Fission of heavy nuclei*

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The problem of the fission of heavy nuclei and the question associated with it of the possibility of realizing a nuclear chain reaction has been discussed in detail at the Conference on the Physics of the Atomic Nucleus in 1939 in Khar'hov.[1] I shall therefore restrict myself in my report to a presentation and an analysis of the principal investigations that have been completed during the intervening time interal.[2]

In the course of the last year there have been no publications of essentially new theoretical concepts on the mechanism of fission. The hypothesis on the instability of heavy nuclei with respect to changes in their shape that has been expressed already by Meitner and Frisch remains even now the principal explanation of the phenomenon of fission. However, a number of quantitative relationships which followed from the calculations of Bohr and Wheeler arising from the same hypothesis are at the present time subject to doubt. These questions are being discussed in a separate paper by Berestetskiĭ and Migdal and therefore I shall not dwell upon them.

During the past year new possibilities of exciting fission of nuclei have been discovered.

Gant[3] carried out a number of preliminary experiments in which he observed by the method of Joliot, i.e., by radioactivity of the fragments, the fission of uranium nuclei under the action of deuterons with an energy of 8–9 MeV. Wells, Haxby *et al.*[4] established uranium fission under the action of x-rays of 6 MeV, obtained in the splitting of fluorine by protons. Finally, Petrzhak and Flerov observed the spontaneous fission of uranium nuclei.

In May 1940 Jentschke, Prankl, and Hernegger[5] published a communication on the fission of ionium nuclei. They showed that thermal neutrons do not produce fission and that it is produced by fast neutrons from a (d,d)-source.

Thus, at the present time the phenomenon of fission can be regarded as established for the following nuclei:

$$U_{92}^{235}, U_{92}^{236}, U_{92}^{238}, U_{92}^{239}, Th_{90}^{233}, Io_{90}^{231}, Pa_{91}^{232}.$$

During the present year progress was made in the problem of the boundaries and fission cross sections for some of the nuclei listed above. As a result of the studies by Nier *et al.*[6] who succeeded in separating the uranium isotopes it was definitely established that thermal neutrons produce fission only of U_{92}^{235}. Experiments were carried out with quantities of U^{238} and U^{235} respectively equal at best to 4 and 0.03 μg. Attempts were made in these same experiments to clarify the possibility of fission of U^{234} by thermal neutrons, but as a result of the small quantities obtained of this isotope and due to the nearness of its mass to the mass of U^{235} this question did not receive a final solution.

A number of studies was carried out with the aim of determining the minimum energy of neutrons producing fission of U^{238} and Th^{232}. Petrzhak and Flerov[7] concluded on the basis of experiments with photoneutrons from beryllium excited by x-rays from radium and thorium and their decay products that the limiting energy of neutrons causing fission of U^{238} is of the order of 1 MeV. Haxby, Wells *et al.*[8] obtaining neutrons in the reaction $Li^7(p, n)$ found that the limit for the fission of thorium lies at 1.1 MeV. Thus, from a comparison of these results it follows that the limiting energies of neutrons are the same in the cases under discussion.

However, this conclusion can turn out to be incorrect, since the determination of the boundaries depend to a great extent on the behavior of the cross section in the adjacent regions of energy, on the sensitivity of the method, and on the number of neutrons from the source. It should be noted that the situation is even worse with determining the boundaries for the fission of ionium and protoactinium; for these elements it is known only that their fission is not brought about by thermal neutrons and, in any case, occurs for a neutron energy of 2 MeV.

The order of magnitude of the limiting energy could have been established from the magnitude of the fission cross section for fast neutrons if one accepts the treatment by Bohr and Wheeler for the energy dependence of the probabilities of inelastic scattering and fission. According to their opinion in regions not too close to the boundary both probabilities vary with energy according to the same law and since inelastic scattering is the only process which can practically compete with fission, the fission cross section must remain constant as the neutron energy is varied. Its values will be the smaller the higher is the boundary, since inelastic scattering will already have a large probability at energies when fission is only just beginning to be possible. The cross sections for the fission of U^{238}, Pa^{231}, Th^{232}, and Io^{230} by fast neutrons are respectively equal to ($5 \cdot 10^{-25}$, $3 \cdot 10^{-24}$, $1 \cdot 10^{-25}$, and $3 \cdot 10^{-25}$ cm^2) and, consequently, the elements undergoing fission must according to these considerations be situated in the order of increasing boundaries in the following manner: U^{235}, Pa^{231}, U^{238}, Io^{230}, and Th^{232}.

