On the Production of Mesotrons

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The recent letter of Schein, Jesse and Wollan[1] makes it seem doubtful that the generally accepted explanation of the atmospheric transition curve of the cosmic rays is valid. If, as the evidence suggests, the primary rays entering the atmosphere are largely protons and not electrons, one must explain the production of both the penetrating component, the mesotrons, and the soft component, electrons and γ-rays, and their intensity curves in the atmosphere. An obvious assumption is that the protons create mesotrons in collisions with nuclear particles. The mesotrons in turn decay, transferring a part at least of their energy into an electronic component which gives rise to the soft component.

Since the nature of the mechanism of these processes is not known, we are suggesting a simplified quantitative model of the process based on a few reasonable assumptions.

The main assumptions we make are (a) the creation is an "explosion" in which the proton loses all of its energy and creates n mesotrons; (b) the mesotrons have roughly equal energy, and (c) the multiplicity n, the average energy of the mesotrons and the production cross section increases with the proton energy over the region from 2×10^9 to 2×10^{10} ev. The multiplicity and the cross section remain constant for higher energies.

If we assume for protons of 10^{10} ev a cross section of 1.6×10^{-26} cm^2 per nuclear particle, and a multiplicity of ten, we find from the solution of the diffusion equation for the mesotron intensity as a function of the pressure, a curve which starts out at zero for zero pressure and rises sharply. In the first 1/12 of the atmosphere it reaches a broad maximum of about twice the initial proton count. It then drops off with a slight positive curvature. The total intensity of the protons and mesotrons has a slightly higher maximum and drops off more rapidly. Since the average mesotron intensity never greatly exceeds two, it follows that most of the mesotrons produced decay near the top of the atmosphere.

Because of the extreme rarity of the atmosphere near the top, the time required to traverse a small fraction of a homogeneous atmosphere is ample to allow disintegration. Thus the average number of mesotrons which have not decayed is very small compared to the multiplicity n. The greater part of the mesotrons which decay in the upper atmosphere will have lost little energy by ionization. There would, therefore, be between 8 and 9 electrons in the upper atmosphere per incident proton. These disintegration electrons with energies of about 5×10^8 ev should give rise to some cascade processes and be responsible for the soft component.

High energy mesotrons should produce a high east-west asymmetry since for high energies the angular divergence of the mesotrons produced should be small. At lower energies there should be some angular spread and consequently less asymmetry. Comparison of the difference curves for the mesotron intensities at Chicago, latitude 51°, and Texas, latitude 38°, shows that the greater part of the mesotrons must be produced by protons of energy above 6×10^9 ev. We would thus expect the cross section to be larger and the multiplicity greater for higher energy protons.

Near the equator where the mean energy of the protons is higher, if the cross section increases with proton energy and the mean energy of the mesotrons increases, one finds a larger number of mesotrons at the maximum due to the lower rate of decay. For the extremely high energy protons which are responsible for the mesotrons below sea level, this mesotron intensity should follow very closely the energy spectrum of the protons if the multiplicity approaches a fixed value. Comparison of these results with experiment is at least qualitatively satisfactory.

Professor R. Serber[2] has kindly pointed out to us the following facts. From the area of Pfotzer's curve the multiplication ratio (intensity at maximum/intensity at top) is about 10.7 whereas experimentally it is about 5. This suggests that only half of the energy appears in ionization, the remainder presumably going into neutrinos. Also the same conclusions follow from the absolute rate at the top determined from absolute sea level count times the experimental ratio of sea level to top, when compared with Bowen, Millikan and Neher's calculation of the incoming numbers. From the cascade theory the multiplication should be about 13.5. The comparison of the multiplication ratios shows that the energy gets into the shower producing component quickly.

These results are only preliminary and suggestive. A more careful analysis is in progress which will be reported at an early date.

[1] Schein, Jesse and Wollan, Phys. Rev. **59**, 615 (1941).
[2] R. Serber, private communication.

Proton-Induced Fission

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Nuclear fission induced by the capture of a charged projectile has been established by the work of Jacobsen and Lassen[1] after some preliminary experiments of Gant.[2] These authors used deuterons of energies between 8 and 9.5 Mev on thorium and uranium targets. For 6.0-Mev protons on uranium, Bohr and Wheeler[3] predict a value of 10^{-28} for the fission cross section, which should be observable.

We have bombarded thorium metal and uranium oxide with the 6.9-Mev proton beam of the Rochester cyclotron. Our previous observations with uranium targets had led us to the conclusion that a (p, n) reaction probably also takes place. For this reason, care had to be taken that fission caused by secondary neutrons from the target was not interpreted as being proton induced.

