Energy Distribution of Neutral Mesons Produced in Cosmic-Ray Stars*

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A cloud-chamber study of the energy distribution of neutral mesons produced in cosmic-ray stars is reported. The cloud chamber contained a NaI scintillation crystal plate and was triggered when a nuclear interaction in the crystal caused a scintillation light pulse. Photons associated with nuclear interactions produced visible soft showers in passing through several lead plates placed below the crystal plate, and their energies are estimated from the sizes of these showers. It is concluded that the majority of photons associated with cosmic-ray stars arise from the usual mode of neutral meson decay, i.e., $\pi^0 \rightarrow 2\gamma$. The energy distribution (differential) of the neutral mesons is given as a power-law spectrum of exponent $\nu = -1.5 \pm 0.2$ for π^0 energy between 400 and 900 Mev and $\nu = -2.7 \pm 0.5$ for π^0 energy between 900 and 2000 Mev. The data are consistent with an extension of the power-law spectrum given above up to a π^0 energy of about 5000 Mev.

I. INTRODUCTION

THE existence of the neutral meson and its decay with a very short lifetime into two photons are well established by a number of experiments[1,2] by the Berkeley group using high-energy accelerator beams. Prior to these machine experiments, however, several cosmic-ray cloud-chamber studies[3] showed that photons are often emitted from energetic nuclear interactions and that these photons could, in many cases, be interpreted in terms of the $\pi^0 \rightarrow 2\gamma$ process.

The first quantitative results on cosmic-ray neutral mesons were obtained by Carlson *et al.*[4] who investigated the properties of photons that materialized in nuclear emulsions exposed at high altitude. In this experiment with nuclear emulsions, it was not possible to determine the origin of individual photons, but the energy spectrum of photons was shown to be entirely consistent with the view that these photons arise from the $\pi^0 \rightarrow 2\gamma$ process. Assuming that the photons arose solely from this process, they deduced the differential energy spectrum of the parent neutral mesons as a power law of exponent -1.5 up to a π^0 energy of about 900 Mev.

Certain aspects of the production and the decay of neutral mesons can be advantageously studied with multiplate cloud chambers: here decay photons materialize in the plates with a good efficiency, and they can be related with very little ambiguity to the particular nuclear interaction that produced the neutral mesons. Thus, with a multiplate cloud chamber, the inference one can make on the parent neutral mesons is much more direct than that, for example, with nuclear emulsions. However, the events observed with a counter-controlled cloud chamber are usually selective in one way or another, and appropriate care must be taken for possible bias effects. In the early cloud-chamber experiments,[3] Geiger counters were placed under the chamber and the selection was biased in favor of high-energy events, especially high-multiplicity cascades.

To minimize selection bias of this kind, Salvini and Kim[5] placed a NaI scintillation crystal plate in their chamber and triggered the chamber whenever the crystal emitted a light pulse of intensity above a certain discrimination level. Since nuclear interactions occuring in the NaI crystal usually emit a number of evaporation particles, they set the discrimination level so that a light pulse induced by one evaporation particle is sufficient to trigger the chamber. In this way they were able to select nuclear interactions in the NaI crystal independently of the number and behavior of the fast charged secondary particles produced in the interactions.

The experiment by Salvini and Kim gave interesting information on the production of neutral mesons, but the statistics were not sufficient to obtain the energy distribution of the neutral mesons. The present experiment is essentially a continuation of that by Salvini and Kim, but it is particularly designed for obtaining the energy distribution of neutral mesons.

To estimate the energy of a photon materializing in a multiplate cloud chamber, one essentially must make use of the size of the shower produced by the photon. The usual method is to count the number of secondary electrons in the shower and from this number infer the energy of the photon that initiated the shower. As is well known, this method is handicapped by the fact that individual showers of a given primary energy fluctuate quite widely around the average size. In the present investigation the fluctuation problem is studied in some detail in the light of the particular characteristics of a multiplate cloud chamber, and a reasonable

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† Now at the Department of Physics, University of Washington, Seattle, Washington.
1 Bjorklund, Crandall, and Moyer, Phys. Rev. **77**, 213 (1950).
2 Steinberger, Panofsky, and Steller, Phys. Rev. **78**, 802 (1950).
3 References to the early cloud-chamber work on neutral mesons are given in reference 5.
4 Carlson, Hooper, and King, Phil. Mag. **41**, 701 (1950).
5 G. Salvini and Y. Kim, Phys. Rev. **88**, 40 (1952).

criterion is adopted in estimating the energies of photons.

II. APPARATUS AND SELECTION OF EVENTS

The apparatus used in the present experiment is in many respects identical to that used by Salvini and Kim[5] and a detailed description can be found in their paper.

The plate assembly and the triggering arrangement for the cloud chamber are shown in Fig. 1. The chamber was triggered by a light pulse from the NaI crystal in coincidence with the discharge of one or more counters of the tray *A* and in anticoincidence with the discharge of any counter of the tray *B*. The light pulse from the crystal was required to exceed an amount corresponding to the energy dissipated by one or more heavily ionizing particles or by 3 to 4 minimum ionizing particles traversing the crystal. With this triggering arrangement, we selected mostly protons and charged pions causing nuclear interactions in the crystal and rejected large air showers by the anticoincidence tray *B*. Since nuclear interactions occuring in heavy elements like Na and I usually emit heavily ionizing evaporation particles, and since no counter is required to discharge under the chamber, the present selection is regarded as independent of the number and behavior of the fast charged particles produced in the interactions. A typical example of the cloud-chamber photographs obtained in the present experiment is shown in Fig. 2. An event of this kind would not have been recorded had we used a selection scheme that requires Geiger counters to discharge under the chamber.

The apparatus was in operation from September, 1952 to May, 1953 at the Inter-Universities High Altitude Laboratory, Echo Lake, Colorado (altitude 10 600 ft). During this period over 10 000 useful pictures were taken with about 15% showing nuclear interactions, or stars, occurring in the NaI crystal. In about 300 stars photon showers emerge from the star origins, and these are classified in Table I according to the number of photon showers associated with each star.

