1$ does not exceed a certain critical value $L(r_1)$. The number of neutrons radiated into space from the outer surface tends to become infinite if the thickness of the layer approaches the critical thickness. If ~~we exceed~~ the critical thickness is exceeded no stationary solution is possible, and a neutron source can bring about an explosion.

~~Suggested Experiment.~~

For small $\frac{\lambda^2}{3f r_1^2}$ and if the neutrons can freely escape from the outer surface we get ~~of the layer the value of the critical thickness L is~~ $L = \frac{\pi}{2\sqrt{3f}}\lambda$. For = 10 cm and f ≈ 1/100 the critical thickness is of the order of magnitude of 100 cm.

Suggested Experiment.

It can be determined by ~~an~~ simple experiments ~~on a small scale~~ whether a given material is able to increase the number or energy of the neutrons by scattering neutrons in a layer of this material of a few centimetres' thickness. The elastic scattering causes some difficulty as it may hide the "non-elastic" effect in which we are interested. If, however, we surround a neutron source, the emission of which has spherical symmetry, by a spherical layer of the scattering material, the elastic scattering in the layer will not upset the spherical symmetry and will, therefore, not affect the total number of neutrons going through some point outside the layer. By measuring the total number of neutrons going through ~~such~~ some such point and comparing the value in the presence of the scattering ~~material~~ layer and in its absence we could see if neutrons are liberated or absorbed in the ~~layer~~ scattering material. Yet the elastic scattering affects the angular distribution of the neutrons going through any point which is close to the scattering layer, and can therefore make it difficult to interpret the measurements.

We could make use of the Fermi effect for measuring intensities of neutron beams i.e. we could measure the activity induced by neutrons in bodies formed of Fermi-active elements and draw conclusions on the number and energies of the neutrons to which these bodies have been exposed. Yet if we use sheets of the Fermi-active elements which we place close to the scattering layer in our experiment, the elastic scattering by affecting the angular distribution of the neutrons will affect the induced activity. (It may be necessary ~~we place these sheets at~~

to place the Fermi-active body close to ~~a great distance from~~ the scattering layer ~~we may not be~~ in order ~~able~~ to get an induced activity which ~~we~~ will yield in an electron counter a sufficiently large number of impulses; a large number of ~~10,000 to 100,000~~ impulses are needed to detect small changes ~~[illegible]~~ in the energy or number of the neutrons.) Fortunately this difficulty can be removed by using a large number of small spheres of the Fermi-active element ~~and by using them~~ in place ~~instead~~ of the Fermi-active sheet, the radii of the spheres being small as compared to their distance from the scattering layer.

It will also be possible to detect changes in the neutron energies apart from changes in the ~~neutron~~ number of neutrons by measuring the ratio of the Fermi-activity induced in several elements. We have theoretical evidence in favour of the forecast that for those heavier elements which have a Fermi effect of the neutron - proton or the neutron - alpha particle type, the activity induced by slow neutrons will strongly increase with increasing neutron energies. ~~An investigation of the non-elastic scattering of elements like iodine which transmutes into its own radioactive isotope under neutron bombardment~~

A systematic investigation of the non-elastic scattering of the elements is interesting from several points of view; it would for instance throw light on the primary process involved in the Fermi effect of iodine and other elements which transmute into their own isotopes. Should it lead to the detection of suitable chain re-actions industrial applications of far reaching consequences would result. Investigations along these lines will be started if the necessary facilities can be obtained.

Trinks

Kohner

Sir,   SZILARD

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It will also be possible to detect changes in the neutron energies apart from changes in the ~~neutron~~ number of neutrons by measuring the ratio of the Fermi-activity induced in several elements. We have theoretical evidence in favour of the forecast that for those heavier elements which have a Fermi effect of the neutron - proton or the neutron - alpha particle type, the activity induced by slow neutrons will strongly increase with increasing neutron energies. ~~An investigation of the non-elastic scattering of elements like iodine which transmutes into the own radioactive isotope under neutron bombardment~~

A systematic investigation of the non-elastic scattering of the elements is interesting from several points of view; it would throw for instance light on the primary process involved in the Fermi effect of iodine and other elements which transmute into their own isotopes. Should it lead to the detection of suitable chain re-actions industrial applications of far reaching consequences would result. Investigations along these lines will be started if the necessary facilities can be obtained.

It is possible to use the Fermi effect as an indicator for the detection of neutron radiations. This may prove to be of special value for the investigation of neutron radiations in the presence of a strong gamma radiation. One might expect that even slow neutrons will induce radioactivity in elements which like iodine transmute in the Fermi effect into their own radioactive isotope, but further experiments are necessary to settle this point. Meanwhile T.A. Chalmers of St. Bartholomews Hospital and I worked out a method of isotopic separation which makes it possible to concentrate chemically the activity in the case of iodine and other elements which show a Fermi effect of this type. We used this method of isotopic separation to searching for new neutron sources. By irradiating 25 grams of beryllium with the penetrating radiation from 150 mgms radium and exposing 100 cc. ethyl iodide to the radiation excited in the beryllium we could induce radioactivity in iodine, and separate chemically the radioiodine from the ethyl iodide in the form of a silver iodide precipitate. This precipitate showed a strong activity decaying with a period of 30 minutes, the initial activity being more than 15 times stronger in the presence of beryllium than in its absence. About half of the residual activity in the control experiment may be due to neutrons coming direct from the radium source, the other half represents the natural background effect of the counter. Apparently the gamma rays of radium liberate neutrons from beryllium which induce a strong Fermi effect in iodine. The 30 minutes and the six hours half periods of bromine can also be strongly excited by these neutrons as we have seen in co-operation with E. Glückauf. I was very much interested to hear just now that Professor McLennan has repeated some of our experiments and was able to confirm our results.

