Cosmic-Ray Induced Nuclear Disintegrations at 11,000 Meters*

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The equivalent absorption depth in air of the star-producing radiation is determined as 125±8 g/cm² by means of the photographic emulsion technique. The energy spectrum of alpha-particles emitted in nuclear disintegrations is obtained. It is found that the fraction of the number of stars with given prong number to the total number of disintegrations is not strongly dependent upon altitude up to elevations of 11,000 m. The contribution of different cosmic-ray particles to star production is discussed. Electrons, photons, and light mesons are ruled out as the major agency for star production from consideration of their altitude dependence, π-mesons from consideration of lifetime and momentum. The results are shown to be consistent with the assumption of neutrons as the main star-producing agency. However, the fact that the penetrating showers also decrease exponentially with an absorption depth of 123 g/cm² suggests that the star-producing particle may be a by-product of penetrating showers, in which case the absorption depth of 125 g/cm² would be a measure of the creation rather than of the absorption of the star-producing radiation.

I. INTRODUCTION

MEASUREMENTS of the absorption of the radiation producing nuclear disintegrations in the atmosphere have been shown by various investigators to follow an exponential law of decrease with atmospheric depth. The first determination of the mean range of this radiation in air by Wambacher[1] gave a value of 80 g/cm² and based on these measurements Bagge[2] concluded that the electron-photon component was responsible for star production. Later investigations[3,4] showed Wambacher's value to be too low and yielded values in the neighborhood of 150 g/cm². In this paper measurements on the altitude variation of cosmic-ray induced nuclear disintegrations have been carried out by means of the photographic emulsion technique and an attempt has been made to draw from the results conclusions concerning the nature and origin of the star-producing radiation.

II. EXPERIMENTAL PROCEDURE

Kodak NTB plates and Ilford nuclear research plates of Type B1 and C2 wrapped in photographic black paper and packed in cardboard boxes were exposed to cosmic radiation on a series of B-29 flights from Inyokern, California, at altitudes ranging from 7000 m to 11,000 m. During the flight time, which was varied from one to ninety hours, the cabin of the plane was temperature-controlled. For each plate exposed at high altitude, control plates from the same batch were left at sea level on the roof of LeConte Hall at the University of California in Berkeley for the entire period of exposure. The control plates, wrapped and processed simultaneously with the high altitude plates, provided the basis for the calculation of the intensity of star production at sea level. Data for intermediate elevations were obtained from plates exposed on Mt. Evans, Colorado, at 4160 m. A 4-mm apochromatic objective and 10× compensated eyepieces (magnification 450) were used in scanning the developed plates.

A star was defined as a nuclear disintegration in which two or more ionizing particles were ejected; however, two particle events were counted as stars only if the interpretation as a large angle scattering of a single particle could be excluded with certainty. The total number of stars counted was about 10,000. An effective elevation of exposure was calculated for each plate by averaging the time spent at each altitude, taking into account the exponential increase shown by the star-producing radiation; the high altitude data were corrected for background as obtained from the control plates. Let r_0 and r_h be the rates of star production in number per hour per cc of emulsion at sea level and at an altitude h; then the relative rate of star production between the two elevations is defined as: $R=r_h/r_0$.

III. RESULTS AND DISCUSSION

While the emphasis of the experiment was on the altitude dependence of the star-producing radiation, a study was made of the charged particles emitted in nuclear disintegrations. To this end it was necessary to identify the star particles; since fast charged particles moving through the emulsion lose energy mainly by ionization, the identification of the particles can be based on their rate of energy change and multiple scattering. Once the particle was identified its energy was obtained from known range energy relations for the emulsion. Mesons, protons, deuterons, alpha-particles, and heavier fragments were identified as the particles which are emitted in star processes.

The energy spectrum of alpha-particles emitted from stars is reproduced in Fig. 1. It shows a pronounced maximum at about 6 Mev and the existence of a lower energy limit at 3 Mev, below which the particle cannot leave the nucleus except by leakage through the potential barrier.

* Assisted by the Joint Program of the ONR and the AEC.
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[1] G. Stetter and H. Wambacher, Physik. Zeits. **40**, 702 (1939).
[2] E. Bagge, Ann. d. Physik **39**, 512 (1941).
[3] E. P. George, Nature **162**, 333 (1948).
[4] D. H. Perkins, Nature **160**, 707 (1947).

The composition of the charged particles emitted in stars remained essentially unaltered from sea level to 11,000 m. The ratio of the number of alpha-particles and heavier fragments to the number of protons and deuterons was found to be about unity throughout this altitude range for stars with a number of tracks less than five.

The relative number of disintegrations with a given prong number for plates exposed at different altitudes shows no significant variation with altitude for stars of three or more prongs. This can be seen from Fig. 2 where the number of stars with prong number $N > n$ is plotted logarithmically *versus* n. This number depends exponentially on n.

