Memorandum

March 12, 1940

A method has been devised for setting up a chain reaction in a system composed of uranium and carbon; this method ~~xxxxbe~~ is described in detail in an unpublished paper which was sent to Physical Review. We may expect that about 10 tons of uranium and perhaps 50 tons of graphite will be needed for maintaining a chain reaction at the point of divergende at which nuclear transmutation will proceed at a rate limited only by the necessity of ~~overheating~~ avoiding overheating.

Human beings will have to be protected by large water tanks from being exposed to the deadly radiations emanating from the chain reaction. The large amounts of energyliberated in the chain reaction may be used for the purpose of producing power, but due to the weight of the water tanks it will not be possible to drive air planes with uranium as a source of power. However, certain classes of naval vessels might make use of uranium as a source of power with the result of vastly increased speed and independence from fuel supply.

Questions relating to the transformation into power of the energy liberated in the chain reaction have been studied as well as questions relating to the regulation of the chain reaction, and methods for avoiding accidental overheating have been devised.

Ten tons of uranium would supply as much power as 20 000 to 50 000 tons of coal. After this amount of power has been produced so much of the active agent contained in the uranium will be used up that the remaining uranium will be of no further use for power production. ~~Since~~ It ~~is in any case~~ unlikely that a supply exceeding 300 tons of uranium per year ~~can~~ Could be obtained for the U.S. and, it appears for this reason alone unlikely that uranium can replace coal or oil as a fuel for a large fraction of the navy, and the use of uranium will necessarily remain limited to certain special classes of naval units.

Since there is an abundant liberation of neutrons in the chain reaction it will be possible to produce radioactive elements for medical purposes in practically any desired quantity by means of these neutrons. Radioactive elements will also be produced in great quantities from the splitting uranium itself, but the properties of the~~se products,~~ latter have not sufficiently been studied for us to know whether any of them will be suitable for medical use.

To Prof Pegram
from L. Szilard May 4th
Handed over May 6th
[1940]

In order to demonstarte a chain reaction in which nuclear energies are liberated we propose to carry out the large scale experiment using up to 160 tons of graphite and 35 tons of uranium oxide or alternatively 15 tons of uranium metal. It is believed that if the facilities can be obtained, such an experiment can be carried out within a year and has a reasonable chance of success, and it is hoped that the quantities of materials actually required will be less than those quoted above. It is proposed that the Government secures the 50 tons of uranium oxide by placing an order for this amount as soon as possible. Delivery could be expected at the rate of 1 ton per week so that the total amount could be secured within a year.

As the first step towards this large scale experiment it is proposed to carry out an experiment on an intermediate scale with 40 tons of graphite and 6 tons of uranium metal. Since it will take 3 to 6 months to obtain delivery of such an amount of uranium metal it is proposed to start the experiment with 8 to 12 tons of uranium oxide and to carry out measurements on this system pending the delivery of the metal. It is considered likely that the chain reaction can be made to work in a system consisting of spheres of uranium metal embedded in graphite and there is also a chance that a similar system composed of uranium oxide and graphite can be made to work.

The system might be improved by surrounding the uranium metal spheres with shells of beryllium metal, choosing the total weight of uranium and beryllium to be about equal, but it is not at present believed that such an improvement will be necessary. Nevertheless, this line of thought will be pursued by laboratory experiments carried out on 150 pounds of beryllium metal.

Eight tons of uranium oxide and 40 tons of graphite have already been ordered out of an existing appropriation of 100,000 dollars, which is at the disposal of the National Bureau of Standards and it is believed that 3 tons of uranium metal can be obtained within the frame-work of this appropriation. An additional 6 tons of uranium oxide out of which 3 tons should be converted into uranium metal might be required for the purposes of the intermediate scale experiment.

It is proposed that, during the performance of the intermediate scale experiment and large scale experiment, laboratory experiments for measuring nuclear quantities involved should go on uninterrupted and it is assumed that about 5 out of a staff of 10 physicists or chemists will be engaged in the actual performance of the intermediate and large sclae experiments while the other 5 will carry on laboratory experiments. It is further proposed that a small appropriation of not more than 15,000. dollars be set aside in the contract covering the intermediate scale experiment for the purpose of preparing the large scale experiment which is to follow.

June 24, 1940

MEMORANDUM

In the memorandum which was submitted in the course of a meeting held under the chairmanship of Dr. Briggs on April 27, 1940, I discussed the possibility of using uranium as a source of power for the purpose of driving naval vessels. In the case of a chain reaction maintained in a system composed of carbon and uranium a conservative estimate leads to the prediction that one ton of uranium will be equivalent to about 3,000 tons of oil. Certain recent developments make it appear conceivable that the conditions can be so chosen as to obtain from 1 ton of uranium as much power as from about a few million tons of oil. Professor Louis A. Turner of Princeton sent me a manuscript in which this possibility is discussed. In discussions which Dr. Turner had with Dr. Wigner and myself he expressed his willingness to have the publication of his paper delayed if required. Certain observations made by Macmillan and Abelson which were published in the June 15th issue of the Physical Review opened up the way for investigating the potential possibility discussed by Dr. Turner. By following up the work of Macmillan and Abelson and by carrying out the contemplated general survey of the nuclear constants it will be possible to decide whether 1 ton of uranium "burned" in a system composed of uranium and carbon is capable of supplying as much power as a few million tons of oil or whether it is only capable of supplying as much power as 3,000 tons of oil, the previously given conservative estimate.

L. Szilard

(Leo Szilard)

June 27, 1940

Memorandum

concerning the possible usefulness of the separation of the uranium isotopes for purposes of power production.

There are several reasons why at present it would appear justified to support work on the separation of the isotopes from the point of view with which this memorandum is concerned. First of all it is not yet certain that a chain reaction can be made to work with unseparated uranium. Just how good the chances for a chain reaction with unseparated uranium are is a point on which there is some divergence of opinion. Fermi does not wish to go beyond saying that it is more probable than not that unseparated uranium will work, whereas I consider a 10:1 bet as a fair expression of the chances of success. This divergence of opinion is not based on the different evaluation of the nuclear constants so far measured or on a different estimate of the experimental error involved, but arises rather out of my inclination of taking into account the possibility of improving the conditions for a chain reaction by using certain setups which are rather different from the setups so far considered and which, I think, will be considerably more favorable though perhaps rather more expensive. Still, if we admit the possibility that a chain reaction will not work with unseparated uranium, then clearly a concentration of the rare isotope in the ratio of perhaps 1:1.3 might make all the difference which is required to make the chain reaction go.

Though the concentration of the rare isotope of uranium in the ratio of 1:1.3 will probably be rather expensive, it may be of considerable significance if the chain reaction cannot be made to work with unseparated uranium in view of the following possibility: Element 94, produced from the more abundant isotope of uranium by neutron capture, may have a large fission cross section for thermal neutrons. If that is the case and if more than two neutrons are emitted in the fission of this element, then it would be possible to make a chain reaction in which the abundant isotope of uranium would be burned. Initially it might be necessary to start with uranium in which the rare isotope is concentrated approximately in the ratio of 1:1.3 in order to be able to start the chain reaction in the course of which the rare isotope of uranium 235 would be quickly used up while a certain amount of element 94 would accumulate and gradually reach a concentration at which the abundant isotope of uranium 238 would be burned in the chain reaction. Of course it is also possible that ordinary uranium can be used for this purpose, and that a concentration of uranium 235 will not be necessary, but this question can be decided only in the course of the next one or two years, and meanwhile methods for the concentration of uranium 235 ought to be studied.

If unseparated uranium can be used for maintaining a chain reaction in a system composed of carbon and uranium, then the significance of the separation of the uranium isotope 235 from the point of view of this memorandum is rather limited, but perhaps still sufficient to deserve attention.

Assuming that only uranium 235 can be burned in the chain reaction in a system composed of uranium and carbon, and this would be the case if element 94 shows no fission with thermal neutrons, we shall be faced with a serious shortage of uranium in this country. If unseparated uranium used, perhaps only one tenth of the 235 content of ordinary uranium can be utilized in the chain reaction. If the rare isotope is concentrated in the uranium a much larger fraction can be utilized. It appears somewhat unlikely that for reasons of economy alone the costly process of concentrating the isotopes should be justified. However, since the country will probably be cut off from the uranium supplies of Belgian Congo in the future, and since no provisions were made to secure such supplies in the course of the past year, there may be no alternative left but the application of a process of extracting the rare isotope, however expensive this may be.

Apart from this it does not seem that the mere fact of having a small concentrated source of energy in the form of the separated isotope uranium 235 would have much significance from the point of view of this memorandum. The necessity of shielding personnel from the neutron radiation emitted in the chain reaction involves the carrying of large tanks of water and the saving in weight resulting from the use of the separated isotope rather than the unseparated uranium would hardly be sufficient to justify the expense connected with the process of extraction. The picture which is occasionally given of a few kilograms of uranium 235 dissdved in a few liters of water producing as much power as is required to drive a boat is rather misleading. Even a perfunctory study which need not utilize more than the most elementary principles of engineering will show that the problems of heat transfer which arise if the energy liberated in uranium to be used for purposes of power production cannot be solved if a small quantity of water is used. As a matter of fact a more detailed study shows that the use of a solution of uranium in water is quite unsuitable for such purposes from the engineering point of view. Something like 20 kilograms of uranium 235 dispersed in ten to 30 tons of graphite would probably be needed for power production of a sufficient large scale.

W We wish to conclude by saying that from the point of view of this memorandum it appears necessary to support the working out of methods for separating the rare isotope of uranium as long as it has not been proved with certainty that a chain reaction can be made to work with unseparated uranium. After that the question may have to be reconsidered. It must be added that for a number of reasons other than from the point of view of this memorandum it would be highly desirable to prepare a few kilograms of the unseparated rare isotope of uranium.

(Leo Szilard)

Memo

July 4, 1940

It is proposed that the work of supervising the project of Fermi and Szilard as well as experiments carried out in different university laboratories be carried out by an organization which has more permanence than ad hoc constituted committees. This organization could have the form of a non-profit association having as its membership the physicists whose names were originally included in the committee appointed by Dr. Briggs. Dr. Briggs, Professor Pegram, Dr. Urey, and Dr. Sachs could act as board of trustees with Professor Pegram as chairman of the board. The seat of the organization would be New York City and Dr. Pegram, Dr. Fermi, and Dr. Szilard could act as executives. The membership would be gradually extended to include representatives of other eastern universities such as Harvard, M.I.T., Yale, and gradually a number of members might become officers of the organization who give their full time to the complex task with which we have to deal. Since most American citizens form this organization are also members of Government committees or sub-committees which concern themselves with uranium it will be easy for the Government to be kept fully informed. For the present the members would meet once a fortnight and the meetings would be held alternately in New York and Washington. The trustees would be in charge of such private funds as can be obtained from private individuals or from foundations and one of the tasks of the organization would be to see to it that no important line of investigation should be neglected for lack of funds. Another task of the organization would be to see to it that all those who work in this field and who are considered to be trustworthy should be kept informed to the extent which is compatible with a certain amount of necessary secrecy.

It is proposed that the seat of the organisation be in New York City , that the board of trustees include the names of Prof. Pegram, Prof, Urey, Prof. Lawrence, Prof. Du-Bridge, Prof. Wigner, Dr. Sachs and if government employees be included the names of Dr. Briggs and Admiral Bowen. It is proposed that Prof. Pegram be chairman of the board and Dr. Sachs act as treasurer.

