March 13th, 1939

Instantaneous emission of fast neutrons in the interaction of slow neutrons with uranium.

Recently it became known[1.)] that uranium can be split by neutrons into two elements of about equal atomic weight with an energy release of about 200 million electron volts. ~~Through this new discovery~~ ~~In view of~~ It ~~is necessary~~ now ~~It appears of interest to investigate~~ ~~necessary to~~ ~~the question~~ appears necessary to find out whether or not it is possible to make use of this new phenomenon for the ~~large scale~~ liberation of nuclear energy and the production of ~~large quantities of~~ radioactive elements ~~on an industrial scale~~. This ~~question~~ ~~question~~ is closely connected with the question whether or not neutrons are emitted in the fission of uranium. ~~If on the average less than one neutron is emitted per fission no practical~~ ~~industrial~~ ~~applications need to be feared in the immediate future.~~ ~~and~~ [illegible] If more than one neutron is emitted per fission ~~the~~ ~~there is~~ possibility of ~~a~~ nuclear chain reaction ~~arises~~ has to be. In such a chain reaction a neutron ~~produces~~ would produce by its interaction with uranium additional neutrons which ~~on~~ in their turn, may escape or again interact with uranium, and produce additional neutrons, which again etc. ~~and so on.~~ ~~until if the condition is stationary~~ ~~It would then be possible to set up an apparatus,~~ Thus the number of neutron ~~output of which would be~~ ~~made~~ ~~much larger than the neutron input~~ diffusing out of ~~uranium~~ a body of U ~~control~~, and ~~the neutron output~~ would be limited only by the necessity of keeping the temperature rise caused by the reaction within bounds.

In the fission of uranium two elements are produced which obviously have a large neutron excess; moreover they are probably produced in an excited nuclear state. One might therefore ~~It seems therefore reasonable to sus-~~

1.) Hahn and Strassmann Naturwiss. 27. 11. 1939
Meitner and Frisch Nature

cape or produce additional neutrons etc.

expect ~~suspect~~ ~~pect~~ that these excited fragments will instantaneously emit neutrons, and that the number of instantaneously emitted neutrons might be of the order of magnitude of one neutron per fission. There may also be a delayed emission of neutrons if - as was ~~first~~ pointed out by Fermi - some of the fragments resulting from the fission while going through a series of beta-transformations land in a state sufficiently highly excited to emit a neutron.

A delayed emission of neutrons in the interaction of both slow and fast neutrons with uranium having a period of about 12 sec. has been reported by Roberts, Meyer and Wang 2) - but it is not ~~known whether in through which process~~ yet established to what type of process they have to be ascribed fission process ~~and might perhaps be explained along these lines~~. However, ~~it should be surprising if~~ a delayed emission of neutrons ~~arising out of~~ from such a process ~~should prove to yield anything approaching~~ can hardly be expected to yield one neutron per fission.

In order to see if there is an instantaneous emission of neutrons from the fission of uranium we have performed the following experiment. We ~~have~~ exposed uranium oxide to a beryllium block from which neutrons which have been slowed down by paraffin wax, using photo neutrons were liberated ~~from beryllium~~ by the gama-rays of radium ~~as our source of neutrons~~. A helium-filled ionization chamber connected to a linear amplifier served as a detector for the neutrons. ~~which we suspected might~~ expected to be ~~emitted from uranium~~. The discharge pulses of the ionization chamber due to the helium recoils ~~was~~ were both visually observed by means of the cathode-ray oscillograph and were recorded by the usual counting arrangement. Such an arrangement ~~which~~ makes it possible to discriminate between high energy and low energy recoils by varying the bias of a thyratron or the gain

2) R., M, and W. Phys Rev 55, 510 - 1939

avoid counts due to
of the amplifier. ~~avoid being disturbed~~

the
By setting our bias so as to ~~be well above the level set~~ by
the action of the radium gama-rays on the ion chamber we obtained
about 25 helium recoils per minute from the photo neutrons of beryl-
II'   & this observation
lium. In ~~experiments in which~~ the ion chamber was shielded by a lead
tube ~~having a ½ 6 mm~~ ~~wall~~
~~cylinder~~ ~~mm~~ ~~thick~~ from scattered gama-rays of ~~Ra~~ Ra. When this
tube   the   spherical box containing 2300 gm
lead ~~cylinder~~ was replaced by a cylinder of uranium oxide (~~2300 gm~~
of ~~the~~ U_3O_8)
~~thick~~ we obtained about 70 helium recoils per minute, i.e. about
40 to 50 additional helium recoils. We attribute these additional
recoils to fast neutrons emitted from uranium in the interaction
slow
with ~~slow~~ neutrons. ~~slowed down by paraffin wax. Preliminary experiments~~
~~which are being carried out in collaboration with H. L. Anderson~~
~~show that the cross section for the fission of uranium is for our~~
~~photo neutrons is so small that their effect can be neglected in~~
~~our experiment.~~

By counting only very high energy helium recoils we obtain about 80 recoils in 10 minutes from uranium as against 4 helium recoils in 10 minutes without uranium.