III. ESTIMATE OF PHOTON ENERGIES

In the present experiment, one of the central problems is how to estimate the energy of a photon from the size of the shower it produces. This problem has been investigated by many workers in the past. But the problem is inherently complex, and there exists as yet no agreed method which can be uniquely applied in every situation.

TABLE I. Classification of stars according to the number of photon showers associated with each star.

No. of photon showers in a star	1	2	3	4	5	6	Total
No. of stars	121	121	29	20	6	1	298

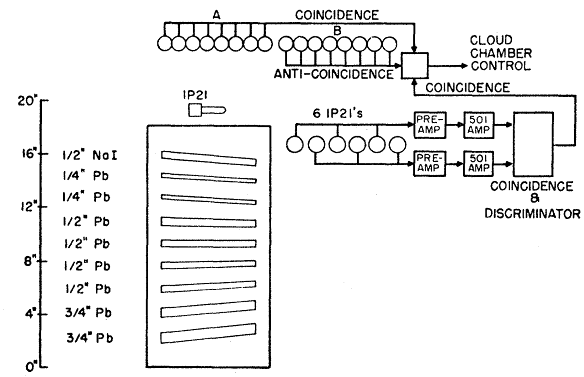

FIG. 1. Plate assembly and triggering arrangement for the cloud chamber.

In general, the shower theory[6] approximately accounts for the average behavior of showers produced by electrons or photons in matter. However, since shower development is a stochastic process, one must also know the fluctuation around the average in order to relate shower development to energy in a statistical way. The study of fluctuation represents a rather difficult mathematical problem, and only relatively recent investigations[7–10] have achieved a partial success in obtaining analytical solutions for the fluctuation. These solutions are, however, quite complicated and difficult to evaluate numerically. Moreover, for showers of low energies (of the order of several hundred Mev) in heavy elements such as lead, many of the physical assumptions made in the theory do not hold well, and the results for both the average and the fluctuation cannot be expected to apply accurately.

Wilson[11] has approached this problem in an empirical way using the Monte Carlo method. In his method, one starts out with a particle (either an electron or a photon) of a given energy and determines its fate in passing through matter of a given thickness by spinning a wheel of chance on which the probability curves for various shower generating processes are drawn. This procedure is repeated at each successive interval of depth until either the particle disappears or its energy is degraded to such a low value that it thenceforth makes negligible contribution to the shower production. Any secondary particle produced on the way is followed in the same manner until all particles in the shower die out. Wilson applied this method to electron and photon initiated showers in lead for energies from 20 to 500 Mev. For each energy he obtained about 100 case

[6] For a general discussion of shower theory, see, for example, B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952).

[7] L. Janossy, Proc. Phys. Soc. (London) **A63**, 241 (1950).

[8] L. Janossy and H. Messel, Proc. Phys. Soc. (London) **A63**, 1101 (1950).

[9] H. Bhabha and A. Ramakrishnan, Proc. Indian Acad. Sci. **32** (1950).

[10] A. Ramakrishnan, Progr. Theoret. Phys. (Japan) **9**, 679 (1953).

[11] R. R. Wilson, Phys. Rev. **86**, 261 (1952).

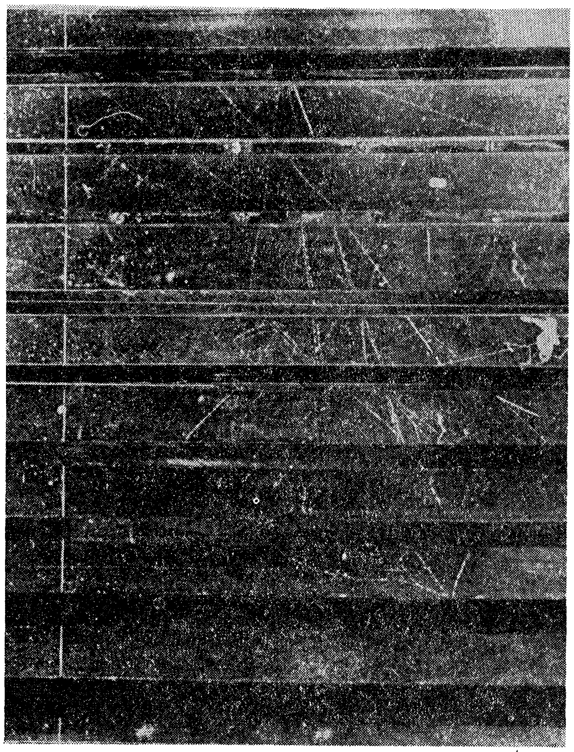

FIG. 2. Example of nuclear interaction in the NaI crystal (the first plate), in which the production of a neutral meson is clearly observed. Both of the two decay photons start shower development at the third plate: the energy of the neutral meson is estimated to be about 1 Bev. In addition, a charged meson of energy about 90 Mev is produced in this event. No charged particle is seen to traverse the chamber completely, and this event would not have been recorded had we used a selection scheme that requires counters to discharge under the chamber.

histories: the statistical accuracy of his data is roughly 10 percent.

The kind of information that can be obtained from Wilson's shower data[12] and is useful in the present application is illustrated in Fig. 3. In this and subsequent treatments of Wilson's shower data, we counted, at each intergral radiation length, secondary electrons of energy greater than 8 Mev.[13] Figure 3(a) shows how the average number of secondary electrons $\bar{n}$ varies with depth t. The plot of $\bar{n}$ *vs* t is usually called a shower curve. Variation in the relative fluctuation,

$$\delta = [\langle (n-\bar{n})^2 \rangle_{Av}]^{\frac{1}{2}}/\bar{n}, \tag{1}$$

is shown in Fig. 3(b). In the same figure is shown for comparison the Poisson fluctuation $\delta_P = 1/(\bar{n})^{\frac{1}{2}}$. If shower particles were genetically independent, one would expect that the values of n of individual showers fluctuate around the average $\bar{n}$ according to Poisson's law. It is of interest to note that at the cascade maximum t_{max}, where the average number of secondary electrons is a maximum, the relative fluctuation is a minimum and close to the Poisson fluctuation, and that the fluctuation tends to increase before and after the cascade maximum. According to the theoretical work of Janossy and Messel,[8] this is a general feature of cascade showers.

