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

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The absorption of the star-producing radiation was studied with the sensitive emulsion method. The results are connected with the behavior of the nucleonic component, as it is indicated, on the basis of some recent experimental data.

I

BY the sensitive emulsion method the production and behavior of nuclear evaporations or stars was studied to some extent. We were mainly interested in the comparison of the absorption of the star-producing radiation** in several materials and in the analysis of the energy and distribution of prongs. Some preliminary results were already given in previous issues.[1]

The experiments were performed partly at the Laboratorio della Testa Grigia*** (3500 meters above sea level****), partly with balloons. The L.T.G. results so far available are those concerning the absorption of the s.p.r. in Pb and in Al, while the balloon results were used to study the absorption of the s.p.r. in air.

Other authors[2] have recently performed similar experiments, and their data will also be considered here.

The plates used were Ilford C2, 100 micron thick, whose processing was either the conventional one, or a two-bath method similar to the one described by Blau and De Felice.[3]

Scanning was usually made with a magnification of about 300x, but now and then some plates were scanned with a high magnification oil-immersion objective as a test. The differences observed between the results obtained by the two scanning procedures were always negligible, whether concerning the stars or the mesons. Furthermore, the results of the scanning of every plate were systematically reproduced on a map. In this way the random distribution of events was continuously checked.

In order to obtain an estimate of star-fading we exposed some plates of different thicknesses and different makes for 80 days at L.T.G., and developed part of them soon afterwards, while the remainder were kept for about 70 days in Rome under more than 50 cm of lead before being developed. Comparing the numbers of stars, we found that star-fading is not at all negligible (about 10 percent per month) and is variable for different samples of the same type of emulsion.

This first part of our work concerns the absorption of the s.p.r. and its connection with the absorption processes of the nucleonic component.

TABLE I. Absorption of the s.p.r. in lead.

Absorber thickness (in g/cm²)	0	23	68	111	152	375
N_S	100	109±4.3	80±4.5	72±5	71±7.5	28±3.2

II

Our absorption experiments in Pb and in Al were made in a very trivial way, using rather large boxes of the absorbing material and placing small packages of plates under different thicknesses.

The boxes were so wide that for every azimuth the angle covered round the vertical direction was not less than 45°. We shall discuss the point of geometrical conditions later. The boxes were placed in the plate-room of the L.T.G., which was particularly safe against moisture and temperature changes. Its walls are of wood and have an average thickness of 1.2 g/cm². During exposure time the average temperature was 12°C.

To avoid confusion with scattering processes we consider only the stars with at least 3 prongs. The stars arising from radioactive contamination were excluded following the usual criterion.

The results of the absorption measurements in Pb and Al are summarized in Tables I and II, where N_S indicates the star population, i.e., the number per cm³ per day of stars having 3 or more prongs (in the tables for convenience the number N_S for the unshielded

TABLE II. Absorption of the s.p.r. in aluminum.

Absorber thickness (in g/cm²)	0	13.7	61	103
N_S	100	93±8	76±6.8	64±5.9

* A short account of this paper was given at the Bristol Symposium on Cosmic Radiation (September 1948).

** In the following, indicated by the initial letters "s.p.r."

[1] Bernardini, Cortini, and Manfredini, Phys. Rev. **74**, 845 (1948); **74**, 1878 (1948); Cortini, Manfredini, and Persano, Nuovo Cimento **5**, 292 (1948); G. Cortini and A. Manfredini, Nature **165**, 992 (1949).

*** In the following, indicated by the initial letters "L.T.G."

**** In the following, indicated by the initial letters "m.s.l."

[2] E. P. George, Nature **162**, 333 (1948). E. P. George and A. C. Jason, Proc. Phys. Soc. **62**, 243 (1949). Harding, Lattimore, Li, and Perkins, Nature **163**, 319 (1949). Lord, Schein, and Vidale, Phys. Rev. **76**, 171 (1949). H. Yagoda, N. Kaplan, and C. H. Conner, Bull. Am. Phys. Soc. **24**, 16 (1949).

[3] M. Blau and J. A. De Felice, Phys. Rev. **74**, 1198 (1948).

plates was normalized to 100). The N_S are corrected by the number of stars generated at sea level, before exposure.