If we determine which elements show a Fermi effect when exposed to neutrons from a gamma ray disintegration we get by means of very simple experiments some information both regarding both the processes involved in the Fermi effects and in the gamma ray disintegration. By using the Fermi effect one could thus supplement in some respects the method of Chadwick and Goldhaber who were the first to detect a gamma ray disintegration in their pioneer work on heavy hydrogen. I wish to take this opportunity to mention that this work has been carried out in the Physics Department of St. Bartholomews Hospital and was made possible by the very kind co-operation of Professor Hopwood.

1

Nuclear chain reactions and the possibility of an active power balance in transmutation processes

~~Sir,~~

~~I wish to draw attention to theoretically possible xxxxxxx xxxxx that belong to a special class of transmutation processes and indicate simple experiments for their detection by which it could be determined if such processes can be maintained in one of the existing~~

Sir,

I wish to draw attention to theoretically possible transmutation processes xxxxxxxxxxxxxxxx of a special type and indicate simple experiments which could lead to their detection. The energy liberated in a process of this type may very well be large as compared to the energy input required for the maintenance of the process ~~i.e. we may have an active power balance.~~

If an element is bombarded by protons or other positive nuclei the vast majority of the moving particles are stopped before they have had a chance to cause transmutation. This does not hold for bombardment with neutrons; one might think however, that the ineffeciency of their generation would rule out the possiblity of an active power balancd. Being aware (for the past twelve months) that we can escape such a conclusion if we succeed in maintaining processes in which collisions of neutrons leading to transmutation do not stop the neutrons from further remaining active in the process but increase their average energy or ~~their~~ number, I gave some thought to the main types of theoretically possible "chain r eactions". xxxxxxxxxxxxxxxxxxx Since There is no conclusive evidence as yet showing that neutrons of the mass number two, or negative protons, etc. ~~or diplons, or other non-positive nuclei~~ which could serve as links in such chains have been actually generated in the laboratory, ~~Therefore~~ it is for the present sufficient to point out

+ In order to ~~get~~ learn something about ~~stationary processes~~ the geometrical influence of and almost? ~~the~~ order of magnitudes of the linear dimensions which are consistent with a stationary ~~chain~~ process ~~we also~~ we wish

X ~~and chains in which that~~ ~~which and chains of that type with~~ and we would then ~~have~~ to deal with a "multiplication" chain, as we shall call them further below

~~for the present~~ that a chain reaction in which only one kind of non-positive nucleus/for instance the neutron ($_0n^1$) forms the links of the chain must necessarily involve a metastable element ~~so~~ whereas if ~~If~~ two different kinds of non-positive nuclei form the links it is theorêtically possible ~~to~~ maintain chains in ~~a~~ mixtures of ~~certain~~ stable elements and perhaps also in certain pure, stable elements ~~pure element or in mixtures of/elements/without involving a metastable element.~~

~~For pure neutron/~~($_0n^1$)~~chains we are limited to elements of that class.~~ ~~Apart from~~ Uran and other radioactive elements which betray their metastable character by their activity ~~we know Beryllium to be metastable.~~ "but there is reason to think that there are ~~non radio~~ metastable elements which among ~~are not~~ ~~radio~~ the non radioaktive element ~~Its mass~~, (as often pointed out, is sufficient to ~~allow~~ The mass of Be) permit a spontaneous disintegration into two alpha particles and a neutron. We do not know why such disintegration is inhibited and some sort of transmutation may be ~~made~~ possible in a nuclear collision with a neutron. A neutron hitting a Beryllium nucleus would then liberate energy without getting captured and could go on hitting/efficiently further Beryllium nuclei, the total number of its efficient collisions and the total amount of the liberated energy being determined by the geometrical conditions: ~~A reaction of this type~~

$$_4Be^9 + {}_1n^0 = {}"_4Be^9" + {}_0n^1 + \text{Energy.}$$

"Be" would be an isomer of Be, which would or would not break up into parts.

Additional neutrons could be liberated along (some) such chains in ~~a certain~~ (some definite) fraction (f) of the nuclear collisions (f<1).* ~~in which that occurs of the~~ ~~and chains~~ ~~the influence~~ ~~will be referred to as multiop~~ ~~get a graph~~

<u>Stability Conditions.</u> ~~In order to show in what idea about the/geometrical conditions~~

We wish to consider as an example a closed spherical layer ~~and~~ assume that a neutron chain is maintained within the layer by a neutron source placed in the centre of the hollow sphere. The density ρ of the neutrons within the layer between the inner radius r_1 and ~~the~~ outer radius r_2 ~~under certain assumptions~~ will be given as a function of the radius r by the equation

$d(r\rho)/dr + 3f/\lambda^2 \cdot \rho = 0$

where λ is the mean free path of the neutrons in the layer for elastic collisions and f the fraction of the collis. that yield an additional neutron. This equation holds in the case of spherical symmetry ~~and yields the right order of magnitudes~~ under certain assumpt. which may be ~~realised~~ suff. closely realised if ~~if the inner radius of the hollow sphere ($r = r_1$)~~ λ/r_1 and f are sufficiently small ~~is large enough as compared to λ, and the fraction of the collisions which yield an additional neutron (f) small as compared to 1. If~~ We assume that the neutrons can escape freely into a space from the outer surface ($r = r_2$) $[\rho(r_2) = 0]$. The ratio of the number of neutrons radiated into space to the number of neutrons emitted by the neutron source in the centre of the sphere tends to become infinite, if the thickness of the sheet $(r_2 - r_1)$ approaches a critical value $l(r_1)$, for which $\frac{d\rho}{dr}(r_1)$ approaches zero. We find

$< l <$

the smaller value ~~holding~~ being the limit for large r_1. If $(r_2 - r_1)$ exceeds the critical value we get an explosion.

