On Nuclear Evaporation in Cosmic Rays and the Absorption of the Nucleonic Component. II.*

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The nuclear evaporations produced by cosmic rays at 3500 m altitude were studied using Ilford C2 and Kodak NT4 plates. The results are discussed in comparison with the results obtained in Berkeley for stars produced by nucleons of controlled energies and with some of the data furnished by the Bristol and Brussels groups. The results are as follows. (1) The frequency of stars *versus* the number of prongs does not change very much in the transition between air and condensed materials. (2) The small transition effect observed in lead is concentrated in the first few cm of the lead and is restricted to the small stars. (3) For greater thicknesses (of the order of the nucleon-nuclei geometrical range) the differences between paraffin and lead seem to be negligible. (4) The differences between the Berkeley and the cosmic ray stars are concentrated in the large stars (more than six prongs), in agreement with the fact that a large fraction of cosmic ray stars (about 80 percent) are produced by secondary nucleons having energies not exceeding some hundreds of Mev. (5) The prongs of the small stars (less than six prongs) produced by cosmic rays show an angular distribution around the vertical which is, at least qualitatively, that which must be expected from the Berkeley results. (6) The large stars show an isotropic distribution in the heavy prongs but not in the "grey" ones, and a correlation between the number of grey and the number of black prongs seems to be evident. On the average, every grey prong is accompanied by about 3.5 black prongs. (7) The energy spectrum of the black proton- and alpha-prongs is given with a statistic based on about 4000 stars. The average excitation energy associated with every black prong is about 35 Mev; the average nuclear excitation corresponding to the black prongs emission is about 150 Mev. (8) A comparison of the experimental proton spectrum with the Weisskopf-Bagge theory seems to show satisfactory agreement, assuming a value for the Gamow barrier of about five Mev. (9) Similarly, the alpha-spectrum is in fairly good agreement with the evaluations of Le Couteur. (10) Some conclusions concerning the nuclear evaporations and the nucleonic cascade are discussed.

I. INTRODUCTION

IN a previous issue[1] (Part I) some features of the behavior of the nucleonic component were examined in connection with quantitative results obtained by studying the stars produced by cosmic rays in sensitive emulsions. It was pointed out that these features seemed to indicate the existence of a fairly close correlation between the star population and the locally-produced penetrating showers. Perhaps today this correlation does not appear to be so close because Cocconi's data in lead were originally uncorrected,[2] but nevertheless it remains, and its origin in the *nucleonic cascade* becomes more and more obvious. From this correlation and from the general information collected so far on the behavior of the nucleonic component,[3] it is evident that in the intermediate atmosphere or in sufficiently thick layers of certain materials, the fast nucleons are accompanied by a large retinue of slow ones, which they have produced through a series of processes occurring as they move along. The *intermediate* stage of this nucleonic cascade (which is initiated in the high atmosphere by primary protons and heavy particles, and terminated by slow neutrons distributed in the atmosphere) is characterized by the production of these rather slow nucleons which are no longer efficient in the production of fast mesons and which lose their energy mainly through induced nuclear evaporations and ionization.

As we mentioned in Part I, there is some direct evidence of the existence of this large retinue of rather slow nucleons, particularly in the work of Adams *et al.*[4] Recently other direct information about this point was given by Conversi.[5] Conversi's data, in agreement with the figures given by Adams *et al.*, indicate the presence in the atmosphere of a large proportion of protons having energies $\sim$0.5 Bev. The decrease in the intensity of such a proton component in the atmosphere is given by an absorption thickness between 140 and 150 g/cm^2, in agreement with the behavior of the stars observed in plates or in ionization chambers. Further, these slow protons observed by Conversi show the same latitude effect as the burst intensity[6] and as the intensity of the *slow neutron component.*[7]

As we also indicated in Part I, the number of these rather slow nucleons must be somewhat high in comparison with that of the residual nucleons which have energies $\geqslant$1 Bev and which are very efficient in the production of the penetrating showers usually observed. Because it is practically certain (see below) that an extremely large fraction of bursts are due to the nuclear stars, and that the stars are the sources of the slow neutrons and (at least under 200 g/cm^2) are in equilibrium with them, it is quite reasonable to associate the stars themselves with slow nucleons like those observed by Conversi. At the same time, the shape of

* A previous account of this paper was given at the Como conference, September 1949, to be published in Nuovo Cimento.
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[1] Bernardini, Cortini, and Manfredini, Phys. Rev. **76**, 1792 (1949).
[2] G. Cocconi, Phys. Rev. **75**, 1074 (1949).
[3] W. B. Fretter, Phys. Rev. **76**, 511 (1949); Lovati, Mura, Salvini, and Tagliaferri, Nuovo Cimento **6**, 207 (1949); B. Gregory and J. Tinlot, kindly communicated by the authors.
[4] Adams, Anderson, Lloyd, Rau, and Saxena, Rev. Mod. Phys. **20**, 334 (1939).
[5] M. Conversi, Phys. Rev. **79**, 749 (1950).
[6] White and Coor, kindly communicated by Prof. Reynolds.
[7] Simpson, Phys. Rev. **73**, 1389 (1948); L. Yuan, Phys. Rev. **74**, 504 (1948).

TABLE I. Transition effects for cosmic ray stars under a lead absorber.

No. of prongs	Stars/cm²/day Without absorber	Stars/cm²/day Under two cm of lead	Number expected under two cm of lead
3	5.04±0.28	6.80±0.39	4.70
4	4.11±0.25	4.60±0.32	3.84
5	1.91±0.17	1.89±0.20	1.78
⩾6	3.07±0.22	2.80±0.25	2.85
Total	14.22±0.48	16.10±0.60	13.30

the energy spectrum of these slow nucleons is suggested by the proton spectrum at 30,000 feet (energy range ~100 to 1000 Mev) given by Adams *et al.*[4] It is characterized by a very peaked maximum around 200 Mev, and shows that these nucleons between 100 and 1000 Mev have an average energy of about 300 Mev.

Consequently, we should be lead to consider a large fraction of the nuclear evaporations produced by cosmic rays as the close relatives of those observed in the Berkeley experiments.[8] In the next paragraphs we shall examine in some detail the features of the cosmic ray stars, with the intention of analyzing their origin and properties and their peculiar differences from the stars of the Berkeley experiment.

II. THE NUMBER OF STARS *VERSUS* PRONGS DISTRIBUTION

A

A first rough classification of the stars is usually made on the basis of the frequency of stars *versus* the number of prongs. In our experiments we exposed the plates either in the open air (supported by materials of different atomic number) or under layers of different materials like Pb, Al, C, paraffin. Concerning the lead, our results are in very close agreement with our own previous results[9] and with those of George and Jason.[10]

The results indicate that at 3500 m altitude no large transition effects are observable concerning the frequency of the stars *versus* multiplicity of prongs. However, in lead a transition effect is evident. It is due to the stars of small size (3 to 4 prongs)[11] and is evident just within the first absorption thickness. For thicknesses greater than five cm the star population seems to decrease regularly following an exponential law.[1] The transition effect is clearly shown in Table I, where in the last column are given the values which must be expected with an exponential absorption[1] (absorption thickness $L=300$ g/cm²). For many reasons, which will be discussed in Part III, its origin is not completely clear (see note added in proof). Perhaps a small transition effect is present also in the plates exposed

TABLE II. Effect of a paraffin absorber on the production of cosmic ray stars.

Paraffin thicknesses (in cm) / Number of heavy prongs	Stars/cm²/day 0	~25	~45	~58
3	6.7 ±0.4	6.9 ±0.5 (6.0)	7.2±0.4 (5.5)	6.3±0.3 (5.3)
4	5.1 ±0.3	4.5 ±0.4 (4.6)	5.0±0.3 (4.2)	4.3±0.3 (4.1)
All stars	1.81±0.65	17.35±0.65 (16.3)	18.6±0.65 (15.0)	16.1±0.64 (14.5)

under paraffin, but if so it shows quite a different behavior. Table II shows the values for the paraffin absorber. The expected values, estimated assuming an exponential absorption with[12] $L=200$ g/cm², are given in parentheses.

