TABLE I. *Number of counts per minute of heavily ionizing particles from the bombardment of uranium and thorium with deuteron-deuteron neutrons for deuteron currents of 0.5 and 1.0 ma at 250 kv.*

	No paraffin		Paraffin	
	$i=1.0$ MA	0.5 MA	$i=1.0$ MA	0.5 MA
U	35	—	69	38
Th	21	11	20	—

around the chamber. Also background counts were made with no uranium or thorium and ran consistently zero over five-minute periods.

Results are given in Table I. The numbers represent counts per minute and are the means of five to ten observations for each case. The paraffin effects in the table were obtained with paraffin around chamber but not between chamber and neutron source. Placing paraffin between source and chamber reduced the counts for uranium to 34 per minute.

The ionization due to nitrogen and oxygen ions produced by neutrons was approximately the same as that due to the natural uranium alpha-particles. Our linear amplifier did not possess a calibrated gain variable over sufficiently wide limits to enable us to determine accurately the ionization produced by the heavy particles. However, on removing one stage of amplification, we were still able to observe the kicks due to heavy particles, and therefore we believe the ionization due to the heavy particles is at least one hundred times that produced by the alphas or recoil ions.

Thus the effect is obtained with 2.4-Mev neutrons for both thorium and uranium. Paraffin doubles the yield for uranium but has no effect on that for thorium. The reality of the effect is confirmed by its proportionality to the intensity of the deuteron beam.

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[1] Hahn and Strassmann, Naturwiss. January, 1939.
[2] Frisch and Meitner, Private Communication from Dr. M. A. Tuve. We are informed by Dr. Tuve that Frisch and Meitner have also observed this effect with thorium on or about January 16, 1939.

Cleavage of the Uranium Nucleus

We have been studying what seemed to be L x-rays from the seventy-two-hour "transuranic" element. These have now been shown by critical absorption measurements to be iodine K x-rays. The seventy-two-hour period is definitely due to tellurium as shown by chemical test, and its daughter substance of two-and-a-half-hour half-life is separated quantitatively as iodine. This seems to be an unambiguous and independent proof of Hahn's hypothesis of the cleavage of the uranium nucleus.

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Resonance in Uranium and Thorium Disintegrations and the Phenomenon of Nuclear Fission

The study of the nuclear transmutations by neutron bombardment in uranium and thorium, initiated by Fermi and his collaborators, and followed up by Meitner, Hahn and Strassmann, and by Curie and Savitch, has brought to light a number of most interesting phenomena. Above all, as pointed out by Meitner and Frisch,[1] the recent discovery of Hahn and Strassmann of the appearance of a radioactive barium isotope as the product of such transmutations offers evidence of a new type of nuclear reaction in which the nucleus divides into two nuclei of smaller charges and masses with release of an energy of more than a hundred million electron volts. The direct proof of the occurrence of this so-called nuclear fission was given by Frisch[2] for thorium as well as for uranium by the observation of the very intense ionization produced in a gas by the high speed nuclear fragments.

In a recent note[3] commenting on the ingenious suggestions put forward for the explanation of the fission phenomenon by Meitner and Frisch, the writer has stressed that the course of the new type of reactions, just as that of ordinary nuclear reactions, may be assumed to take place in two well-separated stages. The first of these is the formation of a compound nucleus, in which the energy is stored in a way resembling that of the heat motion of a liquid or solid body; the second consists either in the release of this energy in the form of radiation or in its conversion into a form suited to produce the disintegration of the compound nucleus. In the case of ordinary reactions, resulting in the emission of a proton, neutron or α-particle from this nucleus, we have to do with a concentration of a considerable part of the excitation energy on some particle at the nuclear surface, sufficient for its escape, which resembles the evaporation of a molecule from a liquid drop. In the case of the fission phenomena, the energy has to be largely converted into some special type of motion of the whole nucleus causing a deformation of the nuclear surface sufficiently large to lead to a rupture of the nucleus comparable to the division of a liquid drop into two droplets. From considerations of statistical mechanics analogous to those applied to the evaporation-like nuclear disintegrations, it follows indeed that the probability of occurrence of fission becomes comparable to that of ordinary nuclear reactions when, with increasing nuclear charge, the deformation energy concerned has decreased to values of the same order of magnitude as that demanded for the escape of a single particle.

