Neutron and Meson Stars Induced in the Light Elements of the Emulsion*

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(Received May 7, 1953)

Laminated emulsions have been exposed to the neutron and positive meson beam at the Nevis cyclotron. In the case of the neutron exposure (300 Mev) it has been found that 21±3 percent of the emulsion stars originate in light nuclei. The number of fast protons and their angular distribution is similar in stars from light and heavy elements. The black tracks in light element stars show a marked forward excess.

The energy range of the mesons incident on the laminated emulsions was from 50–80 Mev. 24–30 percent of the emulsion stars originate in light nuclei. In about 15–20 percent of these cases, the scattered meson emerges from the nucleus. Charge exchange scattering, if present at all, amounts to less than 10 percent of all interactions. More than 70 percent of the interactions (stars) result in absorption of the incident meson. The absorption occurs chiefly in nucleon pairs.

LAMINATED emulsions (gelatin layers sandwiched between emulsion layers) were introduced by Harding[1] in cosmic-ray experiments. Later Menon, Muirhead, and Rochat[2] used the same technique in in experiments with slow negative π mesons. In both cases the gelatin layers were sandwiched between Ilford *C*2 emulsions. Gelatin layers between *G*5 emulsions were first used by Hodgson[3] in cosmic-ray experiments.

The purpose of laminated emulsions is to separate the light and heavy emulsion elements in experiments investigating the cross section or disintegration processes of particles incident on the emulsion. Furthermore, a study of the disintegration of light nuclei is perhaps simpler since the number of nucleons concerned is reduced and therefore effects resulting from statistical factors are diminished.

The main disadvantage of laminated emulsions is that the scanning procedure required is more difficult and lengthy than the scanning of ordinary emulsions. The thickness of the gelatin layers and therefore the number of interacting nuclei must be kept small, since otherwise a relatively large number of shorter prongs ends in the gelatin without reaching the adjacent emulsion. Even with gelatin layers of 5–8 microns, the percentage of lost prongs is not negligible; however, to some extent the number and charge of these lost prongs can be estimated from the known mean charge of gelatin nuclei.

I. STARS INDUCED BY 300-MEV NEUTRONS

A. Exposure

Stratified emulsions consisting of gelatin layers[4] of about 7–8 microns sandwiched between layers of *G*5 emulsion have been exposed to the neutron beam of the Nevis cyclotron originating from a beryllium target. The average energy of this neutron beam is 300 Mev, and the spectrum is peaked at 300 Mev.[5,6]

B. Star-Producing Cross Section in the Light Emulsion Nuclei

The number of stars originating in the gelatin layers was compared with the number of emulsion stars. Areas used for the comparison were scanned twice independently by two observers. From the ratio of stars in gelatin and emulsion layers and the known content of light elements in the emulsion itself, the number of stars which are due to these light elements was determined.

Counting in both emulsion and gelatin all stars with a prong number ≥ 2, we found (considering equal areas) 133 gelatin and 2190 emulsion stars. The ratio of the number of light elements in the emulsion (excluding hydrogen) to the number in gelatin layers has been determined to be 2.95±0.5; therefore, using these data, one finds that the percentage of all stars in the *G*5 emulsion which originate in light nuclei is 18±2 percent.

On the other hand, if we accept all two-pronged stars in the gelatin, assuming that on the average an additional short prong has probably been lost, but accept in the emulsion only two-pronged stars with a distinct recoil prong, we find that 21±3 percent of the emulsion stars have originated in light nuclei. The error in both cases comprises the standard deviation and an uncertainty error of 10 percent made in deducing the ratio of light elements in the emulsion to light elements in the gelatin layers. In the first case (18 percent) the percentage of light-nuclei stars may be underestimated, since 2-pronged stars in the gelatin layers with 1 short prong could have been overlooked, while some of the presumed 2-prong stars in the emul-

* Research carried out under auspices of the U. S. Atomic Energy Commission.

[1] J. B. Harding, Nature 163, 440 (1949); Phil. Mag. 42, 63 (1951).

[2] Menon, Muirhead, and Rochat, Phil. Mag. 41, 583 (1950).

[3] P. E. Hodgson, Phil. Mag. 42, 955 (1951).

[4] The exact ratio of gelatin to emulsion thickness is important for the calculation of the ratio of cross sections in light and heavy elements and has been determined by an x-ray transmission method described in the Appendix.

[5] W. Godell, Nevis Cyclotron Laboratory Quarterly Report June 15, 1951 (unpublished).

[6] Bernardini, Booth, and Lindenbaum, Phys. Rev. 85, 826 (1952).

