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The Spectra and Sign Distributions of Particles from Cosmic Ray Stars at 2 860 metres Altitude.

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Summary. — Measurements have been made on mesons and protons emitted from stars recorded at 2 800 m and compared with published results for balloon altitudes. It appears that, while the multiplicity of showers is greatly reduced at the lower altitudes, the normalized energy spectra are closely similar. The determination of the sign of the charge of particles leads to a preliminary determination of the positive-negative ratio of mesons produced at this altitude, and of πp's primary and secondary to stars.

1. – Introduction.

The possibility of using magnetic deflection within the photographic emulsion to determine the sign of fast charged particles was demonstrated in a previous paper [1]. In this paper are described some results obtained by the method in an investigation of cosmic ray stars at the Pic du Midi (2 860 m) in the French Pyrenees.

Although the maximum field available was only 34 000 gauss, information has been obtained on the relative number of positive and negative mesons

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[1] C. C. Dilworth, S. J. Goldsack, Y. Goldschmidt-Clermont and F. Levy: *Phil. Mag.*, Ser. 7, 61, 1032 (1950).

produced in the stars. The sign ratio of those particles (πp) which could not be identified by combined scattering measurements and grain counting has also been investigated.

The energy spectra, irrespective of sign, of fast particles primary to and emitted from stars have been compared with those obtained by other workers on plates exposed at high altitudes by means of ballon flights.

2. – Experimental procedure.

2·1. *Exposure.* – Plates of Ilford G5 emulsion 400, 600 and 1 200 microns thick were exposed at the Pic du Midi, in a magnetic field which in most cases was 34 000 gauss, though a few plates were exposed in only 22 000 gauss. Some of the plates were of diluted G5 emulsion, which has a gelatine to silver ratio twice that of the normal G5. The scattering coefficient in the diluted emulsion is about 16% smaller than that in the normal emulsion, but the emulsion is more fragile and so requires special care in processing.

2·2. *Selection of tracks.* – The equivalent length of a track for sign determination is $l' = \beta^2 l$ is the true length and β is the velocity in units of the velocity of light. Tracks were chosen for measurements which satisfied the condition $\beta^2 l \geqslant 3$ mm; β being estimated from the grain density. This criterion of selection much reduced the number of protons which were measured since in the energy region where identification is possible protons have velocities $\beta < 1$, and so require longer tracks.

2·3. *Measurement.* – The measurements of scattering and total deflection were made using both the angular method as described by GOLDSCHMIDT (²) and the sagittal method introduced by FOWLER (³).

In a few cases both methods were used on the same track to confirm that the techniques were consistent. The data were analyzed by the method described in the previous paper (¹) in which curves were presented showing the probability of error on the sign for various field strengths. Those curves require amendement for the following reason. The scattering constant used in these calculations was that for a one centimetre track length. If scattering measurements are made using a short cell length, and a cut off applied to eliminate single scatterings, the effective scattering constant may be reduced by as much as 20%. This is equivalent to increasing the magnetic field by

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(²) Y. GOLDSCHMIDT-CLERMONT: *Nuovo Cimento*, **7**, 331 (1950).
(³) P. H. FOWLER: *Phil. Mag.*, Ser. 7, **41**, 169 (1950).

the same amount. Thus, with this method of analysis, and a cell of 100 microns, the curve for 34 000 gauss becomes that previously given for 41 000 gauss. If diluted emulsions are used a further 16% may be gained raising this figure to 47 000 gauss.

On tracks for which the scattering measurement showed a value of $p\beta$ less than 500 MeV/c (p = momentum) grain counting on 1 mm of the track is sufficient to distinguish between mesons and protons. For values of $p\beta$ greater than 500 MeV/c more accurate counts were made. In order to avoid proton contamination in the sign ratio of mesons, tracks for which $p\beta$ was greater than 1 000 MeV/c were considered unidentifiable, and were classed as πp. Due to statistical fluctuations a few tracks slightly less energetic than this, showed a mass value intermediate between that of a proton and that of a meson and were rejected. It did not seem necessary to make an accurate determination of the energy of those particles which could easily be shown to be much heavier than π-mesons after only rough measurements. A part only of each track was measured, giving an accuracy of about 25% on the energy: their signs were not determined. Under these conditions deuterons and tritons and heavy mesons could not have been distinguished from protons. For simplicity this group will be referred to as the proton group.

For meson tracks and for 49 tracks of protons which were fully measured the accuracy was between 10% and 15%.