For $\lambda = 10$ cm, $f = 1/100$ and large r_1 the critical thickness would be 85 cm. The thickness required for doubling the number of neutrons is about two thirds of the critical thickness.

~~Suggested Experiment.~~ Radio-Activity induced by Neutrons.

In order to ~~determine~~ test for a substance its the capacity of increasing the energy or the number of the neutrons which are scattered in it in an experiment on a small scale, it may be convenient to use radio-activity induced by neutrons ~~as an indicator~~ for measuring neutron intensities. This would make it possible to carry out such experiments ~~at any place where~~ by means of ordinary counters ~~are available~~ ~~if~~ radon ~~is supplied from some hospital~~ and beryllium source.

One must not think that because the neutron carries no positive charge the coulombe field of the nucleus cannot prevent processes in which the neutron disappears, a proton appears instead of the neutron and ~~leaving~~ a

If we surround a neutron source with a closed layer of a material in which a chain re-action is maintained by the neutron radiation of the source we can theoretically ~~if this layer is sufficiently~~ thick liberate an unlimited amount of energy; ~~and if additional neutrons are liberated along the chain we can also obtain~~ and similarly if we have ~~an unlimited number of neutrons liberated by some definite number of neutrons emitted by the source.~~ and also an (if we have a multiplication chain) an unlimited number of neutrons. In order to get a rough idea of the geometrical conditions ~~in which a stationary process is possible in the latter case~~ including the order of magnitude of the linear dimensions involved, ~~necessary~~ required to maintain a stationary process in a multiplication chain we shall make some assumptions which will simplify the problem without changing its essential characteristics, and make use of the differential equation which will supply a fairly good description of the process.

We consider a multiplication chain ~~a closed spherical layer~~ in which a neutron chain is maintained by a neutron source placed in the centre of the hollow sphere. ~~If the neutrons can escape freely into space from the outer surface (r = r) of the spherical layer the density of the neutrons within the layer will be zero for r = r.~~ This density (ρ of the neutrons) is ~~sufficiently~~ for our purpose sufficiently well described within the layer by the equation

$$d(r\rho)/dr + 3f/\lambda \cdot \rho = 0$$

where λ is the mean free path of the neutrons for nuclear collisions in the layer and f is the fraction of the nuclear collisions that yield an additional neutron. This equation holds in the case of spherical symmetry under assumptions which may be sufficiently closely realised if λ/r and f are both sufficiently small in the layer. ~~If the neutrons can escape freely into space~~ The ratio of the number of neutrons radiated into space from the outer surface $r = r_2$ to the number of neutrons emitted by the neutron source in the centre of the sphere (and entering the inner surface of the layer ($r = r_1$)) is given by the ~~xxxxx xxxx~~ ratio of the values of ρ for $r = r_2$ and $r = r_1$. This ratio tends to become infinite if $d\rho/dr$ approaches zero for $r = r_1$ and this occurs for a certain ×

critical thickness $r_2 - r_1 = \lambda/\sqrt{3f}$ of the layer. If the neutrons can escape freely into space from the outer surface we have $\rho(r_2) = 0$ and get for the value of the critical thickness: $< \lambda <$

radio-active element is formed which subsequently transmutes into the original element. ~~One should not expect~~ The energy of the proton is ~~xxxxx~~ in such a process necessarily smaller than the energy of the neutron. One should not expect that ~~a~~ such a process would ~~takes~~ take place unless the energy of the ejected proton is sufficient to enable it to penetrate near to the nucleus against the Coulombe field in the inverse process. It ~~should~~ would therefore be surprising if slow neutrons could induce such or similar processes in sufficiently heavy elements (and ~~also~~ equally surprising if they could induce processes in which an alpha particle ~~plays the role~~ instead of the proton, though the energy of the ~~is~~ ejected alpha particle can exceed the energy of the neutron), and if further experiments will confirm our expectation we could estimate a change in the energy and abundance of a neutron beam by ~~measuring~~ comparing the ~~induced~~ activity induced in certain elements of different atomic number.

Suggested Experiment.

~~In order~~ If one wishes to test ~~different~~ the efficiency of some scattering material one has to face the difficulty that the elastic scattering may hide the "inelastic" effect in which we are interested. If we surround a neutron source the emission of which has spherical symmetry, by a spherical layer of the test material the elastic scattering in the layer will not upset the spherical symmetry and will therefore not affect the total number of neutrons going through any point outside the layer. By measuring the total number of neutrons going through such a given point and comparing the value ~~with and without~~ in the presence of the test material and ~~without it~~ in its absence we could, theoretically at least, obtain useful information. Yet the elastic scattering greatly affects the angular distribution of the neutrons going through any point which is close to the layer and would therefore affect the activity induced in a sheet of ~~susceptible material~~ some suitable element placed close to the layer. ~~which we may wish to use~~ If then such a sheet is not close to the layer we loose intensity

~~as indicator.~~ Replacing ~~this~~ such as sheet by a large number of small spheres seems to be the adequate solution of this difficulty; ~~in view of the fact that~~ since we cannot afford to lose ~~much~~ intensity by choosing a large distance between if we wish to observe a change of about 1% in the number or mean energy of the neutrons and have to use a neutron source which is based on radon.

In view of ~~the possible~~ implications ~~for our civilisation of measurement~~ of the inelastic scattering of neutrons in ~~metastable elements~~, I felt I had better not hesitate any longer in raising this subject, since I am not certain whether I shall have an opportunity to carry out such experiments myself.

