Meson Showers and High-Energy Interactions in Light and Heavy Nuclei

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A study has been made of nuclear disintegrations produced in electron-sensitive emulsions exposed to cosmic radiation at 80 000 ft. Of 93 stars containing more than three shower particles, 29 were interpreted as being induced in the light nuclei C, N, O, and 64 in the heavy nuclei Ag and Br. The low-energy tracks appear to be emitted isotropically from a slowly moving nucleus and the forward collimation of the remaining tracks is discussed. The average numbers of shower particles from the heavy and light nuclei are 7.7 and 6.4_5, respectively, and it is shown that these figures are consistent with multiple processes of meson production. The difference between the angular distributions of shower particles from heavy and light nuclei is discussed on the assumption that it is mainly due to scattering.

INTRODUCTION

A STUDY has been made of stars containing meson showers in 400μ Ilford G5 nuclear emulsions exposed at altitudes between 80 000 and 90 000 feet.[1] In order to be certain of the primary direction, stars with three or more shower particles were selected and a few of these, which were close to the air or glass surface or whose primary directions were steeply inclined to the emulsion surface, were omitted. Using this method of selection, 93 stars, 12 produced by neutral primaries and 81 by singly charged particles, were analyzed. In addition, several stars giving meson showers produced by alpha particles and heavier nuclei were studied. The primary directions of large showers produced by neutral particles were estimated as the mean of the shower particle directions. In no case was it assumed that a collimation of nonshower particles was related to the primary direction.

MEASUREMENTS OF TRACKS AND IDENTIFICATION OF TARGET NUCLEI

By measuring the azimuth and dip angles of the tracks, the latter angles being corrected for the shrinkage factor which varied from plate to plate, the angle θ of each track relative to the primary direction in the original undeveloped emulsion was calculated. As the grain density of the tracks also varied with development, the minimum grain density of each plate was measured and grain densities in grains per 50μ were standardized to a minimum of 12. Tracks with grain densities up to 25 percent above minimum were classed as shower particles. The grain density of a completely black track parallel to the emulsion surface was taken as 120, a proton track of range 100μ therefore having a grain density of about 115, corresponding to 5 gaps per 50μ, and an α track of range 100μ having a grain density of 117, corresponding to 3 gaps per 50μ. Checks were made to insure that different observers obtained the same value of grain density for a given track, and graphs were drawn relating these estimated grain densities to the ranges and energies of charged particles.

From the lengths of tracks which ended in the emulsion and from their grain or gap densities, the particles which produced the tracks could often be identified. Where possible, scattering measurements and delta-ray counts were made on long tracks which did not end in the emulsion and these combined with grain density measurements gave a means of identification. Where identification was not possible it was assumed that tracks of range greater than 100μ, excluding shower particles, were protons, those with ranges between 100μ and 30μ were alpha particles, between 30μ and 10μ, lithium nuclei, and recoils less than 10μ were assumed to have a charge 4.

From the above measurements, the total charge Z of the nonshower tracks was estimated. Figure 1B shows the number of stars with a given Z plotted against Z for stars without recoils, and Fig. 1A shows the number of stars with recoils. It is seen from this latter figure that there are no stars with recoils with $Z<13$. The assumption of 4 units of charge for the recoils is probably an underestimate but it is seen that even so no stars were obtained with Z between 8 and 12, and there is a separation between stars having $Z\leqslant 8$ and $Z\geqslant 12$. It is concluded that the stars with $Z\leqslant 8$ are due to the

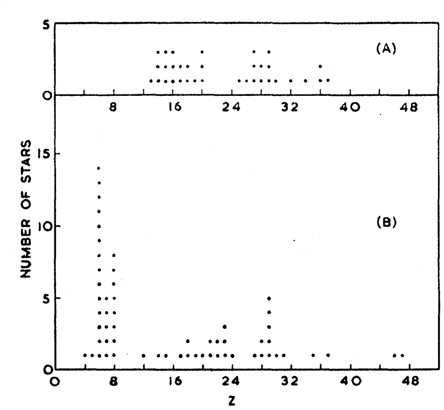

FIG. 1. The number of stars with a given Z is plotted against Z for stars with recoils (A), and without recoils (B), showing the separation of the stars into those produced in light and heavy nuclei.

