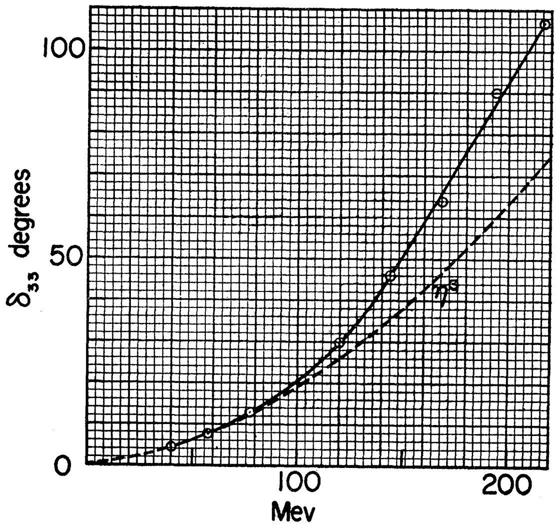

FIG. 1. The $T=3/2$, $j=3/2$ phase shift as a function of energy.

direct π^- scattering cross section at 40 Mev which is much too low compared to that measured by Barnes *et al.*[6] On the other hand, it does fit in with the values of $\sigma(\pi^- \to \pi^-)$ measured at 65 and 26 Mev, both of which are considerably lower than Barnes' value. It will be noticed that with our set of values deduced at 40 Mev, δ_{33} fit very well on the curve of Fig. 1.

δ_1 shows a somewhat erratic behavior (see curve). Our analysis[1] of the 217-Mev point does place δ_1 close to or slightly below zero, but this point might be in error.

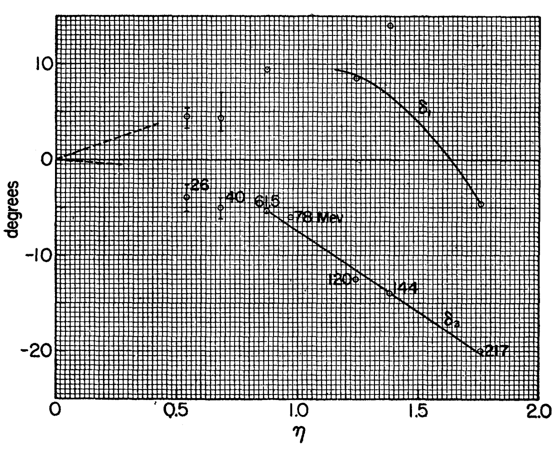

FIG. 2. S state phase shifts as a function of η, the momentum in the center-of-mass system in units of μc.

At zero energy the Panofsky experiment,[7] coupled with the recent determinations of positive photoproduction near threshold at Illinois,[8] enables one to solve for the quantity $(\delta_1-\delta_3)/\eta$. Our analysis of the photoproduction data near threshold and beyond shows that the fraction of the differential cross section for positive photoproduction at 90° which is due to S scattering has the following values: At 175 Mev: 0.88; at 185 Mev: 0.83; at 200 Mev: 0.72; and at 235 Mev: 0.54. Making use of the fraction at 175 Mev and allowing for other corrections, we find $(\delta_1-\delta_3)/\eta = 10.7 \pm 2.5$ degrees. While one knows only the difference in slope, and not the absolute slopes at zero, we have indicated a possible choice which might not be too inconsistent with the phase shift data at 26 and 40 Mev. However, the dotted lines as shown lead to a value at 5 Mev of 4.5 millibarns for the direct π^- scattering between 90 and 180°, as compared with 8 millibarns deduced from very preliminary data of Lederman (private communication).

We wish to emphasize that we do not believe that there need be any discrepancy between the Panofsky value at zero and the very low-energy phase shifts. We believe that the δ_3 curve does show a break in slope near $\eta=0.8$, which might well be a gradual one.

[1] de Hoffmann, Metropolis, Alei, and Bethe, Phys. Rev. (to be published).
[2] H. A. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson and Company, Evanston, to be published), Vol. II.
[3] J. Orear, Phys. Rev. (to be published).
[4] Bodansky, Sachs, and Steinberger, Phys. Rev. **93**, 1367 (1954).
[5] H. P. Noyes and A. E. Woodruff, Phys. Rev. **94**, 1401 (1954).
[6] Barnes, Angell, Perry, Miller, Ring, and Nelson, Phys. Rev. **92**, 1327 (1953).
[7] Panofsky, Aamodt, and Hadley, Phys. Rev. **81**, 565 (1951).
[8] G. Bernardini and E. L. Goldwasser, Phys. Rev. **94**, 729 (1954).