~~In view of the possible~~

Längere Fassung

the theoretical ~~possibility of~~ possible use

On Nuclear Chain Reactions and their ~~Bearing on the Question~~

Suggestion on for ~~of~~ Power Production.

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I wish to draw attention to ~~the~~ theoretically possible transmutation processes of a special type and indicate simple experiments which could (if they exist) lead to their detection. The energy liberated ~~in a process of this type~~ may very well be large as compared to the energy input which is required for the maintenance of the process; ~~if such a process can be realised and is~~ and if it is used for the generation of power, ~~we~~ it ~~may therefore have~~ lead to an active power balance may result. For instance by radiating a metastable element with neutrons it may prove to be possible to maintain a process in which neutrons cause ~~a metastable element to~~ transmutation without ~~their~~ being stopped from further remaining active in the process; such a process ~~and~~ ~~which~~ could increase ~~ing~~ their average energy ~~and~~ or number i.e. we may have a nuclear "chain reaction." It is believed

~~[illegible]~~ The simplest type ~~form is a ready~~ may be ~~[illegible] possibly~~ obtained by radiating a metastable element with neutrons. possibly

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Sir,

I wish to draw attention to the theoretically possible transmutation processes of a special type and indicate simple experiments which could lead to their detection. The energy liberated in a process of this type may very well be large as compared to the energy input required for the maintenance of the process, and if ~~it~~ such a process can be realised and is used for the generation of power we may have an active power balance. [For instance ~~for instance~~ By radiating a metastable element with neutrons it may prove to be possible to maintain a process in which ~~collisions of~~ neutrons ~~with nuclei of the meta-stable element lead to~~ by ~~colliding~~ ~~can~~ ~~cause~~ by their ~~collisions~~ ~~in fact~~ that a transmutation of the ~~latter which does not stop the neutron~~ metastable element without being stopped from further remaining active in the process ~~but~~ and increase~~s~~ ~~the~~ their average energy ~~of~~ and number i.e. ~~of the neutrons.~~ we may have a nuclear chain reaction".–

~~We have reason to believe~~ It is believed that there exist meta-stable elements ~~apart from those elements which betray their metastable character by their radio-activity.~~ The mass of Beryllium/~~is~~ seems to be sufficient to allow its spontaneous disintegration, (for instance into two alpha particles and a neutron,) which is apparently inhibited under ordinary conditions. Such inhibition may, however, be lifted in a nuclear collision with a neutron; a neutron hitting a Beryllium nucleus would then liberate energy without getting captured and could go on hitting efficiently further Beryllium nuclei, the total number of its efficient collisions, and the total amount of the liberated energy being determined by the ~~alone~~ geometrical conditions. ~~only.~~ We shall call a reaction of this type a "chain". ~~and~~

Be + n = " Be " + n + Energy.

"Be" would be an isomer of Be, which would or would not break up into parts.

Additional neutrons could be liberated along some such "chains", which will then be called "divergent" ~~multiplicative chains~~. in this ~~note.~~ letter.

A metastable element must necessarily be involved in a chain in which only one kind of non-positive ~~particular~~ nucleus, for instance only the neutrons form the links of the chain. (singlet chain)

It is theoretically possible to maintain chains in mixtures of stable elements and also in certain pure stable elements if two different kinds of non-positive nuclei form the links of the chain. (doublet chain) ~~As~~ ~~Since there~~ Pending ~~But there is no~~ conclusive evidence ~~as yet~~ showing that negative protons or neutrons of the mass number two, etc. which could, together with the neutron, serve as links in such chains have been actually generated in the laboratory. ~~we postpone~~ the discussion of doublet chains shall be postponed.

Stationary divergent chains.

~~If we surround a nuetron source with a closed layer of a material in which a chain reaction is maintained by the source we can theoretically liberate an unlimited amount of energy and in the case of a divergent chain also an unlimited number of neutrons.~~ We wish ~~In order~~ ~~to get~~ Some ~~idea of~~ information on the geometrical conditions in which a stationary process can be maintained for a divergent chain and an ~~of~~ the orders of magnitudes involved, can be obtained by ~~we wish to~~ ~~we~~ considering ~~therefore~~ a closed spherical layer in which such a chain is maintained by a neutron source placed in the centre of the hollow sphere. In a stationary process within the layer the density ρ of the neutrons as a function of the radius r is sufficiently well described for our purpose ~~as a function of the radius r~~ by the equation

$$d(r\rho)/dr + \frac{3f}{\lambda^2}(r\rho) = 0$$

where λ is the mean free path of the neutrons for nuclear collisions in the layer and f is the fraction of the nuclear collisions that yield an additional neutron. This equation holds in the case of spherical symmetry under assumptions which may be sufficiently closely realised if λ/r and f are both sufficiently small within ~~in~~ the layer.

If r_2 is the outer radius of the spherical layer and r_1 its inner radius, stationary solutions are possible if the thickness of the layer $r_2 - r_1$ does not exceed a certain critical value. For ~~large~~ small $\lambda/\sqrt{f}$ r_1 and of If the neutrons can freely escape from the outer surface $r = r_2$ ~~the~~ we get for the value l of the critical thickness ~~for~~ ~~large~~ ~~r_2~~ ~~close to~~ ~~small~~ ~~values of~~ $\frac{\lambda^2}{r_1^2}$ (for large r_1 and r_2)

$$l = \frac{\pi}{2}\lambda/\sqrt{3f}$$

For $\lambda = 10$ cm and $f = 1/100$ we get ~~for instance l of the~~ an order of magnitude of 100 cm.

The number of neutrons radiated into space from the outer surface tends to become infinite if the thickness of the layer approaches the critical thickness. If we exceed the critical thickness no stationary solution is possible and we would get an explosion. (~~At about 2/3 of the critical thickness~~ however ~~the number of the neutrons radiated by the source~~ in the centre ~~is only doubled by the chain reaction.~~)

Suggested Experiment.

