HIGH-ENERGY NEUTRONS IN COSMIC RAYS

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Multiple-plate ionization chambers were used to detect the fission of heavy nuclei by cosmic rays. The altitude dependence of fission was investigated as well as the angular distribution of the fission-inducing particles. The energy and momentum of the latter were estimated. It is shown that in the great majority of cases the fission of nuclei is induced by the nucleonic component of cosmic radiation.

A number of remarkable phenomena have been discovered through studies of the interactions between cosmic ray particles and matter. Cosmic rays are far from being homogeneous and their energies can be very high. It is known that the fission of heavy nuclei such as uranium and thorium requires excitation energies of only a few Mev independently of the excitation mechanism. It could naturally be expected that cosmic radiation would be able to induce the dission of heavy nuclei. Conversely, the study of fission induced by cosmic rays furnishes additional information about the composition of cosmic rays.

Flerov and Stolyarov detected in 1945 the fission of uranium and thorium by cosmic rays. Flerov's dissertation in 1950 was based on a number of experimental studies of the cosmic ray component which can induce the fission of heavy nuclei.

The fission of heavy nuclei can be recorded by many means such as thick emulsions containing a heavy element, ionization chambers or counters and chemical techniques. We used multiplate ionization chambers, which had previously been employed in the study of spontaneous fission.[1] Substantial improvements in the design of the chambers and in the methods of amplification increased the efficiency of this technique a factor of 50 to 100 compared with the apparatus of 1939 — 1941 and thus made it possible to observe fission induced by cosmic rays, whereas attempts which have been made by means of photographic plates[2,3] did not yield definite results because of the low efficiency of this latter method.

In 1945 an ionization chamber containing uranium was raised to an altitude of 11 or 12 km above sea level. This first chamber contained only 0.3 g of fissionable uranium. In the course of 30 minutes the chamber, which was entirely surrounded by a thick layer of boron, registered 9 ionization pulses, of which 3 or 4 pulses could be attributed to spontaneous uranium fission occurring with a lifetime of about 10^{16} years.

The ionization pulses could be produced by (1) nuclear disintegrations releasing large amounts of energy, (2) cosmic ray showers of large numbers of particles, or (3) nuclear fission. Since this last cause only applied to a chamber containing uranium, another ionization chamber containing plates covered with lead was raised to the same altitude. The absence of any effect in the control chamber eliminated the first two causes so that some of the ionization pulses, after subtracting those resulting from spontaneous fission, could be attributed to the fission of uranium by cosmic rays.

The small magnitude of the observed effect even at high altitudes and the large spontaneous fission background made it practically impossible to obtain quantitative results with a uranium-loaded chamber. We therefore prepared multiplate chambers containing thorium as the working material. Special experiments showed that the spontaneous fission lifetime of thorium is at least 10^{20} years.[4] Experiments with these chambers at high altitudes furnished even more convincing evidence that cosmic rays can cause fission.

The first experiments with the fission-inducing component aimed to establish some basic laws such as the variation of intensity with altitude and the angular distribution of fission-inducing particles. Sounding balloons were used in 1945 — 1948 to investigate the altitude dependence. Measurements were obtained at 9 — 22 km, at geomagnetic latitude $\lambda = 52°$. From 9 km to 15 km the chamber counting rate increased by a factor of about 4 and amounted to 10 fissions per gram of thorium per hour. At greater altitudes the count decreased appreciably instead of increasing, leading to the very important conclusion that the particles which induce fission in the chamber do not belong to the primary cosmic ray component.

At lower altitudes the effect becomes very small

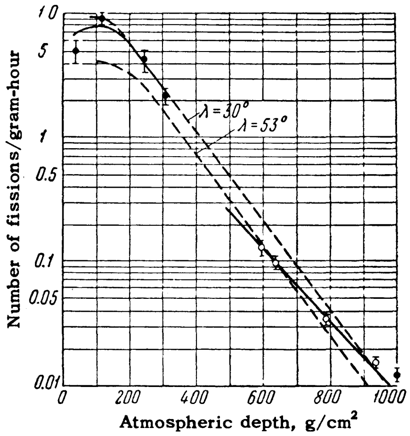

FIG. 1. o – λ = 28° (Pamir), ● – λ = 52° (120 m above sea level); solid curves – experimental, dashed curves – calculated.

(1 or 2 fissions per gram of thorium per day) and measurements are extremely difficult. Thorium fission by cosmic rays was measured at 4700, 3860, and 2200 m (Pamir, λ = 28°) as well as 120 m above sea level (λ = 52°).