At the moment we would like to observe that at an altitude of 3500 m *the transition effects are quite small*[13] (Fig. 1). As is shown by Fig. 2, the stars *vs.* prongs distributions appear to be practically the same in different materials at thicknesses of the order of the geometrical absorption thicknesses, and not much different from the distributions observed in the plates

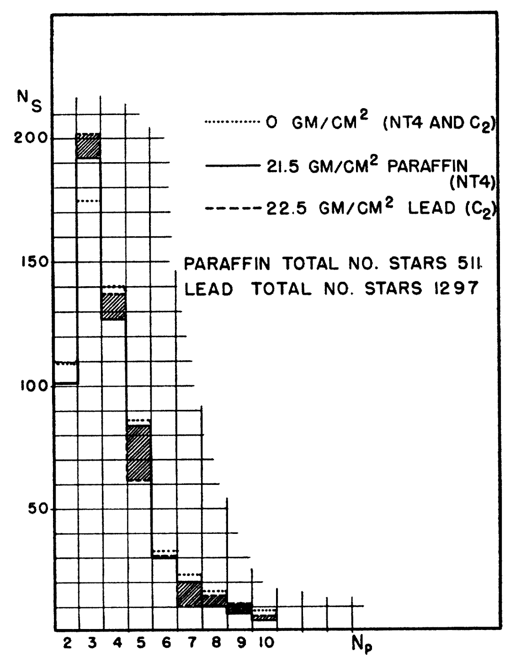

FIG. 1. Transition effects with lead and paraffin absorbers in the distributions of the number of stars N_s having N_p prongs. The histograms are all normalized to the same area (600 stars). The cross-hatched blocks indicate the differences between the lead and paraffin absorbers. The number of small stars (three to four prongs) is possibly relatively larger with lead than with paraffin, and this may be connected with the transition effect.

[8] E. Gardner and V. Peterson, Phys. Rev. **75**, 364 (1949); E. Gardner, Phys. Rev. **75**, 379 (1949).
[9] Bristol's cosmic rays symposium, 1948; Como conference, 1949.
[10] George and Jason, Proc. Phys. Soc. London **62**, 243 (1949).
[11] G. Cortini and A. Manfredini, Nature **163**, 991 (1949).
[12] This value is given for ice by Harding *et al.* (see Part I).
[13] This is not true at high altitudes, near the top of the atmosphere (see below).

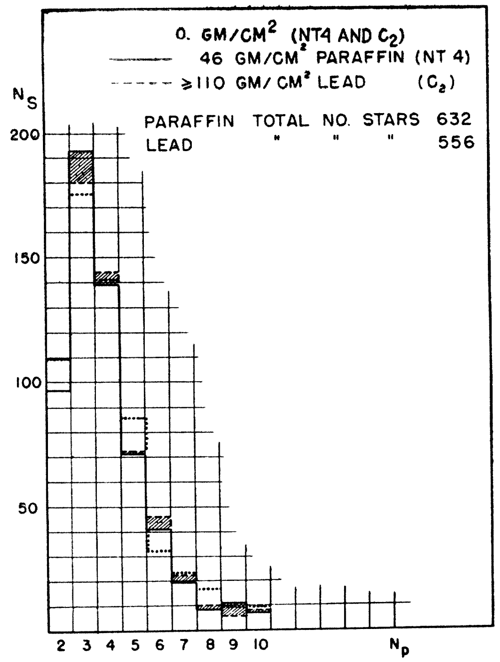

FIG. 2. The distributions of the number of stars N_s having N_p prongs, for larger thicknesses of lead and paraffin absorbers (see Fig. 1). The histograms are normalized to the same area (600 stars).

exposed above the absorbers. Consequently, for a comparison with the Berkeley stars, we first total the different distributions which we have observed in the logarithmic diagram of Fig. 3 (curve II), in which the data concerning the stars produced by deuterons between 90 and 190 Mev in the Berkeley experiments[8] are also reported (curve I). The difference between the distributions I and II is rather marked. While in the Berkeley plates the number of stars present having *more* than five prongs is negligible, in the cosmic ray stars at 3500 m altitude *it represents about 20 percent of the total.* At first sight, comparing curves I and II, one can guess that curve II could be obtained by the superposition of a curve like I and another composed mainly of large stars. After the arguments developed in Part I and in the first paragraphs of this paper, it should be easy to understand this analysis[14] of curve II. Most of the small stars are connected with the fraction of the star-producing radiation which is composed of nucleons (mainly neutrons) having energies of the order of those produced in Berkeley. The "tail" of the large stars is essentially produced by cosmic ray nucleons of higher energies. This perhaps obvious conclusion is emphasized by some recent results obtained at Berkeley with protons of different energies.[15] From these results it is clear that the distributions of the number of stars *versus* the number of prongs are not very sensitive to the value of the energy of the incident protons, at least between about 200 and 350 Mev.

This conclusion is in agreement with the theoretical expectations.[16] On the contrary, the quite large fraction of stars having more than five prongs has no obvious explanation, because the *average* value of the energy released by a *single nucleon* crossing a heavy nucleus without originating any radiative process (emission of mesons) is of the order of 100 Mev, and depends essentially on the range of nuclear forces, and for energies ≫100 Mev, very little on the energy of the incident nucleons.[17] However, as Wouthuysen suggests,[18] the difference can be explained at least partially by

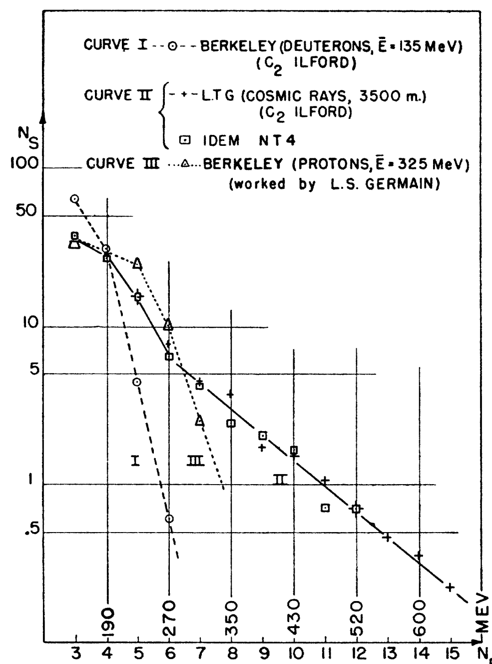

FIG. 3. Comparison between the cosmic ray star distributions and those obtained in the Berkeley experiments. Curve I was obtained from the data of Gardner and Peterson (reference 8) which correspond to 781 stars, and Curve III from the data of L. S. Germain with a total of 290 stars. Curve II corresponds to 5270 stars obtained in C2 plates and to 1870 stars in NT4 plates. The figures given above the axis of the abscissae are the values of the excitation energies as estimated by Le Couteur as a function of the total number of observable prongs (see Sec. IIIE).

[14] We should like to add that in a paper by A. Page, which is not yet published (see reference 22) the division of curve II in Fig. 3 (Page's distribution is in excellent agreement with ours) into two branches is interpreted in a rather different way. That is, by considering that it is due essentially to the contribution of stars produced in light nuclei. In our opinion this is only partly true, because the Berkeley stars are produced in heavy as well as light nuclei and show a different behavior. Furthermore, the curves obtained in the same type of plates for stars observed at very high altitudes (Minneapolis group, Rochester group, Lord and Schein) do not show the two branches appreciably.

[15] The measurements were taken by Dr. L. S. Germain, and were kindly communicated to us by Dr. E. Gardner and Dr. F. Adelman.

[16] W. Horning and L. Baumhoff, Phys. Rev. **75**, 370 (1949).