[1] Darby, Hopper, Laby, and Wilson, Australian J. Phys. 6, 471 (1953).

disintegrations of C, N, and O nuclei in the emulsion, and those with $Z \geqslant 12$ are due to Ag and Br.

Of 29 light nuclei events, 25 of which had charged primaries, only two stars have $Z<6$. From this, it is inferred that practically all the charge of a light nucleus goes into the nonshower tracks since scattering measurements show that these are very seldom due to mesons, and hence the shower tracks must be mainly mesons. (Camerini, Fowler, Lock, and Muirhead[2] have shown that the small admixture of protons amongst the shower tracks is approximately compensated by the number of π mesons of energy less than 150 Mev among the nonshower class.) If this is also true of showers from heavy nuclei, there must in general be for these a residual nucleus, which in some cases may be the observed recoil, while in others would be of too short range to be detected.

ANGULAR DISTRIBUTION OF TRACKS

In Fig. 2, the number of tracks per 0.1 interval of $\cos\theta$ is plotted against $\cos\theta$ for seven intervals of grain density, the results for the shower tracks being discussed later. From this it is seen that a considerable fraction of the high-energy protons is emitted from heavy nuclei in the backward hemisphere, and this supports the contention that the primary direction should not be deduced from any collimation of a group of nonshower particles.

The tracks would be expected to fall into three main categories: (1) The shower tracks created in nucleon-nucleon collisions which should be strongly collimated in the forward direction; (2) knock-on tracks, mainly due to protons that have not suffered many collisions before escaping from the nucleus and should therefore be collimated but to a lesser extent; and (3) lower-energy tracks due to particles which have evaporated from the remaining excited nucleus, and which, but for the slight forward movement of this nucleus, should be isotropically emitted in the laboratory system. A critical test for isotropy is found in the excess forward fraction of tracks $(F-B)/T$, where F and B are the numbers of forward and backward tracks in a given energy range and $T=F+B$. Values are listed in Table I.

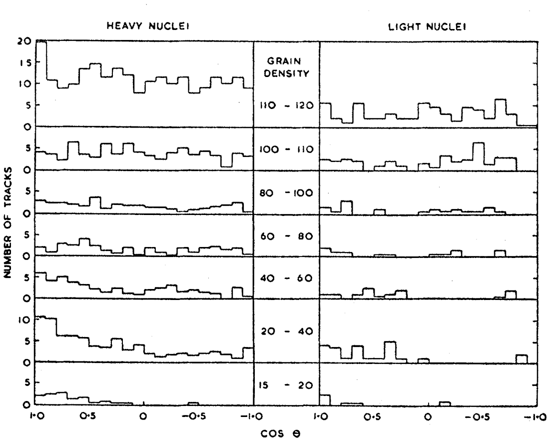

FIG. 2. The number of tracks per 0.1 interval of $\cos\theta$ is plotted against $\cos\theta$ for seven intervals of grain density.

[2] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

Tracks with Grain Density Greater than 60

It is seen from Table I that there is very little departure from isotropy for proton energies up to 50 Mev, the values of $(F-B)/T$ for all tracks up to this energy being 0.11 ± 0.04 and $-0.0_4\pm0.1$ for heavy and light nuclei, respectively. These figures are reasonably consistent with isotropic emission from a moving nucleus. If a very high-energy particle passes through a nucleus which as a result is excited to an energy E, the forward momentum of the excited nucleus will be E/c. If E is taken as the total energy of all the particles, including neutrons, emitted with energies less than 50 Mev, it is estimated from the data given in Table I to be 500 Mev and 130 Mev for the average heavy and light star, respectively. The mean proton energy in this region is 10 Mev and using this value the calculated ratio $(F-B)/T$ is 0.04 and 0.06 for heavy and light stars, respectively.

