# Evidence for Multiple Meson and $\gamma$-Ray Production in Cosmic-Ray Stars

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In a survey of electron sensitive Kodak NTB3 plates flown at an altitude of 100,000 feet we have observed a collision of an extremely energetic primary cosmic-ray alpha-particle with a heavy nucleus (Ag or Br) of the emulsion; this collision gives rise to a very narrow penetrating shower core of some 23 relativistic singly charged particles, this core being surrounded by a more diffuse shower of 33 relativistic particles (Fig. 1). In addition, 18 non-relativistic heavy particles, carrying at least 23 units of charge and a total energy of $\sim$3 Bev, emerge from the star at the origin of the shower.

The dense core ($C$) of the shower of relativistic particles, the majority of which are assumed to be mesons, has a total projected angular spread of 2.5°. The axis of this core is an exact continuation of the direction of the incident $\alpha$-particle. The core is so dense that not all individual tracks are resolvable in the immediate vicinity of the star. At larger distances where resolution is possible all these tracks prove to be minimum ionization tracks. By counting over a given distance the number of grains in the core and dividing by the number of grains of a minimum ionization track we obtain $N_0^{(e)}=23\pm2$ as estimates of the number of charged relativistic particles in the narrow shower.

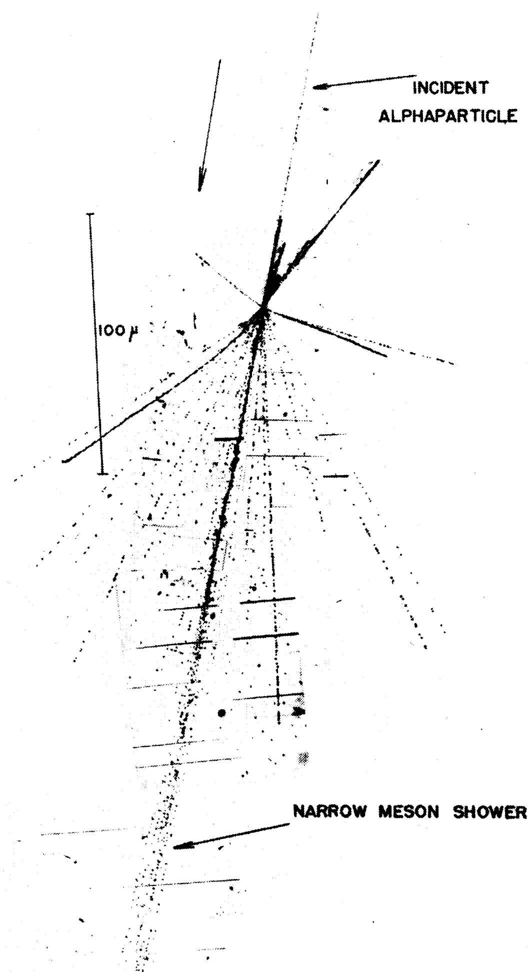

FIG. 1. Incomplete photo-micrograph (slightly retouched) of the shower. (Only a small fraction of the heavy prongs are shown.)

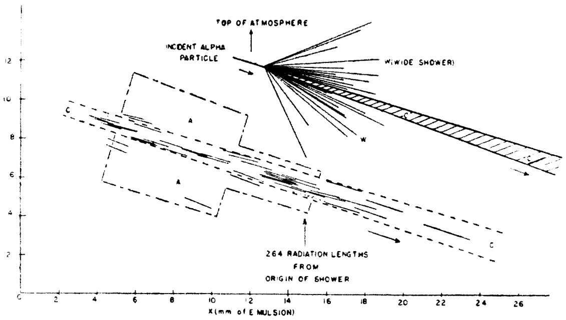

FIG. 2. Schematic diagram of the appearance of the shower in the first and second emulsions.