[17] Above 200 Mev, for a nucleon crossing a nucleus ($A\simeq 100$) and undergoing only elastic or quasi-elastic collisions, the energy release should decrease with increasing energy and should approach a limit that is certainly no larger than about 100 Mev. (Bagge, Ann. d. Physik (V) **39**, 512 (1941); **39**, 535 (1941); Zwanikken, Physica **14**, 530 (1948).)

[18] S. A. Wouthuysen, Phys. Rev. **75**, 1329(A) (1949).

TABLE III. Numbers of stars, $N(s, l)$, having a total of s prongs, with l proton prongs in the approximate energy range 80 to 300 Mev.

No. of prongs	$N_S=\Sigma N(s,l)$ $l=0,1,2\cdots$	$N(s,1)$	$N(s,2)$	$N(s,3)$	$N(s,\geq 4)$	$\frac{N(s,1)}{N_S}$	$\frac{N(s,\geq 2)}{N_S}$	$\frac{N(s,>1)}{N_S}$
3	369	37	2	—	—	0.10	0.005	0.10
4	319	56	12	—	—	0.17	0.04	0.21
5	179	48	18	2	1	0.27	0.12	0.38
6–7	155	37	14	4	1	0.31	0.11	0.42
8–9	44	12	7	3	2	0.3	0.3	0.6
10	74	27	20	8	5	0.35	0.45	0.80

considering, on the basis of the recent nucleon-nucleon scattering experiments,[19] the probability of *knock-on* nucleon-nucleon collisions with a rather high momentum transfer, and the production of recoil nucleons in the inelastic nucleon-nucleon collisions. As a matter of fact, in this way the expected relative yield of differently-pronged, large stars can be deduced from the probability that one or more nucleons (let us say either nuclear δ-rays or recoil nucleons) of energies appreciably greater than 20 Mev ($\sim$Fermi's limit) can be produced inside a nucleus crossed by a fast nucleon. The evaluations made by Wouthuysen (taking into account the energy spectrum of primaries) and, similarly, those made using the Monte Carlo method by Goldberger[20], for energies around[21] 100 Mev, predict a rather high number of primary knock-on and inelastic collisions *inside* the Ag and Br nuclei. According to Wouthuysen, of 100 fast nucleons (energy spectrum $f(E)=E^{\gamma}$ with $2.5\lesssim\gamma\lesssim 3$, magnetic cut-off at $E_0\simeq 3.5$ Bev) crossing a nucleus approximately 20 percent do not give rise to any process, 15 percent give rise to a secondary process, 30 percent to two secondaries, and 35 percent to three or more. These figures, on account of the rather arbitrary hypothesis introduced on the nature of collisions[22] in the spectrum of the primaries, etc., could give us, of course, only an order of magnitude of the expected number of processes, and essentially they must be used to indicate the manner in which a part of the large stars could be explained.

The fast secondary nucleons produced after the bombardment of the nucleus escape immediately from the nucleus itself, but as their number increases the average energy excitation of the residual nucleus also increases, because colliding with other nucleons before escaping they contribute to the excitation itself. In this way it is possible to explain qualitatively the *average* excitation energies larger than about 200 Mev.

As has been mentioned already, in addition to the knock-on nucleons (δ-nucleons), the recoil nucleons produced in a radiative nucleon-nucleon collision are able to produce stars of large size. In this case the evaporation process follows the emission of mesons. Thus, neglecting for the moment the probable local interactions of the mesons themselves, the meson emission from nuclei of rather high atomic number *should* be accompanied by stars having, on the average, a size larger than those produced by nuclei crossed by a single nucleon.

The data reported by the Bristol[23] and Brussels[24] groups indicate that no more than about 25 percent of the stars having *more* than five prongs show meson emission (it may be better to say they emit relativistic particles)[25] at 3500 m. For instance, the Bristol authors

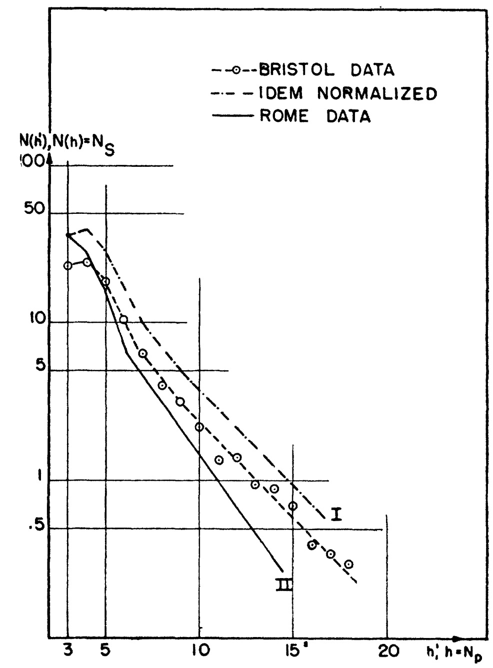

FIG. 4. Comparison between the star distributions as obtained by the Bristol and Rome groups. Curve I shows the data of the Bristol group for the number of stars *vs.* the number of heavy plus grey prongs, while Curve II shows the data of the Rome group for the number of stars *vs.* the number of heavy prongs, for stars produced by cosmic rays at 3500 meters. The Bristol data are also shown normalized to the Rome data at the points corresponding to stars of three prongs.

[19] Hadley, Kelly, Leith, Segrè, Wiegand, and York, Phys. Rev. **75**, 351 (1949).

[20] M. L. Goldberger, Phys. Rev. **74**, 1269 (1948).

[21] In order to obtain the order of magnitude of the probabilities for one or more elastic nucleon-nucleon collisions, Goldberger's results should be extrapolated to higher energies. This involves some difficulties which will be discussed later.

[22] Wouthuysen distinguishes in a very crude way the elastic from the inelastic collisions.

[23] Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. (VII) **40**, 862 (1949).

[24] Cosyns and Occhialini, Como conference, September 1949. To be published in the Nuovo Cimento.

[25] Dr. Powell, in a private communication, kindly informs us that there is evidence that the relativistic prongs for momenta between 300 and 700 Mev/c are, in a very large fraction ($\sim$90

TABLE IV. Angular distribution of the tracks of fast recoil protons from stars.

ϑ(deg)	0–30	30–60	60–90	90–120	120–150	150–180
n	59	63	58	60	112	139

observe for $Nh \geqslant 6$ stars, 419 stars of the type $\geqslant 1_p{}^n$ and 1226 of $0_p{}^n$, and most of the $1_p{}^n$ stars are *not* connected with the emission of mesons.

According to our statistics (Fig. 3), the stars at 3500 m altitude having more than five prongs comprise about 20 percent of the total star population. Consequently, *more than ten percent of the total star population is composed of stars having more than five prongs and not connected with the visible production of relativistic particles.*[26] They must be associated with knock-on collisions or with other not quite evident processes caused by rather energetic particles but not associated with the nuclear emission of mesons.

B

To check this conclusion, and to obtain in this way a clearer view of the star structure, we had to try to detect, in plates exposed to cosmic rays at 3500 m altitude (L.T.G.), protons emitted by the stars and having energies in the approximate range 80 to ~300 Mev. The β-sensitive plates were not completely developed. To calibrate their sensitivity, some very long μ-meson tracks ending in the emulsions were considered and their lengths and granulation measured. The lengths of the tracks considered were, on the average, about 3000 to 4000 microns and correspond to an initial value of $\beta^2=(v/c)^2 \sim 0.2$. By comparison of the grain-densities of these μ-meson tracks with those of the singly charged prongs emitted by the stars, the energy of these prongs was estimated.[27] The first data collected just to obtain a general view of the proton prongs having energies between ~80 to 300 Mev, are summarized in Table III, where $N(s, l)$ is the number of observed stars having a total number s of prongs and l of proton prongs with energies in the above-mentioned range.