The experimental material shows that at least a part of the assertions by Bohr and Wheeler correspond to experiment and actually the fission cross sections of uranium and thorium in regions not adjacent to the boundary do not depend on the neutron energy. Ladenburg, Kanner, Barschall, and van Voorhees (cf., Ref. 9) obtained neutrons monochromatic with respect to their velocities in the (d,d)-reaction. Studying fission under the action of neutrons emitted at different angles with respect to the flux of the incident deuterons they showed that in the range of variation of the neutron energy from 2.1 to 3.1 MeV the

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fission cross sections of uranium and thorium remain constant. Ageno, Amaldi, Bociarelli, and Trabacchi[10] arrived at the same conclusion for the energy interval from 2 to 10 MeV by studying the uranium and thorium fission under the action of neutrons arising in the (d,d)-, (d,B)-, (d,Be)-, and (d,Li)-reactions. In the same study it was shown that the fission cross sections of uranium begin to increase at neutron energies greater than 11 MeV.

In Bohr's opinion this increase is not related to the variation at very great excitations of the ratio of the probability of fission and the probability of emission of neutrons by the U^{238} nucleus. After the departure of the neutron from the nucleus the nucleus, generally speaking, remains excited. It might turn out that the excitation energy will be greater than the fission boundary; then an evaporation of a neutron from U^{239} will be followed by the fission of U^{238}. The addition of this form of fission at high excitations is the reason, according to Bohr, for the increase in the cross section.

The second part of the assertions of Bohr and Wheeler that connects the magnitude of the cross section with the boundary has not yet been tested by experiment.

We now examine the papers on the study of the energy and of the nature of the fragments arising as a result of fission of heavy nuclei. The most thorough determinations of the energy were made by Kanner and Barschall[11] using an ionization chamber upon one of whose electrodes uranium had been deposited and that was then connected to a linear amplifier. They found in the curve of the distribution of pulses with respect to their magnitude two maxima at energies of 65 and 97 MeV. Kanner and Barschall in addition measured directly the total energy of the fragments by placing in the middle of the ionization chamber an aluminum foil upon which a very thin layer of metallic uranium was deposited by cathode sputtering. The total energy of the fragments turned out on the average to be equal to 159 MeV, and this agrees well with the sum of the individual energies of each fragment as determined by them. This energy relates to the most prominent type of fission into fragments with the mass numbers of the order of 100 and 140. According to the data of Kanner and Barschall the halfwidths of the distribution is equal to ~ 30 MeV, and the highest energy liberated in fission is 200 MeV. The calculation of the energy was made using the number of ions formed by the fragments, as usual under the assumption that the average energy expended by a fragment in forming a single ion is the same as it is for an α-particle. In view of the fact that in this way a certain amount of arbitrariness is introduced the work of Henderson[12] who determined the energy of the fragments arising from uranium fission by a calorimetric method is of particular value. In his experiments 13g of metallic uranium were irradiated by an intense beam of slow neutrons from the Berkeley cyclotron. The temperature of the uranium was measured by means of a resistance thermometer; the number of nuclear fissions was determined by means of special experiments carried out simultaneously using a thin layer of uranium in an ionization chamber. Henderson found that the average energy of the fragments is equal to 175 MeV. This value is greater than the kinetic energy of the fragments since a significant part of the soft radiation accompanying the β-decay of the fragments was absorbed in the mass uranium and the copper shields surrounding it.

The physical methods of the investigation yield, as we have seen, certain indications as to the nature of the fragments, but radiochemical investigations play here a decisive role. In this field a large number of investigations have been carried out which to a great extent extended and made more precise the results of the investigations of last year.