Possible Example of the Annihilation of a Heavy Particle*

H. S. BRIDGE, H. COURANT, H. DESTAEBLER, JR.,† AND B. ROSSI
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received June 21, 1954)

THE picture in Fig. 1 and the sketch in Fig. 2 show an unusual cosmic-ray event photographed with the M.I.T. multiplate cloud chamber at Echo Lake, Colorado. The chamber contained eleven brass plates, each 0.50 inch thick (11.1 g cm^{-2}) and was triggered by a penetrating-shower detector placed above it. Two additional views, taken at different angles, are available.

Three electron showers, b, c, d, appear to be associated with the stopping of a charged particle, a, in one of the plates. Within the experimental errors, the axes of the three showers and the direction of the last visible segment of track (a) intersect at one point in the plate.

From the number of small showers with no apparent origin occurring in our cloud chamber, we found an upper limit of 10^{-3} for the probability that either (c) or (d) may be a case of chance association. It is practically impossible to explain shower (b) in a similar way for a survey of about 10 000 pictures has not revealed a single shower of the size of (b), with no apparent origin and going upward.

To estimate the shower energy, E_0, we have made use of the equation: $E=hNt$, where h is a constant, N is the total number of electron tracks appearing in the separate sections of the chamber through which the shower develops, and t is the thickness of the plates, measured in the direction of the shower axis. Nt is an approximate value for the track length of the observable shower electrons which, according to shower theory, is proportional to the energy, E, of the initiating particle. Notice that there is an effective lower limit for the energy of the observable electrons because, as the energy decreases, electrons are more strongly scattered and have less probability of emerging from the plates. The proportionality constant, h, depends on the cut-off energy. We have determined h experimentally from a study of double-cored showers that arise from the decay of π^0 mesons, making use of the equation, $\sin(\theta/2)=m_{\pi^0}c^2/2(E_1E_2)^{\frac{1}{2}}$, which relates the energies E_1, E_2 of the two decay photons to the angle θ between their lines of flight.

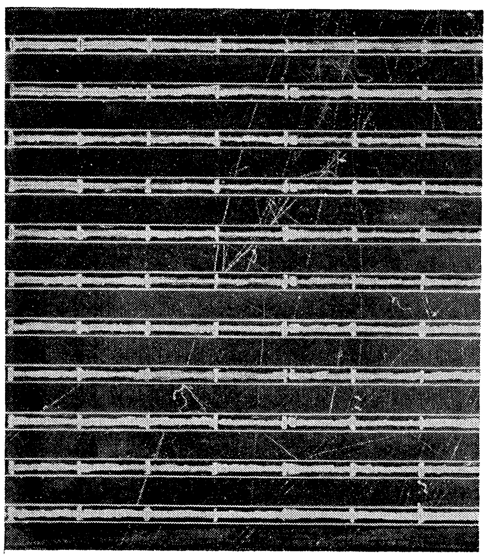

FIG. 1. Cloud-chamber photograph of the cosmic-ray event.

With this method we found $E_b=1170$ Mev and $E_c=300$ Mev for the energies of showers (b) and (c). It was not possible to make a significant estimate of the energy of shower (d), which contains only 4 visible electron tracks. The most serious uncertainty in our energy estimates arises from statistical fluctuations. Although a rigorous treatment of the fluctuation problem as applied to our method of analysis is still lacking, we feel confident that the quoted energy values could not be in error by as much as a factor of two.

Showers (c) and (d) appear to be produced by photons, while (b) could be produced by either an electron or a photon. The momenta of the particles responsible for the three showers do not add to zero. Indeed, the axis of (b) forms an angle of 11° with the plane of the axes of (c) and (d); moreover, the energy of (b) is much greater than the combined visible energies of (c) and (d). The three showers could be produced by three of the four photons arising from the decay of two π^0 mesons, the fourth photon having escaped detection. However, the two π^0 mesons could not have equal and opposite momenta.

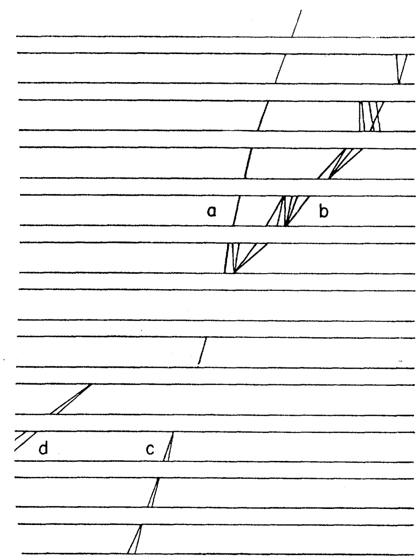

FIG. 2. Sketch of the cosmic-ray event.