It is proposed that the executive be composed of Dr. Pegram, Dr. Urey, Dr. Fermi, Dr. Szilard and Dr. Sachs , all of New York City and that a committee of scientists be responsible for supervising all the work which committee include~~s~~ the names of

H.C. Urey

M.A. Tuve

G. Breit

G.B. Pegram

E. Fermi

L. Szilard

E.P. Wigner

E. Teller

It is proposed that a fund of $ 20.000 be put at the disposal of the trustees of ~~this~~ such an organisation .

June 28, 1940

Memorandum.

It would appear that the chances of a chain reaction with slow neutrons in a system essentially composed of uranium and carbon could be considerably improved by having a lattice of spheres of uranium metal embedded in graphite and each sphere surrounded with a spherical shell of beryllium metal. Beryllium metal has ~~the~~ a density of about 2, and if the shell had a thickness of about 5 cm this would correspond to about 6 times 10^{-23} atoms of beryllium per cm^2. The binding energy of the neutrons in beryllium being only about 1.8 MEV, the fast neutrons emitted from uranium will knock out a certain number of neutrons from the beryllium shell which will contribute towards a positive balance of neutron emission and absorption in the system. If the average cross-section for this knock out process in beryllium were of the order of magnitude of 10^{-24}cm for uranium fission neutrons then we would have a very considerable contribution from the beryllium shell. The velocity distribution of the uranium fission neutrons which was observed by Zinn and myself makes it appear rather promising to improve the condition for the chain reaction by the use of beryllium, and it would appear that testing this point by a small scale laboratory experiment ought to be considered one of the most urgent tasks within the framework of the proposed survey of nuclear constants. The cost of this experiment would be taken care of by item 6 of the estimate of cost drafted by me on June 19th.

If this small scale experiment gives an encouraging result then we ought to attempt to obtain plates of beryllium metal, for instance plates of sizes 5 x 15 x 15 cm and other plates 5 x 5 x 10 cm. Such plates used in conjunction with a cube of uranium metal can be so arranged as to have a cubic layer of beryllium 5 cm thick surrounding the uranium cube. Each uranium cube would require four of the smaller and two of the larger type beryllium plates. The use of beryllium might be of marked advantage even if the cross-section for the knock out process were as low as $10^{-25}cm^2$ for uranium fission neutrons.

(Leo Szilard)

June 28, 1940

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NEW YORK, N.Y.
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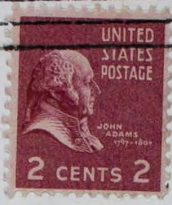

L. Szilard
420 W 116 Str.
N.Y.C.

02595

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(Leo Szilard)

July 4, 1940

MEMORANDUM

If we used in the chain reaction experiment uranium spheres of 5 cm. diameter surrounded by 2½ cm. layer of beryllium metal we would have about six times as much volume of beryllium as uranium and taking into consideration the ratios of the densities about ½ as much beryllium as uranium. Assuming that beryllium metal may be bought at a price of $10.00 per lb. and uranium metal at a price of $5.00 per lb., 10 tons of uranium metal will be about $100,000. and 5 tons of beryllium would be $100,000. making a total of $200,000.

July 4, 1940

MEMORANDUM

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July 19, 1940

In July last year Dr. Szilard devised a method for producing a chain reaction in a system composed of uranium and carbon. If a chain reaction could be maintained in such a system, the energy liberated could be used for the purpose of power production and could possibly be of very great significance for the Navy and other uses in connection with National defense. Dr. Szilard, after consultation with Professor E. P. Wigner of Princeton University, Professor E. Teller of George Washington University and Professor Albert Einstein of Princeton, decided to make an appeal to the Government rather than to private industry for support of this particular line of development. Professor Einstein wrote a letter to the President in which he submitted the matter for the latter's consideration. The letter was submitted through the good offices of Mr. Alexander Sachs and the President appointed a committee composed of Dr. Lyman J. Briggs, Director of the National Burean of Standards as chairman, and representatives from the Army and Navy. This committee met on October 21, 1939 with Mr. Sachs and heard Dr. Szilard, Professor Wigner and Professor Teller. Mr. Sachs and the group asked that the Government should give moral encouragement for raising the funds from Foundations or other private sources which are required to carry out speedily an experiment with 100-200 tons of graphite and 10-30 tons of uranium metal in order to decide whether the chain reaction can be maintained under the conditions indicated by Dr. Szilard. If this experiment gave positive results, steps were to be taken immediately to secure an adequte supply of uranium ore for the United States from the Belgian Congo. It was emphasized that we could could on the collaboration of Columbia University, where Professor Fermi and Dean Pegram are ~~int~~ interested in work on uranium ~~and~~ in general and in the line of work proposed by Dr. Szilard in particular. In order to carry out this suggestion, it was proposed that the committee be enlarged by three or four non-governmental members, one of them being Dean Pegram.

The committee reported to the President and its report, which was communicated to Mr. Sachs by the President, was entirely favorable, adopting all the suggestions which were made during the meeting of October 21st. However, there was apparently no action taken on these recommendations and in March of this year Mr. Sachs received a letter from Professor Einstein advising him of the fact that work on uranium is being carried out in secrecy and on a very large scale in Germany, and raising the question whether the Government intends to support morally or financially the proposed experiments on systems composed or carbon and uranium or whether Dr. Szilard and the others who are interested in this line of work should look elsewhere for the required assistance. Thereupon Mr. Sachs advised the White House of Professor Einstein's letter and a second meeting with the Government representatives ~~resulted~~ took place on April 27th.

Admiral Bowen was present at this meeting, as well as Mr. Sachs, Dean Pegram, Professor Fermi, Dr. Szilard and Professor Wigner. Professor Fermi explained that the proposed experiment would give a positive result and that it was more likely than not that this would be the case. Dr. Szilard and Professor Wigner took a rather optimistic view of the ultimate outcome of the experiment and Dr. Szilard explained that we may confidently expect one ton of uranium to supply as much power as 3,000 tons of oil if used for the purposes of giving a power reserve to battleships. At the same time, the possibility must be borne in mind that one ton of uranium may supply as much power as would correspond to one million tons of oil. Professor Einstein, who was unable to attend the meeting, having discussed with Mr. Sachs the best possible forms in which this work could be supported, expressed his views on the subject in a letter addressed to Dr. Briggs, the chairman of the committee. Admiral Bowen and the other representatives expressed the view that Government rather than private funds ought to be used in carrying out the developmental work, and that the development should be carried out in close touch with the governmental departments interested.

Soon after this meeting, Dean Pegram informed the Government that a preliminary experiment carried out by Professor Fermi and Dr. Szilard on four tons of graphite showed an encouraging result and that ~~the~~further work await the decision of the Government.

A number of conversations and meetings took place since then, with constantly varying memberships. A committee of scientists was constituted for the purpose of advising Dr. Briggs on the matter. Dr. Fermi, Dr. Szilard ~~and~~, Professor Wigner and Professor Teller are not officially members of this scientific advisory committee. Dr. Briggs' committee, on the other hand, is now supposed to be a sub-committee of the committee of Dr. Bush. It appears that Dr. Bush's committee has decided to give a grant of $40,000 towards the proposed experiments and another $100,000 worth of material will be purchased, if required, through the strategic materials board or some other purchasing department.

In September of
~~Further~~ last year I was advised by
Prof W. and Prof E. that

July 19, 1940

~~In July last year~~ Dr. Szilard had devised a method for maintaining a chain reaction in a system composed of uranium and carbon and pointed out that ~~if it were possible to maintain such a chain readtion~~ the energy (in such a system could be conveniently liberated ~~could be~~ used for power production. A conservative estimate shows that ~~we~~ one can expect one ton of uranium to supply as much power as 3,000 tons of oil and that in the circumstances, uranium could be expected to be used as a fuel reserve in warships of the larger type. I understand that ~~There~~ there is perhaps a 50-50 chance that the chain reaction could be maintained under conditions where one ton of uranium would supply as much power as would correspond to the burning of 1 million tons of oil. and if ~~If~~ this were the case fact, then the larger naval units built according to the present naval program would ~~may~~ have to be considered obsolete in the near future.

In order to try out the method proposed, an experiment using 100 to 200 tons of graphite and 10 to 30 tons of uranium metal would have to be carried out. Such an experiment may involve an expense up to half a million dollars, ~~and~~ I have applied for the moral or material aid of the Government. ~~For~~ this project ~~has requested~~ in October of last year ~~through the good offices of Mr. Sachs. At that time~~, when in response to a letter received from Professor Einstein ~~wrote to the~~ the President ~~and subsequently the President~~ appointed a committee with Dr. Briggs ~~of the National Bureau of Standards as chairman~~ of an advisory committee ~~comprising representatives of the Army and Navy~~. I was assisted in submitting The matter ~~was submitted~~ to this committee by ~~Dr. Sachs~~, Dr. Szilard, Professor Wigner of Princeton University and Dr. Teller of George Washington University. A large number of meetings with varying membership have taken place since that time, at which the Government representatives (including Admiral Bowen showed constantly increasing interest and ~~determination~~ desire to provide Government funds for such an experiment. The opinion of a and it was emphasized

that ~~Columbia Univ~~ the collaboration of Columbia University as represented by Dean G.B. Pegram and Prof. E. Fermi cannot be taken for granted large number of scientists was heard, in particular that of Professor Fermi, and ~~even the most conservative scientific opinion~~ who put the chances for a positive outcome of the proposed experiment above 50%. After a number of meetings ~~the~~ a consensus of opinion developed to the effect that the sum of $140,000, which could be freely spent with no strings or red tape attached, would probably be sufficient to bring the project to the stage at which the ultimate success of the whole enterprise might be established ~~without~~ beyond doubt. Up to now, no such appropriation has been made available and all that has developed is a complicated system of committees with rather undefined authority. Professor Fermi, Dr. Szilard, Professor Teller and Professor Wigner are supposed to act as unofficial advisors to a group of 6 scientists who form the official scientific advisory committee to the advisory committee of which Dr. Briggs is chairman, with Prof E. Dr. Sachs, and Professor Pegram as well as representatives of the Army and Navy the members. This committee is supposed to be a sub-committee of the committee appointed by the President, of which Dr. Bush is the chairman. It is understood that the latter committee has now decided to appropriate $40,000 for the proposed experiments and is also going to recommend that $100,000 worth of material be purchased, if required, through some purchasing agency of the Government, but ~~It is also understood that~~ the committee of Dr. Bush has no funds at present, out of which such appropriation could be made.

Urey Tuve Pegram Gunn Beams B

T/K

While $140,000 might be sufficient if this money could be freely spent by a board of trustees, for the experiments to be carried out under the direction of Drs. Fermi and Szilard, it would not be possible to procure the necessary material if we are limited by the regulations pertaining to purchases made through the regular Government purchasing agencies. The material which is needed cannot be bought. Most of the funds would be needed to procure uranium metal, which at present is not for sale in the quantity and quality which is required. We would probably have to approach ~~several~~ two or three firms and by promising them a contract at a fixed price of about $5 per pound for 1 or 2 tons, induce them to embark upon experiments which would enable them to make a binding bid of their own. ~~for 1-5 tons of metal~~. It is to be assumed that the price they would ask would be higher than the price quoted above and in that case the order would go to the lowest bid.

This is just one example to illustrate that the particular task with which we are faced requires greater flexibility than can be achieved through the organization which has so far been set up. ~~and which has been so far envisaged.~~

It is therefore proposed that

Memorandum.

