TABLE II. Energy of gamma-rays.

Number	Gamma-energy	Number	Gamma-energy
1	46.2 kev	15	138.4
2	58.3	16	150.2
3	64.7	17	157.9
4	66.8	18	159.1
5	68.8	19	171.5
6	76.1	20	177.5
7	83.7	21	196.6
8	93.1	22	211.5
9	99.2	23	219.7
10	107.0	24	227.0
11	109.3	25	261.2
12	112.4	26	301.6
13	117.7	27	307.2
14	122.7	28	328.4

It can be noted that a great many numerical identities exist between mathematical combinations of the gamma-energies. For example, ten distinct combinations are observed to add to 374.5 kev. This suggests the possibility of a nuclear level scheme as shown in Fig. 1. While this proposal is undoubtedly not unique, it is remarkable that the 13 levels account completely for the 28 observed gamma-rays. In only a few cases do the gamma-energies deviate from the level differences by as much as 0.3 kev.

The decay of the tantalum shows the presence of activities of half-lives 3.5 days and 123.5 days. The radiations from the short-lived emitter have not been determined. This investigation was made possible by the support of the AEC and the ONR.

[1] J. M. Cork, Phys. Rev. **72**, 581 (1947).

Nuclear Collisions of Heavy Cosmic-Ray Primaries

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April 13, 1949

HEAVY primary cosmic-ray ions, predicted by Alfven[1] and later discovered at high altitudes in photographic plates and cloud chambers,[2] are absorbed in the upper layer of the atmosphere mainly as a result of nuclear collisions. One may classify these collisions according to their effect on the bombarding nucleus as follows:

(a) The incoming nucleus can proceed almost undeflected with undiminished charge. In this case a few nucleons may be ejected from the target nucleus. An example of such a collision is given in Fig. 1.
(b) The incoming nucleus may be completely destroyed in a large nuclear explosion. An example of such an event was published earlier.[3]
(c) Part of the incoming nucleus may be sheared off in the collision. The remaining nuclear matter proceeds with its original momentum either as a compact nucleus of reduced charge or partially or completely dissociated. This type of collision results therefore in a *narrow penetrating shower* consisting in general of relativistic protons, α-particles and heavy fragments.

We have so far observed eight narrow showers of relativistic particles. Most of these were observed in a 3″×10″ stack of 25 electron sensitive Eastman NTB3 plates flown for 6 hours at an altitude of 92,000 ft. off the coast of Cuba ($\lambda=29\frac{1}{2}$°N magn.). In the three cases where the incoming nucleus belonged to the carbon, nitrogen, oxygen group the shower contains only protons or a mixture of α-particles and protons. An example of such a shower is shown in Fig. 2.

In the remaining five cases where the bombarding nuclei have charges $Z=14$, 19, 20, 26, and 26 the shower contained in each case one heavy fragment of charge $Z=10$, 11, 10, 10, and 20, respectively. One example is shown in Fig. 3. The

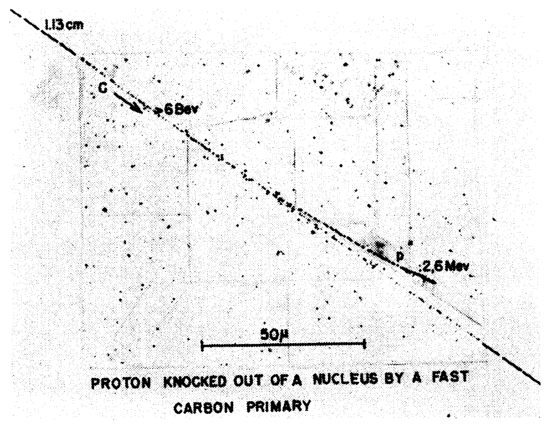

FIG. 1. Proton knocked out of a nucleus by a fast carbon primary (E_{kin} ~10 Bev). The track of the heavy ion in the emulsion was 1.13 cm long and the charge $Z=6$ was determined both by grain counting and δ-ray counting. The energy of the secondary proton is $E_p=2.6$ Mev and the angle between the track of the carbon ion and the proton track is $\vartheta=20°$ ($\vartheta_{\text{proj}}=5°$). Hence the collision could not have been an elastic collision (Ilford C-2 emulsion).

picture shows two sections of the same track in two adjacent photographic plates. The collision occurred in the glass between the emulsions.

The frequency of these showers is comparable (though perhaps smaller) to the number of collisions leading to total destruction of the incoming particle. They have not been observed earlier because all the lighter shower particles being in the relativistic range will only be recorded in electron sensitive emulsions, such as the Eastman NTB3 plates.