Figure 1 shows the altitude dependence of the fission-inducing component. The results obtained with apparatus raised by sounding balloons are seen to be somewhat shifted with respect to those obtained at Pamir. This shift can apparently be attributed to the difference of latitude, which is associated with the geomagnetic effect of primary cosmic rays.

At Pamir the angular distribution of the fission-inducing component was measured at 3860 m. Three pits were dug in the sandy soil, which were 2 m deep and had the shapes of cones with angles $2\alpha = 80$, 60, and 44. The counting rate $N(2\alpha)$ at the bottom of a pit was compared with the rate for the same chamber, $N(\pi)$, at the surface. There was relatively little background from radiation passing through the soil.

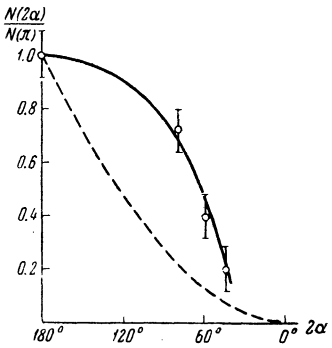

FIG. 2

The results, with a background correction, are shown in Fig. 2, where the dashed curve represents the calculated effect for isotropically directed radiation and the solid curve gives the actual intensity of the fission-inducing component as a function of 2α. A comparison of the two curves shows that the fission-inducing particles are mainly included within a relatively small solid angle around the vertical direction.

Experiments on altitude dependence and angular distribution do not, however, clearly determine the nature of the fission-inducing radiation since, as we know, uranium and thorium can be fissioned at a few Mev regardless of the type of particle which contributes this energy to the nucleus. Accordingly, further experiments were directed toward the study of the fission-inducing particles themselves for the purpose of determining their nature.

The essential properties of a particle are its charge, energy, momentum (mass) and lifetime (if the particle is unstable).

In order to determine whether the fission-inducing component is charged or neutral we ran a series of experiments at 3860 m in which a multiplate chamber registering thorium fission was surrounded on all sides by one or two rows of Geiger counters. Pulses from fission fragments were registered on film, while a special electronic circuit recorded coincidences between fission pulses and counter pulses, thus permitting a rough estimate of the number of ionizing particles as registered by the counter system for all coincidences.

In some runs 690 fissions were recorded in the chamber, of which only 89 were accompanied by counter pulses. These data lead to the conclusion that most of the radiation which induces fission is neutral. The ionizing component apparently does not exceed 15%.

The first experiments on the absorption of the fission-inducing component by lead showed that this component is highly penetrating and completely eliminated the hypothesis that fission might be induced by cosmic gamma rays. We must thus attribute fission to cosmic neutrons.

The energy of the fission-inducing cosmic particles was determined by means of an ionization chamber with bismuth-loaded plates. We know from experiments on heavy-element fission by fast neutrons[5] that for neutron energies of a few tens of megavolts the fission cross section of bismuth is about $10^4 - 10^3$ times smaller than the thorium cross section. The bismuth fission cross section grows quite rapidly with increasing neutron energy and at 100 Mev becomes 3×10^{-2} barns, whereas the thorium fission cross section, which is one barn at a few tens of megavolts, remains practically unchanged in this region. Thus the bismuth-loaded chamber registered essentially only those fission events in which the fission-inducing particle contributes more than 100 Mev to the nucleus, whereas the thorium-loaded chamber can be regarded as integrating the intensity of the fission-inducing component over its energy spectrum because the threshold for thorium fission by neutrons is very low (~ 1 Mev).

In 1949 bismuth-loaded multiplate ionization chambers were carried by balloons to a height of 13 — 20 km. In two ascents lasting two hours at a high altitude 18 bismuth fissions were recorded, comprising about 1.5 fissions per hour per gram of working material. Experiments with a large chamber containing about 40 g of effective bismuth were performed at 3860 m, at which altitude during 370 hours of observation 123 fissions were registered, comprising 0.33 ± 0.03 fissions per hour. By comparison a similar thorium-loaded chamber registered 4.0 ± 0.2 fissions per hour under the same conditions. The ratio of 12 should be determined by the ratio of the mean thorium and bismuth fission cross sections taking into account the cosmic ray spectrum. Assuming that thorium and bismuth fission is caused by neutrons and considering that the thorium fission cross section is not reduced when the neutron energy increases up to 400 Mev (at 380 Mev, $\sigma_{f\,Th} = 0.9$ barns) while the bismuth fission cross section continues to grow (at 380 Mev, $\sigma_{f\,Bi} = 0.074$ barns), we can infer from our results that the fission-inducing neutrons have an effective energy of about 400 Mev. A chamber containing tungsten, which has a fission cross section for 400-Mev neutrons that is about 20 times smaller than the bismuth cross section, yielded practically no result, which indicates that the fission-inducing component contained no neutrons with energies considerably above 400 Mev.