The measurements in Pb demonstrate a small transition effect. Such a feature is not apparent in Al, but errors are very large in this case. The values of N_S in Al and in Pb (when the equilibrium condition is reached) *versus* thicknesses, roughly follows an exponential law. If we consider the total star population as a measure of the intensity of the s.p.r., we can deduce the following absorption thicknesses of the s.p.r. in Pb and in Al from the data collected in Tables I and II:

$$L_{\mathrm{Pb}}=300\pm20 \quad L_{\mathrm{Al}}\simeq200 \text{ g/cm}^2.$$

Similar data were taken for air. In this case the intensity of the star population at several altitudes was obtained by sending some plates up with balloons. During the flights the temperature held between 7 and 18°C. The plates were placed in the upper part of the gondolas, and were wrapped in light materials like board, Bakelite, etc. The storage batteries of the radio equipment were placed beside the plates, about 10 cm apart.

To estimate the absorption thickness of the s.p.r. in air, an exponential absorption law was assumed (see later). Consequently, knowing the values of pressure transmitted during the flight, that is, the behavior of pressure *versus* time, we are able to evaluate the absorption thickness of the s.p.r. in air. We have obtained:

$$L_{\mathrm{air}}=135\pm4 \text{ g/cm}^2.$$

III

It has been pointed out many times[1] that the indicated values of L_{air}, L_{Pb}, and L_{Al}, which are in good agreement with those derived by other authors,[2,3] allows us to exclude the possibility that any appreciable fraction of the star population might be due either to the electron-photon component or to the μ-meson component. Hence it appears almost certain that nucleons and π-mesons play the principal role in the creation of the stars.

Let us briefly examine the contribution of the π-mesons.

The fast π-mesons, i.e., the π-mesons having a kinetic energy larger than 50 Mev cannot strongly contribute to the production of the star-population, because in such a case we should observe a large transition effect between air and condensed materials. On the contrary the values collected in Tables I and II appear to demonstrate only a small transition effect in Pb, which is probably due to slow nucleons and slow mesons.

The slow negative π-mesons (the so-called sigma-mesons in Bristol's phenomenological nomenclature) do not contribute to a great extent to the star population. On the average we found that only about 5 percent of the observed stars were produced by an observable negative π-meson. Concerning this value of the ratio between sigma-mesons and stars, many factors must be taken into account; particularly the fading effect, which can reduce this ratio, and the thickness of the condensed material placed upon the plates during the exposure time. About the fading we have no definite information, but from the figures obtained with different exposure times (ranging between 40 days and 3 months) we can conclude that fading does not change the order of magnitude of the ratio between sigma-mesons and stars.

About the second point, we must observe that because of the shortness of the mean life of the π-meson, the observed sigma-mesons are, of course, locally produced with both unshielded and shielded plates. Most of them certainly originate with the stars themselves in some processes like those of "double stars". But at the same time we may take it for granted that in the condensed materials, like Al and Pb, part of the observed mesons arise from the locally generated hard showers. As a matter of fact, Piccioni[4] showed in a very recent work that the local hard showers are mainly composed of π-mesons of both signs. Now, in a condensed material the negative (fast) π-mesons slow down in a very short time and most of them are captured by the nuclei and do not disintegrate. Consequently, the ratio between sigma-mesons and stars ought to increase from air to condensed materials.

Our statistics on sigma-mesons are rather poor (about 300 cases) but are sufficient to indicate clearly the existence of such an effect, and just of the expected order of magnitude (see Section II). We found, however, that the ratio of the numbers of sigma-mesons to stars never exceeds 10 percent and we believe this is the upper limit of the contribution given by the slow π-mesons to the star population.[5]

Having thus examined every type of known cosmic-ray component, except the nucleonic one, *we are compelled to consider this component as the almost unique intensive radiation able to produce the nuclear evaporations.*

IV

There is a different type of event which appears to be essentially connected with the nucleonic component. This is the so-called local hard shower discovered by Janossy. In the cosmic-ray field they are considered high energy processes. A rough estimate of their energies is possible from the well-known experiments by Janossy and others.[6] One finds that the number of mesons in a hard shower is, on the average, of the order of 10 and

[4] Communicated in an invited paper at the meeting of the American Physical Society, New York, January, 1949; see O. Piccioni, Phys. Rev., to be published.