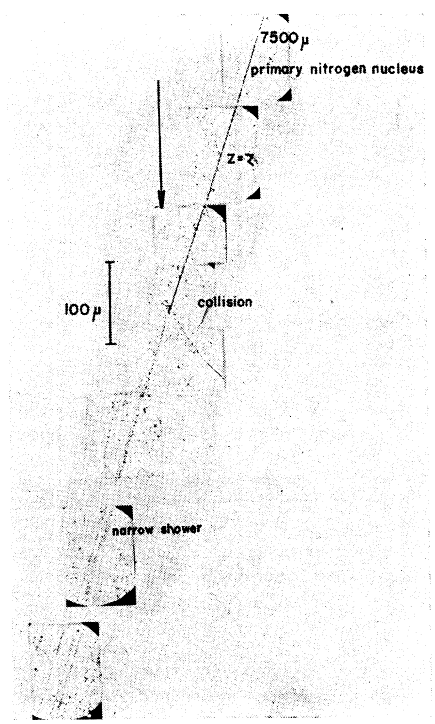

FIG. 2. Narrow shower of protons and α-particles resulting from the collision of a primary nitrogen nucleus. One of the α-particles has a path length of 5 cm in the emulsion. The projected angles between the tracks are 0.033, 0.077, and 0.110 degrees, respectively. (Eastman NTB3 emulsion.)

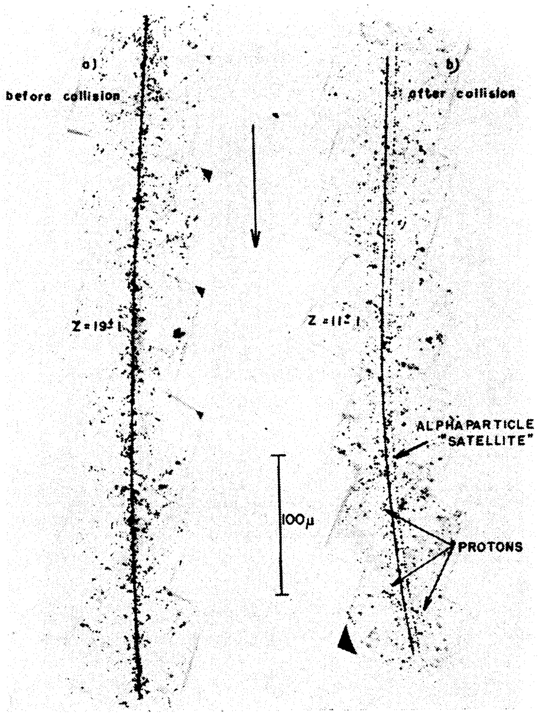

FIG. 3. Figure 3a shows the track of the nucleus of charge $Z=19$ as it appears in three plates before the collision occurs. Figure 3b shows the narrow shower emerging from the glass plate in which the collision occurred. It consists of a heavy fragment of $Z=11$, one α-particle, and 6 protons. The α-particle and 3 protons can be seen in the photograph. The apparent curvature of the tracks is the result of a distortion of the emulsion (Eastman NTB3 emulsion).

Since the tracks can be frequently followed through a whole stack of plates, the angles between the shower particles can be measured with very high precision and can therefore be used to estimate the energy of the incoming particle.

One may expect angles of the order of

$$\vartheta=\langle p_{\perp}\rangle_{\mathrm{Av}}/p_0\approx(2Mc^2\langle E_{\perp}\rangle_{\mathrm{Av}})^{\frac{1}{2}}/E_0,$$

where $\langle p_{\perp}\rangle_{\mathrm{Av}}$ is the average transverse momentum of the nucleons inside the incoming particle (the corresponding energy is $\langle E_{\perp}\rangle_{\mathrm{Av}}\approx(2/3)(3/5)\cdot 20$ Mev$=8$ Mev) and p_0 is the longitudinal momentum per nucleon.

In the shower illustrated in Fig. 3 we have an incoming nucleus of $Z=19\pm1$ and a shower consisting of 6 protons, 1 α-particle, and 1 nuclear fragment of charge $Z=11\pm1$. The angles between the light particles and the heavy fragment projected on the plane of the emulsion vary from 0.0050 to 0.0292 radian, the average projected angle ($\vartheta'=\vartheta/\sqrt{2}$) being 0.017 radian. The deviation of the angles obtained by measuring the change in separation in successive pairs of plates show that the scattering, although measurable, is less than 0.001 radian/cm of glass and therefore does not affect the argument. Hence we estimate that the incoming particle had an energy of the order of 5 Bev/nucleon.

A similar shower produced by an iron nucleus and consisting of 3 α-particles, probably some unobserved protons, and a heavy fragment of $Z\sim10$ has been observed in a stack of plates flown at Minnesota. It leads to an estimate for the total kinetic energy of the primary particle of 0.5×10^{12} ev.