October 5, 1940

If thermal neutrons are absorbed by uranium μ fast neutrons are emitted on the average for every thermal neutron which is thus absorbed. An accurate knowledge of this number μ is of importance, and attempts have been made in the past to obtain its value. ① ② ③

The present memorandum describes a method which may be used to obtain a fairly accurate value for this number.

The principle of the method is the following: A neutron source is placed in the center of a spherically symmetrical arrangement. A spherical shell of ~~water or~~ paraffine wax (or water) forms the boundary of the arrangement, and this ~~hydrogen~~ paraffin shell is sufficiently thick to prevent the escape of an appreciable number of neutrons from the system. There is a spherical core of carbon enclosed by the ~~hydrogen~~ paraffin shell, and within this sphere of carbon ~~the~~ a spherical shell between $r = r_1$ and $r = r_2$ is left free from carbon; ~~and~~ this shell may be left empty or may be filled with uranium. This uranium shell can be shielded from thermal neutrons by inserting thin spherical cadmium shells at $r = r_1$ and $r = r_2$.

The total number of fast neutrons emitted, which includes both the neutrons emitted by the source in the center and the neutrons emitted through fission by the uranium shell is composed of four terms:

1. the number of thermal neutrons absorbed outside the spherical shell r_1, r_2 which contains the uranium. This number can be determined by measuring the thermal neutron density along a radius within the paraffine shell. It ~~is~~ may be not necessary to measure the thermal neutron density within the carbon core as well since the absorption in carbon is small and the radius of the carbon core ~~will~~ can be so chosen that the number of thermal neutrons absorbed by the carbon may be neglected.

2. The number of thermal neutrons which are absorbed by the uranium shell. This number can be determined by measuring the gradient of the thermal neutron density in the carbon at $r = r_1$ and at $r = r_2$.

3. The number R_0 of the neutrons which are emitted from the source and are subsequently absorbed at resonance by the uranium shell before being slowed down to thermal energies. This number can be determined by a method which will be described later.

4. The number R_f of the neutrons which are emitted through fission by the uranium shell and which are subsequently absorbed by the uranium shell at resonance before being slowed down to thermal energies. ~~T~~

This term is much smaller than the other three terms and is of the second order if we use an arrangement in which only a small fraction of the neutrons emitted by the source is absorbed by the uranium. For this reason it is sufficient to estimate the value of this term while the value of the first three terms may (in principle) be measured directly with any desired precision.

~~For this reason it is sufficient to estimate the value of this term while the value of the first three terms may be measured directly with any desired precision.~~

In order to obtain an estimate of the value of R_f from the measured value of R_0 we have to determine the average density of the supra-thermal neutrons, or preferably the average density of the supra-resonance neutrons in the carbon on both sides of the uranium shell/ in a depth about equal to the range of the uranium resonance neutrons in carbon,/ both in the absence and in the presence of fission within the uranium shell. This can be done by shielding the uranium cadmium and then measuring the average density J_3 of, for instance, iodine resonance neutrons in some arbitrary unit and then in another experiment measuring ~~xbxx~~ in the absence of the cadmium again the average density J_4 of the iodine resonance neutrons in the same units. We then may write

$$\frac{R_f + R_o}{R_o} = \frac{J_4}{J_3} \quad \text{or} \quad R_f = R_o\left(\frac{J_4}{J_3} - 1\right)$$

The value of R_f, which is obtained in this way is not strictly speaking correct because the spacial distribution of the uranium resonance neutrons which originate from the neutron source in the center and the spacial distribution of the uranium resonance neutrons which originate through fission in uranium are slightly different.near the uranium shell, and this difference is not being ~~taken~~ fully taken into account by measuring the averages J_3 and J_4. Due to the fact, however, that in the proposed arrangement

2 we have $R_f << R_o$ the proposed estimate for R_f gives a sufficient accuracy in pr .

In order to obtain an accurate value for μ it is necessary to use an arrangement in which a large fraction of the neutrons emitted by the source ~~but~~ is absorbed as thermal neutron by uranium. In order to achieve this a sphere of graphite of about 60 cm. diameter will be imbedded in paraffin or water and the spherical layer of uranium having a diameter of about 40 cm. is embedded in this graphite. The neutron source is placed in the center of the graphite sphere and thermal neutrons are produced both in paraffin or water and in the graphite. A large fraction of the thermal neutrons produced may be absorbed in the uranium layer apart from the thermal neutrons which are produced in the water or paraffin in the proximity of the graphite sphere and which diffuse into the graphite and are ultimately absorbed by the uranium.

The number of thermal neutrons absorbed in the water is determined by measuring $Y = \int \rho r^2 dr$ in four different set-ups. These set-ups are the following:

1. In the absence of both cadmium and uranium layers.
2. In the presence of the cadmium layers but without the uranium layer~~s~~.
3. In the presence both of the cadmium layers and the uranium.
4. In the presence of the uranium layer without the cadmium layers.

In this way we obtain four values for J: J_1, J_2, J_3, J_4

Since the absorption of neutrons in the carbon can be ~~regulated~~ neglected, the value of J_1 obtained in the first experiment gives us a measure of the number N_0 of neutrons emitted by the source.

The second experiment gives us information about the thermal neutrons absorbed in the cadmium since ~~obviously~~ the difference $J_2 - J_1$ can be considered as a measure of this quantity. In the second experiment we can also measure the gradient of the thermal neutron density in the graphite inside and outside of the cadmium spheres at $r = r_1$, $r = r_2$, and if we designate the value of these gradients at A_1 and B_2 we may write for the number of thermal neutrons absorbed by the cadmium ~~sheres~~. shells.

$$J_1 - J_2 = g(4\pi r_1^2 A_1 + 4\pi r_2^2 B_2)$$

The factor g can thus be determined by measuring A_1 and A_2 as well as J in the second experiment.

In the third experiment neutrons are absorbed as thermal neutrons by cadmium and water ~~by~~ and certain ~~free~~ a ~~said~~ ~~number~~ of neutrons R does not reach thermal velocities but will be absorbed at resonance by the uranium layer. We can determine this number R by measuring the gradient (A_3, B_3) of the thermal neutron density in the carbon ~~outside and inside of the spherical layer;~~ at r_1 and r_2 and the value of the integral I_3 in the water we then have.

$$J_1 = J_3 + R - J_3 + g(4\pi r_1^2 A_3 + 4\pi r_2^2 B_3)$$

In the third experiment we may further measure with a cadmium shielded indium, or even better a Cd shielded iodine, indicator, the average intensity of the corresponding resonance neutrons in a 10 cm. layer on both sides of the uranium layer and we thus find for this average resonance neutron intensity some value designated by ~~P3~~. $\mathcal{J}_3$.

In the fourth experiment we shall again measure the gradients of the thermal neutron density A_4 at r_1 B_4 at r_2 the integral of the thermal neutron density in the water I_4 and the average neutron density in the neighborhood of the uranium layer P4.

The number of neutrons, N_u emitted from the uranium in the fourth experiment is then given by

$$N(u) = y_4 + \gamma(4\pi r_1^2 A_4 + 4\pi r_2^2 B_4) + R\frac{\mathcal{J}_4}{\mathcal{J}_3} - y_1$$

In this expression the first term gives the number of neutrons absorbed as thermal neutrons in water.

The second term gives the number of neutrons absorbed as thermal neutrons in uranium.

The third term gives the number of neutrons absorbed by uranium ~~with~~ at resonance.

The fourth term is the number of neutrons emitted by the source.

Accordingly we have ~~four~~ for μ

$$\mu = \frac{N(u)}{\gamma(4\pi r_1^2 A_4 + 4\pi r_2^2 B_4)} = \frac{y_4 - y_1 + R\frac{\mathcal{J}_4}{\mathcal{J}_3} +}{4\pi\gamma(r_1^2 A_4 + r_2^2 B_4)} \|$$

ESTIMATE OF COST FOR A SURVEY OF THE NUCLEAR CONSTANTS INVOLVED IN A CHAIN REACTION WITH SLOW NEUTRONS

Please note that this estimate is based on certain detailed plans for each individual experiment. Each of these experiments may be replaced by another if we succeed in thinking of a better experiment to serve the same purpose, but it is not believed that such changes will considerably affect the total cost of the survey. The question how quickly the survey can be carried out will essentially depend on our luck in finding suitable men as collaborators. It is not proposed to rush into a large number of experiments simultaneously right away, but it is intended to build up gradually as the number of our collaborators gradually increase and as each of them get gradually trained for the specific task to which he is assigned. It is proposed that a semi large scale experiment in which at least 5 tons of uranium would be used ought to have the right of way before the proposed general survey of nuclear values. It is believed that the staff carrying out that survey will be so composed as to be able to take care of the semi large scale experiment and also be able to devise the construction and prepare the blue-prints for a large scale experiment.

The knowledge of the nuclear values which are included in the proposed survey is a necessity if the semi large scale experiment should show a negative result, and most desirable if the semi large scale experiment should show a positive result.

ESTIMATE OF COST

	Materials	Apparatus	Salaries
A. General:			
Rent for a year of 2 Grams of radium to be used as a photo-source	$ 2,500.		
Rent for a year of 2 Grams of radium mixed with beryllium	3,500.		
Two tons of uranium oxide	10,000.		
1. Experiment for determining p requiring 2 Grams of radium to be used as a photo- neutron source; one man for six months			$ 1500.
Apparatus		$ 500.	
2. Experiment for determining by a method similar to that used by H., J., P., and K.; two men for six months			3000.
Apparatus		$ 2000.	
3. Certain cross-sections of uranium for thermal neutrons; in particular the total capture cross-section of uranium for thermal neutrons; one man for six months			1500.
Apparatus		1000.	
4. An accurate determination of the capture cross-section of carbon; two men for six months			3000.
Apparatus and labor		3000.	
5. ~~Unspecified~~ Various urgent experiments to be carried out under the supervision of Fermi; one man for one year			3000.
Apparatus		2000.	
6. ~~Unspecified~~ Various urgent experiments to be carried out under the supervision of Szilard; one man for six months			1500.
Apparatus		1500.	
7. Experiments carried out on a single uranium sphere in graphite; two men for six months			3000.
Apparatus		1000.	
	$16,000.	$ 11,000.	$~~165,000.~~ 16,500

8. For general unforeseen expenses, secretarial work, traveling expenses, etc., assuming that we shall need about $6,500. the estimate of the total expenditure for the completion of this survey would come out to be about the round sum of $50,000.

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6. Unspecified urgent experiments to be carried out under the supervision of Szilard; one man for six months			1500.
Apparatus		1500.	
7. Experiments carried out on a single uranium sphere in graphite; two men for six months			3000.
Apparatus		1000.	
	$16,000.	$ 11,000.	$165,000.