An inference from the relative composition of stars concerning the energy of the star-initiating radiation is not warranted since Gardner[5] has shown that the prong number is only weakly dependent on the energy of the star-initiating radiation. But the similarity of the star distribution at various altitudes is an indication that the relative energy distribution of the star-producing radiation does not vary essentially with altitude.

It is difficult to assign an absolute value to the number of disintegrations occurring per cc of emulsion per hour due to large fluctuations in the sensitivity of the photographic emulsion. It can only be said that the number of stars with two or more prongs lies at sea level between three and six per cc per hour, depending on the type of plate used. The rate of star production was found to increase rapidly with increasing elevation. The ratio (R) of the number of stars at various elevations to the corresponding number at sea level, computed as indicated previously, is plotted as a function of atmospheric depth in Fig. 3. It can be seen from the graph that the decrease of star production is an exponential function of atmospheric depth, with an absorption depth of 125 ± 8 g/cm^2.

The number of heavy particle tracks found in the emulsion showed an exponential decrease with atmospheric depth similar to that of stars; the equivalent absorption depth was determined at 133 ± 7 g/cm^2. It is slightly higher than the absorption depth for stars but its agreement with the latter within 10 percent suggests that the majority of the single tracks found in the photographic emulsion originate in nuclear disintegrations produced in the neighborhood of the photographic plate.

Experiments with the Berkeley cyclotron have shown that several different particles can produce nuclear disintegrations provided they have sufficient energy. However, as shown below, it will be possible to rule out certain components of the cosmic radiation from any major contribution to star production.

The electron-photon component of the cosmic radiation increases by a factor of 100 between sea level and

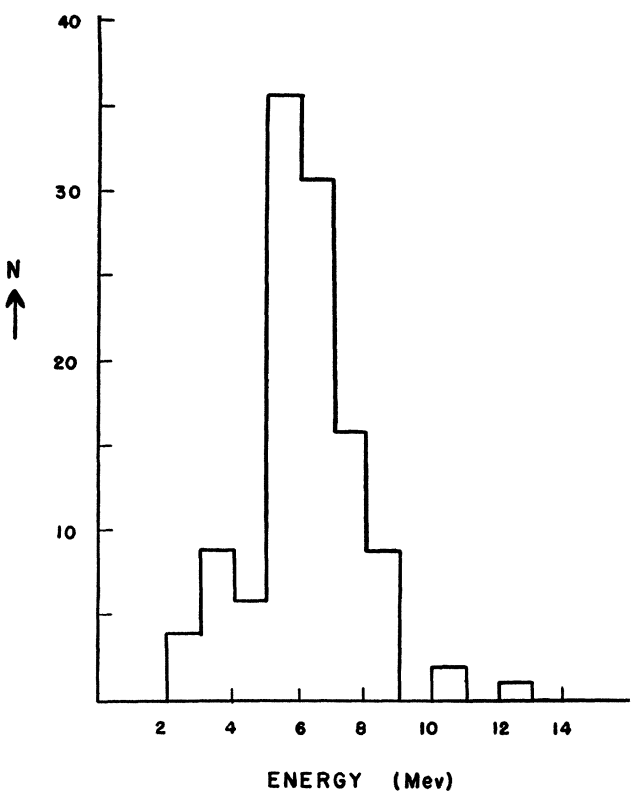

FIG. 1. The energy spectrum of alpha-particles emitted in nuclear disintegrations at sea level.

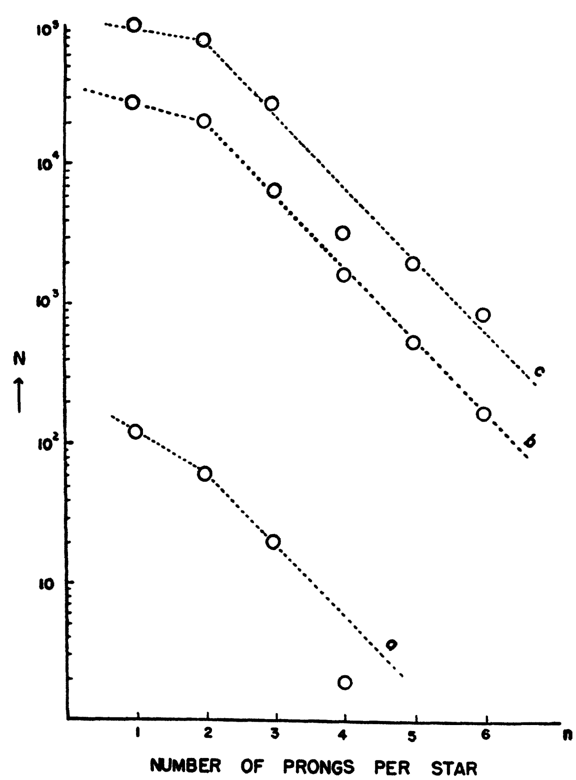

FIG. 2. Number of stars (N) per cc per day with prong number greater than n as a function of n. (a) sea level, (b) 7870 m, (c) 11,300 m.