2·4. *Control of distortion.* – On each plate the distortion vector K was measured; K represents the non-linear part of the displacement of the surface with respect to the glass [4,5] (uniform shearing of emulsion cannot curve a track).

In the plates used in this work K was generally less than 30 microns. This means that a track 1 cm long passing right through the emulsion in a direction perpendicular to the vector K, i.e. in the direction in which there is maximum second order distortion, the total deflection due to distortion was about 0.35°: the similar deviation due to a field of 34 000 gauss of a particle of momentum 10^9 MeV/c is 0.58°. Thus for most tracks the distortion was negligible, since generally the energy was lower, and only a component of the distortion was effective. When necessary a correction was made: a few tracks in which the distortion had changed the apparent sign of the particle were rejected.

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(4) M. COSYNS and G. VANDERHAEGHE: *Bull. Centre Phys. Nucl. Bruxelles*, No. 15 (1950).

(5) J. MAJOR: *Journ. App. Phys.*, 3, 309 (1952).

3. – Experimental results.

3·1. *Energy distribution.* – Among 7 300 stars, 384 tracks were found with $\beta^2 l \geqslant 3$ mm. Of these 145 were identified as due to secondary protons and 111 as due to secondary mesons. Their energy distribution is given in fig. 1.

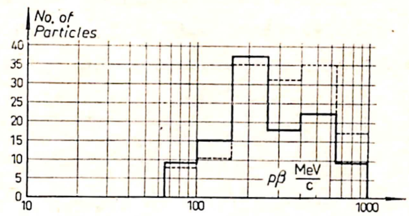

Fig. 1. – Energy distribution of secondary protons (dotted line) and secondary mesons (full line).

—— Identified Mesons;

- - - - - Protons Deuterons and Tritons.

There were 19 secondary πp's which are included in the energy distribution of all secondaries given in fig. 2. The relative numbers of protons and mesons given here is significant only when corrected for the systematic loss at low velocities, in choosing the tracks according to the criterion $\beta^2 l \geqslant 3$ mm. The ratio of the number of protons to that of mesons in a given energy range is (β_p^2/β_π^2) times the ratio observed, β_p being the velocity of a proton, β_π that of a meson in that energy range. This effect is corrected for in the energy spectra, which are given in fig. 3 and 4.

It is interesting to compare these results with those obtained by CAMERINI *et al.* (6) for their observations at 25 000 m. Their curves are given in fig. 3 and 4 normalised to our results. The normalised spectra are substantially the same as those given by our results, although the number of mesons per star in our plates is only one half the corresponding number in the balloon plates. Table I shows the relative multiplicities of shower particles at balloon altitudes (7) Jungfraujoch (8) and the Pic du Midi (present work).

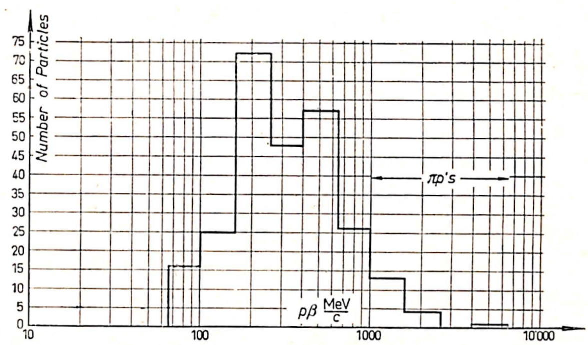

Fig. 2. – Energy distribution of all secondaries.

(6) U. CAMERINI, P. H. FOWLER, W. O. LOCK and H. MUIRHEAD: *Phil. Mag.*, 61, 413 (1950).

(7) U. CAMERINI, J. H. DAVIES, P. H. FOWLER, C. FRANZINETTI, H. MUIRHEAD, W. H. LOCK, D. H. PERKINS and G. YEKUTELI: *Phil. Mag.*, 62, 1241 (1951).

(8) R. H. BROWN, U. CAMERINI, P. H. FOWLER, H. HEITLER, D. T. KING and C. F. POWELL: *Phil. Mag.*, 60, 862 (1949).