III'
In order to estimate the number of fast neutrons emitted per
fission under the conditions of our experiment we replaced the helium
having
ionization chamber by an ionization chamber ~~coated with a thick~~
~~layer of uranium oxide. Using circular plates of uranium oxide of~~
~~4~~ 25 cm^2 ~~[illegible]~~ coated with a thick layer of
~~4 cm dm We obtained~~ about 45 fissions per minute. Assum-
U_3O_8 This chamber gave ~~with this chamber~~
ing the range of the fragments to be about ~~0.013 gm~~ 0.005 gm per cm^2 ~~of in~~
thin a layer of the   the observed 45 fissions take place in   Accordingly
uranium oxide ~~we calculate that 56~~ fissions per minute ~~take place~~
coating weighing 0.13 gm.
in the 2300 gm of uranium oxide used in our experiment. By taking

800,000 fissions must take place
min

into account the solid angle, the size of the helium chamber and the pressure used, and assuming a cross section of 3.5 for an elastic collision in helium of the neutrons emitted from uranium ~~in helium~~, we find the number of neutrons emitted per fission to be about two ~~one~~,

4. ~~and probably larger than one~~. An accurate estimate of this number ~~is now being attempted.~~ It seems, however, to be considerably larger ~~At any rate~~ this number of the order of magnitude of one

While from our observations we can only say that the time delay involved in this "instantaneous" neutron emission appears to be less than one second, we should expect, if our interpretation is correct, this emission to be practically instantaneous.

In our experiment we also looked for a delayed emission of neutrons, ~~and we did this~~ in the following way: We repeatedly irradiated for a length of ~~some~~ time, then quickly removed the radium and watched ~~observed~~

5 for 15 seconds each time the cathode-ray oscillograph for an ~~any sign~~ indication of a helium recoil. After the radium has been removed there is no gama-ray background to set a lower limit for the observable helium recoil energy; the only remaining slight background is ~~being~~ due to the electrical fluctuations of the amplifier. In 50 experiments, corresponding to a total observation time of more than 12 minutes, we observed only two kicks which may or may not have been due to a delayed neutron emission. We conclude that, if a delayed emission of fast neutrons is caused by slow neutrons in their interaction with uranium, the number of neutrons emitted must be very much smaller than the number which we have observed to be "instantaneously" emitted.

6 While ~~it now~~ appears quite likely that the number of instantaneously emitted neutrons ~~is~~ larger than one per fission, this fact in itself

~~would not necessarily mean that a chain reaction can be maintained in uranium~~ with ~~the~~ neutrons slowed down ~~by~~ by hydrogen~~. Neutrons may be captured by uranium itself, leading for instance to the formation of Uranium 238 and not to fission, and such a capture may or may not be sufficient to prevent a chain reaction. If fission caused by slow neutrons in uranium is due to uranium 235 - and Bohr put forward strong arguments in favor of this view - while non-fission capture is due to uranium 238, an increase in the relative abundance of uranium 235 might be envisaged in order to decrease the non-fission capture.~~

containing only [illegible].

is only a necessary but not a
sufficient condition for the
possibility of maintaining a
chain reaction ~~in a [illegible]~~
~~of the [illegible]~~ with ~~the~~ "neutrons
which are slowed down". It may
for instance
be that it will be necessary to concen-
trate . . .

Publi

privat des

Instantaneous Emission of Fast Neutrons in the Interaction of Slow Neutrons with Uranium.

Recently it became known[1) that uranium can be split by neutrons into two elements of about equal atomic weight. In this fission of uranium the two elements produced have a large neutron excess; moreover they are probably produced in an excited nuclear state. One might therefore expect that these excited fragments instantaneously emit neutrons and that perhaps the number emitted is even larger than one per fission.

One might also expect a delayed emission of neutrons ~~it~~ - as was first pointed out by Fermi - if ~~s~~ome of the fragments go through one or more beta-transformations before they emit a neutron. Delayed emission of neutrons caused by the action of both slow and fast neutrons on uranium has recently been reported by Roberts, Meyer and Wang[2), who find a period of about 12 seconds.