[5] E. Gardner and V. Peterson, Phys. Rev. **75**, 364 (1949).

11,000 m, while the star intensity increases by a factor of 790±237 between the same elevations. Moreover, experiments performed by George and Jason[6] under different thicknesses of lead failed to show any transition curve for the star-producing radiation comparable to that of electrons. The contribution of the electron-photon component to star production is therefore of minor importance.

The relative intensity of μ-mesons increases by a factor of 30 between sea level and 11,000 m. It appears therefore from this and other experiments[7] in which no star-initiating particle could be identified with μ-mesons that light negative mesons do not take part in star production.

Since π-mesons decay with a mean life of 10^{-8} sec., their mean free path before decay can be made comparable to the mean free path for star production of the order of 100 g/cm^2 only by assigning to the mesons a momentum of the order of 5×10^{10} ev/c. Such an assumption is not justified; π-mesons, therefore, unless locally produced, cannot be a major factor in star production.

Perkins[4] has suggested that neutral mesons may be responsible for star production. If this be the case, it is possible to obtain an estimate of the minimum mean lifetime of this particle from consideration of the absorption depth of the star-producing radiation. The absorption depth of 125 g/cm^2 in air corresponds to a range, L, of about 10^6 cm at sea level and increases with increasing elevation. If, for a first estimate, the absorption of neutral mesons by star production is considered small as compared with their attenuation by decay, then the range of 10^6 cm corresponds to the mean free path of the particle before decay. The mean lifetime is then $\tau=Lm/P$. It is reasonable to assume that the momentum spectrum of the neutral meson is comparable to that of the μ-meson; if its momentum is taken to be 10^3 Mev/c and its mass as 150 Mev/c, a lifetime of about 10^{-6} sec. is obtained. This, however, is contrary to preliminary experimental results[8] which are being obtained with the Berkeley cyclotron and which indicate a lieftime of the neutral meson of 10^{-12} sec. or less. The lieftime expected from theoretical considerations[9] is of the same order of magnitude. Thus a lifetime larger by a factor of 10^6 would have to be ascribed to the neutral meson in order to account for the attenuation of star production by meson decay. The order of magnitude of the lifetime remains unchanged if the diminution of neutral mesons by star production is taken into consideration. Bernadini, Cortini, and Manfredini[10] have measured the absorption depth of the star-producing radiation in aluminum as 166 g/cm^2.

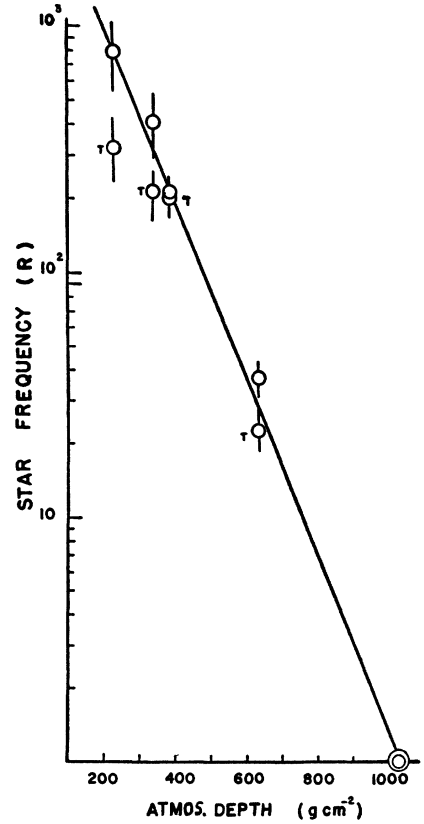

FIG. 3. Ratio (R) of the number of cosmic-ray events at various altitudes to the corresponding number of events at sea level. ○ stars, T single tracks.

From this value and the value of 125 g/cm^2 reported here, calculations carried out analogous to the determination of the decay time of μ-mesons by Rossi, Hilberry, and Hoag,[11] give a mean range of 6×10^5 cm for the neutral meson. This gives again a life time of the order of 10^{-6} sec. Both results seem sufficient to discard the assumption of neutral mesons as the star-producing agency.