In the majority of cases the charge of the element was determined on the basis of its chemical properties; for iodine, tillurium and antimony this was carried out using the characteristic K-rays of the x-ray spectrum. Studies of the variation of activity in time after appropriate chemical separations enabled one to establish with certitude several chains of successive β-transformations. The decay periods and the properties of the radioactive radiation of some fragments coincided with the same quantities for radioactive nuclei obtained as a result of irradiation by deuterons, protons and neutrons of elements in that part of the periodic system. This enabled one to determine the mass numbers of such fragments. The material that is known at present concerning the chains of successive transformations of fragments obtained in the fission of uranium are collected in Table I.

It has to be said that in spite of the large amount of work invested in the chemical investigations of radioactive fragments the material obtained does not provide essential data for an analysis of the fission process. At present, strictly speaking, one cannot establish a single branch for which one could state with certainty the charge of the initial fragments and their mass numbers. And yet, if this were known, then it would have been possible to determine by an independent method, using the difference between the mass number of the compound uranium nucleus and the sum of the mass numbers of the initial fragments of the branch, the number of neutrons accompanying nuclear fission.

It is of interest to note that the ratio of the number of neutrons and protons in the initial light and heavy fragments turn out to be different. While in the heavy fragments this ratio is very close to that characteristic of uranium, in the light fragments it is much lower. As should have been expected, nuclear matter has time to redistribute itself in the uranium before the process of fission itself takes place. Several cases are already known when the light fragments are very close in their mass to stable nuclei. I. P. Selinov in connection with this advanced the possibility of uranium undergoing fission with the formation of a stable light fragment.

At the previous conference the question was discussed in connection with the work by Petrzhak, Jentschke and Prankl concerning the possibility of formation of different kinds of fragments in the interaction of uranium with slow and fast neutrons. From the distribution of ionization pulses with respect to their magnitude it followed that under the action of fast neutrons along with asymmetric fis-

TABLE I.

Light fragments:

$Br_{35}^{83} \xrightarrow{140\ min} Kr_{36}^{83*} \xrightarrow{112\ min} Kr_{36}^{83}$ (stable)

$Kr_{36}^{88} \xrightarrow{170\ min} Rb_{37}^{88} \xrightarrow{18\ min} Sr_{38}^{88}$ (stable)

$Kr_{36}^{89} \xrightarrow{3\ min} Rb_{37}^{89} \xrightarrow{15.5\ min} Sr_{38}^{89} \xrightarrow{54\ days} Y_{39}^{89}$

$Mo_{42} \xrightarrow{67\ hours} Eka\text{-}Mn_{43} \xrightarrow{6.6\ hours} Eka\text{-}Mn_{43}^{(99)}$ (stable)?

$Mo_{42} \xrightarrow{19\ min} Eka\text{-}Mn_{43} \xrightarrow{9\ min} Ru_{44}$ (stable)

$Kr_{36} \xrightarrow{very\ short} Rb_{37} \xrightarrow{80\ sec} Sr_{38} \xrightarrow{6\ hours} Y_{39} \xrightarrow{3.5\ hours} Zr_{40}$ (stable)

$Zr_{40} \xrightarrow{17\ hours} Nb_{41} \xrightarrow{75\ min} Mo_{42}$ (stable)

Heavy fragments:

$Sb_{51}^{127} \xrightarrow{80\ hours} Te_{52}^{127} \xrightarrow[90\ days*]{10\ hours} I_{53}^{127}$ (stable)

$Sb_{51}^{129} \xrightarrow{4.2\ hours} Te_{52}^{129} \xrightarrow[36\ days*]{70\ min} I_{53}^{129}$—(?)

$Te_{52}^{131} \xrightarrow{25\ min} I_{53}^{131} \xrightarrow{8.0\ days} Xe_{54}^{131}$ (stable)

$Xe_{54}^{139} \xrightarrow{1.2\ days} Cs_{55}^{139} \xrightarrow{<0.5\ min} Ba_{56}^{139} \xrightarrow{7\ min} La_{57}^{139} \xrightarrow{86\ min}$ (stable)

$Ba_{56}^{(140)} \xrightarrow{300\ hours} La_{57}^{140} \xrightarrow{44\ hours} Ce_{58}^{140}$ (stable)

$Sb_{51} \xrightarrow{5\ min} Te_{52} \xrightarrow{77\ hours} I_{53} \xrightarrow{2.4\ hours} Xe_{54}$ (stable)

$Sb_{51} \xrightarrow{10\ min} Te_{52} \xrightarrow{60\ min} I_{53} \xrightarrow{22\ hours} Xe_{54} \xrightarrow{5\ days} Cs_{55}$(?)