Since most of the collisions occur in the glass only collisions of class (b) and (c) will in general be observed. If we define collisions as events where the charge of the incoming particle is reduced by at least two units we obtain from 40 collisions in an over-all path length of 520 cm of glass a mean free path $\lambda=33$ g/cm^2 for nuclei of $6\leqslant Z\leqslant8$, and from 26 collisions in 255 cm of glass a mean free path of $\lambda=23.5$ g/cm^2 for nuclei of $10\leqslant Z\leqslant18$. The corresponding collision cross section agrees for both groups with the one calculated for glass, assuming for all nuclei involved an effective collision radius equal to the geometrical nuclear radius $R_0=1.45\cdot A^{\frac{1}{3}}\cdot10^{-13}$ cm diminished by a constant decrement $\Delta R=0.8\times10^{-13}$ cm.

Since as many as 3 nuclear collisions may be required to reduce the charge of an iron nucleus to $Z\sim6$, it may be possible to observe such narrow showers even at low altitude. The appearance of these showers in a cloud-chamber photograph should be similar to the showers of parallel tracks of positive particles reported by Rochester and Butler,[4] for which no satisfactory explanation has thus far been found.

We are greatly indebted to Dr. John Spence of Eastman Kodak Company for preparing the large stack of very sensitive plates used in this investigation, to Dr. E. O. Salant and Dr. J. Hornbostel of Brookhaven National Laboratory for making many of the arrangements for the balloon flight and to the ONR for organizing the flight.

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[3] H. L. Bradt and B. Peters, Phys. Rev. **74**, 1828 (1948).
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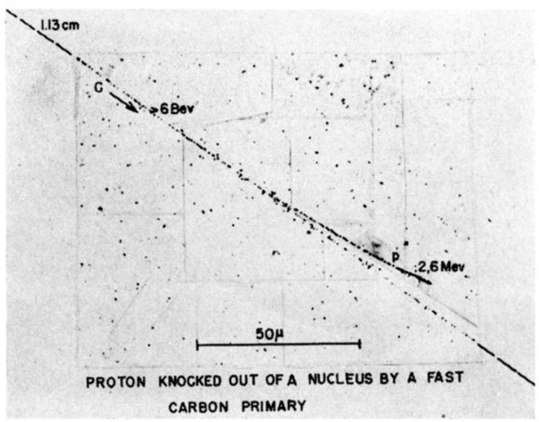

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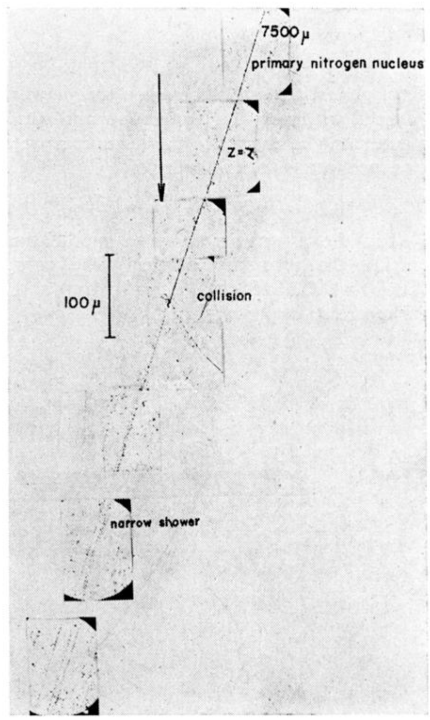

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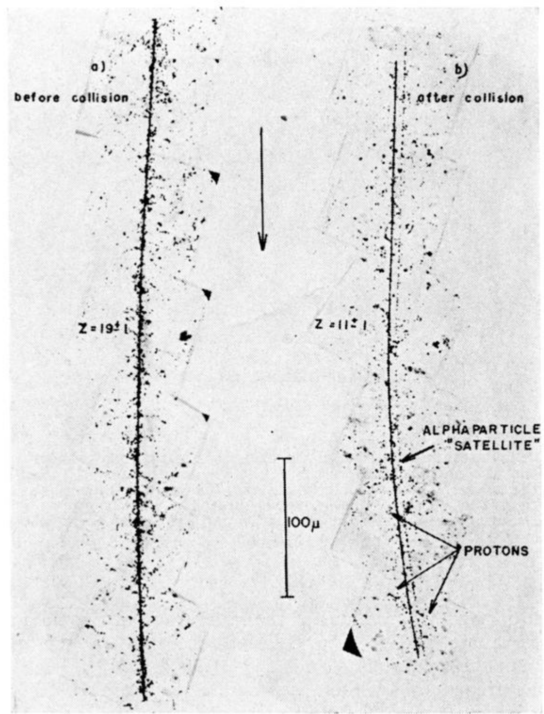

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