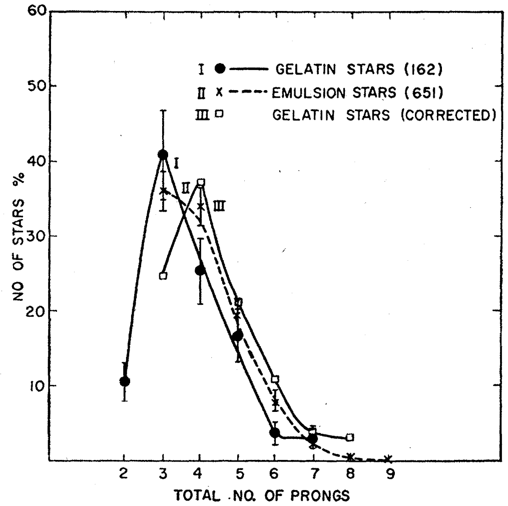

FIG. 1. Prong distribution of gelatin and emulsion stars induced by 300-Mev neutrons.

sion may be scattering events. The second value (21 percent) is probably an overestimate, and the true value should lie between these limits.

Assuming a cross section proportional to $A^{\frac{2}{3}}$, one would expect that 27 percent of all emulsion stars originate in light nuclei. Therefore even the second value (21 percent), implying an overestimate, is still less than the calculated percentage, thus showing a greater transparency of light nuclei.

If one assumes the value 21 ± 3 percent, one finds for neutrons of mean energy 300 Mev a relative opacity[7] of light (14) to heavy (100) emulsion nuclei,

$$(\sigma_{\text{light}}/\pi R^2)/(\sigma_{\text{heavy}}/\pi R^2)=0.71\pm0.11.$$

The calculated value for the relative opacity of these nuclei, based on DeJurens'[8] data for the inelastic cross sections of various elements, is 0.71 for 270-Mev neutrons. From these data the inelastic cross section for emulsion nuclei (light plus heavy) becomes $0.67\sigma_{\text{geom}}$.

Actually the experimental value of 0.71 ± 0.11 should not be directly compared to the ratio of opacity deduced from DeJurens' total inelastic cross sections, since 1-pronged stars and inelastic scattering events without visible star formation were not included in the comparison. Since 3- and 4-pronged stars in light nuclei are probably favored, because of the low binding energy of α particles, the true ratio referring to total inelastic cross sections may still be smaller than 0.71.

For much higher energies—when meson production occurs—the percentage of emulsion stars originating in light nuclei (comparing stars of two or more prongs) will probably approach the calculated percentage of 27 percent corresponding to their geometrical cross sections, since the transparency of nuclei becomes smaller and since at high energies stars of less than 2 prongs in heavy elements are infrequent. For lower energies, the percentage of light nuclei stars can even exceed the value of 27 percent, because the high potential barrier of heavy nuclei tends to reduce the number of stars of 2 or more prongs and also a greater number of collisions will occur in which only 1 or no charged particle is emitted. On the other hand, in light nuclei 3- and 4-pronged stars can originate even at very low energies (20 Mev).

Therefore Harding's result that 36 ± 3 percent of all emulsion stars originate in light nuclei is not necessarily in contradiction with the value found in these experiments. Harding exposed the plates to cosmic rays at mountain altitudes and hence compared stars produced by nucleons of a wide spread of energies including many low-energy neutrons.

C. Prong Distribution

The mean prong number for emulsion stars is 3.65 ±0.1 and for gelatin stars 3.72 ± 0.3. However, for gelatin stars this number has to be corrected for loss

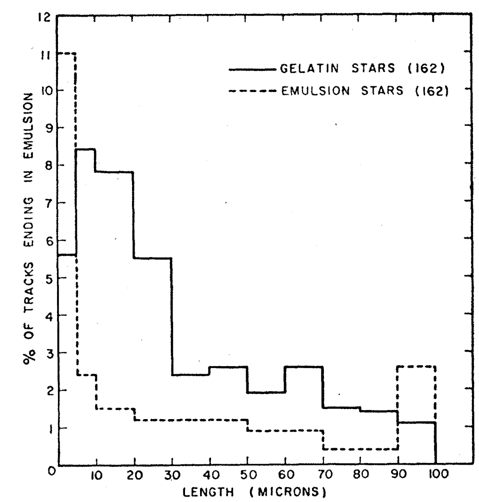

FIG. 2. Range distribution of prongs in 0–100-micron interval from neutron-induced gelatin and emulsion stars.

in gelatin layers. The correction factor depends on the length of the tracks in consideration and is greater for short tracks. The correction factor f is $f=(1-l/2d)$ for $l<d$ and $f=d/2l$ for $l>d$, where l is the length of the track and d the thickness of the gelatin layers. After applying the correction, the mean prong number in gelatin stars increases to 4.4 ± 0.2.