$Sb_{51} \xrightarrow{<10\ min} Te_{52} \xrightarrow{43\ min} I_{53} \xrightarrow{54\ min} Xe_{54}$

$Te_{52} \xrightarrow{\sim 15\ min} I_{53} \xrightarrow{6.6\ hours} Xe_{54} \xrightarrow{9.4\ hours} Cs_{55}$(?)

$Xe_{54} \xrightarrow{15\ min} Cs_{55} \xrightarrow{33\ min} Ba_{56}$(?)

$Ba_{56} \xrightarrow{14\ min} La_{57} \xrightarrow{2.5\ hours} Ce_{58}$(?)

$Xe_{54} \xrightarrow{short} Cs_{55} \xrightarrow{40\ sec} Ba_{56}$(?)

Fragments from symmetric fission:

$Pd_{46}^{(111)} \xrightarrow{17\ min} Ag_{47}^{(111)} \xrightarrow{7.5\ days} Cd_{48}^{111}$ (stable)

$Ag_{47}^{112} \xrightarrow{3.2\ days} Cd_{48}^{112}$ (stable)

$Cd_{48}^{115} \xrightarrow{2.5\ days} In_{49}^{115*} \xrightarrow{4.5\ hours} In_{49}^{115}$ (stable)

$Cd_{48}^{117} \xrightarrow{3.75\ hours} In_{49}^{114} \xrightarrow{117\ min} Sn_{50}^{117}$ (stable)

$Cd^{*} \xrightarrow{50\ min} Cd$ (stable)

The table was compiled by I. P. Selinov, a research scientist at the Leningrad Physicotechnical Institute. An asterisk denotes a metastable state of the nucleus.

sion formation of fragments close in their masses occurs. The experiments of Japanese investigators (Ref. 13) pointing to the formation of radioactive silver and cadmium (cf. Table I) are in some agreement with this conclusion. According to their data these nuclei arise only under the action of fast neutrons.

In concluding this review of papers on the phenomena

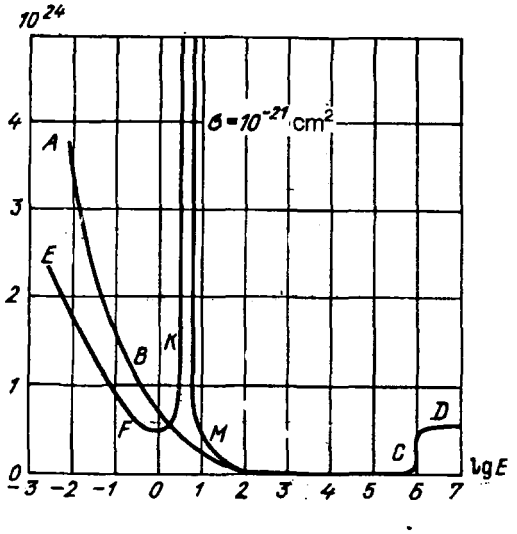

FIG. 1.

of fission several remarks should be made concerning neutron emission connected with these reactions.

Our knowledge concerning neutrons emitted in the fission of uranium are now more reliable primarily due to the valuable work by Zinn and Szilard. They recorded neutrons using the recoil atoms of hydrogen and helium in an ionization chamber employing as a source the not very fast neutrons (the upper limit of the energy was 130 keV) arising under the action of radium rays on beryllium. From the effect due to neutrons arising in fission it was easy to separate out the effect produced by the slower neutrons from the source.

Zinn and Szilard established that for each fission event produced by a thermal neutron 2.3 neutrons are emitted with an energy between 1 and 3 MeV. The method used in the investigation did not provide any information on the period of time that separates the emission of neutrons from the instant of fission of the nucleus, but a number of other experiments have indicated with certainty that the principal number of neutrons observed by Zinn and Szilard cannot be related to processes of delayed emission accompanying the β-decay of the fragments.