In order to see if there is an instantaneous emission of neutrons from the fission of uranium we have performed the following experiment. We exposed uranium oxide to neutrons which were slowed down by paraffin wax, using as a source of neutrons a block of beryllium from which photo neutrons were liberated by the gamma-rays of radium. A helium-filled ionization chamber connected to a linear amplifier served as a detector for fast neutrons. The ionization

---

1) O.Hahn and F.Strassmann, Naturwiss. 27.11.1939
L.Meitner and R.Frisch, Nature, February 1939

2) R.B.Roberts, R.C.Meyer and P.Wang, Phys.Rev. 55, 510 - 1939

pulses of the chamber were observed visually by means of a cathode-ray oscillograph and were recorded by the usual counting arrangement. ~~Such an arrangement makes it possible to discriminate in counting the pulses between high and low energy helium recoils by varying the bias of a thyratron or the gain of the amplifier.~~

Figure 1 shows a diagram of the experimental arrangement. The ionization chamber is covered by a cadmium sheet cap G which prevents the thermal neutrons from penetrating to the helium ionization chamber. A cadmium shield H, 0.5 mm thick, is used to cover the cylindrical box E which contains 2300 gm of uranium oxide. The uranium oxide is screened from the thermal neutrons by this shield and can be exposed to them simply by removing the shield.

We observed about 50 pulses perminute from the helium chamber when we exposed the uranium oxide to the thermal neutrons in the absence of the cadmium shield H, but obtained only 5 pulses per minute when the uranium was screened from the thermal neutrons by the cadmium shield. The difference of about 45 pulses per minute we have to attribute to fast neutrons emitted from uranium under the action of thermal neutrons. It is reasonable to assume that this emission of fast neutrons is connected with the fission of uranium.

Control experiments were carried out in which uranium was replaced by lead. ~~All combinations, both with uranium or lead, in~~ The effect of the presence and absence of the cadmium shield H and the cadmium cap G ~~were~~ was tested.

In order to estimate the number of fast neutrons emitted per fission under the action of thermal neutrons we used an ionization chamber lined with a thick layer of uranium oxide having an area of 25 cm^2. This uranium chamber was put in place of the helium chamber without otherwise materially changing the experimental arrangement. Under these conditions the uranium chamber gave about 45 fissions per minute. Assuming the range of the fission fragments to be about 0.005 gm per cm^2 in uranium oxide we find that the observed 45 fissions per minute should occur in a surface layer, weighing 0.13 gm, of the thick uranium oxide lining. Accordingly, about 800,000 fissions per minute ~~must~~ should occur in the 2300 gm of uranium oxide which was used in our experiment. By taking into account the solid angle, the size of the helium chamber and the pressure used, and by assuming that the "fission neutrons" have an average collision cross section in helium of 3.5 10^{-24} cm^2 ~~in helium~~ we find the number of neutrons emitted per fission to be about two.

This number is of course only a rough estimate, the main cause of uncertainty being the considerable variation of the cross section of helium with the neutron energy in the region around one million volts[3]. A hydrogen-filled ionization chamber is now being used in order to obtain a more accurate estimate. It seems to be established however that the order of magnitude is one neutron per fission.

Anderson, Fermi and Hanstein have independently, and by a different method, carried out experiments on the neutron emission connected with the fission of uranium. Our observations are consistent with their results, and we wish to thank ~~data to us before publication.~~ them for communicating their results to us before publication.

---

[3] Staub and Stephens, Phys.Rev. 55, 131, 1939

While from our observations we can only say that the time delay involved in this "instantaneous" neutron emission appears to be less than one second, we should expect, for theoretical reasons, this emission to take place within less than 10^{-14} seconds.

We have also looked for a delayed emission of fast neutrons by performing the following experiment. The uranium oxide was irradiated for some lngth of time in the arrangement shown in Figure 1. Then the radium was quickly removed from the beryllium block and the cathode-ray oscillograph screen was watched for a period of 15 seconds for an indication of a delayed emission of fast neutrons. After the radium is removed there is no gamma-ray background to set a lower limit for the observable helium recoil energy; the only slight background remaining is due to electrical fluctuations of the amplifier. In 50 experiments, corresponding to a total observation time of more than 12 minutes, we observed only two pulses which may or may not have been due to a delayed emission of fast neutrons. This is to be compared with the emission of 45 fast neutrons per minute, the number observed while the radium is inside the beryllium block. We conclude that, if slow neutrons falling on uranium cause a delayed emission of neutrons which are sufficiently fast for us to observe, their number must be very much smaller than the number of neutrons which we have observed in the instantaneous emission.