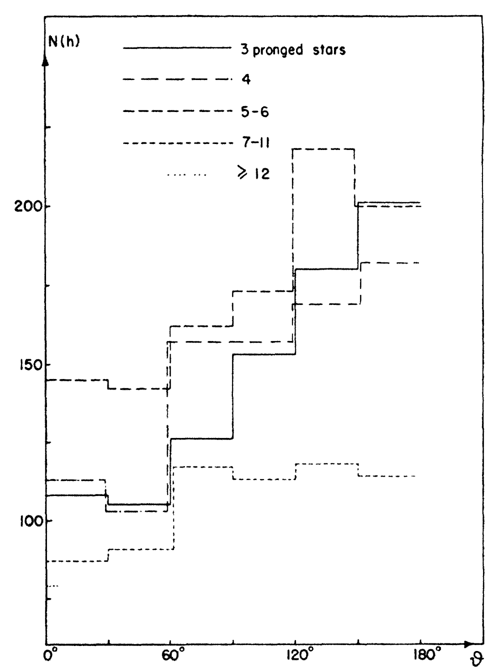

FIG. 5. Angular distribution of the prongs of the cosmic ray stars at 3500 meters around the upward vertical direction.

Together with these protons we must consider the partner neutrons which escape detection. With the probabilities given by Wouthuysen and assuming that a recoil nucleon could be, with equal chance, a proton or a neutron, we find that *on the average* at least 70 percent of the stars having more than five prongs are associated either with some δ or recoil nucleons. An examination of the directions of these fast proton trajectories has shown that most of them are directed *downward* with respect to the vertical. This fact (in agreement with the results communicated by Professor M. Cosyns at the Como conference) is indicated by Table IV, where the number n of the above-mentioned fast protons is given for different angular intervals ϑ. The angles are measured starting from the vertical in the upward direction. At the same time, contrary to what occurs for the fast proton prongs, the heavy prongs of the *large* stars (see below and also Brown *et al.*[23]) are quite isotropically distributed. *This fact seems to exclude the possibility that a large majority of these fast protons could be due to the statistical fluctuations in the nuclear evaporations, and at the same time it strengthens the argument of the secondary origin of these protons.*

By comparison of the data of the Bristol group with ours, it is also possible to obtain an idea of the correlation between the numbers of these δ and *recoil* nucleons (if they are protons most of them can be identified with the "grey" prongs of the Bristol group) and the corresponding stars. In Fig. 4 are plotted, (a) the frequency of stars *versus* prongs (grey and black) for the star-population at 3500 m altitude (curve I); and, (b) our stars-*versus*-heavy prongs distributions (curve II—the same as curve II of Fig. 3).[28] The two curves are normalized at the points corresponding to the three-pronged stars. As is shown by Table III, only about ten percent of these stars are accompanied by a fast proton. On the other hand, the total star population

percent), π-mesons. On the other hand, Dr. Cosyns has recently written to us, confirming the much lower percentage of π-mesons previously reported in his paper at the Como conference.

[26] The Bristol data give a fraction of about 20 percent, but probably some stars having three prongs were lost. However, it is correct to consider this 10 percent as a lower limit.

[27] The error in this energy estimate might be 100 percent.

[28] From the Bristol data concerning the grey prongs it is possible to guess that the stars-*versus*-black prongs distribution is in good agreement with our results. The same can be said about the results of the Brussels group, as communicated by Prof. Cosyns at the Como conference, September 1949.

TABLE V. Number of proton tracks having the projected lengths indicated in the first column and belonging to the star-type indicated in the second and third columns.

Interval (micron)	Stars 3–5 prongs	Stars 6 or more prongs	Total	Calculated total
14.5– 40	138	50	188	
40 – 75	228	87	315	
75 – 120	297	102	399	
120 – 173	224	96	320	
173 – 234	172	87	259	
234 – 306	160	83	243	
306 – 426	141	74	215	227
426 – 666	120	57	177	160
666 –3760	68	61	129	130
⩾3760	1	2	3	5
Totals	1549	699	2248	

TABLE VI. Number of alpha-particle tracks having the projected lengths indicated in the first column and belonging to the star-type indicated in the second and third columns.

Interval (micron)	Stars 3–5 prongs	Stars 6 or more prongs	Total
15.0– 23.4	228	62	290
23.4– 33.6	189	103	292
33.6– 45.4	173	93	266
45.4– 58.0	160	114	274
58.0– 72.7	206	84	290
72.7– 89	205	98	303
89 –112	132	68	200
112 –135	81	49	130
135 –158	52	30	82
158 –185	30	20	50
185 –267	40	25	65
⩾267	17	13	30
Totals	1513	759	2272

given by the Bristol group is rather low (~11 stars/cm^3/day), so probably some small stars were lost in the scanning. Consequently, by normalizing the two curves at the points corresponding to the three-pronged stars, a reasonable comparison can be made between the Bristol and Rome results.

In Fig. 4 the $N(h')$ stars of curve I, having h' "black" plus "grey" prongs, correspond to the $N(h)$ stars of curve II which have h black prongs ($h'-h$ being the *average* number of grey prongs). Roughly speaking, a line in Fig. 4 drawn parallel to the abscissae connects the corresponding stars in the two distributions. It is thus possible to recognize that with stars of more than five prongs, *on the average*, for every grey prong we find rather regularly about 3.5 black prongs; or, considering the partner neutrons of the grey prongs, about two black prongs for every nucleon emitted with energy between about 80 to 300 Mev.[29] Probably, as was indicated by Cosyns at the Como conference,[30] there are some cases in which this correlation between the numbers of grey and black prongs is not so clear. However, considering the statistical fluctuations, it appears that in the large stars, *until the number of grey prongs becomes too high*, these nucleons (grey prongs), immediately-produced and emerging from the struck heavy nuclei, have contributed regularly to the subsequent evaporation of the same nuclei.[31]

The work of Goldberger indicates that also incident nucleons of rather low energies (~100 Mev) can originate particles which emerge immediately after the bombardment of a heavy nucleus, but at low energies a distinction between the immediately-projected and the evaporated black prongs is practically impossible.[32]

C

Another point can be examined to decide what limits we must place on the analogy between the cosmic ray stars and the Berkeley stars.

The Berkeley stars indicate, on the average, a strong projection of prongs in the forward direction with respect to the incident particle.[8] This is not evident in the cosmic ray stars, in which only a very small asymmetry around the vertical was observed.[33] To make this point more precise, the angular distribution around the vertical was examined in Kodak NT4 plates placed alternately in a vertical and horizontal position, over and under 2.5 cm of lead. Some results obtained by scanning the vertically-placed plates are represented in Fig. 5.[34]

The histograms show an evident projection of the prongs in the downward direction. This asymmetry is the more definite for small-size stars and in this case can be represented quite well by the law $f(\vartheta)=(1-k\cos\vartheta)$, where ϑ is the angle with the upward vertical direction and k is a constant of value around $\frac{1}{3}$. For stars having more than six prongs only a very slight asymmetry between backward and forward directions was found.

[29] We would like to observe here that the number of black prongs for every grey one is about the same as the average number of *visible* prongs observed in the Berkeley stars (~3.5). These stars are produced by deuterons (that is, by two nucleons) with energy between 80 and 300 Mev, just in the range of the grey prongs. On the other hand, the Bristol figures on the frequencies of 1_n, 1_p, and 2_p stars support the idea that a knock-on secondary nucleon can be, in about the same percentage, a neutron or a proton.

[30] We are very much indebted to Prof. Cosyns for some very interesting remarks on this point.

[31] From the Bristol data it is possible to see that the stars of the type $\geqslant 2_p{}^n$ have, on the average, about 7.5 black prongs. This is an indication that the nucleons produced in the *inelastic* collisions contribute, of course, to the subsequent evaporation of the residual nucleus (at least if the π-mesons do not contribute directly to the nuclear excitation). At the same time, the stars of the type $1_p{}^n$ have, on the average, about six black prongs. A large majority of these stars must be attributed to an incoming nucleon which suffers at least one elastic collision inside the struck nucleus. As a matter of fact, this is obvious in the case of 1_n stars. For the 1_p that can be guessed from the rather large scattering suffered by the relativistic particle (Fig. 6 of the Bristol paper) and from the fact that most of the events were observed in plates exposed without absorbers. Thus also the $1_p{}^n$ stars might, on the average, indicate the contribution of *one* knock-on nucleon.