The energy of a cascade shower can be estimated from a number of parameters. From the standpoint of a multiplate cloud chamber, the most practical ones are the track length and the cascade maximum, both of which depend on the shower energy approximately linearly. In terms of the shower curve such as given in Fig. 3(a), the cascade maximum represents the height of the curve at t_{max}, while the track length represents the area under the curve. Of the two parameters the track length is undoubtedly preferred from the fluctuation point of view, but to obtain this quantity experimentally one must have the whole shower development available for observation. This condition is difficult to meet in the present experiment since the photons associated with nuclear interactions are generally inclined to the vertical and quite often part of the shower goes out of the illuminated region of the cloud chamber.

In resorting to the cascade maximum, one is faced with larger fluctuations. That is, one must find out, in addition to the energy dependence of $\bar{n}(t_{max})$, how $n(t_{max})$ of individual showers fluctuate around the average. Before going into this problem, however, it

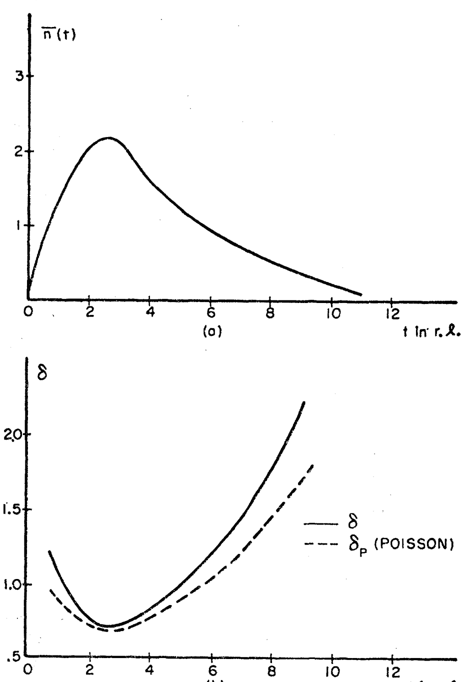

FIG. 3. (a) Average number of secondary electrons as a function of depth t in radiation lengths. (b) Relative fluctuation (full line) and Poisson fluctuation (open line). These figures have been obtained from Wilson's data for 300 Mev photon showers.

[12] The author is greatly indebted to Professor R. R. Wilson for the use of his shower data.

[13] Electrons of energy less than 8 Mev will be scattered randomly in lead and would not contribute significantly to the observable number of secondary electrons. See reference 11.

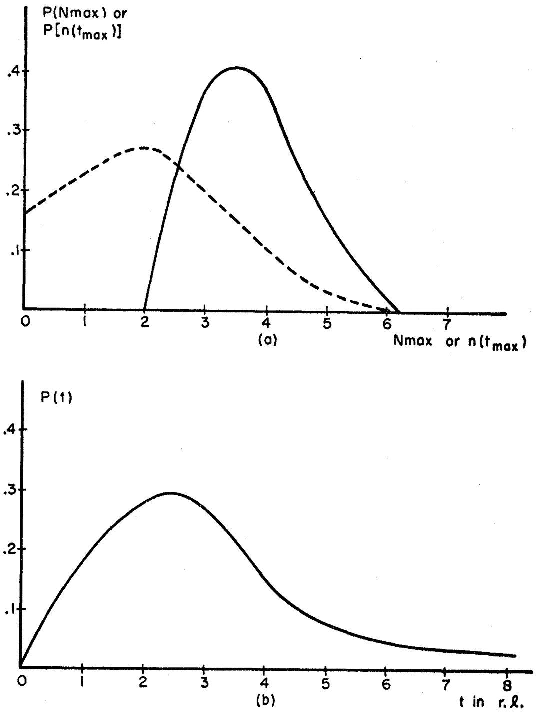

FIG. 4. (a) Distribution in N_{max} (full line) and distribution in $n(t_{max})$ (open line). (b) Distribution in depth t at which N_{max} occurs. These figures have been obtained from Wilson's data for 300-Mev photon showers.

should be pointed out that $n(t_{max})$ is a quantity difficult to obtain in an experiment where one deals with showers of unknown energies. To obtain $n(t_{max})$ one must observe the shower at t_{max}, but t_{max} itself cannot be determined unless the energy is known. In a multiplate cloud chamber one therefore usually observes, instead of $n(t_{max})$, the maximum number of secondary electrons attained in a shower regardless of the depth at which this maximum occurs. Hereafter the maximum so specified will be called an *absolute maximum*, or N_{max}. Hitherto the absolute maximum has not been explicitly distinguished from the cascade maximum,[14] but it turns out quite important to do so, for low-energy showers particularly. As will be illustrated in the following, the significant fact is that the absolute maximum is more desirable as an energy parameter not only from the observational but also from the fluctuation point of view.