Here I should like to show how such considerations would seem to offer a simple interpretation of the peculiar variation with neutron velocity of the cross sections of the different transmutation processes of uranium and thorium observed by Meitner, Hahn and Strassmann.[4] In the light of the new discoveries, the great variety of processes obtained, which could not be disentangled on the ordinary ideas of nuclear disintegrations, would seem, according to Meitner and Frisch, to be reduced to only two types of transmutations. Of these the one consists in an ordinary radiative capture of the incident neutron, resulting in the formation of the normal state of the compound nucleus, which is subsequently transmuted by β-ray emission into a stable nucleus. The other consists in the fission of the excited compound nucleus, which may take place in a large number of different ways, in which a wide range of mass and charge numbers of the fragments may occur. This last point, which makes it impossible without a closer study of the statistical distribution of the fragments to trace a product of given chemical properties and radioactive period back to its origin from some particular isotope of the original element, is, as we shall see, of especial importance for the understanding of certain striking peculiarities in the case of uranium.

For the capture processes, which lead to the radioactive uranium and thorium isotopes of periods 24 and 33 minutes, respectively, Meitner, Hahn and Strassmann found evidence of resonance phenomena for neutrons of comparatively small velocities. In uranium, where the phenomenon was more completely investigated, they found for neutron energies of about 25 volts a capture cross section at least 30 times larger than that for thermal neutrons. Since in this resonance region the cross section amounts to about 10^{-21} cm^2, it is, as they pointed out, obviously necessary from simple arguments of dispersion theory to ascribe the phenomenon to the abundant uranium isotope of mass number 238. From the fact that neither for uranium nor thorium is the resonance capture accompanied by any large increase of the cross section for the fission processes, we may further conclude that the probability of radiation by the compound nucleus in the excited states concerned is considerably larger than the fission probability, and that the normal states of these nuclei, apart from their β-ray radioactivity, are essentially stable.

As regards all other transmutation processes, which are now to be ascribed to fission, marked differences between uranium and thorium were found in the investigations of Meitner, Hahn and Strassmann as well as in the direct experiments of Frisch. With fast neutrons, fission cross sections of the same order of magnitude were found for uranium and thorium, but with neutrons of thermal velocities a large increase of the fission cross section was observed for uranium and not for thorium. The results for fast neutrons are simply explained on the basis of the general picture of nuclear processes outlined above, according to which we should expect the fission probability to increase much more rapidly with excitation than the radiation probability, and to become considerably larger than the latter for the high excitations of the compound nucleus concerned. The peculiar effect in uranium for slow neutrons could obviously, however, not be reconciled with the above considerations if it were to be attributed to the formation of the compound nucleus of mass number 239; but since, as already indicated, the periods of the most frequent radioactive fragments should be independent of the isotope undergoing fission, we have the possibility of attributing the effect concerned to a fission of the excited nucleus of mass 236 formed by the impact of the neutrons on the rare isotope of mass 235.

From the fact that the binding energy of a neutron in a nucleus of even charge number should be appreciably larger if the mass number is even than if it is odd, we should actually expect for a given neutron velocity a higher excitation energy for the compound nucleus 236 than for 239, and accordingly a much denser distribution of resonance levels and a much larger probability of fission in the former than in the latter case. Even for excitations produced by impacts of slow neutrons, we may therefore expect that the probability of fission of the nucleus 236 will be larger than that of radiative capture; and due to the corresponding broadening of the levels, the level distribution of 236 in this region might even be continuous. In any case, provided the fission probability is high enough, we shall expect for small neutron energies cross sections inversely proportional to the velocity, allowing us to account both for the observed yields of the process concerned for thermal neutrons and for the absence of any appreciable effect for neutrons of somewhat higher velocities. For fast neutrons the cross sections can, of course, never exceed nuclear dimensions, and because of the scarcity of the isotope concerned the fission yields will be much smaller than those obtained from neutron impacts on the abundant isotope.

It would thus seem that all the known experimental facts receive a simple explanation without any assumption of peculiarities of special levels. Such assumptions as have hitherto been thought necessary to account for these phenomena would in fact seem difficult to reconcile with general ideas of nuclear excitation. In a forthcoming paper in collaboration with Professor John A. Wheeler, a closer discussion will be given of the fission mechanism and of the stability of heavy nuclei in their normal and excited states.

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February 7, 1939.

[1] L. Meitner and R. Frisch, Nature (in press) where references to the previous literature are given.
[2] R. Frisch, Nature (in press). The manuscript of this note as well as that of Professor Meitner and Dr. Frisch have kindly been communicated to me by the authors. As I have learned from other friendly communications, further most interesting evidence regarding the fission phenomenon has in the meantime been obtained in several laboratories in America and Europe.
[3] N. Bohr, Nature (in press).
[4] L. Meitner, O. Hahn and F. Strassmann, Zeits. f. Physik **106**, 249 (1937); **109**, 538 (1938).