[32] The difference is essentially in the angular distribution, which is isotropic for the evaporation prongs but not for the immediately-projected prongs.

[33] Perkins, Nature, **161**, 486 (1948); Harding, Phil. Mag. VII, **40**, 530 (1949).

[34] A more complete study of the angular distribution of prongs in cosmic ray stars will be given by A. Manfredini in the Nuovo Cimento.

TABLE VII. Distributions of the lengths of proton tracks. The first column gives the middle points of the intervals.

Middle point (micron)	Stars 3–5 prongs	Stars 6 or more prongs	Total
27	7.85 ±0.67	6.30 ±0.89	7.37 ±0.54
57	9.46 ±0.62	8.01 ±0.86	9.01 ±0.50
97	9.58 ±0.56	7.30 ±0.73	8.87 ±0.44
146	6.14 ±0.41	5.82 ±0.59	6.04 ±0.34
203	4.09 ±0.31	4.60 ±0.49	4.25 ±0.26
270	3.22 ±0.25	3.70 ±0.41	3.37 ±0.21
366	1.71 ±0.14	1.96 ±0.23	1.79 ±0.12
546	0.73 ±0.06	0.77 ±0.10	0.74 ±0.06
2200	0.032±0.004	0.064±0.008	0.042±0.005

This asymmetry, as we have already mentioned, is due essentially to the light ionizing particles; i.e., as is shown by Fig. 5, *it practically disappears if we consider particles having energies up to ~80 Mev.* We consider these results to be again in agreement with the idea that the small stars in cosmic rays are produced mainly by nucleons having energies of the same order of magnitude as those of the Berkeley experiments.

Actually, these small stars show a downward projection of the prongs which seems to be more or less of the expected order of magnitude if we consider the angular distribution of the prongs in the Berkely stars and the average angular spread of the nucleonic cascade.[3] In the small stars, observed either in the Berkeley experiments or in cosmic ray plates, the prongs have a forward projection with respect to the direction of the bombarding particle because part of the observed *heavy prongs* are produced in the primary collisions preceding the true nuclear evaporation. This is clearly indicated in the work of Goldberger[20] (see particularly[35] Table I, page 1276, and Fig. 6) and is due to the fact that the colliding particles do not have a very high momentum. On the contrary, if the incident particle has a high energy and transfers a large fraction of its momentum to a nucleon, it will not give rise to a heavy prong but to a fast recoil nucleon of the type observed in great amounts only in the large stars. And in this case, as was observed, only this fast prong is projected in the forward direction, and the heavy prongs are isotropically distributed.

III. THE ENERGY-DISTRIBUTIONS OF THE IONIZING PARTICLES EMITTED IN THE COSMIC RAY STARS[36]

A

The energy distribution of the particles emitted in cosmic ray stars has been studied recently by Perkins.[37] The Perkins energy distribution with regard to proton tracks was obtained by measuring the *granulation* of each prong of a limited number of stars which had at least one "long" prong terminating in the emulsion. From the granulation of the prong terminating in the emulsion (which gave him the energy of this prong) the author obtained a reference for the evaluation of the energies of the other prongs on the basis of their granulations.

From the experimental relations which have been determined regarding the relationship between energy and granulation[38] it is possible to deduce that, in spite of the care taken by the author, the *relative error* in the energy is more than twice the error made in the measurement of the granulation. Now the statistical error in granulation is particularly large for large energies because of the isotropic distribution of the tracks. Consequently, we believe that notwithstanding the high level of the technique achieved by Perkins, any energy measurements based on granulation will be affected by large errors, at least for tracks of small granulation-density making large angles with the plane of the emulsion.[39]

Another and perhaps quite reliable method for obtaining an evaluation of the prong-energies is the following: consider *only* the prongs totally included in the emulsion (that is, only those ending in the emulsion) and then measure the ranges of their projections. From these, reascend to the actual ranges and energies by means of some geometrical considerations and by using energy-range relations. Our data have been obtained from 4007 stars found in Ilford C2 plates 100μ thick; the plates were exposed at the Testa Grigia Laboratory. Some of them were exposed under different layers of lead. But in conjunction with the small differences observed in the number of stars *versus* number of prongs distributions, the differences between the spectrum of

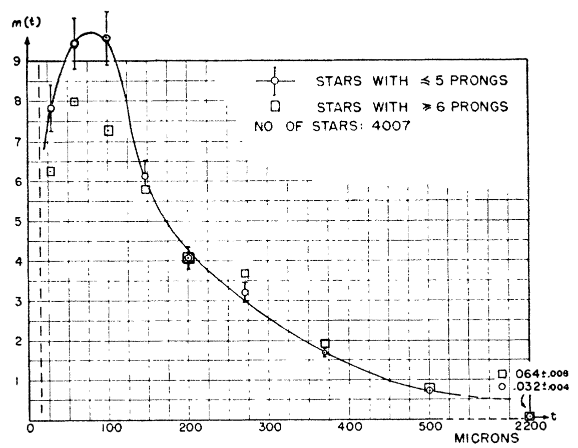

FIG. 6. Frequency distribution of the projected lengths of the proton tracks (number of tracks per unit length).

[35] We believe the opinion to be incorrect that the forward projection of the prongs (reference 16) in the Berkeley stars is due to the recoil velocity of the struck nucleus. For cosmic ray stars this point was directly checked by Harding, Phil. Mag. (VII) **11**, 530 (1949).

[36] For more detailed information about the arguments discussed in this section, see G. Cortini, Nuovo Cimento **6**, 470 (1949).

[37] Perkins, Nature **160**, 299 (1947).

[38] Lattes, Occhialini, and Powell, Nature **160**, 453, 486 (1947).

[39] It can also be observed that granulation measurements are very time-consuming and practically exclude the collection of a large amount of data; as a matter of fact, Perkins' data are based on 15 stars and 80 proton tracks.

track-projections at different thicknesses, if they exist, are completely within the limits of errors and can be neglected.

The length of the projection on the plane of the plate of the tracks terminating in the emulsion was measured and the tracks were classified as those of protons and of alpha-particles. Actually the distinction is between particles with an electronic charge (deuterons and tritons included) and particles with a larger charge; it is possible to state, however, that except for recoil nuclei the only substantial contributions to these two classes of particles come from protons and alpha-particles. In order to exclude the recoil nuclei, tracks with less than 14μ of *projection* have been excluded from the statistics; this also makes it easier to distinguish between particles of different charge, as mentioned above.

Measurements of length were made with ocular micrometers by examination of the plates with an immersion objective and the use of a high degree of enlargement. The ocular micrometers were calibrated by means of an objective micrometer. After the data were gathered, satisfactory checks were made on the consistency and accuracy of the measurements made with different microscopes and on the consistency of the measurements made with different groups of plates.

B

The results obtained are collected in Tables V and VI for protons and alpha-particles respectively. The second, third and fourth columns of Table V give the number of tracks of length specified in the first column for "small" stars (five prongs or less), "large" stars (six prongs or more), and all of the stars. Similar data are given for alpha-particles in Table VI. The last column of Table V will be explained later.

The reason for singling out the results for "large" stars lays not only in the arguments discussed in the previous paragraphs, but also in the fact that the choice of six prongs as a lower limit was considered to be sufficient to exclude practically all of the stars emitted

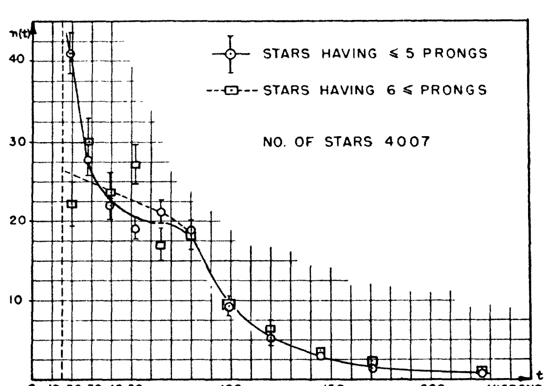

FIG. 7. Frequency distribution of the projected lengths of the alpha-particle tracks (number of tracks per unit length).