TABLE I. – *Percentage of stars.*

Number of shower particles (Grain Density < 1.5 min)	25 000 m CAMERINI *et al.* (7)	3 580 m BROWN *et al.* (8)	2 860 m present work
0	72.5%	86.3%	84.5%
1–3	22.4%	12.4%	14.7%
4–7	2.4%	0.9%	0.7%
8	0.7%	0.4%	0.1%
Average number of shower particles per star	0.53	0.25	0.25

Our proton spectrum is subject to an uncertainty in the number of particles at low energies due to the condition $\beta^2 l \geqslant 3$ mm. In spite of the correction there remain subjective errors due to the observers estimation of grain densities.

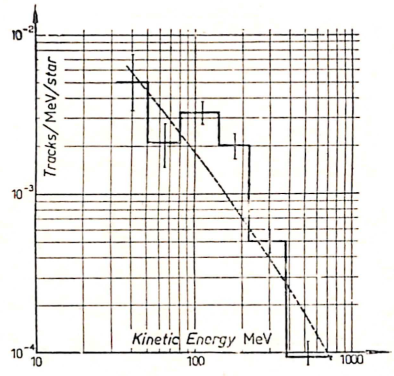

Fig. 3. – Energy spectrum for secondary mesons. The histogram represents the present results at 2 860 m; the curve the results of CAMERINI *et al.* at balloon altitudes normalized to our results.

-------- CAMERINI *et al.* (1950);
——— Present experiment.

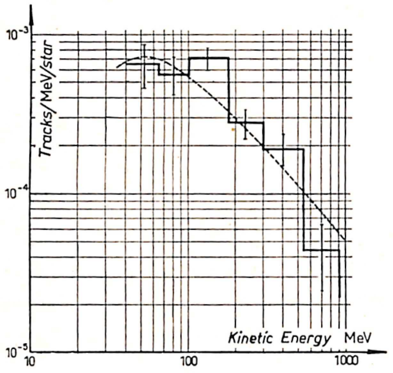

Fig. 4. – Energy spectrum for secondary protons. The histogram represents the present results at 2 860 m; the curve the results of CAMERINI *et al.* at balloon altitudes, normalized to our results.

------- CAMERINI *et al.* (1950);
——— Present experiment.

Fig. 5 shows the energy distribution of all primaries compared with that obtained by CAMERINI *et al.* at 25,000 m (7). A primary being defined according to the convention used in that paper. There were 46 proton primaries, 27 meson primaries and 36 πp primaries.

3·2. *Magnetic deflection.* – The sign of the charge of a given particle is established in each case only with a certain probability. This probability is a function of the value assumed a priori for the ratio (r) of the number of positive to the number of negative particles. The probability $P_i(+)$, that the i^{th} particle is positive is:

$$(1)\qquad P_i(+) = \frac{1}{1+(1/r)e^{-\varepsilon_i}},$$

where ε_i is a function of its velocity, the total angle of deflection, the mean angle of scattering and the length of its track.

For an individual track we usually have no a priori knowledge of the sign ratio. We can only assume that $r = 1$ (Baye's hypothesis) giving

$$(2)\qquad P_i^*(+) = \frac{1}{1+e^{-\varepsilon_i}}.$$

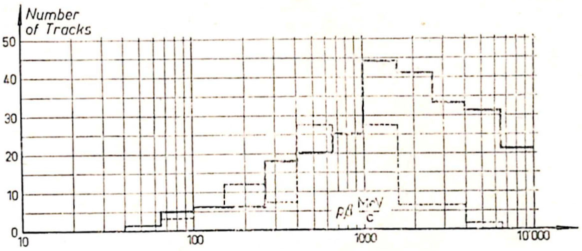

Fig. 5. – The energy distribution of particles primary to stars. The continuous lines are the results of CAMERINI *et al.* at balloon altitudes, the dotted lines are the present results at 2 860 m.

——— CAMERINI *et al.* (1951);
------- Present Experiment.

When we have a group of tracks we can take as a first approximation to the sign ratio r the ratio

$$(3)\qquad r^* = \frac{\sum P_i^*(+)}{\sum (1-P_i^*(+))}.$$

However to obtain the best estimation of r we should solve the equation

$$(4)\qquad r = \frac{\sum P_i(+)}{\sum (1-P_i(+))} = \frac{\sum \dfrac{1}{1+(1/r)\,e^{-\varepsilon_i}}}{\sum \dfrac{1}{1+r\,e^{\varepsilon_i}}}.$$

This can best be done graphically.

This calculation was carried out for the 111 secondary mesons together with the 27 primary mesons. We considered primary and secondary mesons together since the former can be assumed to be produced in the plate-magnet assembly. Putting $r = 1$ we found $r^* = 1.17$; by solving equation (4) we found $r = 1.5$.