[5] This result appears to be in agreement with some preliminary results by I. F. Quercia and B. Rispoli in an experiment with a fast ionization chamber working in coincidence with a set of delayed counters.

[6] See, for instance, D. Broadbent and L. Janossy, Proc. Roy. Soc. **A190** (1947).

that the energy of these mesons is some hundreds of Mev. This picture agrees with the brilliant results recently obtained by the Bristol and Bruxelles groups with the NT4 Kodak plates.[7] It agrees also on the lines of the theory of the multiple production of mesons given by Heisenberg,[8] Oppenheimer *et al.*,[9] and further discussed by Wataghin[10] and Heisenberg.[11] Thus the energy involved in such types of processes is of the order of some Bev.

On the contrary, a nuclear evaporation is usually a low energy process. However, some recent results on the absorption of the hard shower producing radiation demonstrate, with increasing evidence, a quite close correlation between these two phenomena. We would indicate how it appears possible to establish this correlation by merely drawing a comparison between the aforementioned experiments on hard showers and the ones previously described on the s.p.r.

After the recent measurements performed by several authors[12] in aircraft up to about 10,000 m it is possible to deduce that the hard shower producing radiation is absorbed in the atmosphere following an exponential law and that the corresponding absorption thickness appears to be

$$95 \leq \lambda_{\text{air}} \leq 135 \text{ g/cm}^2.$$

The rather large differences between the results of different experiments arise probably from differences existing in the devices employed by the researchers. These devices actually appear to be able more or less to enhance some features of the showers themselves, as for instance their multiplicity, penetration in lead, etc. Thus, in most of them it is believed that the penetrating particles are a mixture of mesons and secondary protons. This is very clearly indicated in the pictures by Lovati, Mura, Salvini, and Tagliaferri[13] and by Fretter[14] obtained with a tray of lead screens in cloud chamber. Because those secondary nucleons very often create some subsequent showers or other nuclear processes, it is clear that the instruments which are more or less able to detect those secondary processes apparently give an absorption thickness larger than the true absorption thickness of the primary radiation (see Wataghin[12]).

TABLE III. Comparison of the absorption thicknesses of the s.p.r. and the hard shower-producing radiation found by various authors in various materials.

	Hard showers of middle energy		Stars				
	Cocconi (s.l.)	Tinlot and Gregory	George Jason	Rome Group	Perkins *et al.*	Schein *et al.*	Yagoda *et al.*
Air	133±7	120	150±7	135±4		148	143±3
Lead	310±30	310	310±20	300±20			
Al				220			
C	140±20						
Ice					200		
Fe		200					

These "cascade processes" in nuclear collisions may be called on to explain the discrepancies observed in the measurements of λ. This conclusion may be stressed by the observation that the lower air limit for λ_{air} was found by George and Jason[12] by comparing the hard shower intensity between 3500 m and sea level with an experimental device highly selective for hard showers composed by particles of very high energy.

One intermediate value of λ_{air}, that is, $\lambda_{\text{air}} = 120$ g/cm^2 is supplied by the results of very careful measurements performed by Tinlot.[12] In Tinlot's experiments two penetrating particles are sufficient to trigger a coincidence, and, consequently, Tinlot's device does not discriminate as much in favor of processes involving such high energies. The upper limit for λ_{air} was obtained by Cocconi[15] with measurements at Echo Lake (3260 m.s.l.) but it is believed that Cocconi's device was sensitive to rather low energy processes, because with that apparatus only one particle was required to penetrate about 20 cm of Pb. For the other particles, ranges of about one inch could be sufficient to bring about a coincidence.

In conclusion *we consider it reasonable to assume as average absorption thickness in air for the hard shower-producing radiation the intermediate value* $\lambda_{\text{air}} = 120$ g/cm^2.