TABLE VIII. Distributions of track lengths for alpha-particles. The first column gives the middle points of the intervals.

Middle point (micron)	Stars 3–5 prongs	Stars 6 or more prongs	Total
19.2	41.0 ±2.7	22.2±2.8	34.5 ±2.0
28.5	27.9 ±2.0	30.3±3.0	28.6 ±1.7
39.5	22.1 ±1.7	23.6±2.5	22.5 ±1.4
51.7	19.1 ±1.5	27.1±2.5	21.7 ±1.3
65.3	21.2 ±1.5	17.1±1.9	19.7 ±1.1
80.8	19.0 ±1.3	18.0±1.8	18.6 ±1.1
99.5	9.6 ±0.8	9.7±1.2	9.5 ±0.7
121	5.3 ±0.6	6.4±0.9	5.7 ±0.5
145	3.1 ±0.4	3.6±0.6	3.3 ±0.4
171	1.7 ±0.3	2.2±0.5	1.8 ±0.3
226	0.72±0.1	0.9±0.2	0.78±0.1

by the light nuclei of the emulsion.[40] But because the heavy nuclei also contribute quite strongly to the number of small-size stars, in the following paragraphs evaluations for the energy spectrum have been made for all the stars in bulk.

From the experimental values given in Tables V and VI the distributions of projections were obtained by dividing the number of tracks by the corresponding interval. They are reported in Tables VII and VIII and are shown in Figs. 6 and 7, where the abscissa indicates the mean values of the considered projection intervals.

C

The data reported above give us the distributions of the track projections, but we are interested in knowing the distributions of the actual lengths of the tracks themselves. This is the source of the larger errors of our method, because we have obtained this distribution by a rough calculation and, further, by introducing some hypotheses on the angular distribution of the tracks.

It was assumed that the spatial angular distribution of the tracks is isotropic, or more specifically, that the angular-distribution function $f(\vartheta)$ is of the type

$$f(\vartheta)+f(\pi-\vartheta)=\text{const}.$$

From the results of Sec. III**B** we can consider that this assumption is quite correct. With this hypothesis, the calculation for obtaining the length distribution was performed in the following manner.

Let x be the actual length of a track, t its horizontal projection, d the thickness of the emulsion. We indicate by $f_p(x)dx$ and $f_\alpha(x)dx$ the number of either proton or alpha-particle tracks having an actual length between x and $x+dx$ per unit solid angle. The number of all the tracks is, consequently,

$$N=4\pi\int_0^\infty f(x)dx. \qquad (1)$$

[40] Either from the results of Perkins (Phil. Mag. 40, 601 (1949)) or from finding for the production of stars a cross section proportional to the geometric one, it is reasonable to attribute to the light nuclei of the emulsion about 30 percent of the *total* number of stars.

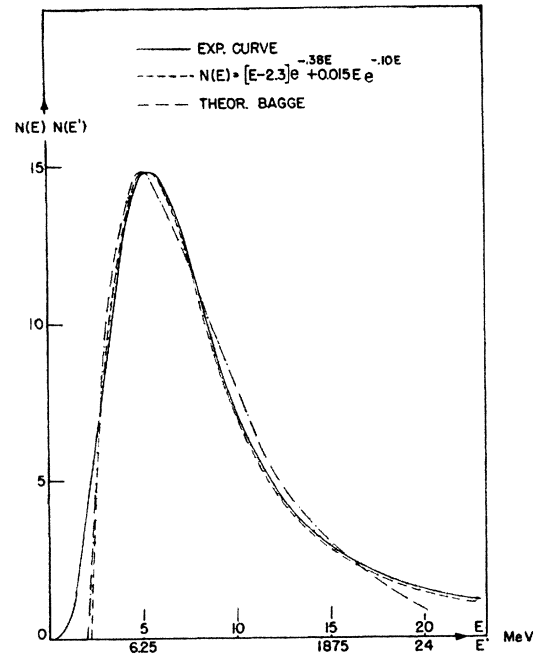

FIG. 8. Energy distribution of the protons from cosmic ray stars. The theoretical curve (Bagge) was obtained from Eq. (6) of the text, with $V'=2$ Mev. The ordinates are in arbitrary units.

The number of tracks ending in the emulsion and having a co-latitude between ϑ and $\vartheta+d\vartheta$ and a range between x and $x+dx$ is $2\pi f(x)\sin\vartheta[(d-x\cos\vartheta)/d]dxd\vartheta$. Introducing the variable t, it is easy to find that the distribution $F(t)$ of the projections is given by

$$F(t)=4\pi\frac{t}{d}\int_t^{(t^2+d^2)^{\frac{1}{2}}}\frac{f(x)}{x}\left[\frac{d}{(x^2-t^2)^{\frac{1}{2}}}-1\right]dx. \qquad (2)$$

Obviously, for $t\gg d$

$$F(t)\simeq 2\pi(d/t)f(t) \qquad (3)$$

and (3) was directly used to obtain the tail of the spectrum toward the high energies. The integral equation (2) was solved by developing the experimental distributions of the projections in functions of the type

$$\psi_i(x/a)=(x/a)^i\exp[-(x/a)^2], \qquad (4)$$

where i is an *even* number and a is some proper parameters selected to fit the experimental curves well. As is indicated by Tables V and VI, *the distributions of both protons and alpha-particles for the small stars seem to differ from those for the large stars.* The differences indicate, as is expected, a larger percentage of higher energies in the large stars. However, for the protons the difference does not exceed the limits of the statistical errors, and it was considered useless to make separate calculations for the small and large stars. For the alpha-particles the situation is a little different for the lower values of the projection lengths, and indicates clearly that for the large stars the maximum is displaced toward the higher energies. Thus we have solved Eq. (2) for the alpha-particles, distinguishing the large from the small stars. From the distribution functions $f_p(x)$ and $f_\alpha(x)$ we have obtained the energy distributions, using the well-known range-energy relations.[41] They are indicated in Figs. 8 and 9, for protons and alpha-particles respectively.

D

The method used in the solution of Eq. (2) is certainly very rough, but the evaluated distribution functions $f_p(x)$ and $f_\alpha(x)$, integrated [Eq. (1)] for all the x-values, give for the *total* number of prongs for all the observed stars a value which is in fairly good agreement with the observed one, i.e., about 15,000 after subtraction of the short prongs. Actually this number is about ten percent smaller than that calculated from f_p and f_α, but we can surmise that this deviation is essentially due to the estimate of the number of proton tracks having energies larger than 30 Mev. In the evaluated distributions there are about 1200 of these tracks, and a large fraction of them, because of their low grain-density and long range, certainly escaped observation in the C2 plates when they were appreciably inclined to the plane of the emulsion.

On the other hand, the observations made with NT4 plates (referred to in Sec. II) indicate that the proton prongs corresponding to energies larger than 30 Mev are just about ten percent of the *total* number of heavy ionizing prongs (and are clearly observable in C2 plates). In any case the figures of the last column in Table V, which were deduced from f_p, demonstrate that the calculations were quite reliable also in the upper part of the spectrum. Only the extreme tail of the spectrum itself was obviously wrong. Consequently, in spite of the crudeness of the method used to solve Eq. (2), we trust that the two deduced energy distributions represent rather closely the actual energy spectra of the singly and doubly charged prongs emitted by cosmic ray stars.

The distribution of the single-charged prongs is rather well represented by the empirical formula[42]

$$f(T)=A\{(T-2.3)e^{-0.38T}+0.015Te^{-0.10T}\} \qquad (5)$$

where T is the kinetic energy of the protons. The curve given by (5) is plotted in Fig. 8.