Particles with energies of a few hundred Mev transfer considerable momentum to fissioning nuclei. The mass of a particle can be determined from its energy and momentum; we therefore ran a series of experiments to determine the recoils of fissioning nuclei which have captured very fast particles. We prepared special multiplate ionization chambers in which the thorium layers were deposited on only one side of each plate. Since the motion of the fission-inducing particles is predominantly in the vertical direction, the momentum of a fissioning nucleus would be revealed by the fact that fission fragments would not have an isotropic spatial distribution but would tend to emerge from the fissioning material in the downward direction of the incident particle. The pulse counting rate would then depend on the ionization chamber arrangement, i.e., on whether the active layers were on the upper or lower surfaces of the plates.

Two identical chambers operating simultaneously, but alternately with respect to the "up" and "down" positions, during 944 hours registered 431 downward fissions and 296 upward fissions, thus establishing an asymmetrical fission fragment distribution. It is easily seen that the difference between the downward and upward effects compared with the total number of fissions is directly proportional to the momentum imparted to the fissioning nucleus. The observed asymmetry is somewhat reduced by the fact that the direction of the fission-inducing particle is not strictly vertical. Allowance for the angular distribution of fission-inducing particles increases the observed effect by about 20%, so that the asymmetry amounts to about 0.23 ± 0.5.

This result was compared with the corresponding data from thorium fission in the same chambers induced by fast 4- or 5-Mev neutrons from a Po + Be source. In this latter case the asymmetry is much smaller, amounting to only 0.034 ± 0.008. Therefore the momentum imparted to a fissioning nucleus by a cosmic particle exceeds that imparted to thorium by neutrons from the given source by a factor of about 7 ± 2. If we assume that the mass of the cosmic particle is of the order of a nucleonic mass we can estimate the mean energy of the fission-inducing particle from the momentum ratio. A rough estimate gives 100 — 400 Mev as the mean energy of the particles that induce thorium fission. In actuality the energy values derived from recoil experiments is considerably reduced through the fact that the momentum imparted to the nucleus by a fission-inducing particle may be partly carried away by a considerable number of fast neutrons escaping from a highly excited nucleus before it fissions.

Thus the rough estimate of neutron energy based on the recoil experiments is not in conflict with the more exact results obtained for bismuth fission; that is, the effective energy of cosmic neutrons which induce the fission of heavy nuclei is about 400 Mev.

We also performed a long series of experiments at 3860 m on the absorption of the fission-inducing component in dense matter (graphite and aluminum) whose atomic weight is close to that of air. These results were compared with data on the altitude dependence of the fission-inducing component intensity. The range of this component in air as determined from the altitude dependence (Fig. 1) is about 140 g/cm^2, which is in good agreement with the 120 g/cm^2 range of the nucleonic component. The ranges of the fission-inducing component in graphite and aluminum considerably exceed the ranges calculated from the mass and

Absorber	Thickness of absorber, g/cm²	Thickness of absorber allowing for its atomic weight, g/cm²	Range of fission-inducing component in g/cm² allowing for atomic weight of absorber	
			Experimental	Calculated
Graphite	119	126	410±120	130
”	136	144	550±100	130
”	177	188	340±90	130
”	195	207	410±80	130
Aluminum	150	120	340±110	170
”	300	240	330±85	170

atomic weight of the absorbers by comparison with the experimental range in air. Thus, the calculated ranges are 130 g/cm^2 for graphite and 170 g/cm^2 for aluminum, while the experimental ranges are ~ 400 g/cm^2 (see the table).