From Fig. 2, it is seen that even above 50 Mev there is a considerable number of nonshower tracks emitted almost isotropically in the backward hemisphere from heavy nuclei, and a few tracks emitted backwards from light nuclei. If E also includes these tracks, plus an equal number emitted in the forward hemisphere, the values of E for the average heavy and light nucleus are 1270 Mev and 220 Mev and the corresponding values of $(F-B)/T$ are 0.10 and 0.11, respectively. Some of these tracks may therefore be due to evaporation particles, but there is still an appreciable forward component which cannot be explained on this hypothesis and which must be associated with knock-on particles.

Tracks of Grain Density Between 15 and 60

Scattering measurements indicate that these tracks are almost always heavier than mesons. The measured forward excess $(F-B)$/star is 2.1 and 1.0, while the total number of these tracks per star is 4.5 and 1.3 for heavy and light nuclei, respectively. The numbers of tracks per star for increasing numbers of shower particles are given in Table II.

It is observed that the number of tracks of grain density 15–60 per star is nearly independent of the mean number $\bar{n}_s$ of shower particles for values of $\bar{n}_s$ from about 4 to 8 for both heavy and light nuclei. There is however a slight increase for large showers ($\bar{n}_s=13.5$) for heavy nuclei. Only two events were observed for light nuclei with $n_s>9$. The results for the heavy nuclei are in good agreement with those plotted by Camerini *et al.*[3] in their Fig. 7 which show

[3] Camerini, Lock, and Perkins, *Progress in Cosmic Ray Physics*, edited by J. G. Wilson (North-Holland Publishing Company, Amsterdam, 1952), first edition.

TABLE I. Excess forward fraction of tracks for different energy regions for light and heavy nuclei.

Grain density	120–110	110–100	100–80	80–60	60–40	40–20	20–15	<15
Proton energy (Mev)	0–8	8–15	15–30	30–50	50–85	85–300	300–800	>800
$(F-B)/T$								
Heavy	0.09	0.17	0.24	0.14	0.26	0.50	0.93	0.90
	±0.05	±0.10	±0.10	±0.10	±0.10	±0.10	±0.2	±0.05
Light	0.0	−0.2	0.1	0.1	0.6	0.8	0.5	0.94
	±0.1	±0.2	±0.3	±0.3	±0.3	±0.2	±0.5	±0.07
Tracks/star								
Heavy	7.8	2.7	1.2	1.2	1.6	2.7	0.4	7.7
Light	2.1	1.3	0.4	0.3	0.4	0.8	0.1	6.4_5

an almost constant number of protons of energy 25–800 Mev for $\bar{n}_s$ from 3 to 6 with a rise of about 2 for $\bar{n}_s=14$, although Camerini *et al.*[4] show a slight rise also for $\bar{n}_s=6$ in the equivalent Fig. 5 of that reference. The inference drawn from Table II is that only a very small fraction of the tracks in this grain density range can be due to meson-nucleon collisions.

If some of these tracks in the grain density region 15–60 are the result of knock-on particles, it might be expected that their number would depend on the number of collisions suffered by the primary nucleon. If the primary particle produces mesons in several successive collisions in the nucleus, the number of knock-on tracks would depend on the number of shower particles n_s. The results thus suggest that in either light or heavy nuclei the primary particle has about the same number of meson producing collisions for $\bar{n}_s=4$ and $\bar{n}_s=8$ with a slight increase for $\bar{n}_s=13.5$ for heavy nuclei. In other words a pluro multiple rather than a plural mechanism is favored for the production of mesons, large showers differing from small ones in the number of mesons produced per collision rather than in the number of collisions of the primary nucleon.