V

In addition to the mentioned experiments, the absorption of the hard shower-producing radiation in several materials was recently studied by Cocconi[15] and, independently, by Tinlot and Gregory.[16] Concerning Cocconi's experiment we wish to consider for the moment only the results of Ithaca, that is, near sea level. The values found by Cocconi for the absorption thicknesses in Pb, Fe, and C are reported in the first column of Table III. In the second column of Table III there are reported the values obtained by Tinlot and Gregory on the top of Mount Evans (4250 m.s.l.). We

[7] Kindly communicated to us by Professor C. F. Powell and Dr. G. P. S. Occhialini.

[8] W. Heisenberg, Zeits. f. Physik **101**, 533 (1936); **113**, 61 (1939); *Cosmic Radiation* (Dover Publications, New York, 1946), p. 124.

[9] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).

[10] G. Wataghin, Phys. Rev. **75**, 693 (1949).

[11] Kindly communicated by the author.

[12] G. Wataghin, Phys. Rev. **71**, 453 (1947); Maze, Freon, Daudin, and Auger, Rev. Mod. Phys. **21**, 14 (1949); J. Tinlot, Phys. Rev. **73**, 1476 (1948); E. P. George and A. P. Jason, Nature **161**, 248 (1948).

[13] Lovati, Mura, Salvini, and Tagliaferri, Nuovo Cimento, VI (1949). The authors gave one estimate of the cross section for the production of stars apparently in very good agreement with our result. But in this estimate they consider without discrimination every type of penetrating particles crossing the lead plates of the cloud chamber. Consequently the value found for the cross section would be an upper limit and it corresponds to the generation process only (the absorption process being, of course, a different matter).

[14] W. B. Fretter, work communicated at the Meeting of the American Physical Society, Pasadena, November 1948. We are grateful to the author for having kindly sent us the manuscript and the photographs.

[15] G. Cocconi, Phys. Rev. **75**, 1074 (1949).

[16] J. Tinlot and B. Gregory, Phys. Rev. **75**, 519 (1949); **75**, 520 (1949).

believe that the experimental arrangement employed by Tinlot and Gregory is better protected than Cocconi's against the spurious showers produced by particles coming in sideways. To compare with the behavior of the s.p.r., the values of absorption thickness L found for this radiation by Perkins *et al.*[2], George and Jason,[2] and by us, are collected in the third to fifth columns of Table III. Correlation between these data and the data of the first and second columns seems to be rather close, and in spite of the fact that the values of L referred to Al and H_2O are larger than those relative to the shower-producing radiation, it appears rather improbable that this correlation is due to pure chance.

Consequently, one would be driven to conceive a common origin for the two processes in spite of the differences in the energies involved.

Usually, because of the energies and the exponential behavior of the intensity of shower-producing radiation, one thinks that the nucleons which originate the hard showers mainly constitute the effective residual of the primary nucleons. This conclusion is very questionable in some experiments which are able to detect showers composed of particles of rather low energy, but it is perhaps reasonable, for instance, in the experiments performed by Janossy *et al.*[6] and by George and Jason,[12] who employed such a set of counters in coincidence that the energy of the showers detected in their apparatus was actually at least of the order of some Bev.

Thus we can assume that the number of nucleons able to produce hard showers is of the same order as the residual of the primary nucleons, and we can see now if it might be possible to attribute also a large fraction of the stars to the residual of the primary nucleonic component. A brief evaluation demonstrates that this is not the case.

VI

If the number of stars/cm³/sec. at a distance h in g/cm² from the top of the atmosphere is N_S, the number I' of nucleons arriving at this altitude and able to produce stars with a cross-section σ' must be:

$$I' = N_S/\sigma'\mathfrak{N}, \tag{1}$$

where $\mathfrak{N}$ is the number of atoms/cm³ from which the stars can be originated.

Taking into account the composition of the Ilford C2 emulsion, we estimate that $\mathfrak{N}$ is 4.72×10^{22}/cm³. The value of N_S at 3500 m.s.l. ($h=685$ g/cm²) is given by our results on the star population. They agree very well with the results recently obtained by George and Jason,[2,17] Yagoda, Kaplan, and Conner.[2] Neglecting the fading effect, we find $N_S=14.2\pm0.5$ stars/cm³/day in plates without any superimposed absorber. The number of stars/cm³/sec. is therefore 1.65×10^{-4}, and consequently we can write

$$\sigma' I' = 3.5\times10^{-27}\ \text{sec.}^{-1}. \tag{2}$$

The true value is certainly higher because of the fading effect. After our measurements on this phenomenon the above stated figures can be enlarged by about 20 percent.