The proton beam entered an evacuated cylindrical brass chamber (Fig. 1A) in which targets could be placed

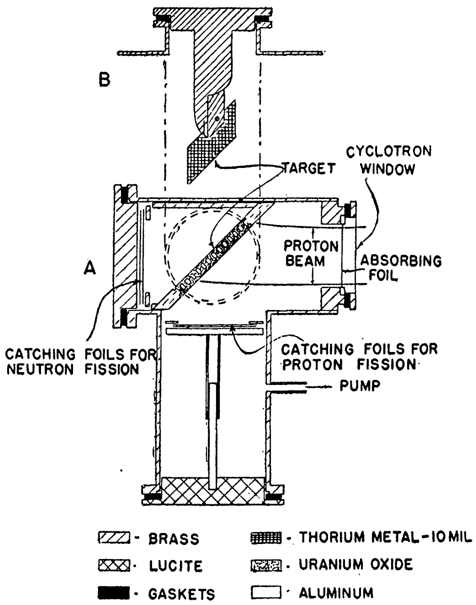

FIG. 1.

in any desired position. In a side tube (which was designed to accommodate a proportional counter) projecting at right angles from the body of the chamber, and well removed from the beam, foils were mounted so as to catch fission fragments emitted from the target surface. A 0.1-mil aluminum foil in front of the catching foils was found sufficient to retain all ordinary radioactive recoil atoms. Aluminum foils placed behind the catchers served to correct for radioactivities induced in them by neutrons or scattered protons.

A 10-mil sheet of thorium, which was found to be thick enough to stop the proton beam and proton-induced fission particles, was oriented so that its normal made angles of 45 degrees with both the beam and the catchers' normal. There are two such positions. In position I (Fig. 1B) the irradiated surface of the target faces the catcher; in position II, the other surface does. The amount of fission fragments caught in position II will be approximately the same as that fraction caught in position I that is due to fission induced by the neutrons from the cyclotron and the target. After a bombardment of 5 μAh in 1.5 hours, radioactivity was observed in a 1-mil aluminum catcher, whose decay could be followed for seven hours. A bombardment of 25 μAh in 8 hours yielded a sample which could be observed for over two and a half days. Identical bombardments with the target in position II gave no effect. When plotted on semi-logarithmic paper, the decay curves show the curvature characteristic of a mixture of many periods.

By replacing the 1-mil aluminum catcher with a stack of 0.1-mil aluminum foils it was found that the maximum range of fission fragments from ${}_{91}Pa^{233}$, the compound nucleus in question, lies between 0.5 and 0.6 mil of aluminum. Reducing the proton energy in successive steps by inserting aluminum absorbers just in front of the cyclotron window gave several points of the excitation function. The lowest proton energy for which we obtained an observable effect was 5.8 Mev. Had our thorium sheet been large enough to insure that no fraction of the proton beam would fail to strike it, we could have collected the background-induced fission fragments behind the target, without turning it into position II and repeating the bombardment.

In the case of uranium, however, we proceeded in this more direct manner. Figure 1A shows the position of a second catcher behind the target. It also shows the elliptic perforated brass plate which was packed and coated with uranium oxide embedded in pyroxylin. The brass provided sufficient cooling, and the oxide-filled channels gave the surface coats a higher stability. Thus we were able to find in a single run that uranium gives an effect (fission of 93^{239}) of the same order of magnitude as that found in thorium, and that the background effect is negligible.

Chemical investigations and experiments employing an ionization chamber for more accurate yield and range determinations are under way.

[1] I. C. Jacobsen and N. O. Lassen, Phys. Rev. **58**, 867 (1940).
[2] D. H. T. Gant, Nature **144**, 707 (1939).
[3] Niels Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).

Note on the Normalization of Dirac Functions

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A VERY simple method of normalizing the Dirac functions in the Kepler problem is given in this note. The normalization of Dirac functions in the Kepler problem was first done by Bechert[1] with the help of certain contour integrals in a complex plane. The calculation was, however, rather complicated. With the functions given in Infeld's form, a much simpler method of normalization leading to a neater result is proposed here. The result is, as I verified, the same as that given by Bechert, but it appears in a completely different form.

It has been shown[2] that the radial Dirac functions are given by

$$\chi_1=C\left\{(\epsilon\kappa-\gamma)^{\frac{1}{2}}\frac{\gamma_2+\gamma_1}{\gamma}\overset{0}{\mathfrak{F}}_{l,\gamma}(x)+(\epsilon\kappa+\gamma)^{\frac{1}{2}}\frac{\gamma_2-\gamma_1}{\gamma}\overset{1}{\mathfrak{F}}_{l,\gamma}(x)\right\} \quad (1)$$

$$\chi_2=C\left\{(\epsilon\kappa-\gamma)^{\frac{1}{2}}\frac{\gamma_2-\gamma_1}{\gamma}\overset{0}{\mathfrak{F}}_{l,\gamma}(x)+(\epsilon\kappa-\gamma)^{\frac{1}{2}}\frac{\gamma_2+\gamma_1}{\gamma}\overset{1}{\mathfrak{F}}_{l,\gamma}(x)\right\} \quad (2)$$

with the following definitions and formulae (C being the normalization factor):

$$\gamma_1=(\kappa-\alpha Z)^{\frac{1}{2}},\quad \gamma_2=(\kappa+\alpha Z)^{\frac{1}{2}},\quad \gamma=\gamma_1\gamma_2=(\kappa^2-\alpha^2Z^2)^{\frac{1}{2}}, \quad (3)$$

$$\epsilon=\frac{E}{E_0}=\left\{1+\frac{\alpha^2Z^2}{(l+\gamma)^2}\right\}^{-\frac{1}{2}}, \quad (4)$$

where l is a positive integer, or zero (only for $\kappa<0$), and κ is an integer, positive or negative, but not zero; $\overset{1}{\mathfrak{F}}_{l,\gamma}$ and $\overset{0}{\mathfrak{F}}_{l,\gamma}$ are the lowest two functions of a ladder of normalized functions defined by