Although the number of tracks in this region of grain density 15–60 might be expected to be proportional to the number of collisions suffered by the primary particle, the constant of proportionality is not likely to be the same for heavy as for light nuclei. Fast nucleons resulting from meson producing collisions of the primary would knock out more fast particles from heavy than from light nuclei because the average distance traveled before escaping from the former is greater. It follows that the ratio of the average number of collisions of the primary nucleon in heavy and light nuclei would be less than 4.5/1.3 and this is confirmed by the analysis in the next section where the average numbers of primary collisions in heavy and light nuclei are estimated as 1.64 and 1.3, respectively. That fast nucleons have more collisions in escaping from heavy than from light nuclei is also suggested by the greater degree of forward collimation of the tracks in the grain density region 15–60 for light nuclei.

[4] Camerini, Davies, Fowler, Franzinetti, Muirhead, Lock, Perkins, and Yekutieli, Phil. Mag. **42**, 1241 (1951).

Also evidence given by Camerini *et al.*[3] suggests that even for stars where only one meson is produced, the number of tracks of grain density 15–60 will be about 2.5 for heavy nuclei. If the number of tracks is proportional to the number of meson producing collisions in the nucleus, 1.8 collisions would be sufficient to produce the observed number 4.5 tracks of grain density 15–60 for heavy nuclei as stated above.

Tracks of Grain Density <15 (Shower Particles)

For the stars studied, the value of n_s ranged from 3 to 19 for the heavy nuclei, the mean being 7.7/star, and from 3 to 14 for the light, the mean being 6.4_5/star. Assuming as a first approximation, that the showers consist entirely of mesons, the ratio of the values of n_s for the average heavy and light stars, *viz.*, 1.19±0.10, can be explained by two quite different models. In the first, the incident particle may have meson producing collisions so frequently on passing through the first half of a heavy nucleus (corresponding in distance to the diameter of a light nucleus) that it has insufficient energy to produce many more mesons in traversing the remainder of the nucleus. This would correspond to a mainly plural interaction. In the second model, corresponding to a mainly multiple interaction, the incident particle has a small cross section for meson producing collisions in nuclear matter and produces several mesons per collision, the number of collisions in heavy nuclei being only slightly greater than the number in light nuclei.

Assuming that the average energy of the primary particles for light and heavy stars is the same, the two solutions can be derived from the following crude

TABLE II. Number of tracks per star related to shower size for heavy and light nuclei.

	Heavy nuclei			Light nuclei		
n_s	3–5	6–9	10–19	3–5	6–9	10–14
$\bar{n}_s$	3.8	7.5	13.5	4.0	7.9	13.5[a]
Grain density	Tracks/star			Tracks/star		
15–60	4.6±0.4	4.1±0.4	5.5±0.9	1.5±0.3	1.1±0.3	1.0
>60	12.5±0.7	11.8±0.8	14.5±1.0	4.2±0.5	4.3±0.5	3.0

[a] Mean of two stars $n_s=13$ and $n_s=14$ having the same numbers of tracks in the two grain density ranges.

model. The nucleus is assumed to consist of nucleons randomly distributed throughout a sphere of radius $1.4A^{\frac{1}{3}}\times 10^{-13}$ cm and the primary particle is supposed to interact with any nucleons in a cylinder of cross section σ which traverses the nucleus. In its first collision with a nucleon in the nucleus it is assumed that m mesons are created, qm in the second, q^2m in the third, and so on; the chance of a given number of collisions depending on the probability of that number of nucleons being present in the cylinder. It is assumed that no mesons are produced in meson nucleon collisions inside the nucleus. (Camerini *et al.*[4] give evidence from which they infer that only a very small fraction of the mesons can interact with nucleons before escaping.) With this model for the average heavy and light star, values of $q=0.75$ and $m=5.1$ will give the required ratio of 1.19. The average numbers of collisions for heavy and light nuclei are 1.64 and 1.3, the corresponding cross section σ being 16 millibarns. For the same value of q, another solution is obtained corresponding to a mainly plural process but this gives the extremely high value of $\sigma=170$ millibarns, and an incident particle would have, on the average, six collisions traversing a light nucleus and twelve collisions traversing a heavy nucleus, the number of mesons created in the last six collisions for a heavy nucleus contributing only $(0.75)^6\times$ the number of mesons created in the first six collisions. The ratio 1.19 can be satisfied for any value of q between 0.5 and 1.0, and for any value of q in this region there are two values of m, the higher corresponding to mainly multiple meson production and the lower to mainly plural production.