Now, considering the absorption of the hard shower-producing radiation in the atmosphere, the intensity of the residual nucleonic component can be evaluated from the intensity of the primary component at the top of the atmosphere.[18]

Using the well-known Gross transformation, the integral intensity observed at any atmospheric depth h is expressed by

$$I = 2\pi I_0\left[e^{-h/\lambda_{\text{air}}} + \frac{h}{\lambda_{\text{air}}} E_i\left(-\frac{h}{\lambda_{\text{air}}}\right)\right]. \tag{3}$$

This formula is deduced by assuming a directional exponential absorption with an absorption thickness λ_{air}. Putting $\lambda_{\text{air}}=135$ g/cm², and $I_0=0.1$ cm⁻² sec.⁻¹ sterad.⁻¹ (that is probably a rather high value; see Rossi[19]) we find

$$I = 5.9\times10^{-4}\ \text{cm}^{-2}\ \text{sec.}^{-1}. \tag{4}$$

Thus, if we attribute the production of the stars to this residual of primary component, comparing (2) with (4) we find

$$\sigma' = 5.9\times10^{-24}\ \text{cm}^2.$$

Now this value is about 7 times larger than the average geometrical cross-section σ of the nuclei in the emulsion.

If we take for λ_{air} the more reasonable value indicated before, that is, $\lambda_{\text{air}}=120$ g/cm², the same evaluation gives

$$I = 2.8\times10^{-4}\ \text{cm}^{-2}\ \text{sec.}^{-1}.$$

and, consequently, a cross section 15 times the geometrical cross section. We can conclude that *the number of nucleons from which the stars arise is at least 10 times larger than the number of residual primary particles.*

VII

In order to understand this conclusion it appears necessary to conceive of the fast nucleonic component as being accompanied by a retinue of nucleons which belong to an intermediate energy range, that is, composed by nucleons having energies of some hundreds of Mev. Before discussing this point it is convenient to set forth some experimental facts which can, in this way, find a reasonable interpretation.

We would examine these facts separately. They are: (a) The proton group observed with a cloud-chamber

[17] In a previous work (see reference 2) these authors gave a rather low value for N_S, that is, 8.5, while in a later communication they give $N_S=14.65$ stars/cm³/d, in very good agreement with our figure.

[18] J. A. Van Allen and H. E. Tatel, Phys. Rev. **73**, 245 (1948); Gangnes, Jenkins, and Van Allen, Phys. Rev. **75**, 57 (1949).

[19] B. Rossi, Rev. Mod. Phys. **20**, 574 (1948).

device at 9000 m by Anderson *et al.*[20] This proton group constitutes a peaked maximum in the spectrum of the positive particles given by these authors.

Among the ionizing particles detected by the apparatus of the Pasadena group, the electrons are mainly excluded. Moreover, these particles are practically coming in from the vertical direction, because the cloud chamber is countercontrolled. Consequently, the number of these particles may be considered as a relative measurement of the intensity of the non-electronic component in the vertical direction.

Anderson *et al.* found that 30 percent of all the particles having a momentum p between 0.4 and 1.6×10^6 gauss-cm are certainly identifiable as protons. For $1.6<p<10\times10^6$ the positive particles, which constitute the peaked maximum mentioned above, appear to be about 30 percent of the particles in bulk, included within the same momentum ranges. It is reasonable to consider the larger part of these particles as protons, too. The absolute intensity of the non-electronic component having a momentum in the ranges indicated before appears to be, after the estimates given by Rossi[19]:

$$0.8\times10^{-1}\text{ cm}^{-2}\text{ sec.}^{-1}\text{ sterad.}^{-1}.$$

Thus the number of these slow protons should be about 2.4×10^{-2} cm^{-2} sec.$^{-1}$ sterad.$^{-1}$. This is just the order of magnitude to be expected from the star population, which, taking into account the above indicated increase with the altitude, would give for the *integrated* intensity of the s.p.r. about 0.1 cm^{-2} sec.$^{-1}$.