It ~~would be~~ is possible to detect for any given material whether it is able to increase the energy or number of the neutrons by ~~experiments~~ on a small scale by ~~in which the neutrons are~~ scattered by a layer of a few centimeter thickness of this material. ~~in the test material.~~ The elastic scattering ~~in the material~~ (in such experiments on a small scale) causes some difficulty as it may hide the "non-elastic" effect in which we are interested. If, however, we surround a neutron source, the emission of which has spherical symmetry, by a spherical layer of the test material, ~~(for instance of a few cm thickness)~~ the elastic scattering in the layer will not upset the spherical symmetry and will, therefore, not affect the total number of neutrons going through any point outside the layer. ~~Yet the elastic scattering greatly affects the angular distribution, going through any point which is close to the scattering layer, and can therefore falsify our measurements. It may for instance be very convenient to make use for our purpose of ~~xxxx xxxxxxxxxxx~~ the Fermi effect and draw conclusions on the number and energy of the neutrons from the activity induced by the neutrons in bodies built of suitable elements placed close to the scattering layer. If such bodies have for instance the shape of a sheet and are placed close to the scattering~~

by scattering neutrons in a layer of a few cm thickness ~~of this material.~~

of this material

By measuring the total number of neutrons going through such a given point and comparing the value in the presence of the test material and in its absence we could see if neutrons are liberated or absorbed ~~theoretically at least, obtain useful information~~. Yet the elastic scattering greatly affects the angular distribution of the neutrons ~~of the intensity in neutron beam~~ going through any point which is close to the scattering layer, and can therefore make ~~the the~~ ~~in practice, falsify our measurements~~ it difficult to carry out the measurem' close. ~~It may for instance be very convenient~~ We could ~~to~~ make use ~~for our purpose~~ of the Fermi effect ~~and~~ i.e. to measure the activity induced by the neutrons in bodies ~~built~~ formed of ~~suitable~~ Fermi-active elements ~~placed close to the scattering layer~~ and draw conclusions on the number and energy of the neutrons ~~going~~ which have gone through ~~these~~ bodies. Yet if ~~such bodies have the shape of a~~ for instance we use a sheet of the Fermi active element in our experiment ~~and are~~ placed close to the scattering layer (~~xx ix~~ and it may be necessary to place them close to the layer in order to induce an activity that will yield a large number of impulses — in an electron counter, sufficiently large to detect changes of 1% in the energy or number of the neutrons), the elastic scattering by affecting the ~~mentioned~~ (as mentioned) angular distribution of the neutrons will greatly affect the ~~observed~~ induced activity. ~~This~~ Fortunately this difficulty can be removed by using a large number of small spheres of the material which is to be activated and ~~replacing~~ by them replacing the above-mentioned sheet.

~~There is very strong~~ We have ~~strong~~ at least theoretical evidence in favour of the ~~assumption~~ forecast that for ~~some of the~~ those heavier elements which have a Fermi effect of ~~a certain~~ the neutron + proton or neutron + K Part type, the activity induced by slow neutrons will strongly increase with increasing neutron energies. This ~~would~~ will make it possible to detect ~~a~~ changes in the neutron energies by measuring the ratio of the activity induced in several elements.

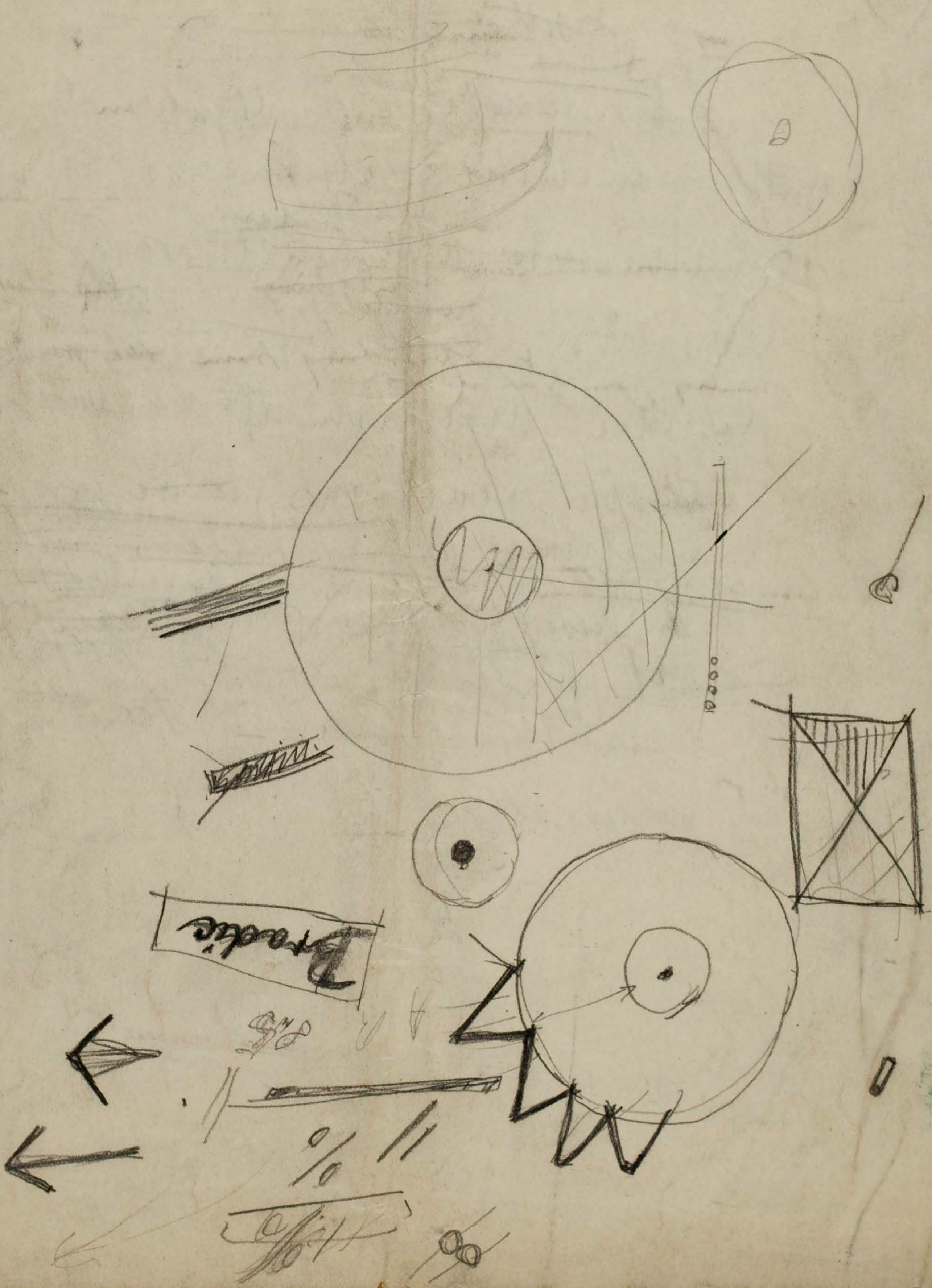
~~The expense involved in~~ a systematic investigation of the "inelastic" scattering of the elements is ~~small.~~ ~~both in its~~ ~~modest~~ would not be expensive. ~~The ratio of the ... [illegible]~~