We are indebted to Dr. S. Seely for his assistance in carrying out some of these experiments. We wish to thank the Department of Physics

of Columbia University for the hospitality and the facilities extended to us, and also wish to thank the Association for Scientific Collaboration for enabling us to use one gram of radium in these experiments.-

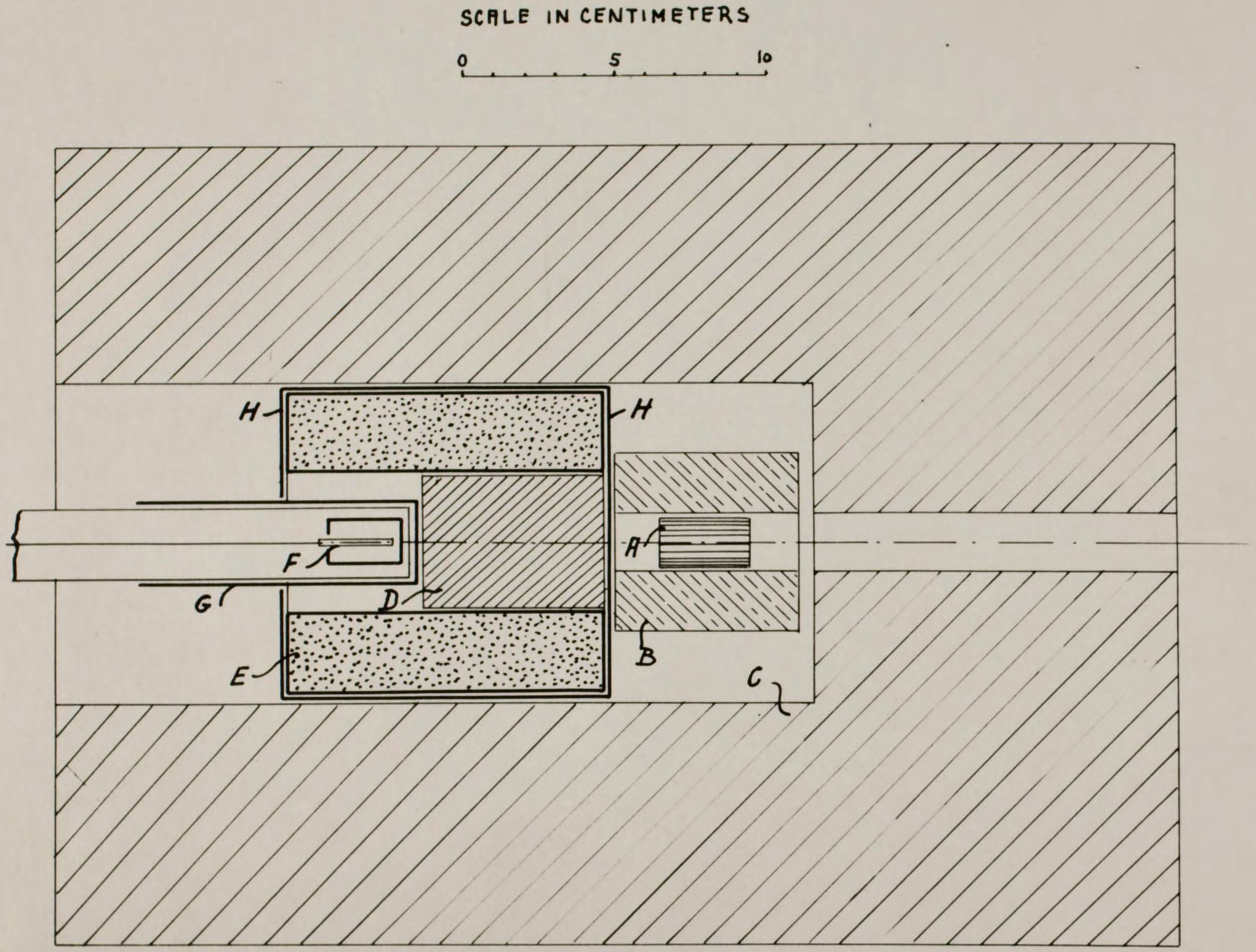
Leo Szilard

Walter H. Zinn

Pupin Physics Laboratories
Columbia University
New York, New York
March 16th, 1939

Figure 1. Arrangement for the observation of the emission of fast neutrons from uranium.

A, Radium. B, Beryllium block, C, Paraffin wax. D, Lead block. E, Box filled with uranium oxide. F, Ionization chamber. G, Cadmium sheet cap. H, Cadmium sheet shield.


SCALE IN CENTIMETERS
0
5
10
H
H
A
F
G
D
B
E
C

publi
prior