Consider showers of a given initial energy, to which definite values of t_{max} and $\bar{n}(t_{max})$ are associated. In an individual shower, the value of $n(t_{max})$ will depend both on the magnitude and on the position of N_{max} of that particular shower. In most cases N_{max} will occur near t_{max}, and the value of $n(t_{max})$ will be close to that of N_{max}. But in some cases N_{max} may occur quite far from t_{max}, and the value of $n(t_{max})$ may be significantly smaller than that of N_{max}. One can therefore regard the fluctuation of $n(t_{max})$ around $\bar{n}(t_{max})$ as arising from two different sources: (a) fluctuation in the values of N_{max}, and (b) fluctuation in the depth at which N_{max} occurs. In order to see these two kinds of fluctuation sources separately, we again consider Wilson's data on 300-Mev photon showers. In each shower the value of N_{max} and the value of t at which N_{max} occurs are obtained. The distribution in N_{max} and the distribution in t are shown respectively in Figs. 4(a) and 4(b). The distribution in $n(t_{max})$ is also shown in Fig. 4(a). One clearly sees that the distribution in N_{max} is relatively narrow, but the distribution in $n(t_{max})$, which is related to both (a) and (b), becomes broad on account of the broad distribution in t. That this is also the case for other photon energies can be seen from Table II. For all energies listed in this table, δ for N_{max} is less than one half of that for $n(t_{max})$. It is thus evident that at these energies the fluctuation associated with the absolute maximum is much smaller than that associated with the cascade maximum.

In a multiplate disposition, one cannot always observe the true N_{max} because it may in some cases be hidden in one of the plates. This fact tends to decrease the observed value of $\bar{N}_{max}$ and increase the value of δ. This point is illustrated in Columns 6 and 7 of Table II, which represent $\bar{N}_{max}$ and δ when the showers are observed at 1, 2, 4, 7, 9, and 11 radiation lengths. This new division of thickness closely represents the plate disposition employed in the present experiment if photons travel essentially vertically in the chamber. For showers inclined to the vertical, $\bar{N}_{max}$ and δ will be respectively smaller and greater than those given here.

At present Wilson's shower data are available up to 500 Mev, and one does not know how $\bar{N}_{max}$ and δ will vary for showers of higher energies. At higher shower energies, however, both N_{max} and $n(t_{max})$ are likely to occur after many stages of shower generating processes, and one would expect that the difference between these two quantities becomes unimportant. For such a region of energy, one would then assume that, in analogy with $\bar{n}(t_{max})$, $\bar{N}_{max}$ is proportional to the energy and the fluctuation is Poissonian.

From the study of Wilson's data (applied to the present plate disposition) for an energy up to 500 Mev,

TABLE II. Average numbers of secondary electrons at cascade maximum and absolute maximum; fluctuations associated with these quantities (obtained from Wilson's shower data).

Photon energy in Mev	Observed at each integral radiation length				Observed at 1, 2, 4, 7, 9, and 11 radiation lengths	
	$\bar{n}(t_{max})$	δ	$\bar{N}_{max}$	δ	$\bar{N}_{max}$	δ
50	0.5	1.6	1.3	0.45	1.0	0.73
100	0.9	1.1	1.9	0.29	1.6	0.45
200	1.5	0.75	2.7	0.33	2.4	0.40
300	2.1	0.70	3.7	0.34	3.1	0.34

[14] W. E. Hazen, Phys. Rev. 65, 67 (1944) actually used the absolute maximum in estimating the shower energy, but he did not clearly distinguish this quantity from the cascade maximum.

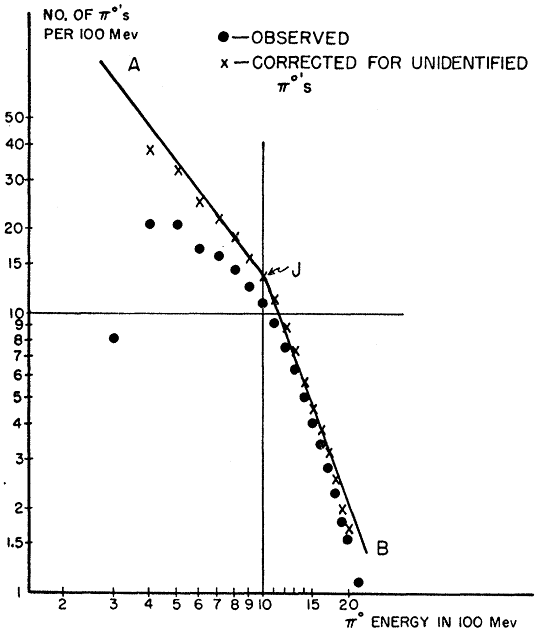

FIG. 5. Energy distribution of identified neutral mesons. The dots indicate the observed values, and the crosses indicate the values corrected for unidentified neutral mesons.

and from the extrapolation of this result to higher energies according to the assumption stated above, we are led to take the following criterion in estimating photon energies: For an observed value of $N_{\max}(\geq 2)$, the energy of the photon will be estimated by $E=KN_{\max}$ with $K=100$ Mev. The fluctuation will be approximated by $\delta=0.5$ for $N_{\max}=2$, 3, and 4; $\delta=1/(N_{\max})^{\frac{1}{2}}$ for $N_{\max}\geq 5$. When the data are treated statistically, it will be further assumed that for an observed value of $N_{\max}$ any value of E between $KN_{\max}(1-\delta)$ and $KN_{\max}(1+\delta)$ is equally probable. The quantity $N_{\max}$ explicitly represents the maximum observable number of fast electrons in the forward half-hemisphere.

IV. RESULTS

A. Energy Distribution of Identified Neutral Mesons

If two or more photon showers are observed to emerge from a star, it is checked whether any pair of these photons satisfies the kinematical relation for the $\pi^0\rightarrow 2\gamma$ decay:

$$(2\sin\tfrac{1}{2}\phi)^2=\epsilon_0^2/E_1E_2. \qquad (2)$$

Here E_1 and E_2 are the energies of two component photons, ϕ is the space angle between the two photons, and ϵ_0 is the rest energy of the neutral meson. A pair of photon showers satisfying this relation is classified as an identified neutral meson. A photon shower which is singly observed in a star or observed together with other photon showers but without a possible π^0 combination is called an isolated photon. Of the total of 566 photon showers observed in the present experiment (see Table I), we obtained 181 π^0 combinations and 204 isolated photons.