~~a the~~ The ratio of the immediate economic
value (of the ~~experiments~~ result of such an investigation) ~~should they tend to the detection of~~
~~results~~ (~~should it tend~~ provided ~~that~~ a metastable is found
~~a metastable chain~~ (material for a chain) to
the expenses involved in ~~the suggested~~
the investigation is ~~of the order of~~ ~~above~~ larger than 10^6
~~magnitude of 10~~

If a material for a metastable chain reaction were to be found the ratio of the immediate economic value of ~~this result of the~~ the proposed investigation to ~~the~~ its expenses would exceed 10^8.—

A systematic investigation of the non-elastic scattering of the elements would not be expensive. If a material for a suitable chain reaction were to be found thereby the ratio of the immediate economic value of the proposed investigation to its expense would exceed 10.

~~Should~~ Would a ~~A~~ systematic investigation of the non elastic scattering of the elements and certain mixtures of elements ~~wanted~~ ~~would have~~ ~~carried~~ ~~; if it~~ ~~should it~~ lead[illegible] from ~~the pure~~ is interesting from energy production point of view: to the detection of suitable chain reactions, ~~have far~~ ~~applications which may be expected~~ ~~[illegible]~~ reaching consequences; ~~such~~ ~~wanted results~~ along these lines [illegible] An investigation will therefore [illegible] forward if ~~when~~ adequate facilities the necessary can be obtained for ~~this~~ such ~~for this work.-~~ work.-



On Nuclear Chain Reactions and their Bearing on the Question of Power Production.

Sir,

I wish to draw attention to ~~the~~ theoretically possible transmutation processes of a special type and indicate simple experiments which could lead to their detection. The energy liberated in a process of this type may very well be large as compared to the energy input required for the maintenance of the prosess; if such a process can be realised and is used for the generation of power we may therefore have an active power balance. For instance by radiating a metastable element with neutrons it may prove to be possible to maintain a process in which neutrons cause a metastable element to transmute without being stopped from further remaining active in the process and increasing their average energy and number i.e. we may have a nuclear chain reaction. It is believed

Sir,

I wish to draw attention to the theoretically possible transmutation processes of a special type and indicate simple experiments which could lead to their detection. The energy liberated in a process of this type may very well be large as compared to the energy input required for the maintenance of the process, and if it is used for the generation of power we may have an active power balance. By radiating a metastable element with neutrons it may prove to be possible to maintain a process in which collisions of neutrons with nuclei of the metastable element lead to a transmutation of the latter which does not stop the neutron from further remaining active in the process but increases the average energy of number of the neutrons.

We have reason to believe that there exist metastable elements apart from those elements which betray their metastable character by their radio-activity. The mass of Beryllium/~~is even~~ seems to be sufficient to allow its spontaneous disintegration into two alpha particles and a neutron, which is apparently inhibited under ordinary conditions. Such inhibition may, however, be lifted in a nuclear collision with a neutron; a neutron hitting a Beryllium nucleus would then liberate energy without getting captured and could go on hitting efficiently further Beryllium nuclei, the total number of its efficient collisions, and the total amount of the liberated energy being determined by the geometrical conditions only.

$$\mathrm{Be} + n = \text{"Be"} + n + \text{Energy.}$$

"Be" would be an isomer of Be, which would or would not break up into parts.

Additional neutrons could be liberated along some such chains, which will then be called multiplicative chains in this note.

A metastable element must necessarily be involved in a chain in which only one kind of non-positive ~~xxxxxxxx~~ nucleus, for instance only neutrons form the links of the chain. It is theoretically possible to maintain chains in mixtures of stable elements and also in certain pure stable elements if two different kinds of non-positive nuclei form the links of the chain, but there is no conclusive evidence as yet showing that negative protons or neutrons of the mass number two which could, together with the neutron, serve as links in such chains have been actually generated in the laboratory.

