Delayed Gamma-Rays from Uranium Activated by Neutrons

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A cloud chamber in a magnetic field was operated in conjunction with a source of neutrons in such a way as to observe gamma-rays emitted during the bombardment of uranium by neutrons and the number emitted about $\frac{1}{2}$ second after bombardment in alternate expansions of the chamber. Although the energy distribution of the gamma-rays seems to be about the same in the two expansions, the total number of gamma-rays emitted during bombardment is considerably greater than those emitted $\frac{1}{2}$ second after bombardment. This means that more gamma-rays are obtained which are coincident (or nearly so) with fission than gamma-rays associated with a period of as much as several seconds.

IN continuing the work previously reported[1] on gamma-rays from the uranium-neutron reaction a comparison has been made between gamma-rays emitted during bombardment and those emitted about $\frac{1}{2}$ second after bombardment. Delayed gamma-rays from the uranium-neutron reaction have been reported by Roberts, Meyer and Wang.[2]

APPARATUS

The neutrons used in these experiments are produced in the deuteron-deuteron reaction by the bombardment of a heavy-ice target with deuterons of about 350 kilovolts energy giving neutrons of 2.5 Mev. The high potential source is an unrectified transformer set capable of producing something over 500 kilovolts built up by cascading discarded x-ray transformers. At the present time three x-ray transformers are being used: two 115-kv units and one 300-kv unit. The three units are mounted on separate insulating platforms and are inclosed in corona shields. A coil wound for 110 volts was added to each high potential end of the transformers, and the old primary windings were discarded. The new 110-volt primary and tertiary windings make it possible to cascade these transformers in the usual commercial fashion. This scheme provides a moderate voltage at a minimum cost.

The three-section accelerating tube is of the same general design as Crane's[3] with the exception that it is mounted horizontally. Textolite insulating supports carry only the vertical load. Atmospheric pressure on the end of the tube provides a force of about 3000 lb. which holds the tube together.

The voltage is distributed over the three sections by means of leads to appropriate points on the transformers.

The grounded end of the accelerating tube projects through an 8″ brick wall into the control room. A motor driven set of contactors automatically controls the operation of the transformers, ion source, cloud chamber and camera.

Figure 1 shows a more or less typical photograph taken during the bombardment of the uranium, in which appears an electron track whose energy is about 5 Mev. The heavy recoil proton tracks will also be noted. (Air and alcohol were used in the chamber in all this work.)

MEASUREMENTS

Two different experiments have been performed in which delayed gamma-rays from the uranium-neutron reaction have been observed by means of their recoil electrons and photoelectrons in a horizontal cloud chamber placed in a magnetic field. Three arrangements of the heavy-ice target and uranium with reference to the cloud chamber are shown in Fig. 2. (For simplicity the coils of the magnet are not shown.) Fig. 2(A) is the set-up used in the previous work on gamma-rays. In an effort to obtain a large yield of delayed gamma-rays the arrange-

[1] J. C. Mouzon, R. D. Park and J. A. Richards, Jr., Phys. Rev. **55**, 668 (1939).
[2] Roberts, Meyer and Wang, Phys. Rev. **55**, 510 (1939).
[3] H. R. Crane, Phys. Rev. **52**, 11 (1937).

ment in Fig. 2(B) was used. Uranium nitrate in thin rubber envelopes was wrapped around the target tube so as to subtend a very large angle. In view of the fact that cloud-chamber photographs were to be made after the bombardment of the heavy-ice target by deuterons had ceased, no lead was necessary between the target and chamber to absorb soft x-rays.