For an identified π^0, its energy ϵ is the sum of the energies of two component photons. Since the energy of each photon is given by a distribution which is uniform between two limits, ϵ will be obtained as a distribution of triangular shape if $N_{\max}$'s of two photons are equal and as a distribution of trapezoidal shape if $N_{\max}$'s are different. The energy distribution comprised of 181 identified π^0's is shown in Fig. 5 by the dots. There are 13 π^0's falling in the energy range of 2 Bev to 5 Bev, but these are not shown in the figure because of the limited statistics.

The data given here are subject to a systematic error in that some of the neutral mesons produced from the nuclear interactions in the crystal had escaped detection because one or both of the two decay photons failed to produce visible showers in the chamber. The detection efficiency of a decay photon, that is, the efficiency with which a decay photon produces a visible shower and is detected, depends on the energy and direction of the photon. And it can be explicitly estimated using Wilson's shower data when both the energy and the direction are known. For photons traveling vertically downward, the detection efficiency is estimated in the present plate disposition to be about 50% for 50 Mev, about 90% for 100 Mev, and almost 100 percent for 200-Mev photons. However, when the inclinations of photons from the vertical are also taken into account, the detection efficiency drops to a trifling value for energies less than about 100 Mev. At such low energies, photon showers tend to get absorbed completely in the very plate in which the shower development began, and the detection efficiency decreases very rapidly as the photon inclines from the vertical. Furthermore, decay photons of low energies are emitted with large angles from the direction of the parent neutral meson, and hence, on the average, with large angles from the vertical. We may therefore assume that the detection efficiency of decay photons is zero for an energy less than 100 Mev, but is 100 percent for an energy above this value. Of course, such a sharp transition in the detection efficiency is artificial, but it is considered a sound procedure in the first approximation.

For the $\pi^0\rightarrow 2\gamma$ process, the energy distribution of decay photons $F(E)$ is a constant between two limits $\frac{1}{2}\epsilon(1-\beta)$ and $\frac{1}{2}\epsilon(1+\beta)$ as shown in Fig. 6, where ϵ and βc are respectively the energy and the velocity of the parent neutral meson. Since the lower limit of this distribution is always less than $\frac{1}{2}\epsilon_0=70$ Mev and the observational cutoff takes place at $k=100$ Mev (according to the assumption stated above), decay photons which fall in the shaded area at low-energy end will not be observed. Partners of these unobserved photons, however, fall in the shaded area at high-energy end where the detection efficiency is good, and they will be generally observed as isolated photons. But these partner photons also should be regarded as unobserved insofar as the identification of neutral mesons is concerned. Thus the detection efficiency of a neutral meson of energy ϵ can be given by the ratio of the unshaded area to the total area, or by

$$\rho=[1-(2k/\epsilon)]/\beta. \quad (3)$$

For ϵ greater than about 500 Mev, β is close to 1 and ρ can be approximated by

$$\rho=1-(2k/\epsilon). \quad (4)$$

Now the correct number of neutral mesons (including the unidentified ones) $N(\epsilon)$ can be obtained from the observed number $N'(\epsilon)$ by

$$N(\epsilon)=N'(\epsilon)/\rho. \quad (5)$$

The values of $N(\epsilon)$ so obtained are shown in Fig. 5 by the crosses. The corrected points seem to lie approximately on straight lines. There is an apparent change in slope at point J which corresponds to an energy of about 1000 Mev. The points are divided into two groups; one for an energy less than 1000 Mev and the other for an energy above this value. The slopes of the best-fit straight lines are found to be

$$JA: \nu=-1.3\pm0.3, \qquad JB: \nu=-2.7\pm0.7. \quad (6)$$

The energy distribution in the range greater than 2000 Mev cannot be obtained with confidence because of the limited statistics, but the data available are consistent with the continuation of the above power law up to an energy of about 5000 Mev.

B. Energy Distribution of Isolated Photons

According to the correction procedure used above, decay photons which fall in the shaded area at the high-energy end of Fig. 6 should appear in the chamber as isolated photons. Since we now know the distribution of unidentified neutral mesons, the energy distribution of isolated photons resulting from these unidentified neutral mesons can be explicitly calculated and can be compared with the distribution of isolated photons that are actually observed in the chamber.

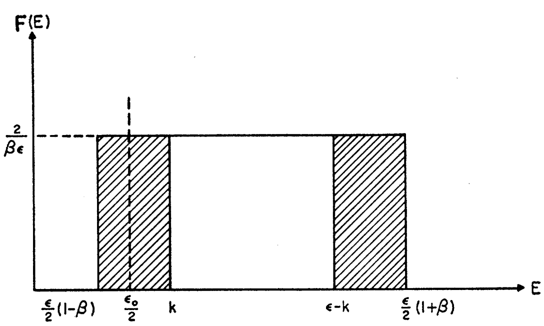

FIG. 6. Energy distribution of decay photons arising from a $\pi^0-2\gamma$ process.

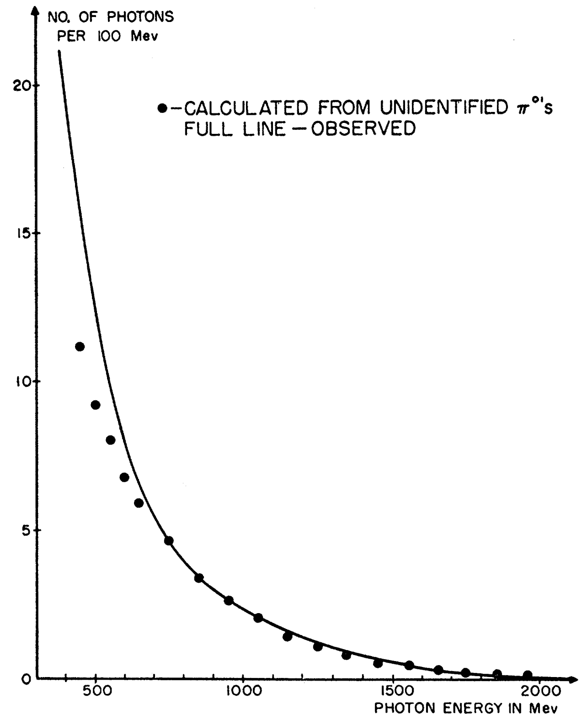

FIG. 7. Energy distribution of isolated photons. The full line is the distribution of isolated photons observed in the chamber, and the dots indicate the distribution calculated from unidentified neutral mesons.