It has now become known that delayed emission of neutrons occurs not only for the β-decay with a half period of 12.5 s. Booth, Dunning, and Slack[14] found delayed emission with a period of 45 s, and Brostrom, Koch, and Lauritsen[15] with a period of 0.1–0.3 and 3 s. However, on the average the number of such neutrons accompanying β-decay of fragments does not exceed a few percent of the number of fissions. This was shown particularly clearly by Gibbs and Thomson,[16] who worked with a pulsed flux of (d,d)-neutrons and who had established that the majority of neutrons emerges earlier than 0.001 s after the fission event.

Zinn and Szilard tend to think that the neutrons that they have observed emerge from the fragments very soon after their formation and that the spread in their spectrum is related to this fact. Under this assumption the energy of a neutron with respect to the fragment is equal to ~ 2

MeV. The maximum energy corresponds to the emission of the neutron in the direction of motion of the fragment, and the minimum energy corresponds to the emission of the neutron in the opposite direction.

Up to the present time it is still not possible to regard that it has been experimentally established that neutrons emerge from the excited fragments and not at the instant of fission itself. This question could be resolved by setting up special experiments.

The data of Zinn and Szilard refer to the case of fission of uranium by thermal neutrons, i.e., to fission of U^{235}. We have no realizable data on the number of neutrons accompanying fission of other nuclei.

We turn to a discussion of the question of a nuclear chain reaction. After it became clear that each fission event is accompanied by the emission of at least two neutrons it became possible to think of initiating a chain reaction. It could be realized in the case if other neutrons accompanying fission at least one would in turn produce fission. It is therefore necessary that $\nu(1-\gamma)>1$ if γ is the probability of such processes of interaction of neutrons with a nucleus as a result of which the neutrons lose their ability to produce fission.

At the 1939 Conference on the Atomic Nucleus questions of realizing a chain reaction using pure uranium and a mixture of uranium with water were discussed in detail.

Let us first discuss the second system. It is known that the variation of the cross section for uranium fission as a function of neutron energy has two regions of large values shown in the figure by the lines AB and CD. The variation of the cross section for neutron absorption which does not lead to fission is shown for the given system by the line EF which varies according to the same law as AB, and the line KM. The segment EF is to some extent due to the absorption of slow neutrons by hydrogen, while the segment KM is due to the absorption only by uranium, which leads to the formation of a transuranic radioactive isotope but does not lead to fission.

Neutrons accompanying fission have, as we have seen, an energy of several MeV. In slowing down to thermal velocities they pass through the dangerous region KM and a fraction of them are absorbed here. If ν neutrons arise in fission, then only νp neutrons will attain thermal velocities, where p is the probability of their passing through the region KM. Thus, the phenomenon of fission will give rise to $\nu p\varkappa$ neutrons; $\varkappa$, which is equal to $AL/(AL+EL)$ gives the ratio of the fission cross section to all the cross sections for the absorption of thermal neutrons. In order that a chain reaction would be possible it is necessary that $\nu p\varkappa > 1$.

It is not difficult to see that the most favourable conditions for achieving a chain reaction will occur for a quite definite ratio between the number of atoms of hydrogen and of uranium in the mixture.

For very large concentrations of hydrogen the coefficient p will be large, since neutrons will be more intensely slowed down in the mixture, but then the coefficient $\varkappa$ will be small since the probability of absorption of thermal neutrons by hydrogen will increase. On the other hand very high concentrations of uranium although leading to bigger values of $\varkappa$ will make the coefficient p small. At the 1939 Conference a very thoroughly carried out investigation by Zel'dovich and Khariton [2] was reported devoted to the analysis of this problem. The authors concluded that even in the case of the most favorable ratio of the components of the mixture (4 atoms of hydrogen for 1 atom of uranium) the product $\nu p\varkappa$ is equal to 0.82, i.e., a chain reaction in a uranium–water mixture is impossible.

Already last year Bohr pointed out, using simple theoretical considerations, that the section AB in the cross section curves is related to the rare isotope U^{235}, while the sectors EF, CD, and KM refer to the abundant isotope U^{238}. Thus, the possibility presented itself, as noted by Zel'dovich and Khariton, to realize the chain reaction in the water–uranium system by enriching uranium with the U^{235} isotope. It would be possible without changing the coefficient p to increase $\varkappa$ and to bring the product $\nu p\varkappa$ to a value greater than unity.