Of all gelatin stars, 25 ± 3 percent[9] have prongs with range ≤5 microns; these prongs probably correspond to recoils with charge >2; in stars occurring in light elements occasionally Li^8 and Be^8 recoils have been ob-

[7] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).
[8] J. DeJurens and B. J. Moyer, Phys. Rev. **81**, 919 (1951).
[9] P. E. Hodgson (reference 3) finds for cosmic-ray exposure at mountain altitude that 22 ± 6 percent of all stars from light elements have recoils.

served here and by other authors.[10] From the total mean charge of gelatin nuclei, the mean prong number and the mean number of and charge of recoil fragments, the ratio of doubly to singly charged particles per star and the degree of disintegration can be estimated. Assuming a mean charge for the recoil fragments of 3.5 as a mean between charge 3 and 4 (since particles with charge 5 are seldom observed), this ratio becomes 0.75±0.06. Harding and Perkins[11] find in light-element cosmic-ray stars (mountain altitudes) an α/p ratio between 0.7 and 1.

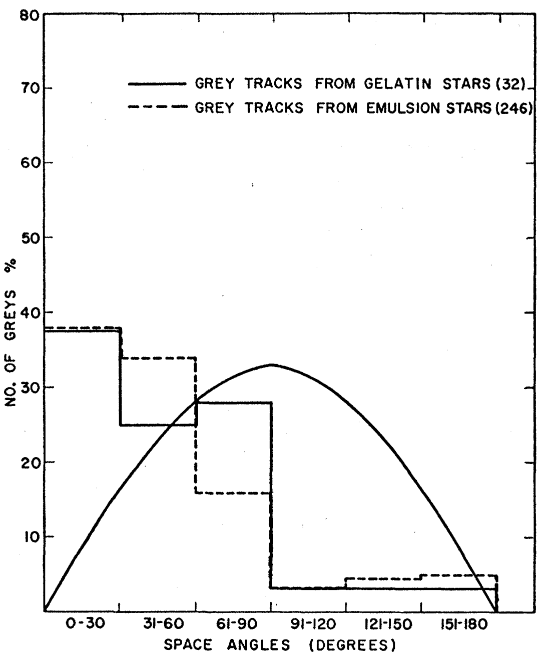

FIG. 3. Angular distribution of grey tracks in neutron induced gelatin and emulsion stars. (Smooth curve represents isotropic distribution.)

Figure 1 compares the prong distribution (black and grey tracks) in gelatin and emulsion stars. Knowing the relative number of C, N, and O nuclei in gelatin and assuming a cross section proportional to $A^{2/3}$, it has been attempted (curve III-0) to distribute the calculated missing prongs ($\leq 5\mu$-recoil, 5-100μ-α, $>100\mu$-proton) among the stars of different prong number, so that the mean charge in the distribution becomes equal to 6.8, the mean charge of gelatin nuclei. Although the distribution is more or less arbitrary, it probably is similar to the true one.

Figure 2 gives for emulsion and gelatin stars the range distribution of tracks ending in the emulsion up to 100 microns (14 Mev if the particles are α particles). In the case of gelatin stars the actual number has been corrected for loss. In both cases the equivalent range in normal emulsion has been calculated taking into account the ratio of stopping power in gelatin and emulsion.[12]

The observed preponderance of short prongs (with exception of recoil fragments, more frequent in stars from heavy elements) in gelatin stars can easily be explained by the low Coulomb barrier in light elements.[2,11] This fact can be used for identification of stars from light elements within the emulsion, at least in the energy interval considered here.

D. Number and Energy Distribution of Fast Protons

The energy and angular distribution of grey tracks in gelatin and emulsion stars is very similar within the meager statistics (in the case of gelatin stars). The energy of the grey tracks was determined by grain counting up to grain densities of 4 times minimum, corresponding to protons of 60±6 Mev. In both gelatin and emulsion stars fast protons up to 300 Mev were observed, however, the number increases with decreasing energy. In both cases about 50 percent of the grey tracks have energies between 60 and 100 Mev.

We found for gelatin stars, based on 118 stars only, that 37±5 percent of the stars have fast protons; in the emulsion, based on 760 stars, 31±2 percent of all stars have grey tracks. One would expect a greater percentage of fast protons in light nuclei to escape. However, the shorter path of the primary neutron inside the light nuclei tends to produce smaller nucleonic cascades and hence tends to counteract the first effect. One can estimate these effects by considering the collision mean free path in nuclear matter; it is found that they should approximately cancel each other, and this explains why the percentage of fast protons in gelatin and emulsion stars is approximately the same. In Table I the percentage of stars having at least one grey track ≥ 60 Mev (if proton) is listed for gelatin and emulsions stars as a function of the number of black tracks.

In emulsion stars the percentage of stars with at least one grey track decreases with prong number as expected. However, in gelatin stars the percentage increases or at least stays constant within the wide statistical errors; this can be understood in terms of alpha-particle breakup and the limited number of nucleons present in light elements.

TABLE I. Neutron-induced stars. Percent of stars having at least one track $E \geq 60$ Mev.