Let $M(\epsilon)=N(\epsilon)-N'(\epsilon)$ be the distribution of unidentified neutral mesons and $I(E)$ be the distribution of the isolated photons which results from $M(\epsilon)$. An unidentified π^0 of energy ϵ contributes to $I(E)$ in the range of E between $\epsilon-k$ and $\frac{1}{2}\epsilon(1+\beta)$ with intensity $1/\Delta(\epsilon)=1/[\frac{1}{2}\epsilon(1+\beta)-(\epsilon-k)]$. For a given value of E, $I(E)$ is then obtained from the integration

$$I(E)=\int_{\epsilon_1}^{\epsilon_2}\frac{M(\epsilon)d\epsilon}{\Delta(\epsilon)}, \quad (7)$$

where ϵ_1 and ϵ_2 are related to E by

$$E=\tfrac{1}{2}\epsilon_1(1+\beta_1), \quad \text{and} \quad E=\epsilon_2-k.$$

In the energy range where $\beta_1=[1-(\epsilon_0/\epsilon_1)^2]^{\frac{1}{2}}$ is close to 1, we may use the approximation

$$I(E)=\int_E^{E+k}\frac{M(\epsilon)d\epsilon}{k}\simeq M(E+\tfrac{1}{2}k). \quad (8)$$

The values of $I(E)$ calculated from (7) and (8) are shown in Fig. 7 by the dots. In the same figure, the full line indicates the distribution of the isolated photons that are actually observed in the chamber. The two distributions seem to be in good agreement both in shape and in magnitude. Such a striking agreement is rather fortuitous in view of the limited statistics; nevertheless, it indicates that the correction procedure we adopted

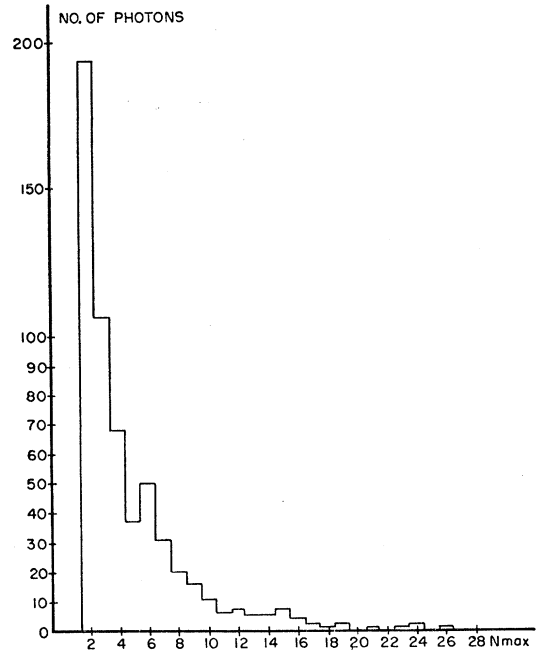

FIG. 8. Distribution in $N_{\max}$ of 566 photon showers all of which emerge from the nuclear interactions in the NaI crystal.

is reliable to the degree desired in the present investigation. This agreement, in turn, may be taken as support for the view that the isolated photons arise also from the $\pi^0 \rightarrow 2\gamma$ process.

The calculated points, however, begin to deviate from the observed distribution at an energy of about 700 Mev. As the energy decreases, the calculated values give fewer isolated photons. This indicates that the correction we applied for unidentified neutral mesons may not be sufficient for low-energy neutral mesons.

C. Energy Distribution of All Photons

In identifying a neutral meson, we used the condition that a pair of photons emerging from a nuclear interaction satisfies the kinematical relation (2) for the $\pi^0 \rightarrow 2\gamma$ process. Such an identification, however, is not conclusive and always leaves the doubt that the combination adopted could have been a coincidental one. This uncertainty, which may reflect itself in the energy distribution, can be eliminated if we take all photons together without reference to the individual neutral meson combinations. In this treatment, we explicitly assume that all the photons we observe arise from the $\pi^0 \rightarrow 2\gamma$ process, and obtain a relation

$$E|dF/dE| = 2N(\epsilon = E + \epsilon_0^2/4E), \qquad (9)$$

where $N(\epsilon)$ and $F(E)$ are the energy distributions of neutral mesons and decay photons, respectively. For $E \gg \epsilon_0$, this relation is approximated by

$$|dF/dE| = 2N(E)/E. \qquad (10)$$

The distribution in $N_{\max}$ of 566 photons, all of which emerge from nuclear interactions in the crystal, is shown in Fig. 8. This is further converted to the energy distribution $F(E)$, and the results are shown in Fig. 9. The points appear to lie on straight lines, with an apparent change in the slopes at point J which corresponds to an energy of about 850 Mev. The slopes of the best-fit straight lines are found to be

$$\begin{aligned} JA: \nu &= -1.5 \pm 0.2, \\ JB: \nu &= -2.7 \pm 0.5. \end{aligned} \qquad (11)$$

The energy distribution of photons obtained here is converted to the distribution of the parent neutral mesons, but the values of exponents are essentially the same as those given in (11).

The values given in (11) closely agree with those given in (6), which were obtained directly from the identified neutral mesons. The position of the junction point J differs in these two sets of data by about 200 Mev, but this discrepancy is not taken seriously in view of the crudeness of the energy estimate. The position of J is in the vicinity of 900 Mev. For the energy range below 900 Mev, (11) gives $\nu = -1.5$ while (6) gives $\nu = -1.3$. It was previously suggested that the correction for unidentified neutral mesons is probably too low for π^0 energy of about 700 Mev or less; therefore the value of $|\nu| = 1.3$ is probably too low. The value of $\nu = -1.5$, on the other hand, is obtained from the photon distribution without such a correction, and is regarded as more reliable.