Although Bohr's considerations appears convincing, it was only the year 1940 when experiments were conducted using separated isotopes that brought final confidence in the correctness of the assumption on the distribution of separate portions of the $ABKMCD$ curve between different isotopes and at the same time also the solution in principle of the problem of utilizing the energy stored inside the nucleus in the process of a chain decay of uranium.

The practical solution of the problem by this route naturally represents great difficulties in view of the fact that it is associated with changing by a factor of two the content of the light isotope in large masses of uranium.

Before going over to a discussion of chain processes in other systems it is also necessary to make one remark concerning the conclusion of Zel'dovich and Khariton on reactions in a system of unenriched uranium–water. In view of the fact that the exact variation and the position of the resonance absorption band KM has not yet been established (Anderson[17] gave in this year, for example, for the resonance energy the value 5 eV instead of the 25 eV which were previously adopted from the work of Hahn and Strasman) Zel'dovich and Khariton in determining the coefficient p for different concentrations of components of the mixture employed the following method.

According to their calculations the coefficient is equal to

$$p=\exp\left(-\alpha\sqrt{\frac{C_U}{C_H}}\right),$$

where C_U and C_H are the concentrations of uranium and hydrogen in the mixture, and α is a constant. It was determined by Zel'dovich and Khariton from experiments by Halban, Kowarski, and Savitch in which for a number of pairs of values of C_U, C_H the value of p was measured. Knowing the value of α it is obviously possible using the preceding formula to calculate p for mixtures of different composition with the result of the calculations being independent of the shape and position of the resonance level KM.

It is possible to attempt to realize the chain reaction for the fission of the U^{235} isotope using for slowing down not protons, but also other light nuclei. In view of the fact that the relative concentration of the moderating nuclei in the mixture must be large in order to ensure small absorption of neutrons in the dangerous zone, only very small values of the absorption and thermal neutrons by such nuclei, of the order of 10^{-27}–10^{-25} cm^2 are allowable. The majority of light elements absorb neutrons weakly, but the exact values of the cross sections have been determined unreliably (due to the difficulty of measuring such small interactions of neutrons with matter) and even last year it was not possible for any of the moderating nuclei with the exception of the proton to make a reliable analysis of the conditions of the development of a chain reaction.

In May of this year there was published a report by Burst and Harkins[18] who had measured the cross section for neutron capture by deuterons on the basis of the number of decays of the nuclei of the isotope of hydrogen of mass 3 formed as the result of such absorption. This absorption cross section turned out to be equal to $3 \cdot 10^{-28}$–10^{-28} cm^2, i.e., significantly lower than that critical value ($3 \cdot 10^{-27} cm^2$) which would be sufficient for the development of chains. The realization of a chain disintegration of U^{235} in an unenriched uranium-heavy hydrogen system is therefore possible.

In this system one can avoid the separation of uranium isotopes but instead of that there arises the necessity of separation of hydrogen isotopes in large quantities, sot hat the realization of the experiment also in this case is associated with great practical difficulties. The calculations carried out by Zel'dovich and Khariton show that the amount of heavy water needed for the realization of a chain reaction is equal approximately to 15 tons. In such a case the reaction could be realized with this quantity only if the cross section for the absorption of thermal neutrons by oxygen does not exceed 10^{-27} cm^2. If it is greater than that the reaction could be carried out only using chemically pure hydrogen; the required amount of gas depends strongly on its pressure and could be obtained from 15 tons of heavy water only if the hydrogen could be compressed to pressures of several thousand atmospheres.[2)]

The question of the suitability of He^4, C^{12}, and O^{16} as moderating nuclei still has not been completely clarified, but the requirements on the cross section for neutron capture by these nuclei which should be respectively lower than $3 \cdot 10^{-27}$, $1.5 \cdot 10^{-27}$, and $1{,}2 \cdot 10^{-27}$ cm^2 make the possibility of using them for realizing a nuclear chain reaction highly improbable.

We now examine the conditions for the development of chains in a mass of the pure element undergoing fission under the action of fast neutrons. We will have to assume in view of the absence of experimental data that both the number and the energy of the secondary neutrons will be same as in the case of fission of U^{235}.