The region where the narrow shower $C$, after passage through some 2-cm glass penetrates the next plate of the stack (the dotted area $C$ of 0.25 cm² in Fig. 2) was surveyed for tracks of such length and orientation that they can be assumed to be caused by the explosion; 44 tracks of relativistic particles were found, 38 inside and six near the edge of the dotted cone $C$, that is 11 more tracks than were originally contained in the narrow shower. In surveying an additional area $A=0.29$ cm² for tracks satisfying identical criteria only six more tracks were found, all but one lying very close to the core and probably also belonging to the shower. We conclude that considerable multiplication of singly charged relativistic particles (electrons) has occurred in the core. Two electron pairs of energies $\sim$10 Bev and $\sim$50 Bev (as estimated from the magnitude of the very small angles between the two tracks of the pair)[1,2] were created in the emulsions of both the first and the second plate. One of the pairs within the core gives rise to another pair; this fact supports the assumption that the additional charged particles appearing in the narrow core are fast electrons produced by high energy $\gamma$-rays (or possibly other neutral particles).

At least eight and probably about ten pairs are created in the core over an average path length of 0.26 radiation units of glass and emulsion; the number of $\gamma$-rays in the core must therefore at least be equal to $N_c^{(\gamma)}\sim35$.

The energy $E=4\gamma$ Mc² of the primary $\alpha$-particle can be estimated from the angular width of the narrow core:

$$\Delta\theta\sim\frac{1}{8}=(1-\bar{\beta}^2)^{\frac{1}{2}}=\left(\frac{2}{\gamma+1}\right)^{\frac{1}{2}}\sim\frac{1}{30},\quad \gamma=2000,\quad E_\alpha=0.8\times10^{13}\text{ ev.}$$

($\bar{\beta}$ = velocity of the center of mass system of a nucleon of the incident $\alpha$-particle and a nucleon of the target nucleus.)

A more detailed study shows that the value of $\gamma$ obtained from the angular distribution of mesons in the core $C$ does not vary too much if different not too extreme assumptions concerning the energy distribution of the mesons emitted isotropically in the center-of-mass system are made.* The average separation of tracks in the second plate indicates that the average $\gamma$-ray energy cannot be greatly in excess of 10 Bev. It is most probable that three or four nucleons of the incident $\alpha$-particle contribute to the narrow shower. Hence, if the $\gamma$-rays result from the decay of neutral mesons, whose numbers do not exceed the number of charged mesons, the collision leading to the narrow shower should not be considered to be completely inelastic, since a completely inelastic collision (with $\gamma=2000$) would give an average $\gamma$-energy of $\sim$50 Bev.

Unless we assume an extremely anisotropic angular distribution of mesons in the c.m. systems (emission within a double cone of opening $\vartheta\sim1/\bar{\gamma}$), the diffuse shower of $\sim$30 relativistic particles cannot result directly from the primary encounter producing the narrow core. We thus conclude that the diffuse shower is the result of secondary and tertiary meson production in the same nucleus by some of the nucleons emerging from the primary encounter.[3] To summarize we conclude that the event described (which may be the initial stage of development of an Auger shower) gives direct evidence for the multiple production of high energy $\gamma$-rays. If the $\gamma$-rays result from the decay of a neutral meson of rest mass $\sim$150 Mev (see following letter) we can, by assuming that the $\gamma$-rays are converted immediately into electron pairs, obtain an upper limit for the proper lifetime of the neutral meson of $\tau_0 \lesssim 10^{-13}$ sec.

A more detailed report will appear in the Helvetica Physica Acta. This work was assisted by the Joint Program of the ONR and the AEC.

We are greatly indebted to Dr. R. E. Marshak for many valuable discussions.

* The above energy estimate is reduced by a factor seven if an angular distribution $f(\vartheta) \sim \cos^4\vartheta$ is assumed in the c.m. system.

[1] M. Stearns, Phys. Rev. **76**, 836 (1949).
[2] H. S. Snyder and W. T. Scott, Phys. Rev. **76**, 220 (1949).
[3] L. Leprince-Ringuet *et al.*, Comptes Rendus **229**, 163 (1949).

## Remarks on Multiple Meson and Gamma-Ray Production

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LEPRINCE-RINGUET *et al.*[1] have supplied strong evidence for the multiple production of mesons by their observation in electron-sensitive plates of a cosmic-ray star with 55 prongs of which 28 were minimum ionization tracks. Their analysis of the angular distribution of the minimum ionization tracks led to an estimate of the energy of the event ($\sim 10^{10}$ ev) and to the reasonable hypothesis that plural as well as multiple production of $\pi$-mesons had taken place. The latest star observed by Kaplon, Peters, and Bradt (see preceding letter) with its 74 prongs and 56 minimum ionization tracks is not only much more energetic (by a factor[2] of 100–1000) but supplies definitive evidence for pluro-multiple production of $\pi$-mesons (assuming that the minimum ionization tracks do not represent to any appreciable extent electrons or as yet unknown particles[3]).