From these considerations, we conclude that the differential energy distribution of neutral mesons observed in the present experiment follows a power law

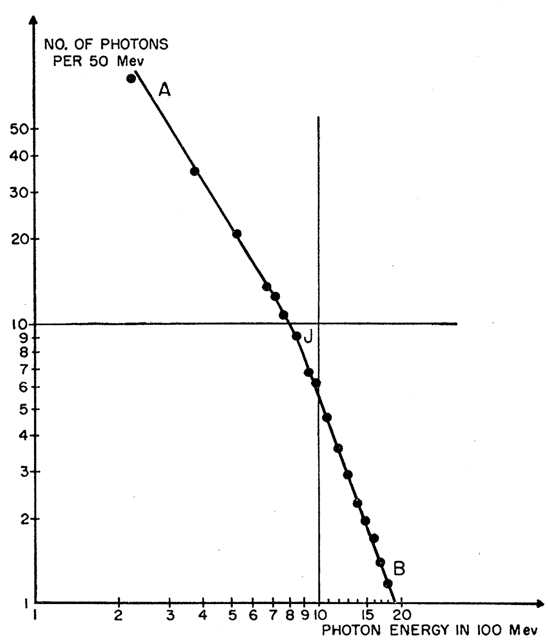

FIG. 9. Energy distribution of all photons.

of exponent $\nu=-1.5\pm0.2$ for π^0 energy between 400 and 900 Mev, and $\nu=-2.7\pm0.5$ for π^0 energy between 900 and 2000 Mev. The errors given here are the statistical errors associated with the numbers of the neutral mesons observed. For the energy range between 2000 and 5000 Mev, the data are consistent with the continuation of the power law given above. The distribution for the energy range less than 400 Mev cannot be obtained reliably. In this energy range, both of the two decay photons often escape detection, and the estimate of detection efficiency becomes very complicated.

D. Origin of Photons

In the foregoing analysis of the data, we assumed that photons associated with stars arise from the $\pi^0\rightarrow2\gamma$ decay. This decay, however, is believed to take place with a lifetime of only about 10^{-15} sec, and one can hardly expect to observe cases in which the presence of π^0 can be inferred geometrically. In fact, nearly all photons observed in the present experiment are directed toward the star origins and appear as though they were produced directly from the stars. In spite of this appearance, the present data provide a fairly strong argument for the $\pi^0\rightarrow2\gamma$ process.

First consider Table I, which classifies the stars according to the number of photon showers associated with each star. We note that the number of stars with two photons is about equal to the number with one photon, and that the number of stars with four photons is again comparable with the number with three photons. This kind of distribution would be rather unexpected if photons were produced directly from the stars, since for this case one would expect that the number of stars gradually decreases as the multiplicity (the number of photons produced) increases, in a manner similar to that observed in the case of charged meson production in cosmic-ray stars. Of course, no definite conclusion can be reached from these data alone. But Table I would be easily explained if one assumes the $\pi^0\rightarrow2\gamma$ process as the primary source of photons.

The reality of the $\pi^0\rightarrow2\gamma$ process is further strengthened by the internal consistency of the results already presented. It was shown that the isolated photons observed in the present experiment fit very well with the picture that these photons result from the neutral mesons which are unidentified as such because one of the decay photons has a low energy (less than 100 Mev) and escapes detection. It was also shown that the energy distribution of neutral mesons deduced from the energy distribution of photons, under the assumption that all photons arise from the $\pi^0\rightarrow2\gamma$ process, agrees closely with the energy distribution obtained directly from the identified neutral mesons. From these facts, we conclude that the majority of photons associated with cosmic-ray stars result from $\pi^0\rightarrow2\gamma$ process.

Some other possible sources of photons should be mentioned, however. According to Anand,[15] neutral mesons produced from cosmic-ray stars occasionally undergo the decay process $\pi^0\rightarrow e^++e^-+\gamma$. This alternate decay, however, is reported to be only about 1% of the $\pi^0\rightarrow2\gamma$ process,[15] and it will not affect the present results. The process $\pi^0\rightarrow4e$, another possible alternate decay, is expected to be even less frequent. Unstable heavy mesons and hyperons are currently observed copiously in cosmic-ray stars, and these particles might affect the present results if they decay into photons with very short lifetimes. However, again the frequency with which these unstable heavy particles are produced is rather small in the energy range investigated in the present experiment: only two neutral and two charged V particles were observed. Also, present indications are that the lifetimes of the unstable heavy particles that lead ultimately to π^0 or γ decay products are significantly longer than necessary to distinguish them in the present experiment.

V. COMPARISON WITH OTHER WORK

Since in the present experiment very little bias is introduced in the selection of stars (see Sec. II), we can compare the present results directly with those obtained by the Bristol group using nuclear emulsions. In their initial work, Carlson *et al.*[4] investigated the energy spectrum of photons that materialized in nuclear emulsions exposed at an altitude of 70 000 ft. From this spectrum they deduced the energy distribution of neutral mesons as a power law of exponent $\nu=-1.5$ up to an energy of 900 Mev. Later Hooper *et al.*[16] extended this work for higher photon energies by studying nuclear emulsions exposed at 95 000 ft, and obtained a power law spectrum of exponent $\nu=-1.5$ for π^0 energy between 200 and 800 Mev and $\nu=-2.7$ for 800 to 5000 Mev.