Number of black tracks	Gelatin stars	Emulsion stars
1		100
2	23±2.2	43±8
3	26±2.6	30±8
4	30±11	21±7
5	46±22	18±3
6	50±35	11±10

[10] P. E. Hodgson, Phil. Mag. 42, 207 (1951).
[11] Harding, Lattimore, and Perkins, Proc. Roy. Soc. (London) **196**, 325 (1949).
[12] J. J. Wilkins, Atomic Energy Research Establishment Report G/R 664, 1951 (unpublished).

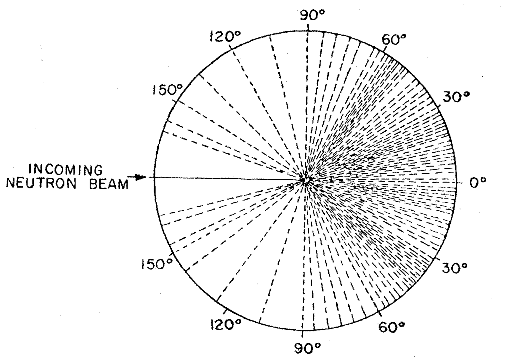

FIG. 4. Space-angle distribution of grey tracks with respect to incoming neutron beam (emulsion stars).

E. Angular Distribution of Black Tracks

Figure 3 gives the angular distribution (polar angle) of fast protons in gelatin stars in comparison to emulsion stars; the distribution is the same within the statistical error. The main direction of the neutron beam has been established by plotting the grey tracks in emulsion stars (see Fig. 4), knowing their forward peak[6] and weighting the center; this checked with the known geometry of exposure.

In Fig. 5 the angular distribution of black tracks (polar angle) of 50 gelatin stars is plotted. There is a forward excess of 37±5 percent. The percentage of fast knock-on protons in the range of 30–60 Mev and pickup deuterons[13] contributing to this forward effect is estimated[14] to be at most 6 percent; therefore the major share of this effect is due to protons with energies smaller than 30 Mev and to α particles.

It is difficult to estimate if this forward excess is connected with a center-of-mass motion of the evaporating nucleus, if it is meaningful to speak in light elements about evaporation at all. It may be due to a kind of dragging forward resulting from the attractive forces of particles emitted with high velocity or may involve the lower-energy knock-ons in the nuclear cascade.

The forward excess found in emulsion stars (projected angle) is in good agreement within the error limits with results by Bernardini, Booth, and Lindenbaum.[6] In combining the distribution found here for emulsion stars and gelatin stars, one obtains for heavy elements alone a forward excess of 33 percent. Therefore the share of black knock-ons emitted in heavy elements is even larger (33 percent) than the lower limit of 25 percent claimed by these authors.[6]

F. Conclusions

21±3 percent of emulsion stars with at least 2 prongs and a recoil track originate in light nuclei when bombarded by neutrons of 300-Mev mean energy. At this energy the mean prong number in stars from light nuclei is greater than in heavy nuclei. The α/p ratio for light nuclei is approximately 0.75, and 25±5 percent of all stars have a recoil with charge ≥ 3. The number of fast protons and their angular distribution is similar in stars from light and heavy elements. The black tracks in light element stars show a marked forward excess (37±5 percent). With this angular distribution and the percentage of light element stars the forward excess of black prongs in heavy elements has been determined to be 33±3 percent; therefore, at most, 70 percent of black prongs in heavy elements are due to nuclear evaporation.

II. STARS INDUCED BY POSITIVE π MESONS OF 50–80 MEV

A. Exposure

Stratified emulsions were exposed to the positive meson beam of the Columbia cyclotron. In one experiment the meson energy was between 70–80 Mev and in the other case 60±5 Mev. The plates during exposure were parallel to each other in grooves in Bakelite boxes, and the meson beam after passing through the cover of the box entered the emulsion surface at angles of 7 and 10 degrees, respectively.

The relation between thickness of emulsion and gelatin layers was, for the one set of exposures used to determine the ratio of gelatin to emulsion stars, the same as in the neutron experiment.

The incident mesons were identified mainly by grain count, position, dip, and projected angle. Laminated emulsions are not suitable for scattering measurements and nearly always show some distortion. Therefore scattering measurements were used only to discriminate between low-energy protons and mesons emitted in the observed nuclear disintegrations.

The energy-grain density relation in these emulsions was established by grain count of minimum tracks and of μ mesons decaying in the emulsion. Only mesons with a grain count between 1.25 and 1.55 times minimum corresponding to energies between 50–80 Mev were accepted for this investigation. The angular spread of the meson tracks accepted was $\pm 4°$ in the plane of the emulsion and $\pm 4°$ in the vertical plane. The mean grain density, mean azimuthal angle, and dip angle of the meson tracks were found by plotting grain density of tracks *versus* dip angle and azimuthal angle of tracks entering the emulsion.