A more accurate comparison would require some information about the angular spread of the secondary nucleons round the direction of the primary ones. However, it is easy to observe that a larger fraction of the nucleons which create the stars are neutrons. In fact, if the number of slow protons having an energy under 1 Bev and coming in near the vertical direction is about 2×10^{-2} cm^{-2} sec.$^{-1}$ sterad.$^{-1}$, the number of nucleons having energies larger than 1 Bev and coming in in the same direction can be estimated (and that is a lower limit) directly, considering these nucleons as the residual of the primary component. Near the vertical direction, at 9000 m.s.l., this residual would be about

$$0.1\times e^{-305/120}=0.8\times10^{-2}.$$

Consequently it would appear that the number of slow protons is only about 3 times the fast nucleons, in disagreement with the number of nucleons evaluated as starting from the star population. This clearly means that for energies under 1 Bev, neutrons contribute strongly to the production of stars. More exactly, if we assume that the ratio between slow and fast nucleons is about 10, the number of neutrons in the s.p.r. must be at least twice the number of protons.

(b) One draws a quite similar result from the experiments performed by Alikhanian *et al.*[21] at 3250 mi. above sea level with a completely different technique. The results of these experiments indicate the presence of a group of ionizing particles (named "third component" by the authors), having moments between 0.7 and 2.0×10^6 gauss-cm. The interpretation of this group given by the authors is perhaps rather questionable. From some range measurements it appears to them to be composed of particles having masses of the order of 1000 m_e.

We like to consider this group as a slow proton group having the same origin as the group detected at 9000 m by the researchers of Pasedena. This opinion is supported by the following arguments.

Its intensity is 10 percent of the total mesonic component. After Rossi's figures it is easy to conclude that its absolute intensity is about 1.7×10^{-3} cm^{-2} sec.$^{-1}$ sterad.$^{-1}$. Consequently, the ratio between the proton group observed at 9000 m and this one at 3250 m is about 12.

If we consider an exponential decrease with an absorption thickness of 140 g/cm^{-2} (see Table III) between 9000 m (315 g/cm^{-2}) and 3250 m (700 g/cm^{-2}), we find an attenuation factor of about 15 in fairly good agreement with the preceding estimate.

We would also remark that, evaluating the integral intensity of the s.p.r. at 3500 m as was indicated in Section VI, one finds that the *total flux* of s.p.r. is about 4.10^{-3} cm^{-2} sec.$^{-1}$; that is, about 25 percent of the total mesonic flux. The comparison with the relative intensity of the proton group found by Alikhanian *et al.* give us again the indication that a large fraction (about $\frac{2}{3}$) of the s.p.r. is composed of neutrons.

A similar conclusion was reached by George and Jason[2] but we believe that they overestimate the fraction of neutrons. Actually, these authors start their evaluation from the particles identified as protons in the well-known Blackett spectrum at sea level where the slow protons are probably underestimated on account of the countercontrol device. This device selects protons coming in close to the vertical, while, on the contrary, the star-producing neutrons and protons are very probably distributed rather isotropically. Moreover, they consider, as a cross section for the production of stars, the one deduced from the absorption thickness of the s.p.r. in the emulsion (that is, 200 g/cm^{-2}). Now we believe that this is not correct, because absorption thickness is essentially determined by the fast nucleons which support the prevailing part of the s.p.r., i.e., the nucleons having energies around 200 Mev and in equilibrium with the fast ones. (*Note added in proof.*—See Part II of this work.) On the contrary, we assumed in the preceding estimates, as a cross section for the production of the stars by these

[20] Adams, Anderson, Lloyd, Rau, and Saxena, Rev. Mod. Phys. **20**, 334 (1939).

[21] Alikhanian, Alikhanov, and Weissenberg, J. Phys. U.S.S.R. **9**, 97 (1947).

slow nucleons, the geometrical one (nuclear radius $R=1.5\times10^{-13}\ A^{1/3}$).[22]

(c) The intensity of bursts and their behavior in the atmosphere is in very good agreement with the similar features concerning the star population. Indeed the corresponding absorption thickness in air found by several authors[23] is $L_{\mathrm{air}}=138$ g/cm^2.