In what follows we consider three possible interpretations of the event described.

1. Spontaneous decay.—Since the primary particle is electrically charged, and there is no secondary charged penetrating particle, one of the decay products must be an electron or, alternately, a π meson which undergoes charge exchange in the plate of production. Moreover, conservation of momentum requires that there be at least one invisible decay product of a total energy not less than about 500 Mev. Thus, if the process is a spontaneous decay, we conclude, on energy grounds, that the mass of the primary particle cannot be smaller than that of a proton. This conclusion implies the existence of a boson of superprotonic mass, at least if one accepts the current view that heavy fermions (such as nucleons and Λ particles) cannot change into light fermions.

2. Nuclear absorption.—In order to interpret the event as the nuclear absorption of a negative particle, one must assume (a) the existence of a boson with mass considerably greater than 1000 electron masses (although not necessarily greater than the proton mass) and (b) the possibility that, when such a particle is captured by a nucleus, practically all of its rest energy may appear in the form of photons.

3. Annihilation process.—In view of the difficulties of interpreting the event as a decay or an absorption process, one should consider the possibility that the event represents the annihilation process of two heavy fermions. For example, the incident particle might be an antiproton (or an antihyperon) that undergoes annihilation with an ordinary proton. A large fraction of the energy liberated in such a process may well be changed into π^0 mesons and thus ultimately appear in the form of γ rays.

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
† National Science Foundation Predoctoral Fellow.

Anomalous Event Observed in Photographic Emulsion*

J. H. Noon, M. F. Kaplon, and J. Crussard
University of Rochester, Rochester, New York
(Received June 21, 1954)

In a stack of 400μ G-5 stripped emulsions flown at high altitude an anomalous interaction of a fast heavy nucleus has been observed (Fig. 1). A fast Be

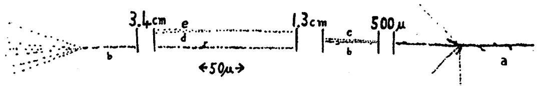

Fig. 1. A fast Be nucleus (a) interacts in emulsion, making a star. Two of the prongs are relativistic triply (b) and doubly (c) charged particles emitted in the forward direction. The triply charged particle makes a star of 6 minimum tracks, and the doubly charged particle appears to decay into 2 minimum tracks d and e.

nucleus (a) interacts producing a $6+1_{\text{Be}}$ star. Two of the prongs are relativistic particles of charge 3 and 2, each making an angle less than 2×10^{-3} radian with the primary. The triply charged particle (b) interacts after 5.09 cm, giving a $0+6_{\text{Li}}$ star. The doubly charged particle (c) travels for 1.37 cm, at which point it splits into two fast singly-charged particles (d and e); there is no observational evidence of nuclear interaction and the event $c\rightarrow d+e$ is coplanar within the accuracy of measurement. Since it is reasonable to assume in interactions of fast heavy nuclei that the fast heavy fragments observed originate from the incident nucleus, the charge of the fragments should not exceed that of the parent. The violation of this aspect of charge conservation provides the anomaly.

The charge of the primary was determined by gap-count comparison with slow protons and by comparison of the δ-ray count with that of fast α particles. The former gave $I_a/I_{\min}=16.2\pm0.2$ and the latter $n_\delta(a)/n_\delta(\alpha)=4.06\pm0.7$; thus $Z_a=4\pm0.1$, establishing particle a as Be. For particle b, $n_\delta(b)/n_\delta(\alpha)=1.9\pm0.3$, giving $Z_b+2.76\pm0.2$. Since b interacts giving 6 minimum ionizing tracks it cannot be a slow α particle; thus b is established as Li. For c we find $n_\delta(c)/n_\delta(\alpha)\approx1$ and $I_c/I_0\approx4$, giving $Z_c=2$.

Though the track length per emulsion averaged 6.5 mm, the only meaningful measurements were relative scattering measurements. The relative scattering was measurable between b–c for 2 emulsions and between b–d, b–e, and d–e for $2\frac{1}{2}$ emulsions using 500- and 1000-μ cells with noise elimination. The relative scattering angles per 100μ ($\bar{\alpha}_{xy}$) are given in Table I.

$$\bar{\alpha}_{xy}=k[(Z_x/A_xP'_x\beta_x)^2+(Z_y/A_yP'_y\beta_y)^2]^{\frac{1}{2}},$$

where $A_x=M_x/M_{\text{nucleon}}$ and $P_x'=P_x/A_x$. In Table II we give in radians the horizontal (H) and vertical (V) components of the angles between the tracks (θ_{xy}).