A test run without the beam on was first made and out of about 240 pictures only one electron track of energy as much as 2.1 Mev was observed, its energy being 2.14 Mev. (Only the horizontal projections of the tracks are measured.) A series of 890 photographs was then made with a one-second delay after a 1–2-second bombardment of the uranium. Only 15 recoil electron tracks with energies greater than 2.1 Mev were found. Seven of these had energies of 3 Mev or more. From these measurements compared to those on gamma-rays emitted during bombardment one might conclude that most gamma-rays are emitted immediately on or a very short time after the absorption of neutrons by the uranium nuclei. However, because of the uncertainty in the relative neutron intensities in these two experiments, this conclusion might be questioned. A further cause of uncertainty is the fact that if the majority of

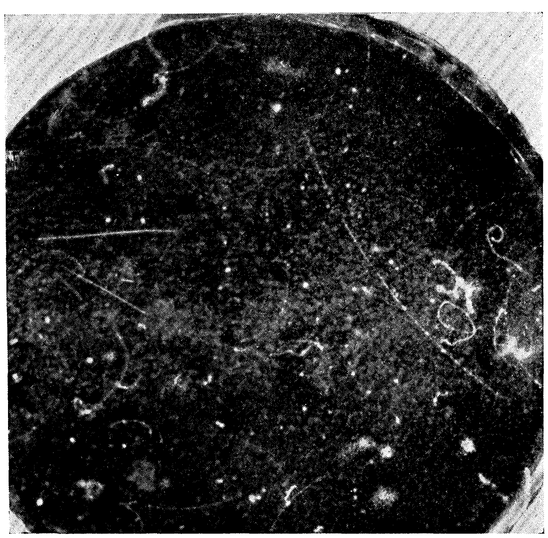


FIG. 1. A typical photograph of a high energy recoil electron track due to a gamma-ray from the uranium-neutron reaction. The energy of this electron is about 5 Mev.

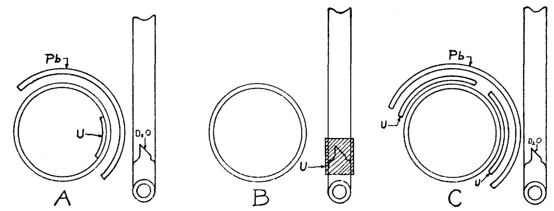


FIG. 2. Relative positions of heavy-ice target, uranium, and cloud chamber in three experiments. Arrangement (A) refers to the previous work on gamma-rays. (B) and (C) refer, respectively, to the first and second experiments on delayed gamma-rays.

the delayed gamma-rays have a half-life of the order of several seconds, then the time of bombardment of 1–2 seconds was not sufficient to activate the uranium fully.

A second experiment designed to make a direct comparison between delayed gamma-rays and the gamma-rays emitted during bombardment was performed. The control apparatus was adjusted so that alternate photographs (and corresponding cloud chamber expansions) could be made during and $\frac{1}{2}$ second after the bombardment of the uranium. The ion beam was on about three seconds at the time the direct photographs were made, and an eleven second bombardment preceded the delayed photographs. The time between photographs was about 30 sec. This alternate method of bombardment made certain that the average neutron intensity was the same during the two bombardments of the uranium. Fig. 2(C) shows the relative positions of the deuterium target, uranium and cloud chamber. The lead around cloud chamber served to absorb the soft x-rays from the tube. About 600 direct and the same number of delayed photographs were taken. The uranium was then removed and a check run made to get an idea of the number of gamma-rays due to radiative capture of the neutrons in lead and the other material present. Integral curves of the results of these measurements are plotted in Fig. 3 showing the energy distribution of the gamma-rays. The curves A and C correspond to the photographs taken while the ion beam was on with and without the uranium present, respectively. Curve B shows the energy distribution of delayed gamma-rays with uranium present, and curve D (based on only two tracks) gives the delayed gamma-ray distributio without

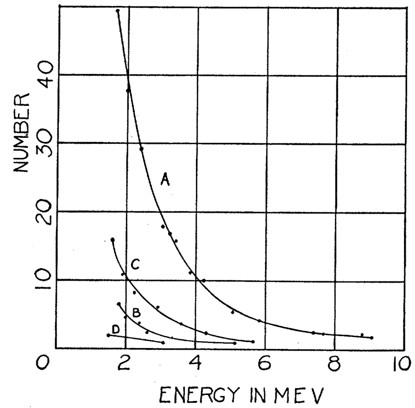


FIG. 3. Energy distributions of gamma-rays *vs.* total number of tracks. (These are integral curves.) A. Cloud chamber expanded during bombardment of uranium. B. Expansion delayed $\frac{1}{2}$ sec. after bombardment of uranium ceased. C. Cloud chamber expanded with ion beam on but with uranium removed giving gamma-rays due to radiative capture of neutrons in the material around the chamber. D. Cloud chamber expansion $\frac{1}{2}$ sec. after the ion beam was shut off with no uranium present. All curves correspond to the same number of photographs and to approximately the same neutron intensity.