Of course Eq. (5) is only a simple analytical representation of the empirical results, but its form suggests a division of the prongs into nuclear evaporation prongs and knock-on prongs.[43] The average energy for the proton (single-charged) prongs between 0 and 25 Mev is $\simeq$8.2 Mev; for the alpha-particles it is $\simeq$11 Mev.

[41] Lattes, Fowler, Cuer, Proc. Phys. Soc. London **59**, 883 (1947), and reference 38. Edmont, J. de phys. et rad. (VIII) **10**, 22 (1949).

[42] We are very grateful to Mr. L. Lederman for suggesting this formula to us and for some interesting discussions on the topics of this paper.

[43] See Bagge, reference 17.

As was mentioned earlier, *there is not very much difference between the distributions of large and small stars.*[44] Consequently, these figures can be used for both. Considering our experimental data, the ratio between alpha and proton prongs is $\simeq 0.35$. This is in agreement with the results previously obtained by other authors.[45] The number of neutrons, in comparison with the charged prongs, can be estimated to be $\simeq 1.2$ (see below). Thus the average energy associated with the emission of one black prong is $\simeq 35$ Mev (the usual nuclear physics figures for the binding energies—$A=100$ —were used) and the *average* energy released per nucleus through the black prongs is $\simeq 150$ Mev (the average number of heavy prongs observed by us was $\simeq 4.7$).

E

The experimental data obtained on the structure of the stars can be more thoroughly discussed using the theoretical considerations suggested by Bagge (reference 17) and more recently by Fujimoto and Yamaguchi,[46] and particularly the very deep and extensive analysis made by Le Couteur.[47] From Le Couteur's discussion we can believe that when Bagge's dilatation of the Gamow barrier is considered, for heavy nuclei like Ag and Br the statistical considerations can be applied also for very high excitation energies. It is required only that the excitation energy be much less than the total binding energy. For Ag and Br nuclei that means less than ~ 500 Mev.

We believe it to be correct to consider as thermodynamic processes only those connected with the rather slow (heavy) prongs; certainly we cannot include among the true "evaporated" prongs most of the grey prongs, which are observed in large stars, and which have energies much larger than Fermi's limit (~ 20 Mev). For instance, the evaluations of Goldberger[20] show clearly the distinction between the immediately-projected prongs and the subsequent thermodynamic excitation, even for incident nucleons of only about 100 Mev. The angular distribution of prongs in small stars is, as we have said, an indication of the correctness of this argument. Similarly, in large stars the fastest nucleons directly produced by the incident particle (most of the grey prongs and their neutron partners) are not to be included.

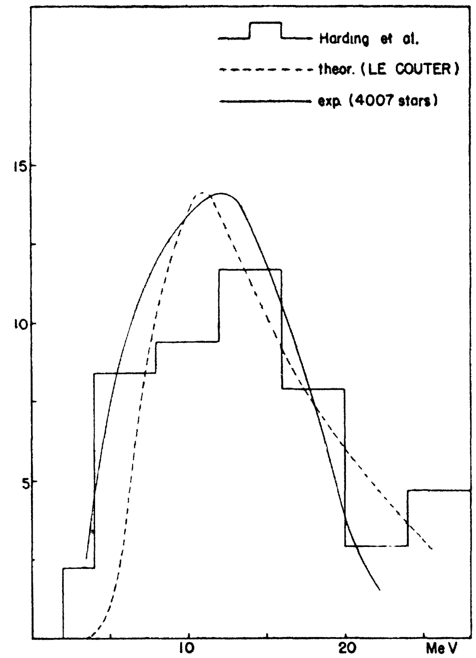

FIG. 9. Energy distribution of the alpha-particles from cosmic ray stars having more than 5 proofs. The ordinates are in arbitrary units.

Thus the application of the nuclear-thermodynamic considerations to the rather large stars produced by cosmic rays can be justified provided that: (1) only the heavy prongs (energies ~ 20 Mev) are considered; (2) in considering the total energy lost by the incident particle a distinction is made between the energy developed through the "true" evaporation and the energy belonging (after the emission from the struck nucleus) to the fastest knock-on nucleons. This distinction is necessary also because the number and energy associated with the *neutral* particles which are emitted together with the charged ones is, of course, different in the two stages of the process.

According to Bagge, taking into account the dilatation of the Gamow barrier, the energy spectrum of the protons should be given by

$$f(E)dE=\left(\frac{E-V'}{E}\right)\times\frac{E}{E+E_0}e^{-E/T_0}dE$$

$$=\frac{E-V'}{E+E_0}e^{-E/T_0}dE \quad (6)$$

where E_0 is practically the binding energy of the neutrons ($\simeq 8$ Mev) and T_0 is the temperature[48] $1/T_0 = dS_0/dU$ of the initial nucleus excited to energy U. Using for S the approximate expression $S\simeq 0.63(AU)^{\frac{1}{2}}$

[44] The absence of large differences between the two distributions is due to the following facts: (1) The heavy as well as the light nuclei contribute strongly to the small stars; (2) but in the case of the light nuclei, a larger fraction of the prongs is made up of alpha-particles (Perkins, Phil. Mag. 7 series **40**, 601 (1949)); (3) thus the difference is essentially concentrated in the alpha-particles and not in proton prongs. (4) As we will see later, the shape of the energy-spectrum of evaporating protons is not very sensitive to the energy excitation.

[45] Perkins, see reference 40; Addario and Tamburino, Como conference, 1949; A. Page, Proc. Phys. Soc. London (to be published) (we are very much indebted to Dr. G. Rochester and Dr. A. Page for sending us the manuscript).

[46] These authors kindly forwarded to us the manuscript of their work.

[47] We are very grateful to Dr. G. Rochester, who kindly gave us the opportunity of reading the interesting manuscript of Dr. K. J. Le Couteur.

[48] V. Weisskopf, Phys. Rev. **52**, 295 (1937).

suggested by the Fermi gas model, we find

$$T_0 \simeq 3.2(U/A)^{\frac{1}{2}}. \quad (7)$$

As was mentioned earlier, taking into account the binding energies and the ratio between the number of protons and the number of alpha-particles,[49] we find that the average energy connected with the *emission* of every visible prong is about 35 Mev, the average number of prongs for a star (including two-pronged stars) is 4.7, and consequently $\bar{U} \simeq 150$ Mev. From (7), assuming $A=100$, we have

$$T_0 \simeq 3.9 \text{ Mev}. \quad (8)$$

This means that formula (6) should be written as

$$f(E) \simeq [(E-V')/(E+8)]e^{-0.256E}. \quad (9)$$

The value of V' must be estimated. It represents the average value of the Gamow barrier during the evaporation process, the Bethe and Konopinski penetration being considered.[50] The following is a semi-empirical formula suggested by Le Couteur:

$$V' \simeq 0.7V/[1+(U/200)]. \quad (10)$$

In our case $V' \simeq 0.4V$. We find that the best value for V', which must be selected to obtain a good theoretical representation of the experimental spectrum, is $V' \simeq 2$ Mev. Thus $V \simeq 5$ Mev, which is very reasonable. In Fig. 8 the theoretical curve evaluated for $V'=2$ Mev is plotted. The agreement is so good that an overestimate of the reliability of the thermodynamic treatment might be possible, but we believe that this agreement is partially a happy case. For instance, following the brilliant explanation of the emission of protons of very low energies ($\simeq 2$ Mev) given by Fujimoto and Yamaguchi,[51] and then Le Couteur, the percentage of these slow protons, which are due essentially to the "governor" imposed by the ratio Z/A, should be larger than that which can be estimated by our analysis of the proton spectrum. Of course, this depends on the value selected for V', for the shape of the proton spectrum is very sensitive to this value, and we are inclined to believe that our V' value is actually too low. However, it is certain that the thermodynamic treatment based on the Fermi gas model represents quite closely the general behavior of the nuclear evaporations induced by cosmic rays. For example, the ratio between alpha- and proton prongs turns out to be approximately 0.35, in excellent agreement with Le Couteur's evaluations and with the results of other authors.[45] Further, the alpha-spectrum evaluated by Le Couteur, who was considering only the large stars,[52] represents fairly well the spectrum observed by us. That is shown in Fig. 9, where the spectrum evaluated for the alpha-particles emitted with excitation energies of 400 Mev ($A \simeq 100$) is represented together with Perkins' data on 150 stars, and with our data.[53]

Finally, we would like to remark that because our experimental value for the average energy connected with every visible black prong ($\simeq 35$ Mev) is smaller than the average energy for prongs estimated starting from Le Couteur's evaluations by a factor of about 0.85, in Fig. 3 the excitation energies given on the abscissae should be reduced by the same factor.[54]

The quite definite and quantitative results obtained in this paper on cosmic ray stars will be very useful in the discussion of the nucleonic cascade which will be presented in Part III of this work.