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Estimate of Cost for the Intermediate Scale Experiment. October 26, 1940

	Non exp.Mat. Bulk orders	Non exp.Mat. exp. orders	Labor, rent salaries,etc.
For the purchase of 40 tons of graphite	$ 20.000		
For the purchase of 5 tons of uranium oxide	25.000		
For special quality of U metal, graphite, and other materials		$ 5.000	
For conversion of 1 ton of uranium oxide into other forms of uranium (U metal)			$ 7.500
For conversion of 4 tons of uranium oxide into other forms of uranium (U metal)			17.500
For studies on uranium and graphite, and tests of samples			2.500
For salaries of research ass.			10.000
For renting radium, photo neutron and radium beryllium sources			7.500
For expenses in connection with the actual performance of the intermed. scale experiment			5.000
	$ 45.000	$ 5.000	$ 50.000

Estimate of Cost for the Intermediate Scale Experiment. Grand Total $90.000

	Material	Labor & Salaries
For the tests on graphite		$ 5.000
For the purchase of ~~20~~ 45 tons of graphite	$ 20.000	
For the purchase of 5 tons of uranium oxide	25.000	
Test on uranium metal		5.000
For the conversion of 1 ton of uranium oxide into uranium metal; experimental order		10.000
For the conversion of 4 tons of uranium oxide into uranium metal; bulk order		20.000
For the actual performance of the intermediate scale experiment		5.000
		$ 45.000
	$ 45.000	

Grand Total $ 90.000

Alternative Estimate

For the tests on graphite		5.000
For the purchase of ~~20~~ 40 tons of graphite	15000 ~~20.000~~	5000 Exporder Graphite
For the purchase of 5 tons of uranium oxide	25.000	
Test on uranium metal		5.000
For the conversion of 1 ton of uranium oxide into uranium metal; experimental order		10.000
For the conversion of 4 tons of uranium oxide into uranium metal; bulk order		20000 ~~25.000~~
For the actual performance of the intermediate scale experiment, salarys, labor		5 10.000
	$ 45.000	$ 55.000

Grand Total $ 100.000

October 10, 1940

ESTIMATE FOR URANIUM COMMITTEE, October 16, 1940 - G.B.P.

1940 Nov. 1 — 1941 Jan. 1 — Mar.1 — May 1 — July 1 — Sept.1 — Nov.1 — 1942 Jan. 1

				Part 1 First contract Salaries, etc.	Part 1 First contract Totals by type of items	Part 1 First contract Non-expendable materials	Part 2 Second contract Salaries, etc.	Part 2 Second contract Totals by type of items	Part 2 Second contract Non-expendable materials
Salaries, scientific and technical assistants	H. Anderson $200.00 a month	14 months	$2,800.	$ 1,600.			$ 1,200.		
	L. Szilard $333.33 " "	14 "	4,667.	2,667.			2,000.		
	Physicist $300.00 " "	14 2	4,200.	2,400.			1,800.		
	Technician $150.00 " "	14 "	2,100	1.200.			900.		
	Physicist $250.00 a month	12 months	3,000.	1,500.			1,500.		
	Technician $150.00 " "	12 "	1,800.	900.	$10,267.		900.	$ 8,300.	
Running expenses of the research	Supplies, small apparatus, shop work, clerical work, etc. $1,000. a month for 14 months		14,000.	8,000.	8,000.		6,000.	6,000.	
Rental of radium for neutron sources	Use of USN radium, 1g., at expense of mixing with Be		150.	150.					
	Rental of 2g. radium for photo-neutron source - 12 months		5,000.	3,000.			2,000.		
	Rental of 1 g. radium and expense of mixing with Be and unmixing - 12 months		2,900.	1,600.	4,750.		1,300.	3,300.	
Special construction of equipment for containing or handling C and U			3,000.	1,000.	1,000.			2,000.	
Uranium	2 tons U_2O_8		10,000.			$10,000.			
	Allowance for investigations of metallurgy of U and of production of metallic U in form desired		5,000.	5,000.	5,000.				
	25 pound sphere of metallic U		1,000.			1,000.			
	4 tons U_3O_8		20,000.						$20,000.
	Metallurgical expense to get metal from oxide		40,000.						40,000.
Carbon	4 tons pure graphite		2,000.			2,000.			
	36 tons pure graphite		18,000.						18,000.
Paraffin	10 tons paraffin		1,600.						1,600.
Cadmium	400 lbs. sheet cadmium		1,000.						1,000.
					$29,017	$13,000.		$19,600.	$80,600.

ESTIMATE OF COST

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1. Experiment for determining p requiring 2 Grams of radium to be used as a photo-neutron source			
one man for six months	------	----	---- $ 1500.
Apparatus	------	-- $ 500.	
2. Experiment for determining by a method similar to that used by H., J., P., and K.			
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Apparatus	------	-- 2000.	----
3. Certain cross-sections of uranium for thermal neutrons; in particular the total capture cross-section of uranium for thermal neutrons.			
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Apparatus	------	---- 1000.	
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two men for six months	------	----	---- 3000.
Apparatus and labor	------	---- 3000.	----
5. Unspecified urgent experiments to be carried out under the supervision of Fermi; one man for one year	------	----	---- 3000.

	Materials	Apparatus	Salaries
5. (continued)			
Apparatus	------ $	-- $ 2000.	-- $
6. Unspecified urgent experiments to be carried out under the supervision of Szilard. One man for six months	------	--	-- 1500.
Apparatus	------	-- 1500.	
7. Experiments carried out on a single uranium sphere in graphite. Two men for six months.	------	--	-- 3000.
Apparatus	------	-- 1000.	--
	$16,000.	$ 11,000.	$ ~~165,000.~~ 16,500

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November 3,1940

Memorandum concerning the use of beryllium

It may be that conditions for a chain reaction are considerably more favorable by surrounding the uranium spheres with a spherical layer of a few centimeters thickness of beryllium and distributing such beryllium quoted uranium spheres throughout the mass of graphite. The few neutrons emitted in the process of fission from the uranium passes through the beryllium coating and a fraction of the first neutrons having energies above 1.8 million volt are capable of disintegrating the beryllium and thus leading to the liberation of an additional neutron. In order to estimate the magnitude of the improvement which can be achieved by the use of beryllium it is proposed to perform an experiment similar to the experiment set forth in the memorandum of October 5th. The spherical uranium shell can be sandwiched between two spherical beryllium shells of a few centimeters thickness each. Otherwise the arrangement is the same as described before. It will be best to use metallic beryllium for this purpose. A preliminary test shows that beryllium flitters which are commercially obtainable can be compressed to form a uniform mass and that at the pressure of 100 tons per 27 sq. centimeters one obtains a bulk density of 1.54 grams per cc. If the facilities for obtaining the rather expensive beryllium are unavailable one might perhaps perform the experiment with beryllium oxide. A preliminary test shows that at the above pressure beryllium oxide calcined at 1450° C are brought to a bulk density of 1.68 grams per sq. cent. and beryllium oxide calcined are brought to a bulk density of 2 grams per cc but using higher pressures the bulk density can be presumably materially increased.

The Beryllium Corporation of Pennsylvania advises me by letter dated July 5,1940 that they are able to furnish beryllium flakes 96% pure at forty-five dollars per pound, and the Brush Beryllium Company advises me by letter dated August 8, 1940 that their price for small quantities of beryllium oxide is seven dollars per pound.

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Nov. 6th - 40

Memo concerning Fast Neutron Reaction.

The purpose of the proposed experiment is to obtain an estimate of the chances of a nuclear chain reaction maintained by fast neutrons in uranium metal.

It would seem that certainty in this respect can be obtained only in actually performing a large-scale experiment, and this is due primarily to the fact that the velocity distribution of the neutrons in a chain reaction maintained in a large mass of uranium is different from the velocity distribution of fission neutrons which may be established in smaller masses of uranium. The proposed experiment is not free from this defect. Nevertheless, its performance might provide a fair forecast either in the positive or in the negative sense concerning the chances of a chain reaction with fast neutrons.

It seems to me that a fair estimate of these chances would be very difficult to obtain by an investigation in which uranium is exposed to fast neutrons arising out of an artificial source, such as for instance the D+D source. If such neutrons were used to produce fission in uranium the neutrons produced in the process of fission would have a velocity distribution so very different from the velocity distribution of the primary neutrons that it would be rather difficult to know whether the balance of the two competing processes, i.e. the production of fast neutrons through fission, and the loss of neutrons which have sufficient velocity to cause fission (either by inelastic collisions or by capture) is favorable or unfavorable.

In the proposed experiments photo neutrons of radium beryllium would be used as primary neutrons, and the fission caused in uranium by these neutrons will be almost negligible. Part of the mass of the uranium used will be exposed to thermal neutrons whereas the whole mass of the uranium used will be exposed to the fast neutrons emitted by those uranium atoms which split ~~from~~ under the action of thermal neutrons.

It is proposed to use a spherically symmetrical arrangement with a photo neutron source in the center and two concentric spherical layers of uranium separated by a thin spherical shell of cadmium. The outer uranium shell is surrounded by a spherical shell of paraffine wax. A spherical uranium coated fission chamber, which is protected by a cadmium shield against thermal neutrons, is placed at some distance from the outer uranium shell in a spherical gap between this uranium shell and the paraffine wax shell. The number of fissions registered by this chamber is to be determined both in the presence and in the absence of the inner uranium shell.

If the distribution of the thermal neutrons were the same in both experiments, and if the cadmium shell shielded the inner uranium shell perfectly from the action of slow neutrons, we could then consider an increase in the fission count in the presence of the inner uranium shell as an indication of the fact that the interaction of the fast neutrons arising out of the fission ~~with~~ of uranium with a mass of uranium leads to an increase in the number of fissions producing fast neutrons. If we ~~then are~~ were free to assume that the velocity distribution of the fission neutrons arising from the splitting uranium with thermal neutrons is substantially the same as the velocity distribution of the fission neutrons arising out of splitting uranium with fast neutrons, we could then further conclude that a chain reaction with fast neutrons has to be considered as a very serious possibility. It is proposed to check the approximate identity of these two velocity distributions by a separate experiment in which D+D neutrons may be used for producing fast neutron fission.

Since naturally the distribution of thermal neutrons will differ in the two experiments, and since the cadmium shields do not protect uranium completely from the action of slow neutrons, it is necessary to apply certain corrections. We obtain these corrections by taking a fission count in the arrangement used in further experiments in which both the inner and the outer uranium shell are shielded with cadmium from the action of thermal neutrons, and also by measuring in all the experiments the thermal neutron density along one radius within the uranium shell and in the gap between the outer U shell and the paraffin wax shell.

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November 25,1940

Memorandum concerning the possible use of Bismuth for the purpose of increasing the efficiency for chain reaction.

So far all attempts to produce radium E from Bismuth by means of thermal neutrons have failed and until proved to the contrary it has to be assumed that Bismuth has an exceedingly small capture cross-section for thermal neutrons. Neglecting the capture of ~~thermal~~ neutrons in bismuth ~~to~~ and taking into account their scattering in bismuth it can be shown that conditions for a chain reaction may be considerably improved in certain geometrical arrangements by interposing a layer of bismuth between the uranium and the graphite. That the interposition of a scattering layer between the uranium and the graphite increases the fraction of the neutrons which are absorbed by the uranium in the thermal region ~~and decreases the fraction of the neutrons which are absorbed by the uranium at resonance~~ would be evident without any calculation if graphite had no absorption for thermal neutrons. ~~Thenxthexthermalxxneutronsx~~ for such a scattering layer reduces the fraction of neutrons which are absorbed by uranium at resonance and if the absorption of thermal neutrons in carbon can be neglected it follows that the fraction of the neutrons absorbed by theuranium in the thermal region is increased.

Further below an example will be given in which a finite capture cross-section of carbon for thermal neutrons is taken into account and in which q the fraction of the neutrons absorbed by the uranium isincreased by more than 10% by having a layer of bismuth between the uranium and carbon layers. In view of this situation it is proposed to reinvestigate the formation of radium E from bismuth both with thermal neutrons and with faster neutrons. In order to obtain an increased sensitivity it is proposed to carry out an isotope separation of the radium E from bismuth by using a suitable compound perhaps bismuth-tri-ethyl.