In these nuclear emulsion experiments, it was essential to assume that all photons observed in the nuclear emulsions were the decay products of the $\pi^0\rightarrow2\gamma$ process and that these photons had not been modified by electromagnetic interactions during their passage through the atmosphere. Both of these assumptions appear to be very reasonable, but there is no way of assuring them directly. In the present cloud-chamber experiment, however, these points are verified directly, and the energy distribution is obtained directly from the neutral mesons identified as such from a pair of photons as well as indirectly from the energy distribution of individual photons. In this respect, the present results may be regarded as considerably more direct than that of the Bristol group.

It is of interest to compare the energy distribution of the neutral mesons with that of the charged π mesons. Camerini *et al.*[17] investigated the energy spectrum of

[15] B. M. Anand, Proc. Roy. Soc. (London) **A220**, 183 (1953).
[16] Hooper, King, and Morrish (unpublished, 1951); Professor G. T. Reynolds (private communication from Dr. D. T. King).
[17] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

TABLE III. Differential energy distribution of cosmic-ray π mesons.

Authors	$\pi^{\pm}$ or π^0	Target material	Method	Energy range in Mev and the value of ν	
Camerini *et al.*[a]	$\pi^{\pm}$	Emulsion	Nuclear emulsion exposed at 70 000 to 110 000 ft	250–1400 −1.5	≥1400 Consistent with −2.5
Sands[b]	$\pi^{\pm}$	Air	Deduced from μ-meson spectra at various altitudes	250–1000 −1.5	1000–5000 −2.5
Olbert[c]	$\pi^{\pm}$	Air	Deduced from μ-meson spectra at various altitudes	450–1000 −1.5	1000–5000 −2.5
Carlson *et al.*[d]	π^0	Air and emulsion	Nuclear emulsion exposed at 70 000 ft	300–900 −1.5	...
Hooper *et al.*[e]	π^0	Air and emulsion	Nuclear emulsion exposed at 95 000 ft	200–800 −1.5	800–5000 −2.7
Kim[f]	π^0	NaI	Multiplate cloud chamber at 10 600 ft	400–900 −1.5	900–5000 −2.7

[a] See reference 17.
[b] See reference 18.
[c] See reference 19.
[d] See reference 4.
[e] See reference 16.
[f] Present experiment.

charged pions emitted from stars originated in nuclear emulsions exposed at 70 000 to 100 000 ft, and obtained a power law spectrum of exponent $\nu=-1.5$ for pion energy (total) between 250 and 1400 Mev. For higher energies, they indirectly estimated that ν is consistent with a value of -2.5. The energy spectrum of charged pions produced in the atmosphere can be deduced from the μ-meson energy spectrum since the μ-mesons in the atmosphere arise predominantly from the $\pi\rightarrow\mu$ decay process. Prior to the work of Camerini *et al.* Sands[18] obtained the energy spectrum of charged pions by this method, and gave the values of $\nu=-1.5$ for pion energy between 250 and 1000 Mev and $\nu=-2.5$ for 1000 to 5000 Mev. Olbert[19] later improved the μ-meson energy spectrum originally used by Sands, but when it is converted to the pion energy spectrum the difference becomes insignificant.

The results of various workers presented above are summarized in Table III. From a comparison of these results, one may conclude that the energy distributions of the π mesons created in cosmic-ray nuclear interactions are similar for charged and neutral mesons and can be expressed as a power law of exponent of -1.5 for an energy up to about 1000 Mev, but the value of the exponent decreases to about -2.6 in the energy range between 1000 and 5000 Mev. It also appears that the energy distribution is rather insensitive either to the altitude or to the nature of the target nuclei in which the π mesons are produced.[20] These results, however, refer to nucleon-nucleus or pion-nucleus collisions and may not necessarily apply for more fundamental single nucleon-nucleon or pion-nucleon collisions.

ACKNOWLEDGMENTS

The author is deeply indebted to Professor G. T. Reynolds and Professor G. Salvini for the continued interest in this work and for helpful discussions.

[18] M. Sands, Phys. Rev. **77**, 180 (1950).
[19] S. Olbert, Phys. Rev. **92**, 454 (1953).
[20] Camerini *et al.*[17] find no appreciable differences in energy spectra of charged mesons produced in different elements of nuclear emulsions and suggest that the energy spectrum does not strongly depend on the nature of the target nucleus.

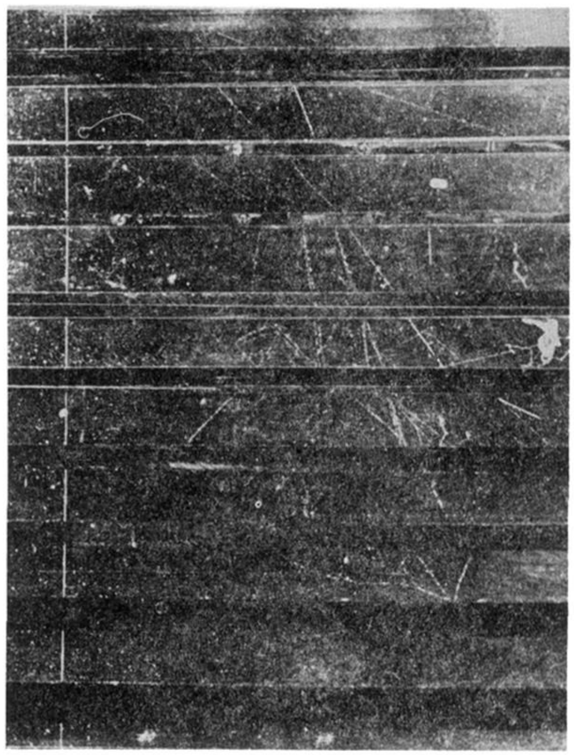

FIG. 2. Example of nuclear interaction in the NaI crystal (the first plate), in which the production of a neutral meson is clearly observed. Both of the two decay photons start shower development at the third plate: the energy of the neutral meson is estimated to be about 1 Bev. In addition, a charged meson of energy about 90 Mev is produced in this event. No charged particle is seen to traverse the chamber completely, and this event would not have been recorded had we used a selection scheme that requires counters to discharge under the chamber.