B. Star-Producing Cross Section in the Light-Emulsion Nuclei

For the comparison of star production in gelatin and emulsion, area scanning was used since scanning along the track has proven too lengthy especially in relation to the thin gelatin layers. The percentage of meson stars in the light elements of the emulsion was found

[13] G. Chew and M. Goldberger, Phys. Rev. **77**, 470 (1950); J. Heidemann, Phys. Rev. **80**, 171 (1950); J. Hadley and H. York, Phys. Rev. **80**, 345 (1950).

[14] In 20 percent of the gelatin stars the number of prongs with grain densities corresponding to proton energies between 30 and 60 Mev has been determined.

to be 0.3±0.12 percent. The large error is due to the small number of gelatin stars found in our experiment, since only one set of plates with the lower exposure time could be used for this comparison.

Another possibility of evaluating this ratio consists in the identification of stars resulting from light elements among the emulsion stars. The Coulomb barrier in heavy elements does not permit the emission of α particles below a minimum energy of 8 Mev; furthermore, emission of recoil particles from heavy elements is very improbable on account of the low kinetic energy of the incoming meson and, as will be pointed out later, because of the nearly isotropic distribution of the particles emitted in the disintegration. Finally, it is to be expected that the number of charged particles emitted in the disintegration of light elements will in most cases be equal to or greater than 3 and that therefore most of the smaller stars originate in heavy elements.

Applying these criteria to emulsion stars, one estimates that at least 24 out of 93 emulsion stars or 26 percent of the emulsion stars originate in light elements.

Taking into account that some 1-pronged stars originating in heavy nuclei may have been missed in our method of scanning and estimating these amounts by the results on prong distribution of emulsion stars published by Bernardini and Levy,[15] the lower limit for the contribution of stars in the light elements of the emulsion becomes 24 percent while the upper limit is estimated to 30 percent.

In this comparison inelastic scattering events without accompanying stars are not included and an additional correction has to be applied. The number of these events in relation to star events, as well as the inelastic cross section of the emulsion nuclei as a whole, has been published by these authors for various meson energies.[15] In light elements the energy loss of 20 Mev of the scattered meson can lead to star formation, but in the heavy elements at the most 1 charged particle can leave the nucleus. Therefore the error introduced will not be appreciable if one attributes all the scattering events (scattering without star formation) observed by these authors in the emulsion to the heavy-emulsion nuclei.

By increasing the total number of events found in these experiments in the proportion found by Bernardini and co-workers[15] in order to correspond to the sum of stars plus inelastic scattering, the percentage of events found in the light elements alone (only stars) decreases to 21.8 percent, and introducing the cross section 0.67 barn[15] found for the "emulsion nuclei," one obtains as lower $0.6\sigma_{\text{geom}}$ for the light-emulsion nuclei in the energy between 50 and 80 Mev.[16]

[15] G. Bernardini and F. Levy, Phys. Rev. 84, 610 (1951).
[16] A. M. Shapiro, Phys. Rev. 84, 1063 (1951).

C. Prong Distribution

The mean prong number in gelatin stars is 4.7±0.1. After applying a suitable correction for loss of prongs in the gelatin layers, the mean prong number becomes 5.36±0.5. The mean charge released in gelatin stars is 7.8, taking into account the additional charge of the incoming meson.

The number of particles emitted in the disintegration is essentially the same as in neutron stars (300 Mev), considering again the additional charge contributed by the meson. The proportion of α particles, protons, and particles with charge >2 among the emitted disintegrations products can only be estimated in the same way as in the case of neutron stars.

From the number of emulsion stars with very short prongs, identified as stars from light elements, and the number of these prongs in gelatin stars (corrected for loss in the gelatin layers), one can estimate that in 20–25 percent of all light element disintegrations, particles with charge >2 are emitted. Attributing to these recoil particles a mean charge of 3.5 as in the case of neutron stars, one obtains an α/p ratio between 0.6 and 0.8. In about 50 percent of the cases, 4 singly charged particles leave the nucleus. The situation in this respect is similar to the case of neutron stars. On the other hand, it seems that the energy left to the disintegrating nucleus after the emission of fast particles is even somewhat higher than in the neutron case (in spite of the lower energy available), since the average range of the slow particles, presumably predominantly α particles, is greater in the meson case. The higher excitation energy can be accounted for by the characteristic absorption process of mesons in this energy