The main reason for breaking the chain here is not the absorption of neutrons in secondary processes which is small at the high velocities of these particles, but the loss by them of energy through inelastic scattering.

TABLE II.

Element	Uranium	Protoactinium	Ionium	Thorium
Fission cross section cm^2	$5 \cdot 10^{-25}$	$3 \cdot 10^{-24}$	$3 \cdot 10^{-25}$	$1 \cdot 10^{-25}$
Cross section for inelastic scattering, cm^2	$1.1 \cdot 10^{-24}$	0	$1.3 \cdot 10^{-24}$	$1.5 \cdot 10^{-24}$
γ	0.69	0	0.81	0.94
$\nu(1-\gamma)$	0.71	2.3	0.44	0.14

The value of the cross sections for inelastic scattering of neutrons are now known to us better than last year due to the work of Nikitinskaya and Flerov. They have shown for a number of elements that the cross sections for such processes of inelastic scattering of neutrons from a (Rn +Be)-source after which these neutrons can no longer produce fission of uranium and thorium are expressed by the formula

$$\sigma = \pi\ (1.3 \cdot A^{1/3} \cdot 10^{-13})^2,$$

where A is the mass number of the nucleus. We have to assume that practically each fast neutron colliding with the nucleus experiences inelastic scattering with a large loss of energy.

From this it follows that the cross section for inelastic scattering for elements in which fission occurs (direct measurements could not be made in this case) will complement the fission cross section up to the geometrical cross section of the nucleus. Since the fission cross sections of uranium, protoactinium, ionium and thorium are now known for neutrons from a (Rn+Be)-source one can easily obtain the inelastic scattering cross sections for the same neutrons for the nuclei listed above. They are shown in Table II. In the third line of the table is given the coefficient γ, and in the fourth the quantity $\nu(1-\gamma)$, which characterizes the possibility of initiating a chain reaction. We see that only for protoactinium is $\nu(1-\gamma)$ greater than unity and, consequently, only in this case is it possible to realize a chain reaction for fast neutrons.

These conclusions apparently are quite realistic. The fact that the cross sections for the neutron spectrum accompanying fission cannot, as I think, have a particularly essential significance since the ratio of the cross sections for fission and inelastic scattering as has been established experimentally, at least for uranium, do not depend strongly on the neutron energy in regions not too close to the fission boundary. Also one could hardly think that the number of neutrons accompanying fission will be very strongly different for different nuclei.

In conclusion I would like to emphasize once again that although in principle the question of realizing a nuclear chain reaction has been solved in the positive sense, there are tremendous difficulties in the path of its practical realization in the systems that have been investigated up to the present. This is clearly seen from Table III in the second column of which are shown the minimum quantities of materials required for a chain reaction, in the third column

TABLE III.

System	Minimum quantity of materials required for the reaction, in tonnes	Available amounts in laboratories, in tonnes	Ratio of the required amount to the available amount
Enriched uranium and hydrogen H^1	Uranium with the rare isotope enriched by a factor of 2, 0.5	$2 \cdot 10^{-12}$	$2.5 \cdot 10^{11}$
Ordinary uranium and H^2	Heavy water 15	0.5	30
Pa	Protoactinium ~0.02	$1 \cdot 10^{-6}$	$2 \cdot 10^{4}$

their total amount available in all the laboratories of the world, and in the fourth column the ratios of the two quantities.

Perhaps the next few years will bring us other ways of solving the problem, but if this will not happen then only new, very effective methods of separating isotopes of uranium or hydrogen will guarantee the realization of a nuclear chain reaction.

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[1)]See Usp. Fiz. Nauk **25**(2), 241 (1941). Report at the Conference on the Atomic Nucleus in Moscow in 1940

[2)]It is now becoming clear that the development of a chain in a mixture of unenriched uranium—heavy hydrogen is impossible. The most recent measurements of Hill and Goldhaber have shown that the decay half life of H^3 is equal not to 150 days, as had been accepted according to the data of Alvarez, Burst and Harkins, but to 30 years. As a result of this for the cross section for the capture of slow neutrons by a deuteron one obtains the value of $2 \cdot 10^{-26}$ cm^2, i.e., greater than the critical value ($3 \cdot 10^{-27}$ cm^2).

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Translated by G. M. Volkoff