Though it is in principle possible from our data to determine the individual $\bar{\alpha}_x$, the values are not too meaningful unless these are of comparable magnitude. The most precisely determined value is $\bar{\alpha}_d$, leading to $P_dc=2.76\pm0.7$ Bev. Since $I_d/I_0=0.92\pm0.04$, d must be a proton.[1] In addition, the similarity of $\bar{\alpha}_{b-d}$ and

Table I. Relative scattering angles in degrees per 100μ between the tracks a, b, c, d, and e.

	b–c	b–d	b–e	d–e
$100\bar{\alpha}$	0.326±0.09	1.052±0.28	0.43±0.12	0.98±0.26

$\bar{\alpha}_{d-e}$ imply that $(Z/M)_e\leqslant\frac{1}{2}$ if P_b' and P_e' are not appreciably less than P_d; this is verified by the similarity of $\bar{\alpha}_{b-c}$ and $\bar{\alpha}_{b-e}$. Since $I_e/I_0=0.87\pm0.04$, we conclude that e is either a deuteron or triton. With the further assumption of comparable momenta per nucleon for b, c, and e, we obtain $2.8\leqslant P'c(\text{Bev})\leqslant7.5$. These values are consistent both with the angular distribution of the Li star and the angle θ_{bc}.

We may characterize the possible reactions for this event as follows:[2]

$$\text{Be}^9+\text{“}p\text{”}(\text{“}n\text{”})\rightarrow\text{Li}^{6(7)}+\text{He}^{4(3)}+(\pi^-);$$
$$\text{He}^{4(3)}+\text{“}n\text{”}\rightarrow\text{H}^1+\text{H}^{3(2)}+n;\quad(1)$$

$$\text{Be}^9+\text{“}p\text{”}(\text{“}n\text{”})\rightarrow\text{Li}^{6(7)}+\text{He}^{*4(3)}+(\pi^-);$$
$$\text{He}^{*4(3)}\xrightarrow{\text{decay}}\text{H}^1+\text{H}^{3(2)};\quad(2)$$

$$\text{Be}^9+\text{“}p\text{”}(\text{“}n\text{”})\rightarrow\text{Li}^6+\text{He}^3+n+(\pi^-);$$
$$\text{He}^3+\text{“}n\text{”}\rightarrow\text{H}^1+\text{H}^2+n;\quad(3)$$

$$\text{Be}^9+\text{“}p\text{”}(\text{“}n\text{”})\rightarrow\text{Li}^6+\text{He}^{*3}+n+(\pi^-);$$
$$\text{He}^{*3}\xrightarrow{\text{decay}}\text{H}^1+\text{H}^2.\quad(4)$$

Here “p”(“n”) means a proton or neutron of the target nucleus and He* an excited state. Reactions (1) and (2) are pickups while (3) and (4) are charge exchange. Though it is impossible to rule out completely a nuclear interaction as the cause of the He breakup, the observed coplanarity tends to favor the occurrence of a decay in flight with a time τ in the rest system satisfying $0.6\times10^{-11}\leqslant\tau(\text{sec})\leqslant1.6\times10^{-11}$. Assuming that a two-

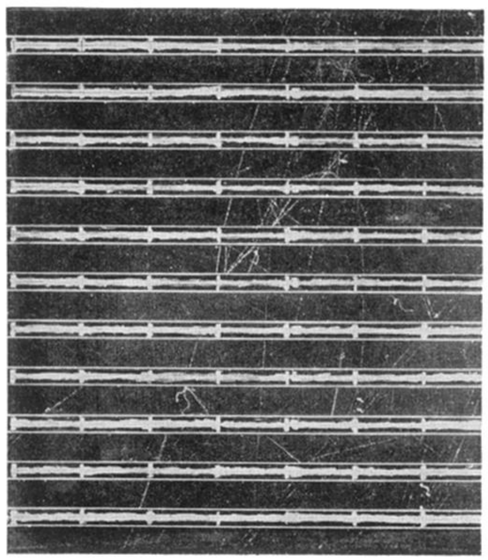

FIG. 1. Cloud-chamber photograph of the cosmic-ray event.