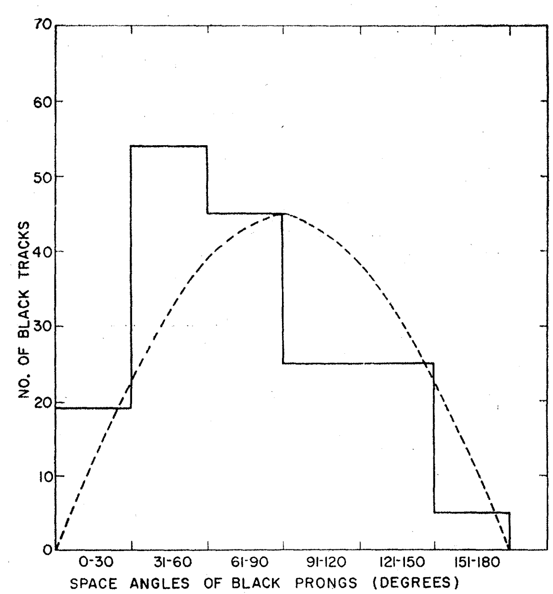

FIG. 5. Space-angle distribution of black prongs in neutron-induced gelatin stars. (Smooth dotted curve represents isotropic distribution.)

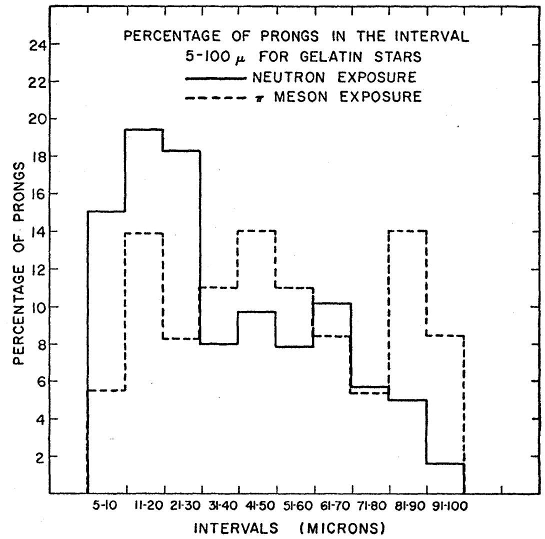

FIG. 6. Range distribution comparison of short prongs (≤100 microns) in neutron- and meson-induced gelatin stars.

interval. In Fig. 6 the percentage of prongs in different energy intervals—normalized to the total number of prongs ending between 5 and 100 microns—is plotted for meson and neutron stars.

In Table II are listed 39 gelatin and 93 emulsion stars classified according to their number of black and light tracks. The small number on the upper right side of the figures represents the number of stars with outgoing inelastically scattered mesons, identified by grain count and scattering. Among the gelatin stars 3 with outgoing mesons in the energy interval between 15 and 20 Mev have been found.

In two cases of probably incomplete stars with 2 heavy prongs (charge is apparently not conserved and, therefore, at least 1 additional prong is missing) the outgoing fast particle could be a meson; however, in both cases the tracks are too short to decide between proton and meson. Considering in addition the stars from light elements identified among the emulsion

TABLE II. π^+-induced events. Frequency of stars *versus* prongs.

No. of outgoing light tracks		No. of outgoing black tracks[a]							
		1	2	3	4	5	6	7	8
0	gelatin			2	3	3	6		
	emulsion	1	4	13	16^1	14	6	1	1
1	gelatin		4	6^2	5^1	1	1		
	emulsion	3^1	10^1	6^2	7^2	2	1		
2	gelatin			5	3				
	emulsion	4	1	3					

[a] Superscript number designates number of events that have an outgoing meson. These events are included in the number of stars.

stars, one finds 5 more cases in which the scattered meson leaves the nucleus. In one case, the disintegration of a carbon nucleus, all prongs end in the emulsion and the outgoing meson has a relatively low energy of 7.6 Mev.

Therefore, out of 53 stars originating in light elements, 8–10 cases or 15 to 20 percent are the result of inelastic scattering of the incoming meson.

In 8 out of 39 gelatin stars, or 12 out of 53 gelatin plus emulsion light-element stars (that is, in about 22 percent of the cases), one observes two fast protons

TABLE III. π^+-induced events. Energy distribution of grey tracks.

	Energy in Mev				
	30–60	90	120	150	180
Gelatin stars					
14 with 1 grey track	4	3	3	2	2
8 with 2 grey tracks	12	3	1		
Emulsion stars					
24 with 1 grey track	4	5	7	5	3
8 with 2 grey tracks	6	7	3		

leaving the nucleus. In about 37 percent only 1 fast proton is emitted in the disintegration.

Table III gives the energy distribution of grey tracks in gelatin and emulsion stars separately for stars with 1 and 2 fast protons.

The angular distribution (polar angle) between incoming meson and outgoing fast particle is listed in Table IV for gelatin and emulsion stars and again separately for stars with one and two fast prongs. The distribution in both cases is very wide,[15] contrary to the findings in neutron stars. Finally in Table V, for

TABLE IV. π^+-induced events. Angular distribution of grey tracks.