If we surround a nuetron source with a closed layer of a material in which a chain reaction is maintained by the source we can theoretically liberate an unlimited amount of energy and in the case of a divergent chain also an unlimited number of neutrons. In order to get some idea of the geometrical conditions in which a stationary process can be maintained for a divergent chain and of the orders of magnitudes involved we wish to consider a closed spherical layer in which such a chain is maintained by a neutron source placed in the centre of the hollow sphere. In a stationary process the density of the neutrons within the layer is sufficiently well described for our purpose as a function of the radius r by the equation

$$d(r\ )/dr + 3f/\ .\ = 0$$

where is the mean free path of the neutrons for nuclear collisions in the layer and f is the fraction of the nuclear collisions that yield an additional neutron. This equation holds in the case of spherical symmetry under assumptions which may be sufficiently closely realised if /r and f are both sufficiently small within ~~in~~ the layer.

If r is the outer radius of the spherical layer and r its inner radius, stationary solutions are possible if the thickness of the layer r - r does not exceed a certain critical value. If the neutrons can freely escapt from the outer surface r = r the value l of the critical thickness is for large r close to

l = .

For = 10 cm and f = 1/100 we get for instance l of the order of magnitude 100 cm.

The number of neutrons radiated into space from the outer surface tends to be come infinite if the thickness of the layer approaches the critical thickness. If we exceed the critical thickness no stationary solution is possible and we would get an explosion. At about 2/3 of the critical thickness the number of the neutrons radiated by the source is only doubled by the chain reaction.

Suggested Experiment.

It would be possible to detect for any given material whether it is able to increase the energy or number of the neutrons by experiments in which the neutrons are scattered in the test material. The elastic scattering in the material causes some difficulty as it may hide the "inelastic" effect in which we are interested. If, however, we surround a neutron source the emission of which has spherical symmetry, by a spherical layer of the test material the elastic scattering in the layer will not upset the spherical symmetry and will, therefore, not affect the total number of neutrons going through any point outside the layer. Yet the elastic scattering greatly affects the angular distribution, going through any point which is close to the scattering layer, and can therefore falsify our measurements. It may for instance be very convenient to make use for our purpose of the Fermi effect and draw conclusions on the number and energy of the neutrons from the activity induced by the neutrons in bodies built of suitable elements placed close to the scattering layer. If such bodies have for instance the shape of a sheet and are placed close to the scattering

By measuring the total number of neutrons going through such a given point and comparing the value in the presence of the test material and in its absence we could theoretically at least obtain useful information. Yet the elastic scattering greatly affects the angular distribution, going through any point which is close to the scattering layer, and can therefore in practice falsify our measurements. It may for instance be very convenient to make use for our purpose of the Fermi effect, ~~and~~ measure the activily induced by the neutrons in bodies built of suitable elements ~~placed close to the scattering layer~~ and draw conclusions on the number and energy of the neutrons going through these bodies. Yet if such bodies have the shape of a sheet and are placed close to the scattering layer (~~as is~~ and it may be necessary to place them close to the layer in order to induce an activity that will yield a large number of impulses in an electron counter, sufficiently large to detect changes of 1% in the energy or number of the neutrons), the elastic scattering by affecting the mentioned angular distribution will greatly affect the observed induced activity. This difficulty can be removed by using a large number of small spheres of the material which is to be activated and replacing by them the above mentioned sheet.

There is very strong theoretical evidence in favour of the assumption that for some of the heavier elements which have a Fermi effect of a certain type the activity induced by slow neutrons will strongly increase with increasing neutron energy. This would make it possible to detect a change in the neutron energy by measuring the ratio of the activity induced in several elements.

A systematic investigation of the non-elastic scattering of the elements would not be expensive. If material for a suitable chain reaction were to be found thereby the radio of the immediate economic value of the proposed investigation to its expense would exceed 10.

1

Längere Fassg.

Sir,

I wish to draw attention to theoretically possible ~~[illegible]~~ that belong to a special class ~~of~~ transmutation processes and indicate simple experiments for their detection by which it could be determined if such processes

can be maintained in one of the existing

Sir,

I wish to draw attention to theoretically possible transmutation processes ~~[illegible]~~ of a special ~~[illegible]~~ type and indicate simple experiments which could lead to their detection. The energy liberated in a process of this type may very well be large as compared to the energy input required for ~~[illegible]~~ the maintenance of the process i.e. we may have an active power balance.

If an element is bombarded by protons or other positive nuclei ~~[illegible]~~ the vast majority of the moving particles ~~[illegible]~~ are stopped before they have had a chance to cause transmutation. This does not hold for bombardment with neutrons; one might think however, that the ineffeciency ~~[illegible]~~ of their generation would rule out the possiblity of an active power balance. Being aware for the past twelve months that we can escape such a conclusion if we succeed in maintaining processes in which collisions leading to transmutation do not stop the neutrons from further remaining active in the process but increase their energy or their number I gave some thought to the main types of theoretically possible "chain reactions"; ~~[illegible]~~ There is no conclusive evidence as yet showing that neutrons of the mass number two, negative protons or diplons or other non-positive nuclei which could serve as links in such chains have been actually generated in the laboratory. Therefore it is sufficient to point out for the present that a chain reaction in which only one kind of non-positive nucleus for instance the neutron (n) forms the links of the chain must necessarily involve a metastable element. If two different kinds of non-positive nuclei form the links it is theorâtically possible to maintain chains in a mixtures of certain elements and perhaps also in certain pure elements ~~pure element or in mixtures of elements~~ without involving a metastable element.