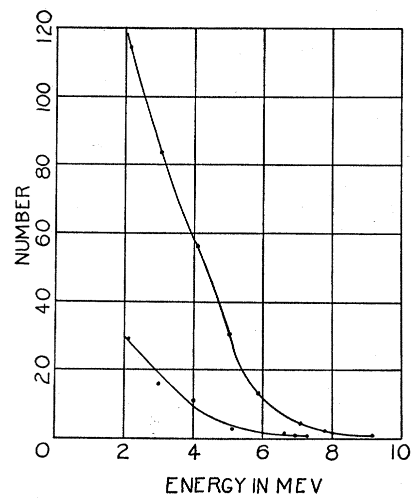


FIG. 4. Energy distribution of gamma-rays from the earlier experiment. Gamma-rays observed with and without uranium present are shown in the upper and lower curves, respectively.

uranium. Curves C and D were adjusted to correspond to the same neutron yield and the same number of photographs as curves A and B. An estimate of the neutron yields was made by counting recoil protons in the nondelayed pictures with and without the uranium.

RESULTS

For comparison the energy distribution of the gamma-rays previously studied is reproduced in Fig. 4. The marked similarity between the upper curves of Fig. 3 and Fig. 4 will be noted, showing good agreement between the two experiments. The data for Fig. 3(A) were taken with the uranium outside the cloud chamber, while the data for the upper curve of Fig. 4 were taken with the uranium contained in a 0.85-mm lead envelope inside the chamber. By comparing curves A and B of Fig. 3, it appears evident that the majority of gamma-rays from this reaction are emitted at the instant of fission or a very short time thereafter. This means that more gamma-rays are obtained which are coincident (or nearly so) with fission than gamma-rays associated with a period of as much as several seconds. No accurate conclusions can be reached regarding the periods of the delayed gamma-rays from this experiment, although these delayed gamma-rays may very well be associated with the periods reported by Roberts