Bismuth has a scattering cross-section of 8.9 and a density of 9.8 gm/cc. Accordingly λ_{Bi} the mean free path in bismuth ~~for~~ $\lambda_{Bi} = 4$ ~~2.5~~ cm.

The example which we wish to consider consists in two plain layers of uranium which are treated here as if they were black for thermal neutrons as well as for resonance neutrons that are separated by a graphite layer having a thickness of 2s. Two layers of bismuth each having a thickness of p cm. can be produced between the uranium layer and the graphite and the two cases with or without the bismuth are being compared. It is further assumed in this example that the production both of the thermal neutrons and the resonance neutrons is uniform within the carbon, the former being smaller corresponding to the absorption of resonance neutrons by uranium.

These assumptions give in the absence of bismuth

$$q = \left(1 - \frac{B_1}{A} / x\right) \frac{1}{x} \frac{e^x - e^{-x}}{e^x + e^{-x}} \; ; \quad B_1 = B \frac{e^{s/B} - e^{-s/B}}{e^{s/B} - e^{-s/B}} \cong$$

$$x = \frac{s}{A} \; ; \qquad \cong B \text{ for } s >> B$$

A is range of thermal neutrons in graphite
B is range of resonance neutrons in graphite

Of interest is the maximum value of q which can be obtained by choosing the corresponding value of s.

In the presence of bismuth we obtain

$$q = \left(1 - \frac{B_1}{A} C^* \frac{1}{x}\right) \frac{1}{x} C_A \frac{e^x - e^{-x}}{e^x + e^{-x}}$$

$$C^* = \frac{1}{\frac{e^{+s/B} - e^{-s/B}}{e^{s/B} + e^{s/B}} + \frac{p}{B} \frac{\lambda_c}{\lambda_{Bi}}} \cong \frac{1}{1 + \frac{p}{B} \frac{\lambda_c}{\lambda_{Bi}}} \text{ if } s >> B \; ; \quad C_A = \frac{1}{1 + \frac{e^x - e^{-x}}{e^x + e^{-x}} \frac{p}{A} \frac{\lambda_c}{\lambda_{Bi}}}$$

Of interest in this case the maximum value of q wich can be obtained by choosing the optimal valuesof s and p.

Example ~~$\frac{B}{A} = \frac{1}{5}$~~ : $\frac{B}{A} = \frac{1}{5}$

Without Bismuth optimum at about $x = 0.8$; $q_m = 0.62$

With Bismuth layer ~~thk~~ of about 2 B the thickness optimum at about $x = 0.4$ $q_m = 0.69$

The advantage of Bi is in reality greater since one has to take into account that the production of resonance neutrons in the graphite is greater close to the Uranium layers.

(Perhaps elements other than Bismuth could also be used as scatterers, ~~tod~~ for instance Sulphur or $CaCO_3$; the latter has a λ of 24 cm. — or $CaTiO_3$ or Ti. —)

It should be pointed out that a very low capture cross-section in the case of bismuth ~~which~~ would have considerable ~~theoretic~~ interest from the point of view of the theory of the nucleus particularly if this cross-section is abnormally small not only in the thermal region but also for photo neutrons of radium-beryllium and for D plus D neutrons.

Korr.

December 4, 1940

Memorandum for Professor Pegram concerning the use of Beryllium:

If beryllium metal or beryllium oxide is used in the way described in the memoranda dated June 28, July 4 and November 3, 1940, which are in your files, the amounts of beryllium which may be ultimately needed in an intermediate scale or large scale experiment are approximately equal by weight to the amount of uranium metal or less, used, and perhaps 1/10 by weight of the amount of graphite used. Since the beryllium would be so located as to be at a place where the thermal neutron density is at a minimum, a moderate thermal neutron absorption by the impurities contained in the beryllium would not be very disturbing. If we can obtain those 150 lbs. of beryllium metal for which we have asked, the experiments which we are preparing will allow us to say whether the thermal neutron absorption of this material can be neglected for our purposes.

Should our experiments show that it is desirable to use beryllium in the intermediate scale experiment, we would then have to make an attempt to obtain one to five tons of metal of a specified purity. A possible recipe for such an intermediate scale experiment would be five tons of uranium metal, three tons of beryllium and fifty tons of graphite.

If another group of workers proposes to investigate the possibility of using beryllium or beryllium oxide in place of graphite for slowing down the neutrons, they would have first to investigate the thermal neutron absorption of this material by using at least one ton ~~one to four tons~~ in the form of a sphere or in the form of a cube. Only if it can be established that the thermal neutron cross section for absorption is very small does the use of this material in place of graphite appear to be possible.

The theory of such absorption measurements have been worked out both for the case of the sphere and for the case of the cube, and the chief difficulty would lie in obtaining the material in quantities of one ton with sufficient purity at an acceptable price. Perhaps it would be easier in this respect to work with beryllium oxide rather than beryllium metal. Unfortunately the oxide has ~~a~~ the drawback that its beryllium content has a lower density than the metal. However, if the material can be obtained experiments carried out on a lot of one ton might supply valuable information concerning the thermal absorption of beryllium, and perhaps the material could subsequently be used upon in an intermediate scale experiment in which the bulk of the slowing down material consists in graphite.

If such absorption experiments should show that the absorption of beryllium for thermal neutrons is negligible, there still would ~~ramin~~ remain the difficulty that a very large quantity, perhaps thirty tons of this material, would be needed for a large scale experiment if beryllium is used in place of graphite, and the present price for these materials would seem to make the cost almost prohibitive. Nevertheless, as long as it has not been proved that the chain reaction can be made to work with unseparated uranium by using graphite, the possibility of using beryllium in place of graphite should be borne in mind.

L. Sz.

(Leo Szilard)

P. S. The results of preliminary tests, designed to find out what densities of beryllium oxide and beryllium metal can be obtained by applying high pressure to powders of these materials, are summarized in the memorandum of November 3, 1940.

Memorandum on Graphite.

Conversation with Mr. Macpherson and V. C. Hamister on December 11, 1940.

Lamp black graphite having an ash content of .04 to .08% may be manufactured in a size 6 x 5 x 2½ inches. Unfortunately the National Carbon Company manufactures this type of graphite at the Fostoria Plant which is boron infested. Apparent density 1.55 to 1.6. Thermal conductivity. See enclosed sketch.

Petroleum coke graphite. Ash .08 to 1%. High thermal conductivity. See enclosed sketch.

Recommended book: Zoellner "Die technische Kohle".

Petroleum coke graphite contains some beryllium. Real density 2.2 to 2.25. Apparent density 1.53 to 1.7, whereas lamp black graphite has a real density of 2.10 and an apparent density of 1.55. Purest ~~beryllium~~ petroleum coke graphite, manufactured by National Carbon Company, is designated by A.G.K.T. having a total ash of 0.08%. Ash analyzed gave in one case 24% iron oxide and in another case 6% iron oxide. In one case the vanadium oxide content of the ash amounted to 2%, in another case to 4%.

Powdered graphite designated by 2301 has less than .07% ash and usually less than .03% ash. Bulk density may be brought up to 1.5 by applying high pressure, but the product is springy and crumbles.

Natural graphite: Cylon graphite containing 3% ash and Madagascar graphite containing less than 3% ash can be purified and the powder can be pressed, having a bulk density of 1.75 to 1.9 gm per cc. Bodies so pressed do not crumble. Ceylon graphite may be obtained from Pettinos Graphite Co. Chester, Pa., Madagascar graphite may be obtained from the Asbury Graphite Co., New York State.

Lamp black, if pressed, remains stringy and its bulk density cannot be increased beyond 1.3. Moreover, it contains hydrogen. Hamister thinks acetylen carbon may perhaps be free from hydrogen (to be obtained from Schwinegen Carbide Corp. ?)

14 August, 1940

MEMORANDUM REPORT

ON PROPOSED EXPERIMENTS WITH URANIUM

Objective of the Experiment

To get, if possible, energy from uranium through nuclear fission by means of a self-sustaining nuclear reaction without the necessity of separating the uranium isotopes. Such reaction would supply:

(1) Power - through heat developed in the reaction and utilized by means of a heat engine, e. g. a steam turbine;

(2) Neutrons in large amount usable for

  (a) Production of artificial rad~~ium~~o-active substances;

  (b) ~~For~~ Biological and therapeutic uses.

Primarily the reaction would involve only the uranium 235 isotope which constitutes about 1/140th part of ordinary uranium, most of the rest being uranium 238. By a secondary reaction uranium 238 will also become involved and there is a good possibility that part, at least, of the uranium 238 can be made to contribute to the fission with very obvious advantages.

Stages of the Research

Immediately upon the discovery, early in 1939, in Europe and in this country of the large amount of energy liberated in the fission of uranium nuclei after capturing ~~the~~ neutrons, it became conceivable that if, as seemed plausible, a sufficient number of free neutrons are released in the splitting of a uranium nucleus, the new supply of neutrons from fissions might be picked up by other uranium nuclei causing new fissions, and so on cumulatively, or in a so-called "chain reaction". The release of energy in such nuclei reactions could be enormous since the energy released per atom of uranium is about 200 million electron volts, while the energy of the strongest chemical union is only about five electron volts per atom of one of the substances combining.

It was soon realized that in ordinary uranium there are two different types of fission, (a) fission upon capture of a neutron with negligible kinetic energy (slow neutron capture) and (b) fission on entrance of a high energy neutron into the uranium nucleus (fast neutron capture). It is with fission of the first type by "slow neutron capture" that these proposed experiments have to do. It was surmised by Bohr and Wheeler and others, and proven early this year by Nier, Booth, Dunning and Grosse that it is the uranium isotope of atomic weight 235 present to the extent of only about one part in one hundred forty in ordinary uranium which gives fissions upon capture of slow neutrons. Nearly all of ordinary uranium is uranium 238, which gives fission only when hit by fast neutrons having energy of the order of one million electron volts.

The general arrangement to obtain slow neutron chain reaction would be to have uranium 235 distributed through a mass of some substance that would slow down the neutrons shaken off in a fission, which neutrons are of pretty high speed when first emitted so that they would stand a good chance of being captured by uranium 235 before traveling too far away or entirely out of reach of the uranium 235. Ordinarily hydrogen is the best substance with which to slow down neutrons, but if ordinary uranium even in pure metallic form were mixed with a hydrogen compound such as water as a slowing-down agent a chain reaction could not result, for hydrogen has a rather large capture cross-section for slow neutrons and the uranium 238 present has a high cross-section for neutrons of about ten electron volts energy, and would capture a large number of neutrons before they got slowed down to normal slow-neutron velocity, corresponding to about 1/40th of an electron volt. On the other hand the uranium 235 isotope, if it could be separated in sufficient quantity, should, when mixed with water, sustain a chain reaction if the mass used is made large enough.

The factors that are favorable for a chain reaction are (1) an average number of neutrons emitted in one fission considerably greater than one, so that after allowing for the capture of neutrons by the slowing down material and other substances present there would be more than one neutron free to bring about, in turn, the fission of another nucleus; (2) a sufficiently low probability of capture of neutrons by any uranium isotope present in a way that does not produce fission; (3) the slowing down material to bring the neutrons emitted in fission down to normal molecular speed in a short distance - the shorter this distance the smaller the volume of the mixture that would be required for a chain reaction if otherwise possible; (4) a low probability of capture (small capture cross-section) of neutrons, slow or fast, in the slowing-down material; (5) a sufficient mass of uranium and slowing-down material to make the peripheral escape of neutrons relatively small, and an appropriate geometrical distribution of the uranium in the slowing-down material; (6) a high probability of capture of slow neutrons (large fission cross-section) of the uranium 235; (7) the absence of materials other than the necessary uranium and the slowing-down material, since other materials would capture some neutrons.