	0–30°	60°	90°	120°	150°	180°
Gelatin stars						
14 with 1 grey track	3	5	2	3	1	
8 with 2 grey tracks	2	3	3	5	1	2
Emulsion stars						
24 with 1 grey track	4	5	5	4	1	5
8 with 2 grey tracks	4	5	3	2		2

events with two outgoing fast protons, the angles between these two prongs are listed.

The energy and angular distribution in the events with two fast prongs is not inconsistent with the two-nucleon absorption process $(\pi^+ + p + n \rightarrow 2p)$,[17] if we consider the possibility of additional scattering of the fast prongs and the uncertainty involved in angular measurements.

In one case, where the angle between the two outgoing fast particles is $170 \pm 5°$, both fast particles have

[17] Byfield, Kessler, and Lederman, Phys. Rev. 86, 17 (1952).

an energy of 65±5 Mev, estimated by grain count. Therefore this case could be explained by a meson coming to rest before being absorbed in a proton-neutron pair.

In this connection another star found among the emulsion stars is of interest (Fig. 7). Track 1 is the incoming meson with energy 65±7 Mev; track 2 is a proton of 68±5 Mev, prong 3 has a range of 10 microns and shows the typical hammerhead plus fast electron; finally, track 4 is black and leaves the emulsion after 136 microns and cannot be identified. Since it is improbable that prong 3 can be emitted in the disintegration of a heavy element because of its low energy, one has to assume for reasons of charge conservation (total charge should be 7.8), that this prong is B^8 and not Li^8. Here it seems possible, judging from momentum conservation considerations, that the incoming meson has been initially scattered, exciting the nucleus before being absorbed in a *n-p* or *n-n* pair; while the forward emitted nucleon leaves the nucleus without collision, the backwards emitted particle completes the disruption of the excited nucleus. The disintegrating nucleus is probably carbon if track 4 is a proton or deuteron and nitrogen if track 4 is an alpha particle and the absorption occurred in a *n-n* pair.

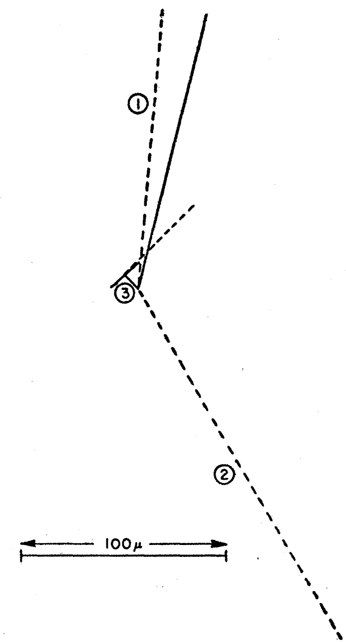

FIG. 7. Facsimile drawing of meson-induced star.

TABLE V. π^+-induced events. Angular relation between grey tracks.

	Angle between grey tracks					
	0–30°	60°	90°	120°	150°	180°
8 gelatin stars	0	0	3	3	2	0
8 emulsion stars	0	0	4	1	2	1

On the other hand, there are 6 cases among stars with 2 fast protons in which the energy of at least 1 of the emitted particles indicates that the absorption was not preceded by inelastic scattering.

In judging the frequency of events with 2 fast tracks, one has to consider the small probability that both fast particles leave the nucleus with energies ≥30 Mev. Therefore, the actual number of events corresponding to the two-nucleon absorption process will be greater, and some additional events in the classes of stars with one or no fast particles will belong to the same process, while others out of these two classes could account for the absorption of the meson in neutron pairs.

However, there are a few cases among the gelatin and emulsion stars—10 percent among the stars of light nuclei—where the energy of the single fast prong is too high to be consistent with the 2-nucleon absorption process. Nevertheless, these events also have to be interpreted as absorption processes, since the kinetic energy of the outgoing protons alone, and therefore certainly the total energy dissipated, is greater than the kinetic energy of the incoming meson. These events can be accounted for by multinucleon absorption processes.[2,18] The actual percentage of events caused by multi-nucleon absorption will probably be greater than 10 percent, since cases where the absorption process is preceded by meson scattering or succeeded by scattering of the emitted fast proton will not be recognized as belonging to the same group. From the experimental results and the known mean free path of protons for the energy interval under consideration, the highest possible contribution of multi-nucleon absorption is estimated to be 30 percent and therefore definitely smaller than the 2-nucleon absorption process. That is

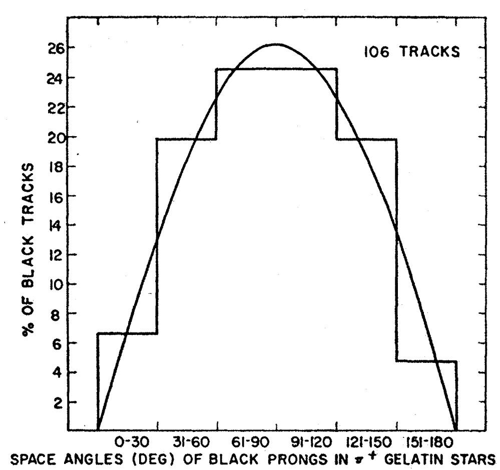

FIG. 8. Space-angle distribution of black prongs in meson-induced gelatin stars. (Smooth curve represents isotropic distribution.)