A similar but somewhat smaller effect has been observed by a number of investigators of the absorption of the nucleonic component in dense matter.[6] However, the complex processes which occur when cosmic particles pass from air into a dense medium make it very difficult to interpret the experimental results. In free air different portions of the nucleonic component are approximately in equilibrium, with a relatively small number of pions present in virtue of their short lifetime. The relative number of pions is strongly enhanced in dense matter, as noted by G. T. Zatsepin in 1949 during a discussion of these results. The observed low absorptivity of graphite and aluminum compared with air could be accounted for by an additional number of fissions under dense matter due to the pion excess. We might then expect that under dense matter the ratio of fissions induced by neutral and charged particles would change strongly in favor of the latter. However, it was found that an ionization chamber surrounded by counters connected for coincidence with fission fragments and placed under an 80-cm graphite absorber registers, as previously, an overwhelming majority of fissions induced by neutral particles. The percentage of registered coincidences compared with the total number of fissions under the absorber is somewhat increased (~ 20%), but the nature of the effect suggests that a considerable fraction of the coincidences results from the fact that the chamber under the absorber also registers large dense showers (0.5 particle/cm^2). This also follows from experiments on enhanced ionization in a tungsten-loaded chamber surrounded by counters. In the open air this counter revealed no practically measureable effect, whereas under an 80-cm graphite absorber a considerable number of pulses was observed, all accompanied by the triggering of all or a large fraction of the counters. We can thus assume that under an absorber thorium fission is induced mainly by neutrons. The extra number of thorium fissions under a dense material could be attributed to some difference in the neutron spectra within the atmosphere and under an absorber such as graphite. Indeed, the interaction of neutrons with atmospheric nitrogen involves a (n, α) reaction which can considerably attenuate the flux of neutrons possessing energies of a few tens of megavolts. It is difficult to calculate this effect exactly; an experimental estimate was obtained by measuring the number of fissions in a thorium-loaded chamber surrounded by 20-cm thick paraffin under a graphite absorber and in air. However, these experiments showed that the relative number of neutrons with 10 — 20 Mev is small in both cases, that there is no essential observable difference and that this effect can therefore not account for the absorption data.

It is therefore most reasonable to associate the unusually long range of the fission-inducing component with the extra number of pions in dense substances. Experiment has shown, however, that fission is not induced directly by pions, but evidently by neutrons which appear as a result of pion-induced nuclear reactions in dense matter. The given measurements as a whole therefore suggest that the enhanced ionization registered by the ionization chambers was produced by fragments from fissions induced mainly (~ 85%) by the neutron portion of the nucleonic component.

An effective nucleonic energy ~ 400 Mev was estimated from experiments with bismuth as well as from the recoils of fissioning nuclei after neutron capture.

The angular distribution of particles which induce the fission of heavy nuclei was found to be sharply anisotropic, with most of the particles within a solid angle of about 60 — 80° about the vertical direction.

It follows from the altitude dependence of the fission-inducing component that its intensity rises approximately exponentially with the exponential index 140 g/cm^2. A peak of the altitude dependence was observed at a depth of the order of 100 g/cm^2 from the top of the atmosphere, thus indicating the secondary character of these particles.

Finally, our experiments permitted an estimate of neutron flux at a few hundred Mev. Since the thorium fission cross section in this energy region is practically invariant at about one barn, the flux can be estimated from the measured counting rate in a chamber containing a known amount of active thorium. The latter quantity was determined by comparison of the counting rates produced by a Ra + Be neutron source in two chambers of identical dimensions loaded with thorium and uranium, respectively. The ratio of the uranium and thorium fission cross sections was taken to be 4. The amount of active uranium was computed from the number of spontaneous fissions in the uranium-loaded chamber. It was also shown that the pulse-height distribution resulting from cosmic-ray-induced fission does not differ generally from that induced by neutrons from a Ra + Be source (Fig. 3).

At 3860 m above sea level (atmospheric depth 655 g/cm^2) a chamber containing 11 ± 1 g of thorium (2.85×10^{22} atoms) registered 741 fission events in 672 hours. Thus the nucleon flux, assuming $\sigma_{f\,Th} = 1$ bn, was 10^{-2} nucleon/cm^2-sec. The accuracy of this flux measurement is not better than 10% without including the uncertainty introduced by using the given cross section for thorium fission. A comparison can be made with calculations of nucleon flux at different heights recently published by Benioff.[7] Figure 1 gives the calculated total nucleon flux with energies ≥ 40 Mev plotted against elevation for geomagnetic latitudes $\lambda = 30°$ and $53°$. With allowance for the accuracy of the experiment (solid curve) and of the calculation the agreement at different elevations is quite satisfactory. There was also good agreement between experiment and calculations with respect to the position of the maximum on the altitude curve, the magnitude of the geomagnetic effect and the neutron-proton ratio in the total nucleon flux.

Experiments on the passage of the fission-inducing component through air and through dense absorbers lead to the conclusion that under dense absorbers an essential role in fission is played by neutrons which apparently result from interactions between pions and absorber nuclei.

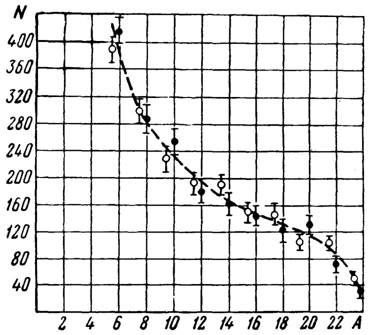

FIG. 3. ○ – Th fission induced by neutrons from a Ra + Be source; ● – Th fission induced by cosmic rays; N – number of pulses; A – pulse height in relative units.

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134