Professor E. Fermi[1] and Dr. Leo Szilard[2] at Columbia University in the summer of 1939 came to the conclusion that it might be possible to obtain the desired chain reaction by the use of metallic uranium (ordinary uranium containing both U_{235} and U_{238}) with carbon in dense graphite form as the slowing-down material. At that time knowledge of the nuclear properties of uranium and carbon was quite inadequate to support any sound prediction as to the possibility of obtaining a chain reaction by the use of uranium and carbon. Measurements of the number of neutrons released per fission had been made at Columbia University and in Paris

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[1] Enrico Fermi, formerly professor in the University of Rome, since 1938 professor of physics in Columbia University.

[2] Leo Szilard, a native of Hungary by birth, who had resided in Vienna, in Berlin, and latterly, until the fall of 1938, at Oxford University in England, since early in 1939 a research guest in the Department of Physics, Columbia University.

without close agreement and without much precision in either case. No reliable measurements had been made of the capture cross-section of carbon for slow neutrons. Additional measurements were required. It was realized that better measurements of the factors involved might give a definitely negative answer as to the possibility of a chain reaction, they might give a definitely positive answer, or the results might still have so large a margin of error that they would give no definite answer, in which case they would probably give valuable information on which to design further experiments to test the possibility of the chain reaction. It was believed that the possibility of achieving the release of nuclear energy from uranium was large enough to justify the expenditure of a considerable sum of money on further research, and that because of the possible military significance of uranium energy, the Federal Government would be quite justified in supporting such research.

The first approach to government officials on this subject was made in March, 1939, when, through arrangements made by Prof. George B. Pegram of Columbia University, with the office of Mr. Charles Edison, Assistant Secretary of the Navy, Prof. Fermi conferred with certain officers of the Navy, indicating the possibility of the energy to be derived from uranium becoming a matter of military importance. The naval officers were interested and requested that the Navy be kept informed of any developments. In the fall of 1939, through a letter from Prof. Albert Einstein and through personal representations of Dr. Alexander Socks[1], the desirability of supporting research on the prob-

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[1] Dr. Alexander Socks is an economist with the firm of Lehman Bros., New York.

lem of power from uranium was presented to President Roosevelt. The President appointed a committee, composed of Dr. Lyman J. Briggs, director of the National Bureau of Standards, chairman, Col. Adamson, Ordnance Department, U.S.A., and Commander Hoover, U.S.N., to do something about supporting research on this problem. Funds to the extent of $6,000 were provided by the Army and the Navy. Partly by allotments from these funds the Uranium Committee supplied four tons graphite, costing about $2,000, and amounts of sheet cadmium and of paraffin costing a few hundred dollars, and also about $1,200 worth of measuring apparatus to enable experiments to be done at Columbia University in the spring of 1940 by Prof. Fermi, Dr.Szilard, Mr. Anderson and certain other assistants. No government money was expended for salaries or any general laboratory equipment.

From these experiments better measurements than had been previously available were obtained for the capture cross-section of carbon for neutrons, of the resonance absorption of neutrons by uranium 238 and of the slowing down of neutrons in carbon.

It is not easy to measure these quantities with accuracy without the use of very large amounts of material. The net results of these experiments in the spring of 1940 were that the possibility of the chain reaction was not definitely proven, while it was still further from being definitely disproven. On the whole, the indications were more favorable than any conclusions that could have been fairly claimed from previous experiments.

The whole question of an uranium-carbon chain reaction in the light of the 1940 experiments of Fermi and Szilard was the subject for discussion by a special advisory group assembled by Dr. Briggs to advise the Uranium Committee. This group, composed of Messrs. Briggs, Urey, Tuve, Wigner, Breit, Fermi, Szilard and Pegram, met at the Bureau of Standards on June 13, 1940. After full discussion, the recommendation of the group to the Uranium Committee was that funds should be sought to support research on the uranium-carbon experiment along two lines: (A) further measurements of the nuclear constants involved in the proposed type of reaction; (B) experiments with amounts of uranium and carbon equal to about one-fifth to one-quarter of the amount that could be estimated as the minimum in which a chain reaction could sustain itself. It was estimated that about $40,000 would be necessary for the further measurements of the fundamental constants and that approximately $100,000's worth of metallic uranium and pure graphite would be needed for the "intermediate scale" experiment.

The desirability of the measurements of the nuclear constants is obvious. It should be remarked that the immediate value will be to enable the "intermediate experiment" recommended as"B" above, and, subsequently, a full-scale experiment, to be designed with more knowledge than would be possible without the measurements under recommendation "A" above.

As to recommendation "B", the "intermediate experiment", the argument in its favor is the following. As nearly as can be estimated at present the smallest amount of materials necessary to secure a chain reaction with uranium and carbon would be 25 tons of uranium metal and 60 tons of graphite. This would represent an expenditure of perhaps $500,000. However, even if this rather large amount of material were in hand it would be advisable to proceed only by stages to set up the mass of material presumed necessary for the chain reaction. Measurements taken on the behavior of neutrons in intermediate amounts of the uranium-carbon mixture will not only be of the greatest value in predicting the total amount of material necessary, but will be absolutely essential, from the standpoint of safety, to the persons who are working on the experiment. Since the amount of material required for the chain reaction is certainly not in hand, and since it would cost a large sum of money, it is obvious that progress should be attempted by stages, and it is believed that the first stage should make use of not more than one-quarter of the amount which, so far as present knowledge goes, would be the minimum required for sustaining a chain reaction. It is not believed that there would be any danger in working with this intermediate amount of material, particularly since even this amount of material would not be put together all at once but would be assembled in stages and measurements taken at the several stages. Some question has been raised as to whether this intermediate experiment should be carried out in a university laboratory or in some more isolated spot. Prof. Fermi thinks there would not be the slightest hazard in carrying out the experiment in any laboratory.

After the formation of the National Defense Research Committee, the Uranium Committee appointed by the President was informed that it would become a sub-committee of the National Defense Research Committee. The chairman of the Uranium Committee transmitted to the National Defense Research Committee on July , 1940 a recommendation that the proposed experiments on the uranium-carbon reaction should be supported by an allotment of $140,000.

Proposed Experiments at Columbia University

Obviously the question of how much expenditure on the proposed experiments is justifiable will depend, in part, on the scientific knowledge gained in the researches, but much more upon the value, from the standpoint of power production, to be attached to the accomplishment of release of nuclear energy from uranium. As indicated above, it is likely that an uranium-carbon set-up that will actually produce power through a chain reaction, will cost something of the order of half a million dollars. It would be a very concentrated source of a very large amount of energy, that is, very concentrated as compared with existing power plants and fuel piles. The most obvious application would be for the powering of a ship. It would probably be well worth the investment

It is proposed that the National Defense Research Committee contract with Columbia University through George B. Pegram, professor of physics and dean of the Graduate Faculties, for researches on the uranium-carbon chain reaction problem to be made in the Department of Physics at Columbia University, and for reports on results, with suitable arrangements for the payment to Columbia University of appropriate amounts for the expenses of the experiments. The following is a brief outline of the proposed investigations, together with an estimate of cost.

At the present state of development of the technique we cannot hope to obtain a sufficiently accurate knowledge of the interactions of neutrons with uranium and carbon as to permit a mathematical prediction of the success of a chain reaction experiment. However, it seems worth while to continue and improve our study of these properties, not so much in order to make such a prediction possible, but rather to permit a rational planning of the best arrangement to be used. In order finally to decide whether a mixture of carbon and uranium of a certain size can give a chain reaction it will be necessary to perform an intermediate experiment on a sample of the mixture of about one-quarter or one-fifth of the estimated total amount necessary to sustain a chain reaction. Accordingly, it is proposed to divide our program into two parts.

A. Study of the interaction of neutrons with uranium and carbon; determination of the important nuclear constants.

B. "Intermediate experiment" with the appropriate mixture of uranium and carbon.

PART A

It is proposed to carry out the following measurements:

(1) To determine more accurately the number of new neutrons emitted per thermal neutron captured by uranium, and resulting in a fission. An approximate value was obtained by Anderson, Fermi and Szilard (Phys. Rev., Vol. 56, p. 284, 1939). A method for this

measurement consists in comparing the activity produced by neutrons slowed down in water or carbon with or without masses of uranium of suitable geometrical disposition spread through the slowing-down material. The accuracy of these measurements can be increased by using larger amounts of uranium oxide than were available in the above quoted research, and by using strong sources of neutrons.

(2) To measure the fraction of neutrons absorbed by uranium in the resonance band during the slowing-down process. This fraction is largely dependent upon the geometry used. We plan to vary the geometry so as to get an estimate of this magnitude for different configurations. One possible method requires the knowledge of the self-absorption curve of the uranium resonance neutrons. Such a curve has been determined by Anderson (Phys. Rev. in print). It is not possible, however, to measure this curve for very thick absorbers on account of the scattering. We shall attempt, therefore, to get an estimate of this fraction by measurements of the intensity of neutrons having energies above and below that of the resonance band.

(3) Study of the slowing-down of neutrons in carbon. This research, which is already in progress, has as its purpose to determine the length of diffusion of the neutrons during the slowing-down process. The method consists essentially in the determination of the activity of a detector sensitive to neutrons just above the thermal energies in masses of carbon of a shape suitable for calculation.

(4) Absorption of thermal neutrons in carbon. A measurement of the absorption cross-section of carbon for thermal neutrons was made last spring, using about four tons of graphite. With larger amounts of graphite available the experiment could now be repeated under more favorable conditions. Since a very precise knowledge of this cross-section is very essential in planning the final experiment it might also be desirable to repeat this experiment, using an essentially different geometrical arrangement.

(5) Tests of what would essentially be a single unit of the large-scale experiment, namely a single sphere of uranium metal, approximately 10 cm. in diameter, surrounded by a graphite mass of approximately 60 cm. in diameter. Measurements of the density of neutrons at various distances from the uranium sphere would have to be performed, placing sources of neutrons outside of the graphite mass.

(6) Measurements of scattering absorption and fission cross-sections of uranium with improved accuracy. Measurements of the absorption and fission process already in progress will be performed by comparing these cross-sections with those of manganese and gold. A new measurement of the total cross-section of uranium for thermal neutrons is desirable since the samples used by various investigators in previous measurements have proved to be contaminated by considerable amounts of hydrogen.

(7) Measurements of neutron absorption by other elements which might be present as impurities or which might be introduced for mechanical purposes, as, for example, in order to form a really fusible alloy of uranium.

An estimate of what would be needed for carrying out Part A above is the following: Besides the general laboratory equipment which would be made available by Columbia University, this Part A of the program would require:

(a) Special measuring instruments which have already been constructed under contract with the National Bureau of Standards (Uranium Committee).

(b) All of the experiments require strong sources of neutrons and the stronger the sources the more accurate and more readily attained will be the results of the experiments. A source consisting of one gram of radium mixed with beryllium powder will be sufficient for some of the experiments. It is hoped that a gram of radium already ordered by the Navy Department will be available for this neutron source. For the cost of making up the source and mixing the radium with beryllium and for separating the radium again after the termination of the research an allowance should be made of about $250.