Disregarding any radiation as yet unknown, the proton-neutron component remains as the only radiation that has not been discussed with regard to star production. If it is assumed that protons and neutrons are generated in equal numbers and have equal cross sections for star production, the majority of nuclear disruptions will be caused by neutrons since most protons will be stopped by ionization losses before they have a chance to produce a nuclear disintegration. This reasoning is borne out by the large number of nuclear disintegrations observed in cloud chambers where no ionizing particle initiating the disruption could be detected. The hypothesis that neutrons are the star-producing radiation is compatible with measurements by Hildebrand and Moyer[12] who found a value of 95

[6] E. P. George and A. C. Jason, Proc. Phys. Soc. London **A62**, 243 (1949).
[7] W. M. Powell, Phys. Rev. **69**, 385 (1946).
[8] Private communication.
[9] R. J. Finkelstein, Phys. Rev. **72**, 415 (1947).
[10] Bernadini, Cortini, and Manfredini, Phys. Rev. **74**, 1878 (1948).
[11] Rossi, Hilberry, and Hoag, Phys. Rev. **57**, 466 (1940).
[12] R. Hildebrand and B. J. Moyer, Phys. Rev. **72**, 1258 (1947).

g/cm^2 for the mean free path for nuclear interactions of 90-Mev neutrons.

The foregoing considerations indicate that if the star-producing radiation comes from the top of the atmosphere then it consists largely of neutrons. If on the other hand, it is created throughout the atmosphere, then the measured absorption depth of 125 g/cm^2 is in reality a measure for the decrease of the creation of the star-producing radiation. In this connection the absorption depth of 123 ± 10 g/cm^2 obtained by Fretter[13] for penetrating showers is significant and suggests that star and penetrating shower production are related phenomena. The fact that slow protons and neutrons are produced abundantly in penetrating showers is further evidence for this assumption. This would mean that the absorption depth of 125 g/cm^2 is not the mean free path for star production but rather measures the creation of star-producing radiation.

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[13] W. B. Fretter, Phys. Rev. **76**, 511 (1949).

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Avalanche Transformation during Breakdown in Uniform Fields

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The transformation of the avalanche into an anode-directed streamer is considered in the case of uniform field gaps, submitted to minimum breakdown voltage.

I. INTRODUCTION

BREAKDOWN voltages or field strengths can be calculated with a satisfactory accuracy by means of Meek[1] or Raether[2] equations. Results in the case of uniform field are compiled in Table I. In accordance with Meek's mechanism, after crossing the gap the avalanche electrons are laid on the anode, the remaining positive ion charge causing an additional field

$$X_1 \sim 5.27\times10^{-7}\frac{\alpha e^{\alpha x}}{(x/p)^{\frac{1}{2}}}. \tag{1}$$

Breakdown occurs when, for $x=d$, field $X_1=KX_s$ (X_s the applied field, K a numerical factor between 0.1 and 1). Equation (1) is derived on the assumption of a positive ion density at the anode

$$N_+=(\alpha e^{\alpha d})/(\pi r^2), \tag{2}$$

where

$$r=[0.133(x/p)]^{\frac{1}{2}}, \tag{3}$$

the radius of the avalanche head. Raether computes the radial field at the avalanche head, from the total number of electrons

$$n_-=e^{\alpha x}, \tag{4}$$

concentrated in a sphere of radius r. Equating the radial tip field to the impressed field, Raether obtains

$$e^{\alpha x}=2\times10^8 x, \tag{5}$$

which equation for $x=d$ (or $x=0.8d$) constitutes the breakdown condition.

In spite of the fact that the above conditions can be considered equivalent, as leading to about the same values of breakdown voltages (see Table I), the mechanisms adopted by the authors mentioned above are substantially different. Raether assumes that the avalanche, after crossing at constant velocity ($\sim1.25\times10^7$ cm/sec.) a distance x_k at which $\alpha x_k\sim20$, is transformed into a streamer starting from the tip and progressing to the anode at a higher speed ($\sim8\times10^7$ cm/sec.). At the moment at which this streamer reaches the anode, a rectrograde streamer starts from the anode and crosses the gap at a speed of 1 to $2\cdot10^8$ cm/sec. Meek does not consider the existence of an anode directed streamer and assumes that the avalanche grows regularly until it reaches the anode, the resulting positive charge field causing the formation of the cathode directed streamer.

It is interesting to examine which of the above mechanisms represents more accurately the actual conditions, under minimum breakdown voltage in uniform field, since the transformation of the avalanche into an anode-directed streamer under overvoltages is an experimental fact.[3]

Raether[2] gives a considerable argument on behalf of

[1] J. M. Meek, Phys. Rev. **57**, 722 (1940); L. B. Loeb and J. M. Meek, *The Mechanism of the Electric Spark* (Stanford University Press, Stanford, 1941).

[2] H. Raether, Zeits. f. Physik **117**, 375 (1941).

[3] H. Raether, Zeits. f. Physik **112**, 464 (1939).