Fig. 6 is a histogram showing the distribution of the actual sign probabilities calculated for each track. A track at the extreme right is certainly positive, while one at the extreme left is certainly negative; a track giving a probability around 50% gives no information about its sign. This distribution is given both for $r = 1$ ($P^*(+)$) and for the value $r = 1.5$ obtained from the experiment.

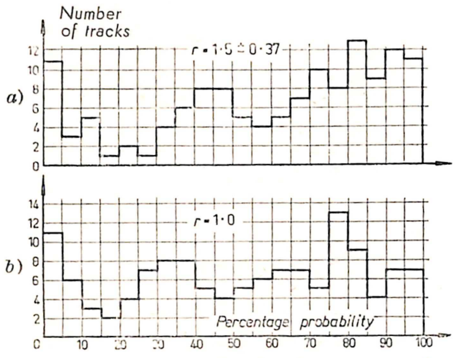

Fig. 6. – Sign probabilities calculated for mesons tracks, (*a*) with $r = 1.0$, (*b*) with $r = 1.5$.

The analogous treatment of the 49 protons which were completely measured is illustrated in fig. 7. In this

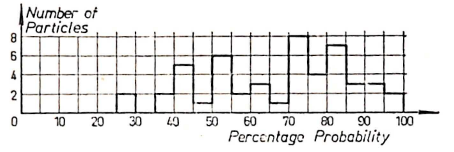

Fig. 7. – Sign probabilities calculated for proton tracks with $r = 1.0$.

case equation (4) has no real solution. The most probable value for the positive-negative ratio is infinite. Thus only the distribution with $r = 1$ is given. The second distribution would consist of a single column at the extreme right hand side.

Since each track has an error on the sign determination the total error on r is clearly greater than that obtained from a similar number of tracks for which the sign of each was certain. In the latter case the standard error on the estimate of a positive negative ratio r from N tracks is

$$\varepsilon(r) = \left\{\frac{r(r+1)^2}{N}\right\}^{1/2}.$$

When the sign is determined for each track with only a certain probability $P_i(+)$, it can be shown that the preceding formula can still be used for a large sample by replacing N by N' where N' is the effective number of tracks and is given by

$$N' = N\left(\frac{\overline{P_i(+)^2}(1+r)^2}{r} - 1\right).$$

Where $\overline{P_i(+)^2}$ is the mean square of $P_i(+)$.

For the 138 mesons $\overline{P_i^2(+)}$ is 0.48, which leads to $N' = 0.5N$. The error on the positive negative ratio is therefore $\varepsilon(r) = 0.37$. In figs. 8*A* and 8*B* are shown the energy distribution of the positive and negative mesons separately. For this purpose a track was reckoned positive if its probability was greater than 50% with $r = 1.5$. There may be expected to be considerable cross contamination of the spectra. Fig. 9 shows the distributions of the sign probabi-

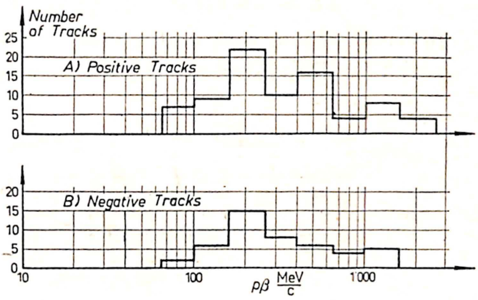

Fig. 8. – Energy distributions (*a*) of positive meson secondaries, (*b*) of negative meson secondaries.

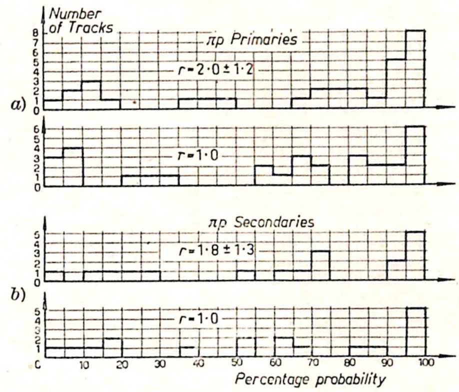

Fig. 9. – Sign probabilities of (*a*) πp primaries (*b*) πp secondaries.

lities for the πp's (particles with $p\beta > 1\,000$ MeV/c) for the 36 primaries and 19 secondaries separately. The effective numbers of tracks in these cases are 18 and 10 respectively. The positive negative ratio for the primaries is 2.0 ± 1.0 for the secondaries it is 1.8 ± 1.2.