(c) For some of the experiments still stronger neutron sources will be needed and can

probably be rented. Photo-neutron sources, consisting of one to three grams of radium inserted in a beryllium cylinder can be used and can probably be rented for	$2,000.
(d) Two tons of uranium oxide for experiments 1 and 2 - estimated cost	10,000
(e) A sphere of uranium metal, about 10 cm. in diameter for experiment 5 - estimated cost	1,000.
(f) Four tons of pure graphite, in addition to four tons already in hand - estimated cost	2,000.
(g) Experimental constructions, such as containers for the various materials - allowance	2,000.
(h) Miscllaneous expenses for supplies, small apparatus, shop work, etc. - $1,000 a month for twelve months	12,000.
(i) Salaries of research assistants for one year	10,750.
Total for Part A	$40,000.

PART B

The research assistants allowed for under Part A can also work on Part B with no additional item for salary proposed within the year.

This intermediate experiment will need 12 tons of pure graphite, more than half of which will be already on hand. The cost of the remainder should not be more than $3,000. The chief expense will be for five tons of uranium metal in spheres or blocks, whose size will be better determined after results have been obtained from Part A of the program. It is impossible to predict accurately what uranium metal in the proper form will cost. It is proposed that an allotment of $100,000 for this intermediate experiment be made and that as much uranium metal and other materials will be purchased as this amount will provide. An amount up to $5,000 should be at once available for preliminary metallurgical experiments to determine how uranium metal best suited to the purpose can be obtained. It may be pointed out that the materials used in this experiment will form part of those required for the final experiment on a scale sufficiently large to obtain a chain reaction if this full-scale experiment should ultimately be performed. Otherwise these materials - uranium and graphite - will have some salvage value either on the market or for use in other lines of experimentation.

Proposed Personnel

It is proposed that Prof. Pegram represent the University officially in connection with this research and that Prof. Fermi should be directly engaged in the research itself. Profs.Pegram and Fermi will, of course, receive no salary. Dr. Szilard, as one of the originators of the project, should be engaged with Prof. Fermi in the immediate direction of the research. It is proposed that a salary be paid to Dr. Szilard at the rate of $4,000 a year. It is proposed that Mr. Herbert L. Anderson, a recent Ph.D. graduate of Columbia University, who is well known in this field through his work for the past year with Prof. Fermi, be one of the research assistants at a salary of $2,400 a year.

It is not possible definitely to propose the names of additional assistants at the present time. If the University is assured of this contract it is likely that efforts will be made to induce Dr. Walter Zinn, of the Department of Physics of the College of the City of New York, who has been engaged in research in this field for the past few years at Columbia, to try to secure leave of absence from his City College post in order to work on this problem. In any case, in addition to Dr. Zinn and Dr. Anderson, two more men will be needed. It is, of course, desirable that the personnel for this research should consist of physicists who have already worked in this field.

Suggestions as to Contract with Columbia University

The following suggestions are made as to items of the contract between the National Defense Research Committee and Columbia University:

(1) The contract should be for researches to be made under the direction of appropriate members of the University staff, in general accordance with the experiments proposed in the preceding section, and for the reporting of results to the National Defense Research Committee.

(2) The contract should specify that the University will provide the direction of the experiments, the necessary laboratory space and the general equipment of a physics laboratory such as the University already has available.

(3) The contract should specify that the University should be reimbursed for all the direct expenses of the research, including:

- (a) The cost of materials.
- (b) The cost of supplies and apparatus necessary for the prosecution of the research.
- (c) Salaries paid to research assistants.
- (d) Such minor and incidental outlays on the part of the University as the prosecution of the research may necessitate.

(4) The contract should specify that the results of the research should be kept confidential and reported only to the National Defense Research Committee.

(5) The contract should specify that all personnel employed in connection with the research should be subject to the approval of the National Defense Research Committee.

(6) The contract should provide for interim reports on the research at intervals of two or three months and a complete report at the end of one year.

(7) The term of the contract should probably be for one year.

(8) The contract should specify that all important quantities of materials purchased for these researches should become the property of the National Defense Research Committee.

(9) The contract should specify that all apparatus and supplies purchased or constructed for this research should become the property of Columbia University after the termination of the contract. This would constitute a small return to the University for what it supplies in the contract. If it should, for any reason, not be desirable to have the apparatus become the property of the University, provision should be made for payment of a small sum to the University - say, $500 to $1,000 - for the inevitable cost to it of services, such as clerical work, which it would be difficult to itemize.

(10) The contract may provide that in the case of materials or apparatus of which the cost is large, purchase may be made through the University, with subsequent reimbursement, or the materials may be purchased through an appropriate government agency and supplied to the University.

Bk f. 8A

Excerpt from bottom of p.6 to bottom of p.8

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It was soon realized that in ordinary uranium there are two different types of fission, (a) fission upon capture of a neutron with negligible kinetic energy (slow neutron capture) and (b) fission on entrance of a high energy neutron into the uranium nucleus (fast neutron capture). It is with fission of the first type of "slow neutron capture" that these proposed experiments have to do. It was surmised by Bohr and Wheeler and others, and proven early this year by Nier, Booth, Dunning and Grosse that it is the uranium isotope of atomic weight 235 present to the extent of only about one part in one hundred forty in ordinary uranium which gives fissions upon capture of slow neutrons. Nearly all of ordinary uranium is uranium 238, which gives fission only when hit by fast neutrons having energy of the order of one million electron volts.

The general arrangement to obtain slow neutron chain reaction would be to have uranium 235 distributed through a mass of some substance that would slow down the neutrons shaken off in a fission, which neutrons are of pretty high speed when first emitted so that they would stand a good chance of being captured by uranium 235 before traveling too far away or entirely out of reach of the uranium 235. Ordinarily hydrogen is the best substance with which to slow down neutrons, but if ordinary uranium even in pure metallic form were mixed with a hydrogen compound such as water as a slowing-down agent a chain reaction could not result, for hydrogen has a rather large capture cross-section for slow neutrons and the uranium 238 present has a high cross-section for neutrons of about ten electron volts energy, and would capture a large number of neutrons before they got slowed down to normal slow-neutron velocity, corresponding to about 1/40th of an electron volt. On the other hand the uranium 235 isotope, if it could be separated in sufficient quantity, should, when mixed with water, sustain a chain reaction if the mass used is made large enough.

The factors that are favorable for a chain reaction are (1) an average number of neutrons emitted in one fission considerably greater than one, so that after allowing for the capture of neutrons by the slowing down material and other substances present there would be more than one neutron free to bring about, in turn, the fission of another nucleus; (2) a sufficiently low probability of capture of neutrons by any uranium isotope present in a way that does not produce fission; (3) the slowing down material to bring the neutrons emitted in fission down to normal molecular speed in a short distance - the shorter this distance the smaller the volume of the mixture that would be required for a chain reaction if otherwise possible; (4) a low probability of capture (small capture cross-section) of neutrons, slow or fast, in the slowing-down material; (5) a sufficient mass of uranium and slowing-down material to make the peripheral escape of neutrons relatively small, and an appropriate geometrical distribution of the uranium in the slowing-down material; (6) a high probability of capture of slow neutrons (large fission cross-section) of the uranium 235; (7) the absence of materials other than the necessary uranium and the slowing-down material, since other materials would capture some neutrons.

Professor E. Fermi[1] and Dr. Leo Szilard[2] at Columbia University in the summer of 1939 came to the conclusion that it might be possible to obtain the desired chain reaction by the use of metallic uranium (ordinary uranium containing both U_{235} and U_{238}) with carbon in dense graphite form as the slowing-down material. At that time knowledge of the nuclear properties of uranium and carbon was quite inadequate to support any sound prediction as to the possibility of obtaining a chain reaction by the use of uranium and carbon. Measurements of the number of neutrons released per fission had been made at Columbia University and in Paris

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[1] Enrico Fermi, formerly professor in the University of Rome, since 1938 professor of physics in Columbia University.

[2] Leo Szilard, a native of Hungary by birth, who had resided in Vienna, in Berlin, and latterly, until the fall of 1938, at Oxford University in England, since early in 1939 a research guest in the Department of Physics, Columbia University.

without close agreement and without much precision in either case. No reliable measurements had been made of the capture cross-section of carbon for slow neutrons. Additional measurements were required. It was realized that better measurements of the factors involved might give a definitely negative answer as to the possibility of a chain reaction, they might give a definitely positive answer, or the results might still have so large a margin of error that they would give no definite answer, in which case they would probably give valuable information on which to design further experiments to test the possibility of the chain reaction. It was believed that the possibility of achieving the release of nuclear energy from uranium was large enough to justify the expenditure of a considerable sum of money on further research, and that because of the possible military significance of uranium energy, the Federal Government would be quite justified in supporting such research.

The first approach to government officials on this subject was made in March, 1939, when, through arrangements made by Prof. George B. Pegram of Columbia University, with the office of Mr. Charles Edison, Assistant Secretary of the Navy, Prof. Fermi conferred with certain officers of the Navy, indicating the possibility of the energy to be derived from uranium becoming a matter of military importance. The naval officers were interested and requested that the Navy be kept informed of any developments. In the fall of 1939, through a letter from Prof. Albert Einstein and through personal representations of Dr. Alexander Socks[1], the desirability of supporting research on the prob-

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[1] Dr. Alexander Socks is an economist with the firm of Lehman Bros., New York.

lem of power from uranium was presented to President Roosevelt. The President appointed a committee, composed of Dr. Lyman J. Briggs, director of the National Bureau of Standards, chairman, Col. Adamson, Ordnance Department, U.S.A., and Commander Hoover, U.S.N., to do something about supporting research on this problem. Funds to the extent of $6,000 were provided by the Army and the Navy. Partly by allotments from these funds the Uranium Committee supplied four tons graphite, costing about $2,000, and amounts of sheet cadmium and of paraffin costing a few hundred dollars, and also about $1,200 worth of measuring apparatus to enable experiments to be done at Columbia University in the spring of 1940 by Prof. Fermi, Dr. Szilard, Mr. Anderson and certain other assistants. No government money was expended for salaries or any general laboratory equipment.

From these experiments better measurements than had been previously available were obtained for the capture cross-section of carbon for neutrons, of the resonance absorption of neutrons by uranium 238 and of the slowing down of neutrons in carbon.

It is not easy to measure these quantities with accuracy without the use of very large amounts of material. The net results of these experiments in the spring of 1940 were that the possibility of the chain reaction was not definitely proven, while it was still further from being definitely disproven. On the whole, the indications were more favorable than any conclusions that could have been fairly claimed from previous experiments.

The whole question of an uranium-carbon chain reaction in the light of the 1940 experiments of Fermi and Szilard was the subject for discussion by a special advisory group assembled by Dr. Briggs to advise the Uranium Committee. This group, composed of Messrs. Briggs, Urey, Tuve, Wigner, Breit, Fermi, Szilard and Pegram, met at the Bureau of Standards on June 13, 1940. After full discussion, the recommendation of the group to the Uranium Committee was that funds should be sought to support research on the uranium-carbon experiment along two lines: (A) further measurements of the nuclear constants involved in the proposed type of reaction; (B) experiments with amounts of uranium and carbon equal to about one-fifth to one-quarter of the amount that could be estimated as the minumum in which a chain reaction could sustain itself. It was estimated that about $40,000 would be necessary for the further measurements of the fundamental constants and that approximately $100,000's worth of metallic uranium and pure graphite would be needed for the "intermediate scale" experiment.

The desirability of the measurements of the nuclear constants is obvious. It should be remarked that the immediate value will be to enable the "intermediate experiment" recommended as "B" above, and, subsequently, a full-scale experiment, to be designed with more knowledge than would be possible without the measurements under recommendation "A" above.