The real novelty of the R(ochester) star lies not so much in its clear-cut evidence for multiple charged particle production but in its strong evidence for multiple neutral particle production in high energy nucleon-nucleon collisions. The fact that very close charged pairs (most probably electrons) are observed to originate in the emulsion within the narrow core and that appreciable charged particle multiplication takes place over a sizeable fraction of a radiation length (in the glass plate between the two emulsions) favors a gamma-ray origin for these charged particles.[4] The number of high energy gammas required to explain the observed number of electron pairs in the narrow core is very large and comparable to the number of charged particles observed initially in the narrow core. Direct nucleonic production of the gammas (bremsstrahlung) is therefore certainly excluded if the charged $\pi$-mesons possess spin zero and probably even if they possess spin one.[5]

If the analysis of the $R$ star is combined with the results of the Berkeley experiments[6] on high energy gamma-rays, the most likely picture which emerges is as follows: the high energy gamma-rays originate in both experiments from the rapid decay of a neutral meson with a mass of about 300 electron masses. The upper limit on the lifetime ($\sim 10^{-13}$ sec.) obtained from the $R$ star favors a spin zero neutral meson[7] as does the excellent agreement found for the gamma-ray curves in the Berkeley experiment for the forward and backward directions on the assumption of two gamma-rays arising from a neutral meson decay.[8] The rough agreement found between the gamma-ray yields and the charged meson yields[9] at Berkeley and that found between the number of charged mesons and number of gamma-rays in the $R$ star also favor the neutral meson hypothesis. The high multiplicity of gamma-rays found in the $R$ star ($N \sim 10$ for a nucleon energy $E_0 \sim 10^{12}$ ev) may, when extrapolated according to an $E_0^{\frac{1}{4}}$ variation and combined with the expected increase in the number and energy of the gammas towards the center of the angular aperture defined by $(2M/E_0)^{\frac{1}{2}}$ (on the basis of a neutral meson origin), explain the failure of several experimenters[10] to find multiple cores in the large Auger showers. Indeed, the analysis of the decoherence curves in the latter experiments may throw interesting light on the angular and energy distribution of the neutral mesons (and therefore of all mesons) in the original nucleon-nucleon collision responsible for the Auger shower.

Once the neutral meson hypothesis is accepted, the electron pairs supply an approximate measuring scale for the meson energies which enable one, together with the angular distribution in the laboratory system of the charged mesons, to test various theories[11] about the primary nucleonic meson-producing collision. Thus, Kaplon, Peters, and Bradt have shown that it is very difficult to reconcile all features of their star with the assumption of isotropy of the produced mesons in the c.m. system of the nucleons and total inelasticity of the collision. This conclusion does not depend sensitively on the assumed energy spectrum of the mesons in the c.m. system. While the $R$ star is only one event, the statistics are nevertheless good and it does appear that a pseudoscalar meson theory (for both charged and neutral mesons), in which the singularities are taken less seriously than in the Low paper[11] (see, however, p. 136) will lead to the lowering of the predicted multiplicity and to deviations from isotropy and total inelasticity which seem necessary for the actual situation.