For pure neutron (n) chains we are limited to elements of that class. Apart from Uran and other radio-active elements which betray their metastable character by their activity we know Beryllium to be metastable. Its mass, as often pointed out, is sufficient to ~~allow~~ permit a spontaneous disintegration into two alpha particles and a neutron. We do not know why such disintegration is inhibited and some sort of transmutation may be made possible in a nuclear collision. A neutron heating a Beryllium nucleus would then liberate energy without getting captured and would go on hitting efficiently further Beryllium nuclei the total number of its efficient collisions and the total amount of the liberated energy being determined by the geometrical conditions.

$$\mathrm{Be} + n = \text{" Be "} + n + \text{Energy}.$$

"Be" would be an ísomer of Be, which would or would not break up into parts.

Additional neutrons could be liberated along such a chain in a certain fraction (F) of the nuclear collisions (f 1).

Stability Conditions.

We wish to consider as an example a closed spherical layer and assume that a neutron chain is maintained within the layer by a neutron source placed in the centre of the hollow sphere. The density of the neutron within the layer between the inner radius r and the outer radius r will be given as a function of the radius r by

$d(r\ )/dr + 3f/\ .\ = 0$

Where is the mean free path of the neutrons in the layer for elastic collisions. This equation holds in the case of spherical symmetry and yields the right order of magnitudes in the inner radius of the hollow sphere ($r = r$) is large enough as compared to , and the fraction of the collisions which yield an additional neutron (f) small as compared to 1. If we assume that the neutrons can escape freely into a space from the outer surface ($r = r$) the radio of the neutrons radiated into space to the neutrons emitted by the neutron source in the centre of the sphere tends to become infinite if the thickness of the sheet ($r - r$) approaches a critical value $l(r)$. We find

the smaller value holding for large r. If ($r - r$) exceeds the critical value we get an explosion.

For $= 10$ cm, $f = 1/100$ and large r the critical thickness would be . The thickness required for doubling the number of neutrons is about two thirds of the critical thickness.

~~Suggested Experiment~~. Radio-Activity induced by Neutrons.

In order to ~~determine~~ test for a substance its capacity of increasing the energy or the number of the neutrons which are scattered in it in an experiment on a small scale it may be convenient to use radio-activity induced by neutrons as an indicator. This would make it possible to carry out such experimmnts at any place where ordinary counters are available ~~provided~~ if radon is supplied from some hospital.

One must not think that because the neutron carries no positive charge the coulombe field of the nucleus cannot prevent processes in which the neutron disappears, a proton appearing instead of the neutron and leaving a radio-active element is formed which transmutes into the original element. ~~One should not expect~~ The energy of the proton ~~would~~ is smaller than the energy of the neutron. One should not expect that such a process takes place unless the energy of the ejected proton is sufficient to enable it to penetrate near to the nucleus against the Coulombe field in the inverse process. It should therefore be surprising if slow neutrons could induce such processes in sufficiently heavy elements (and also if they could induce processes in which an alpha particle plays the role of the proton, though the energy of the ejected alpha particle can exceed the energy of the neutron), and if further experiments will confirm our expectation we could estimate a change in the energy and abundance of a neutron beam by ~~measuring~~ comparing the ~~induced~~ activity induced in elements of different atomic number.

<u>Suggested Experiment.</u>

~~In order~~ If one wishes to test the efficiency of some ~~different~~ scattering material one has to face the difficulty that the elastic scattering may hide the "inelastic" effect in which we are interested. If we surround a neutron source the emission of which has spherical symmetry, by a spherical layer of the test material the elastic scattering in the layer will not upset the spherical symmetry and will therefore not effect the total number of neutrons going through any point outside the layer. By measuring the total number of neutrons going through such a given point and comparing the value ~~with and without~~ in the presence of the test material and without it we could theoretically at least obtain useful information. Yet the elastic scattering affects the angular distribution of the neutrons going through any point which is close to the layer and would therefore affect the activity induced in a sheet of suscpptible material placed close to the layer which we may wish to use as indicator. Replacing this sheet by a large number of small spheres seems th bhethe adequate solution of this difficulty, in view of the fact that we cannot afford to lose much intensity if we wish to observe a change of about 1% in the number or mean energy of the neutrons and have to use a neutron source which is based on radon.

In view of the possible implications for our civilisation of measurement of the inelastic scattering of neutrons in metastable elements, I felt I had better not hesitate any longer in raising this subject, since I am not certain whether I shall have an opportunity to carry out such experiments myself.

If we surround a neutron source with a closed layer of a material in which a chain re-action is maintained by the neutron radiation of the source we can theoretically liberate an unlimited amount of energy; and if additional neutrons are liberated along the chain we can also obtain an unlimited number of neutrons liberated by some definite number of neutrons emitted by the source. In order to get a rough idea of the geometrical conditions in which a stationary process is possible in the latter case including the order of magnitude of the linear dimensions involved, we shall make some assumptions which will simplify the problem without changing its essential characteristics, and make use of the differential equation which will supply a fairly good description of the process.

We consider a closed spherical layer in which a neutron chain is maintained by a neutron source placed in the centre of the hollow sphere. If the neutrons can escape freely into space from the outer surface ($r = r$) of the spherical layer the density of the neutrons within the layer will be zero for $r = r$. This density is described within the layer by the equation

$$d(r\ )/dr' + 3f/\ .\ = 0$$

where is the mean free path of the neutrons for nuclear collisions in the layer and f is the fraction of the nuclear collisions that yield an additional neutron. This equation holds in the case of spherical symmetry under assumptions which may be sufficiently closely realised if $/r$ and f are both sufficiently small. ~~If the neutrons can escape freely into space~~ The radio of the number of neutrons radiated into space from the outer surface $r = r$ to the number of neutrons emitted by the neutron source in the centre of the sphere is given by the ~~ratio ratio~~ ratio of the values of for $r = r$ and $r = r$. This radio tends to become infinite if approaches zero and this occurs for a certain