As to recommendation "B", the "intermediate experiment", the argument in its favor is the following. As nearly as can be estimated at present the smallest amount of materials necessary to secure a chain reaction with uranium and carbon would be 25 tons of uranium metal and 60 tons of graphite. This would represent an expenditure of perhaps $500,000. However, even if this rather large amount of material were in hand it would be advisable to proceed only by stages to set up the mass of material presumed necessary for the chain reaction. Measurements taken on the behavior of neutrons in intermediate amounts of the uranium-carbon mixture will not only be of the greatest value in predicting the total amount of material necessary, but will be absolutely essential, from the standpoint of safety, to the persons who are working on the experiment. Since the amount of material required for the chain reaction is certainly not in hand, and since it would cost a large sum of money, it is obvious that progress should be attempted by stages, and it is believed that the first stage should make use of not more than one-quarter of the amount which, so far as present knowledge goes, would be the minumum required for sustaining a chain reaction. It is not believed that there would be any danger in working with this intermediate amount of material, particularly since even this amount of material would not be put together all at once but would be assembled in stages and measurements taken at the several stages. Some question has been raised as to whether this intermediate experiment should be carried out in a university laboratory or in some more isolated spot. Prof. Fermi thinks there would not be the slightest hazard in carrying out the experiment in any laboratory.

After the formation of the National Defense Research Committee, the Uranium Committee appointed by the President was informed that it would become a sub-committee of the National Defense Research Committee. The chairman of the Uranium Committee transmitted to the National Defense Research Committee on July , 1940, a recommendation that the proposed experiments on the uranium-carbon reaction should be supported by an allotmentof $140,000.

Proposed Experiments at Columbia University

Obviously the question of how much expenditure on the proposed experiments is justifiable will depend, in part, on the scientific knowledge gained in the researches, but much more upon the value, from the standpoint of power production, to be attached to the accomplishment of release of nuclear energy from uranium. As indicated above, it is likely that an uranium-carbon set-up that will actually produce power through a chain reaction, will cost something of the order of half a million dollars. It would be a very concentrated source of a very large amount of energy, that is, very concentrated as compared with existing power plants and fuel piles. The most obvious application would be for the powering of a ship. It would probably be well worth the investment.

It is proposed that the National Defense Research Committee contract with Columbia University through George B. Pegram, professor of physics and dean of the Graduate Faculties, for researches on the uranium-carbon chain reaction problem to be made in the Department of Physics at Columbia University, and for reports on results, with suitable arrangements for the payment to Columbia University of appropriate amounts for the expenses of the experiments. The following is a brief outline of the proposed investigations, together with an estimate of cost.

At the present state of development of the technique we cannot hope to obtain a sufficiently accurate knowledge of the interactions of neutrons with uranium and carbon as to permit a mathematical prediction of the success of a chain reaction experiment. However, it seems worth while to continue and improve our study of these properties, not so much in order to make such a prediction possible,, but rather to permit a rational planning of the best arrangement to be used. In order finally to decide whether a mixture of carbon and uranium of a certain size can give a chain reaction it will be necessary to perform an intermediate experiment on a sample of the mixture of about one-quarter or one-fifth of the estimated total amount necessary to sustain a chain reaction. Accordingly, it is proposed to divide our program into two parts.

A. Study of the interaction of neutrons with uranium and carbon; determination of the important nuclear constants.

B. "Intermediate experiment" with the appropriate mixture of uranium and carbon.

PART A

It is proposed to carry out the following measurements:

(1) To determine more accurately the number of new neutrons emitted per thermal neutron captured by uranium, and resulting in a fission. An approximate value was obtained by Anderson, Fermi and Szilard (Phys. Rev., Vol. 56, p. 284, 1939). A method for this

measurement consists in comparing the activity produced by neutrons slowed down in water or carbon with or without masses of uranium of suitable geometrical disposition spread through the slowing-down material. The accuracy of these measurements can be increased by using larger amounts of uranium oxide than were available in the above quoted research, and by using strong sources of neutrons.

(2) To measure the fraction of neutrons absorbed by uranium in the resonance band during the slowing-down process. This fraction is largely dependent upon the geometry used. We plan to vary the geometry so as to get an estimate of this magnitude for different configurations. One possible method requires the knowledge of the self-absorption curve of the uranium resonance neutrons. Such a curve has been determined by Anderson (Phys. Rev. in print). It is not possible, however, to measure this curve for very thick absorbers on account of the scattering. We shall attempt, therefore, to get an estimate of this fraction by measurements of the intensity of neutrons having energies above and below that of the resonance band.

(3) Study of the slowing-down of neutrons in carbon. This research, which is already in progress, has as its purpose to determine the length of diffusion of the neutrons during the slowing-down process. The method consists essentially in the determination of the activity of a detector sensitive to neutrons just above the thermal energies in masses of carbon of a shape suitable for calculation.

(4) Absorption of thermal neutrons in carbon. A measurement of the absorption cross-section of carbon for thermal neutrons was made last spring, using about four tons of graphite. With larger amounts of graphite available the experiment could now be repeated under more favorable conditions. Since a very precise knowledge of this cross-section is very essential in planning the final experiment it might also be desirable to repeat this experiment, using an essentially different geometrical arrangement.

(5) Tests of what would essentially be a single unit of the large-scale experiment, namely a single sphere of uranium metal, approximately 10 cm. in diameter, surrounded by a graphite mass of approximately 60 cm. in diameter. Measurements of the density of neutrons at various distances from the uranium sphere would have to be performed, placing sources of neutrons outside of the graphite mass.

(6) Measurements of scattering absorption and fission cross-sections of uranium with improved accuracy. Meqsurements of the absorption and fission process already in progress will be performed by comparing these cross-sections with those of manganese and gold. A new measurement of the total cross-section of uranium for thermal neutrons is desirable since the samples used by various investigators in previous measurements have proved to be contaminated by considerable amounts of hydrogen.

(7) Measurements of neutron absorption by other elements which might be present as impurities or which might be introduced for mechanical purposes, as, for example, in order to form a really fusible alloy of uranium.

An estimate of what would be needed for carrying out Part A above is the following: Besides the general laboratory equipment which would be made available by Columbia University, this Part A of the program would require:

(a) Special measuring instruments which have already been constructed under contract with the National Bureau of Standards (Uranium Committee).

(b) All of the experiments require strong sources of neutrons and the stronger the sources the more accurate and more readily attained will be the results of the experiments. A source consisting of one gram of radium mixed with beryllium powder will be sufficient for some of the experiments. It is hoped that a gram of radium already ordered by the Navy Department will be available for this neutron source. For the cost of making up the source and mixing the radium with beryllium and for separating the radium again after the termination of the research an allowance should be made of about $250.

(c) For some of the experiments still stronger neutron source will be needed and can

	probably be rented. Photo-neutron sources, consisting of one to three grams of radium inserted in a beryllium cylinder can be used and can probably be rented for	$2,000.
(d)	Two tons of uranium oxide for experiments 1 and 2 - estimated cost	10,000.
(e)	A sphere of uranium metal, about 10 cm. in diameter for experiment 5 - estimated cost	1,000.
(f)	Four tons of pure graphite, in addition to four tons already in hand - estimated cost	2,000.
(g)	Experimental constructions, such as containers for the various materials - allowance	2,000.
(h)	Miscellaneous expenses for supplies, small apparatus, shop work, etc. - $1,000 a month for twelve months	12,000.
(i)	Salaries of research assistants for one year	10,750.
	Total for Part A	$40,000.

PART B

The research assistants allowed for under Part A can also work on Part B with no additional item for salary proposed within the year.

This intermediate experiment will need 12 tons of pure graphite, more than half of which will be already on hand. The cost of the remainder should not be more than $3,000. The chief expense will be for five tons of uranium metal in spheres or blocks, whose size will be better determined after results have been obtained from Part A of the program. It is impossible to predict accurately what uranium metal in the proper form will cost. It is proposed that an allotment of $100,000 for this intermediate experiment be made and that as much uranium metal and other materials will be purchased as this amount will provide. An amount up to $5,000 should be at once available for preliminary metallurgical experiments to determine how uranium metal best suited to the purpose can be obtained. It may be pointed out that the materials used in this experiment will form part of those required for the final experiment on a scale sufficiently large to obtain a chain reaction if this full-scale experiment should ultimately be performed. Otherwise these materials - uranium and graphite - will have some salvage value either on the market or for use in other lines of experimentation.

Proposed Personnel

It is proposed that Prof. Pegram represent the University officially in connection with this research and that Prof. Fermi should be directly engaged in the research itself. Profs. Pegram and Fermi will, of course, receive no salary. Dr. Szilard, as one of the originators of the project, should be engaged with Prof. Fermi in the immediate direction of the research. It is proposed that a salary be paid to Dr. Szilard at the rate of $4,000 a year. It is proposed that Mr. Herbert L. Anderson, a recent Ph.D. graduate of Columbia University, who is well known in this field through his work for the past year with Prof. Fermi, be one of the research assistants at a salary of $2,400 a year.

It is not possible definitely to propose the names of additional assistants at the present time. If the University is assured of this contract it is likely that efforts will be made to induce Dr. Walter Zinn, of the Department of Physics of the College of the City of New York, who has been engaged in research in this field for the past few years at Columbia, to try to secure leave of absence from his City College post in order to work on this problem. In any case, in addition to Dr. Zinn and Dr. Anderson, two more men will be needed. It is, of course, desirable that the personnel for this research should consist of physicists who have already worked in this field.

Suggestions as to Contract with Columbia University

The following suggestions are made as to items of the contract between the National Defense Research Committee and Columbia University:

(1) The contract should be for researches to be made under the direction of appropriate members of the University staff, in general accordance with the experiments proposed in the preceding section, and for the reporting of results to the National Defense Research Committee.

(2) The contract should specify that the University will provide the direction of the experiments, the necessary laboratory space and the general equipment of a physics laboratory such as the University already has available.

(3) The contract should specify that the University should be reimbursed for all the direct expenses of the research, including:

- (a) The cost of materials.
- (b) The cost of supplies and apparatus necessary for the prosecution of the research.
- (c) Salaries paid to research assistants.
- (d) Such minor and incidental outlays on the part of the University as the prosecution of the research may necessitate.

(4) The contract should specify that the results of the research should be kept confidential and reported only to the National Defense Research Committee.

(5) The contract should specify that all personnel employed in connection with the research should be subject to the approval of the National Defense Research Committee.

(6) The contract should provide for interim reports on the research at intervals of two or three months and a complete report at the end of one year.

(7) The term of the contract should probably be for one year.

(8) The contract should specify that all important quantities of materials purchased for these researches should become the property of the National Defense Research Committee.

(9) The contract should specify that all apparatus and supplies purchased or constructed for this research should become the property of Columbia University after the termination of the contract. This would constitute a small return to the University for what it supplies in the contract. If it should, for any reason, not be desirable to have the apparatus become the property of the University, provision should be made for payment of a small sum to the University - say, $300 to $1,000 - for the inevitable cost to it of services, such as clerical work, which it would be difficult to itemize.

(10) The contract may provide that in the case of materials or apparatus of which the cost is large, purchase may be made through the University, with subsequent reimbursement, or the materials may be purchased through an appropriate government agency and supplied to the University.

Pegrams Memo dated aug 14. 1940. Exhib. D.

Excerpt from bottom of p.6 to bottom of p.8

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