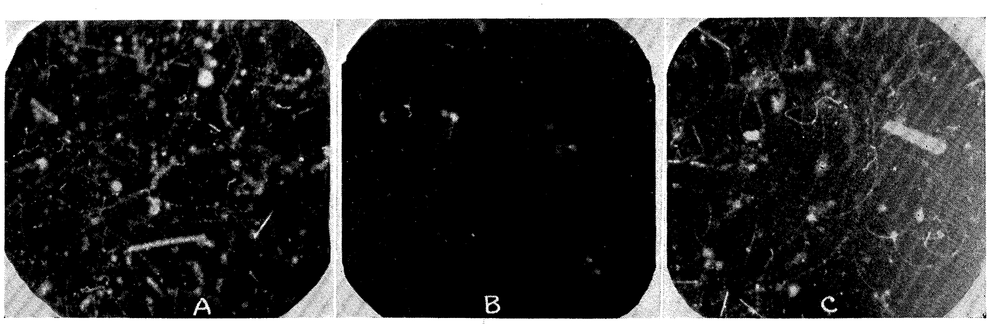


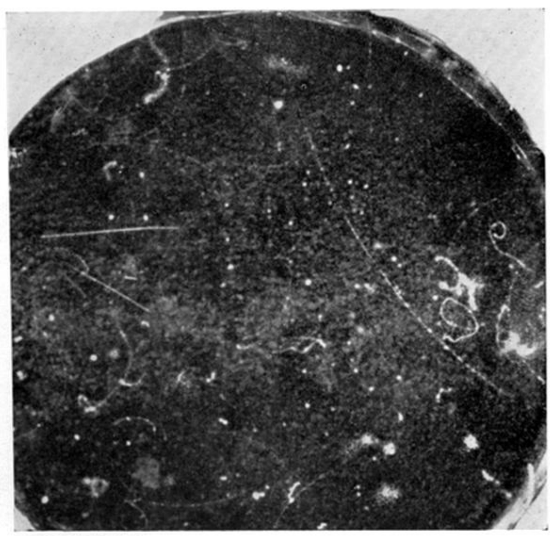
FIG. 5. Regenerative fission (?) (See photograph (A)). Three successive cloud-chamber photographs separated by 30 sec. B is delayed $\frac{1}{2}$ sec. after 11 sec. of neutron bombardment of the uranium.

et al.[2] On the other hand, these measurements do not show any definite difference in the general energy distribution of the gamma-rays emitted during bombardment and after a delay of $\frac{1}{2}$ second after bombardment. One delayed track (photographed in the first delay experiment discussed) had an energy of the order of 9 or 10 Mev, and the trend of curve B of Fig. 4 indicates that there might very well be high energy delayed gamma-rays.

We should like to call attention to an interesting photograph obtained during this work, Fig. 5(A). Fig. 5 shows a series of three successive photographs with 30-second intervals between them. (A) and (C) are taken during the bombardment of the uranium while (B) is the delayed picture. Picture (C) shows more than the average number of electron tracks on it, none of which have energies as great as 2 Mev. In picture (A) are seen many fairly high energy tracks, most of which show definite curvature, and most of which are about the same age. In only one other picture that we have taken have there been as many as two electrons of energies greater than 2 Mev. This is, therefore, a very exceptional photograph. The magnetic field was only 990 gauss which means that the energies are under 10 Mev. Because of the very large number of tracks it is difficult to measure many of them. (Four of these tracks were measured to have energies less than 8 Mev.) The occurrence of such a large burst of electrons might be attributed at once as being due to a cosmic-ray shower. If so, the shower did not occur near the cloud chamber because the directions of the tracks seem to be random. Also the energies involved are lower than is usual in cosmic-ray showers, although it is believed that such low energy showers have been photographed with a vertical cloud chamber. Another more interesting interpretation of this photograph would be that it shows a case of multiple fission, perhaps due to a regenerative or chain process.

Although the cloud chamber with air and alcohol was not very sensitive to neutrons, we do have evidence for delayed neutrons[2] in our delayed photographs. However, they are not numerous enough to warrant a systematic study.

In conclusion, we wish to acknowledge the aid of the Duke University Research Council in this work, and also the valuable criticisms of associates in the Physics Department.



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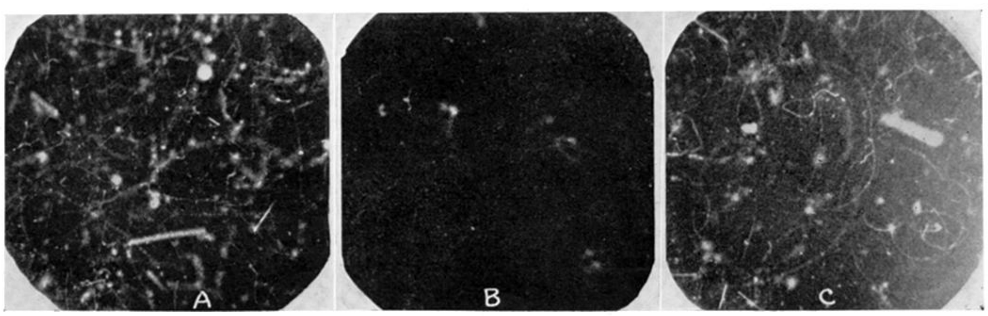

FIG. 5. Regenerative fission (?) (See photograph (A)). Three successive cloud-chamber photographs separated by 30 sec. B is delayed $\frac{1}{2}$ sec. after 11 sec. of neutron bombardment of the uranium.