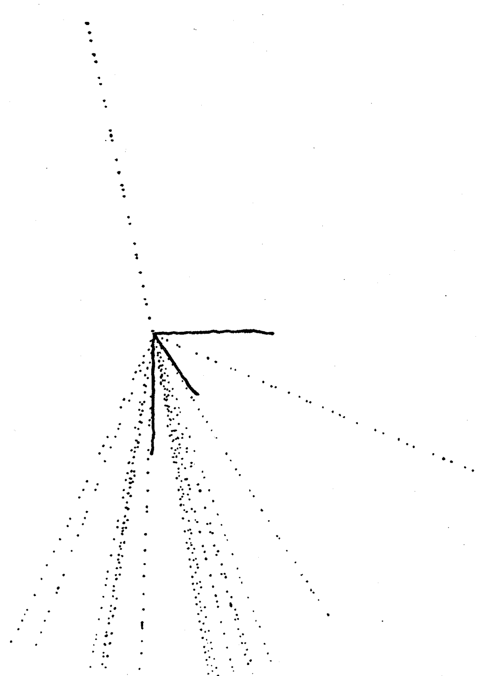

FIG. 3. Star produced from disintegration of a light nucleus giving fourteen shower particles. (Z is estimated as 6 from the nonshower particles.)

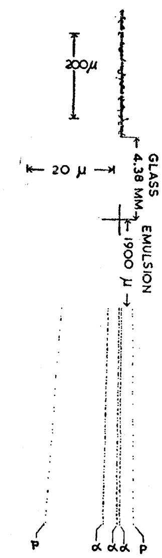

FIG. 4. An oxygen nucleus with energy ~60 Bev/nucleon interacts with a nucleus in the glass backing of the emulsion and does not produce a meson shower.

No solutions for the latter case were acceptable since σ and hence the number of collisions would be too large to explain the apparent independence of the number of nonshower tracks on the number of shower particles as is seen in Table II. Lock and Yekutieli[5] estimate that for stars produced by protons of energy up to 800 Mev, the mean value of the scattering cross section is 30 millibarns. For protons of energy several Bev, which produce stars with meson showers, the higher value of σ which corresponds to plural production thus seems unlikely. It is concluded that meson production is mainly a multiple process and for the stars considered the average multiplicity is 4 to 5 charged mesons per collision.

The hypothesis of multiple meson production is also supported by consideration of some individual stars. Figure 3 shows a star from a light nucleus with an estimated value of Z for the nonshower particles of 6, and 14 shower particles. The evaporation prongs were most probably two alpha particles and a proton, and there was in addition one fast proton of energy 250 Mev. If the nucleus was correctly identified as a light one, a maximum of six nucleons can take part in the meson producing collisions, and several mesons must therefore be produced at single collisions.

The fact that very high-energy particles can interact without meson production also contradicts the assumption that σ is high and that a nucleon suffers many collisions in passing through a nucleus. An example of an event which illustrates this is shown in Fig. 4, where a primary particle with charge 8 and an energy of about 60 Bev/nucleon interacts with a nucleus in the glass backing of the emulsion and produces no meson shower.

[5] W. O. Lock and G. Yekutieli, Phil. Mag. 43, 231 (1952).