IV. DISCUSSION AND CONCLUDING REMARKS

Even postponing any discussion of the nucleonic cascade to a following paper, some conclusions which arise immediately from the figures reported can be examined conveniently at this time.

It seems to have been proven that most of the stars produced by cosmic rays can be interpreted in a quite direct manner, taking as a model the nucleon-nuclei collision studied by Goldberger[20] and others.[16] For the arguments indicated in this paper and in Part I, the stars are usually generated by nucleons having moderate energies, i.e., some hundreds in Mev. In this energy range, and in fair agreement with theoretical expectations, the characteristics of the stars (frequency *versus* number of prongs, energy of prongs, etc.) depend very slightly on the velocity of the incident nucleons. Thus the stars of the first branch of curve II in Fig. 3 are mostly caused by nucleons distributed in a quite large energy range, say between about 100 and 500 Mev, and show correctly the same characteristics as do the stars produced in the Berkeley experiments with deuterons and protons. Strictly speaking, as has been shown by Goldberger, considering the prongs of a star as a whole they are due not only to an evaporation process, and the agreement with the Bagge theory is partially only a happy accident. Some of the prongs are directly emitted after the collision with the incident nucleons, and demonstrate this origin in their forward projection, but their energies are largely included in the common energy ranges of the nuclear evaporations. A distinction between the two types of prongs (evaporation and knock-on prongs) which is based only on the energy is thus not possible, as has been already pointed out,[55] and probably would be quite meaningless.[56]

[49] In this estimate the difference between tritons and protons, etc., can be neglected.

[50] Bethe and Konopinski, Phys. Rev. **54**, 130 (1938).

[51] Fujimoto and Yamaguchi, Prog. Theor. Phys. **3**, 4621 (1948).

[52] In this case the distinction is necessary because of the appreciable contribution of the light nuclei.

[53] The curve is that corresponding to the large stars. This distinction was not made for the protons, as was mentioned before, on account of the slight difference in the proton spectra of large and small stars.

[54] Also, concerning the behavior of the proton spectrum, the difference between Le Couteur's evaluations and our results is a factor of about 0.85 in the abscissae. If the abscissae of Fig. 8 were to be increased by this factor, the agreement between Le Couteur's spectrum and the experimental one would be excellent.

[55] We want to thank Dr. M. Cosyns for some very useful remarks concerning this argument.

[56] As we said before, a differentiation between immediately projected and evaporated prongs could be made using Fermi's

The situation is slightly different for the large-size stars, that is for the stars of the second branch of curve II in Fig. 3, showing six or more prongs. They are mostly due to the explosion of heavy nuclei strongly excited by the *simultaneous* action of the incident nucleon and some fast secondary nucleons produced inside the struck nucleus itself. In this case the distinction between the different kinds of prongs, which is based on their energies,[57] is clearer and is supported by the more evident differences in the angular distribution. But this distinction remains obviously a quite rigid scheme. However, because the *average* energy losses suffered by a fast nucleon depend, as we have already seen, very little upon its own energy, all the secondaries produced by a primary nucleon and emerging with energy above approximately 50 Mev, must contribute to the same extent to the emission of slower prongs. This must be true independently of any subtle differentiation between projected and evaporated heavy prongs, and is in agreement with the correlation found between the *average* numbers of "heavy" and "grey" prongs. From the energy spectra of the heavy prongs it is to be believed that the excitation energy (in Mev) of an evaporating nucleus emitting N_h visible "heavy" prongs is about $35N_h$. Since some energy is directly transferred to the emerging "grey" prongs, this value does not represent *all* of the energy released to the struck nucleus by the incident nucleon. Roughly, for the correlation existing between "grey" and "black" prongs, attaching to any visible "grey" prong an *initial* average energy of about 100 Mev or more,[58] we can estimate that the total energy released in the production of a large star (six heavy prongs or more, and at least one "grey" prong) is about $70N_h$ Mev or more. The Berkeley nucleons are thus generally unable to produce stars having more than six black prongs, as has been actually observed.

On the contrary, cosmic ray nucleons quite frequently have sufficient energy to produce a large star.

energy limit as a dividing point. It would be better to consider as projected prongs those emitted during a period of time which is less than the nuclear period, but of course this is beyond the possibilities of the nuclear emulsion technique.

[57] A strongly excited nucleus has to emit evaporation prongs having an average energy which is larger than that resulting from a weak excitation (see Figs. 6 and 7), but the number of evaporation prongs having energies around 100 Mev, like the "grey" prongs, is always very small *up to* excitation energies for which the thermodynamic model has no further meaning (reference 47).

[58] Every visible "grey" prong represents, on the average, two nucleons escaping with an energy of $\sim$50 Mev.

If the preceding interpretation of star production is correct, usually a large size star must be considered essentially as the result of the development of a nucleonic cascade inside a nucleus.[59] This point of view could be invoked to explain the *exponential* behavior of the frequency of stars *versus* number of prongs for the large stars (more than five prongs), but the uncertainties concerning the energy spectrum of the star-producing nucleons, the corresponding cross sections, and so on, would make any speculation in this direction almost meaningless.[60] However, some general remarks can be made on this point. As was mentioned in Sec. II, only about 25 percent of the large stars (more than five prongs) observed at 3500 m show relativistic prongs. We can add now that about the same proportion is indicated in the data collected by Lord and Schein.[61] Even assuming that all the observed minimum ionization prongs are mesons, we must conclude that about 75 percent of the large stars are not connected in any evident or direct manner with the inelastic nucleon-nucleon collisions.

Consequently, it would seem that these large stars must be produced by knock-on collisions. But whether we extrapolate the Goldberger results (with a $1/E$ law), or use the evaluations made by Zwanniken,[62] it is clear that the number of large stars is extremely high in comparison with that which should be expected taking into account the probabilities for the knock-on collisions. This point is strengthened if we consider that the large stars are produced by nucleons of high energy representing only a small fraction of the star-producing radiation.[63] We are thus inclined to believe that while the large stars show, in the black prongs, the normal characteristics of highly-excited nuclear evaporations, the process by which the grey prongs are created with such high frequency is quite obscure.

[59] L. Jánossy, Phys. Rev. **64**, 345 (1943).

[60] See Part III.

[61] T. Lord and M. Schein, Phys. Rev. **77**, 19 (1950).

[62] See Zwanniken, reference 17. The evaluations of this author are made assuming a Yukawa potential, which favors the high momentum transfers.

[63] Incidentally, this means that also in the nucleonic cascade the collisions accompanied only by the projection of fast nucleons are more frequent than those in which π-mesons are produced. The observations on the penetrating showers made with the cloud chamber method (Butler and Rochester, communicated by Blackett at the Como conference) seem to support this conclusion.

Note added in proof: In a recent issue of the Nuovo Cimento **7**, 99 (1950), Dalla Porta, Merlin, and Puppi gave a brilliant interpretation of the transition effect in the star population observed in lead.