[1] LePrince-Ringuet, Bousser, Fong, Jaundeau, and Morellet, Comptes Rendus, **229**, 1 (1949); see also Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. **307**, 862 (1949).
[2] See preceding letter; we shall use the value $10^{12}$ ev per nucleon for our rough estimates.
[3] A small fraction may be relativistic protons.
[4] A neutral meson decaying directly into an electron pair is very unlikely in view of the Berkeley experiment and the theoretical predictions on the lifetime of such a process.
[5] L. I. Schiff, Phys. Rev. **76**, 89 (1949); using Schiff's notation, $W = 0.003$ for a meson of spin zero and an energy of 1.5 Bev (approximate average energy of mesons in the $R$ star) in the c.m. system, whereas $W = 0.05$ for a spin one meson with the same energy. The sensitive dependence of the vector formula on the energy makes the exclusion of a vector charged meson origin less decisive.
[6] Bjorkland, Crandall, Moyer, and York, Phys. Rev. (to be published).
[7] R. J. Finkelstein, Phys. Rev. **72**, 415 (1947) found a lifetime of $2 \cdot 10^{-11}$ sec. for the decay of a vector neutral meson into three gammas and $10^{-16}$ sec. for the decay of a pseudoscalar meson into two gammas. J. Steinberger (Phys. Rev. **76**, 1180 (1949)) has recalculated the lifetimes using Pauli regulators and finds $10^{-3}$ sec. for a vector meson and $10^{-14} - 10^{-10}$ sec. for spin zero mesons. If Steinberger's values are correct, the Berkeley experiment would exclude the vector neutral meson (a conclusion already reached by Steinberger); if Finkelstein were correct, the $R$ star would have to be invoked to exclude the vector neutral meson.
[8] I am indebted to Mr. M. Kaplon for computing the gamma-ray curves; the same calculation was performed at Berkeley by Mr. T. Taylor.
[9] C. Richman (private communication).
[10] R. W. Williams, Phys. Rev. **74**, 1689 (1948) and Cocconi, Tongiorgi, and Greisen, Phys. Rev. **76**, 1020 (1949). Williams finds that the cores are less than a meter apart for $E \sim 10^{16}$ ev which would be consistent with an angular aperture of $(2M/NE_0)^{1/2} \sim 4 \cdot 10^{-5}$ in place of $(2M/E_0)^{1/2} \sim 6 \cdot 10^{-4}$, especially if the number-energy variation of the gammas in the core is taken into account. I wish to thank Professor Greisen for a useful conversation on this point.
[11] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948); see also W. Heisenberg, Nature **164**, 65 (1949).

## Magnetically Biased Transistors

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PUBLISHED data by Bardeen and Brattain[1] on semiconductor amplifiers indicate considerable reduction in the value of $\alpha(\Delta I_{\text{collector}}/\Delta I_{\text{emitter}})$ at frequencies above 4 Mc. Recent experiments at the Naval Ordnance Laboratory have led to the discovery of new physical principles which substantially extend this range. The principal cause associated with the loss of gain at

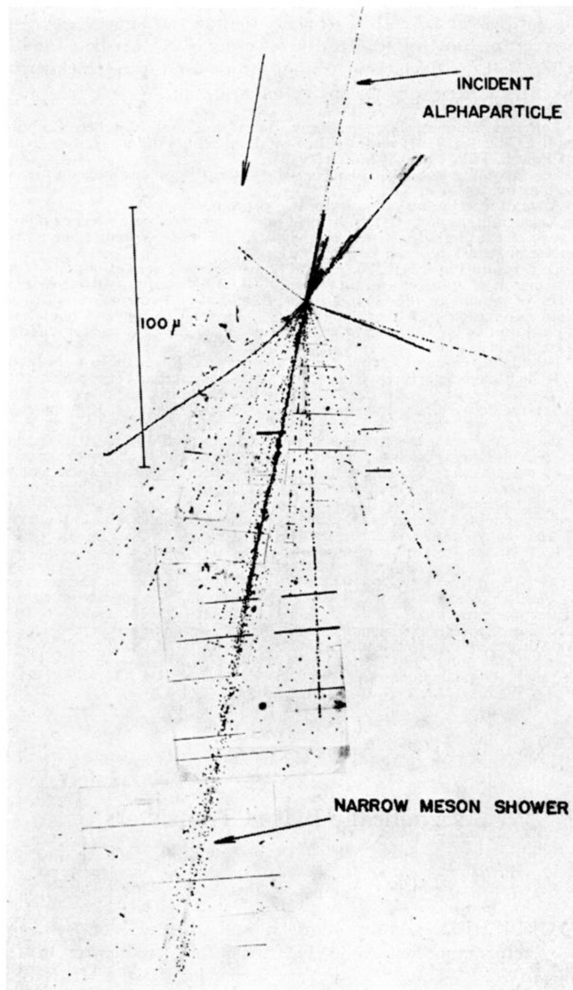


FIG. 1. Incomplete photo-micrograph (slightly retouched) of the shower. (Only a small fraction of the heavy prongs are shown.)