4. – Discussion.

4·1. *Energy Distributions.* – The energy spectra of secondary particles agree quite well with those obtained at 25 000 m. The primary spectrum shows a shift towards lower energies and the multiplicity is about one half of that in stars produced at balloon altitudes. It seems therefore that multiplicity is much more sensitive to primary energy than is the form of the secondary energy spectrum.

4·2. *Magnetic deflection.* – Among the mesons produced in the plate-magnet assembly there is a positive excess of 1.5 ± 0.37. Among πp's there is an excess of 2.0 ± 1.0 for the primaries and 1.8 ± 1.2 for the secondaries.

The last value can be compared with the results of BARKER and BUTLER from cloud chamber work [9]. They found for all particles with $p \geqslant 1\,000$ MeV/c

[9] K. H. BARKER and C. C. BUTLER: *Proc. Phys. Soc. Lond.*, A, 64, 4 (1951).

TABLE II.

	No. of mesons	$p\beta$	Sign	Primary
1	2	1 100 650	— 88 % + 70 %	Uncharged
2	2	300 500	— 63 % — 98 %	Uncharged
3	2	320 270	— 99 % + 97 %	Charged
4	2	220 770	+ 20 % + 83 %	Charged
5	2	460 1 000	+100 % —100 %	Uncharged
6	2	280 250	— 91 % — 98 %	Uncharged
7	2	180 480	— 66 % + 75 %	Charged
8	2	9 500 510	Distorted —100 %	Charged
9	3	200 240 110	— 73 % + 55 % — 54 %	Uncharged
10	4	220 400 500 600	— 77 % — 66 % + 76 % + 61 %	Uncharged
11	5	320 200 280 25 150	+ 63 % + 55 % + 57 % — 55 % + 71 %	Uncharged

a positive negative ratio of 2.7 ± 0.7. To compare this with our result we must first correct for those protons whose momentum is greater than 1000 MeV/c but for which $p\beta < 1000$ MeV/c. It can be deduced from emulsion data that for every 100 tracks taken as πp under our convention BARKER and BUTLER would include a further 28 protons. Correcting for these the result of BARKER and BUTLER becomes 1.9 ± 0.5, in good agreement with the value found in this work.

There is no significant difference between the spectra of positive and negative mesons. The bulk of the statistics are in the higher energy region, where there seems little reason to expect any difference: the effects of Coulomb repulsion at nucleus and of the excess of neutron primaries should not have much effect above about 200 MeV.

Eleven stars had two or more meson secondaries each, all measured. The results for all such complete stars measured are shown in Table II.

Conclusion.

The method of magnetic deflection inside the emulsion can be used for a statistical study of the signs of fast charged particles produced in cosmic ray stars in the photographic emulsion. The measurements on a given track do not in general determine the sign with complete certainty, so that the error on a positive negative ratio is greater than the statistical error which the same number of tracks would give if the signs were certain. It is convenient to refer to an effective number of tracks which is the number which would give the same precision if the signs were determined with certainty. With the field at our disposal, and taking all tracks with $\beta^2 l \geqslant 3$ mm this effective number proves to be about one half of the actual number of tracks.

With a field of the order of 50000 gauss such as is now available in the Merlin-Someda magnet (private communication), the same efficiency of sign determination could be obtained on twice as many tracks for the same number of stars. The increase in the number of complete stars should be much greater roughly proportional to $(50/34)^{2n}$, where n is the number of shower particles in a given star.

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We wish to express our gratitude to our colleagues, especially to Dr. NORA PAGE, for their help in this work.

We acknowledge gratefully the assistance of the scanning teams of both laboratories and in particular of Mlles. CORNIL and VANDENCAMP who made a part of the measurements.

RIASSUNTO

Sono state eseguite misure sui mesoni e protoni emessi da stelle osservate in emulsioni nucleari esposte a 2 800 m di altitudine. I risultati sono stati confrontati con quelli già pubblicati, relativi a quote stratosferiche. Si vede che mentre la molteplicità degli sciami si riduce grandemente a bassa quota, gli spettri di energia normalizzati sono simili. La determinazione del segno della carica delle particelle conduce a un valore preliminare del rapporto mesoni positivi/mesoni negativi prodotti alla suddetta altitudine, e dei π-p primari e secondari.

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