An accurate comparison of the absolute intensities is not possible because of the production of stars in the walls of the ionization chamber and owing to the cut-off acting on the pulse size. But the absolute intensity of the observed bursts is of the right order of magnitude with regard to the star population detected in our plates.

It was already pointed out by Rossi[19] that in the burst curve there is some evidence for a transition effect near the top of the atmosphere. This indicates that the intensity of the star-producing radiation decreases in the first layers of the atmosphere much less than the assumed intensity of the residual primary component.

In other words, as was stated by Rossi,[19] the absorption curve of the burst in the atmosphere diverges markedly from that which can be evaluated with the Gross transformation, assuming an absorption thickness of 135 g/cm^2. The intensity of bursts at 3500 m.s.l. is just about 10 times that which could be expected if its generating radiation were submitted to a directional exponential absorption with the absorption thickness now indicated. Of course, this fact becomes clearly understandable if one assumes that after some absorption lengths an equilibrium condition is reached between the primary nucleons and the secondary ones able to produce bursts, the multiplicity of secondary creation being about 10 as we have evaluated before.

(d) A clear transition effect of the same type was indeed very recently observed by Schein *et al.* in plates screened with different thicknesses of lead and exposed at about 30,000 m.s.l.[24]

(e) Qualitative, but strong evidence of the production of secondary nucleons in penetrating showers is given by several pictures by the authors quoted in footnotes 13 and 14.

(f) Some direct evidence of stars connected by a fast prong identifiable with a proton was recently obtained by G. Occhialini *et al.*,[25] and by us, in NT4 Kodak plates.

VIII

The arguments stated above substantiate the idea that in crossing the atmosphere the nucleonic component undergoes a cascade process through which a *primary proton gives rise on the average to more than 10 secondary nucleons having energies of the order of magnitude of some hundreds of Mev.*

It is easy to conceive the origins of this cascade process. They are the production of fast secondary nucleons both in inelastic and quasi-elastic collisions in nuclear matter.[26] Actually it is easy to see that even in the case of a totally inelastic collision, a primary nucleon having an energy of some Bev may be able to produce two secondary nucleons of several hundreds of Mev.

At the same time it is possible to argue that a fast nucleon crossing the nuclear matter has a probability of some percent to transfer a rather high momentum to one secondary nucleon in a quasi-elastic collision. In this way inelastic and fast knock-on nucleons greatly (and rapidly) increase the percentage of $\sim$100 Mev nucleons and are very efficient in the production of stars. The nuclear cascade might supply a reasonable interpretation of some puzzling questions, as the nuclear size dependence on the absorption thickness for hard shower-producing radiation and for s.p.r. and the rather large values of the corresponding absorption thicknesses in comparison to the geometrical ones.

All these questions will be examined in the second part of this work and in a paper by B. Ferretti, after a deeper and more quantitative discussion about star structure and the corresponding energies.

We are very glad to express our acknowledgments to Professor B. Ferretti who informed us in several useful discussions of the results obtained developing quantitatively some arguments expressed in this paper. We thank Professor W. Heisenberg and Professor E. Amaldi for some interesting discussions and advice.

[22] We do not know to what extent this assumption can be considered correct. For instance, the cross section measured by Gardner for the stars in photographic emulsion initiated by α particles appears to be smaller than the geometrical one by a factor larger than two.

If these figures could be extended to the nucleons of about 200 Mev, we should find that the s.p.r. would be composed of about 80 percent neutrons. The numerical evaluation deduced in Section VI by Anderson's measurements and by our data concerning the star population should be modified in the same direction. Particularly the evaluated multiplicities of secondary nucleons from which the stars arise would be increased by about a factor 2.

[23] See B. Rossi, reference 19, p. 552.

[24] Kindly communicated by author. A similar effect was found by Freier, Ney, and Oppenheimer, Phys. Rev. **75**, 1451 (1949).

[25] Kindly communicated by author.

[26] We are much indebted to Dr. S. A. Wouthuysen for a very interesting discussion about this point.