Scattering of the Shower Particles

Although the average numbers of shower particles from heavy and light stars are almost the same, there is a considerable difference in the angular distribution of their tracks. The half-angle, *viz.*, that angle containing half the shower particles, for the average showers of multiplicity n_s is given for heavy and light nuclei in Table III. It should be pointed out that for any given value of n_s for a light atom or for a heavy atom there are considerable fluctuations about the mean half-angle and on the mainly multiple hypothesis these can be explained by different degrees of inelasticity at the nucleon-nucleon encounter.[6]

It is seen that the half-angles are consistently larger for heavy than for light nuclei. In order to study the effect in more detail, P, the fraction of tracks per unit interval of $\cos\theta$ emitted at an angle θ to the primary direction, is plotted against $\cos\theta$ for heavy and light nuclei in Fig. 5, and this confirms the wider distribution of shower particles from heavy nuclei. If we make the assumptions that the difference is solely due to scattering, and that there is twice as much scattering in a heavy nucleus as in a light one since the former has twice the diameter of the latter, then the average distribution of mesons from nucleon-nucleon interactions will be as shown in the figure. This curve is obtained by adding to the light curve the difference between the curves for light and heavy nuclei.

If this explanation is correct and mesons are in fact scattered before escaping from the nucleus in which they are produced, it will be of interest to speculate how such scattering occurs. If the scattering takes place with nucleons, an increase of the number of tracks in the grain density interval 15–60 with increasing n_s would be expected, and this is not in accord with the results of Table II. An alternative suggestion might be that the mesons are scattered by alpha groups or larger combinations of nucleons. This interpretation, requiring the temporary existence of nuclear aggregates inside the nucleus, is similar to that suggested by Camerini *et al.*[3] to explain the emission of high-energy fragments from nuclei. In this case the energy per nucleon imparted to the scattering center may not be sufficient for it to escape and would then be added to the thermal excitation energy.

TABLE III. Dependence of mean half-angles on number of shower particles.

n_s		3, 4	5, 6	7, 8	9–12	13–19
Half-angles	Heavy	25°	35°	27°	27°	17°
	Light	23°	17°	13°	13°	15°

[6] W. Heisenberg, Z. Physik **126**, 569 (1949).

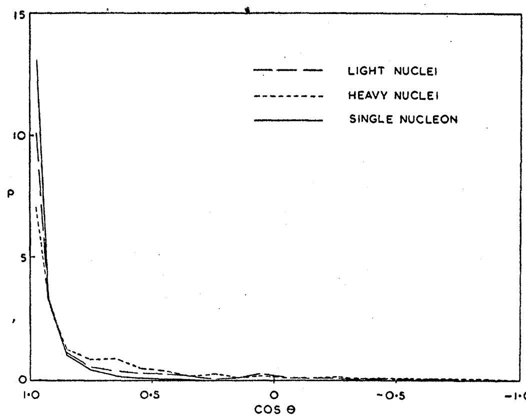

FIG. 5. P, the fraction of tracks per unit interval of $\cos\theta$ emitted at an angle θ to the primary direction, plotted against $\cos\theta$ for the shower tracks from light and heavy nuclei. The estimated angular distribution of shower tracks from the average nucleon-nucleon collision is also plotted.

CONCLUSION

For high-energy interactions such that at least three shower particles are produced, stars induced in light nuclei C, N, O can be separated from those induced in heavy nuclei Ag, Br. In both cases, the low-energy tracks can be explained on the assumption of evaporation from a moving nucleus, but there is a forward collimation of tracks in the grain density interval of 15 to 60 grains/50μ which cannot be explained in this way. This forward component must be related to the primary event and the apparent independence of the number of tracks in this interval on the number of shower particles show that they are not due to meson nucleon interactions and also suggests that the number of primary collisions does not depend to any marked extent on the number of shower particles. This, coupled with the observations of the average number of shower particles from heavy and light nuclei, favors a multiple rather than a purely plural mechanism for meson production. To explain the independence of the number of tracks in the nonshower group on the number of shower particles, it is suggested that the meson scattering inside the nucleus is from nuclear aggregates.

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