[18] S. Tamor, Phys. Rev. 77, 412 (1950); also see R. Marshak, *Meson Physics* (McGraw-Hill Book Company, Inc., New York, 1952).

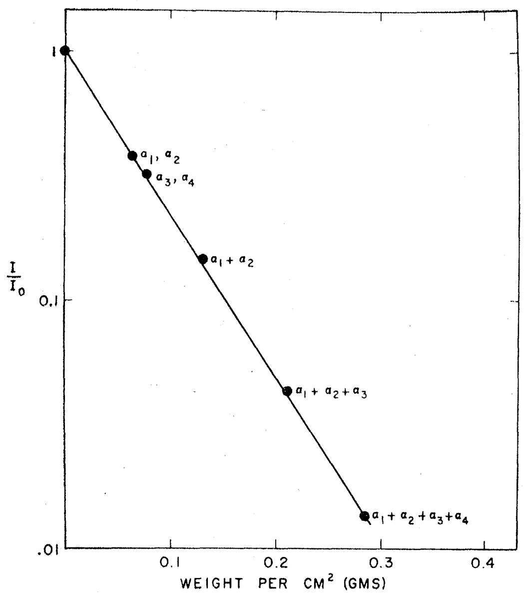

FIG. 9. X-ray transmission ratio *versus* weight of emulsion (Eastman NTB3 pellicles).

Summarizing the results in stars in light-emulsion nuclei induced by positive mesons in the energy interval of 50–80 Mev, one can state that 24–30 percent of emulsion stars originate in the light nuclei of the emulsion; as lower limit of the opacity of light nuclei the value 0.64 has been found. In about 15 to 20 percent of the cases the meson emerges from the light nucleus after having suffered inelastic scattering. Charge exchange scattering, if present at all, is very small (<10 percent). In most cases absorption of the incoming meson takes place. The absorption occurs chiefly in nucleon pairs. This follows from the great number of stars with 2 fast protons emitted with wide angular separation and the small number of single protons emitted with energy greater than 120 Mev. Multi-nucleon absorption occurs in less than 30 percent. It cannot be decided to what degree the absorption is preceded by inelastic scattering; however, the higher frequency of 2-nucleon absorption in comparison to the multi-nucleon process prevalent in the absorption of mesons at rest suggests that in most cases the meson does not lost its entire energy, even if initially scattered.

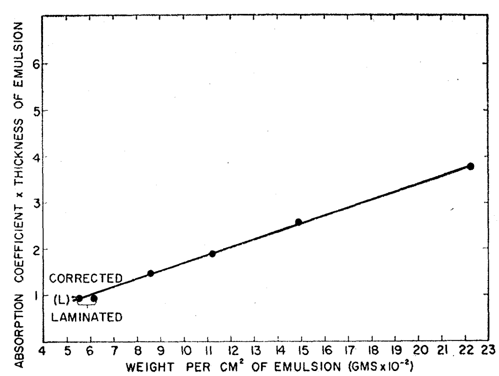

FIG. 10. X-ray absorption *versus* weight of emulsion (Ilford).

different from the case of slow meson (at rest) absorption, where multi-nucleon absorption is the predominant process.

Among 14 stars in light elements without fast prongs are 5 cases where, because of possible loss of prongs in gelatin layers or uncertainty in the identification of tracks, it is impossible to judge the energy dissipated in these stars relative to the energy of the incoming meson. Therefore it is not impossible that at least in some of these cases charge exchange may have occurred; the contribution of charge exchange in light elements, if present at all, is then at the most 10 percent.

D. Angular Distribution of Black Tracks

Figure 8 shows the angular distribution (polar angle) of black tracks in gelatin stars. Contrary to the case with neutron stars, the distribution is isotropic within the limits of error.

One finds a similar difference comparing emulsion stars induced by neutrons and mesons. In the later case the distribution of black prongs is nearly isotropic. In the case of light elements the difference in the distribution could be connected with the difference in momentum transfer to the nucleus as a whole. However, in stars of heavy nuclei the low momentum transfer of neutron or meson to the nucleus cannot influence the distribution of emitted particles. Therefore it is more reasonable to assume that, in both cases, stars in light and heavy elements, the angular distribution of black tracks is strongly influenced by the presence of low-energy knock-ons. Since in meson stars the distribution of fast prongs is very wide, the low-energy knock-ons will be nearly isotropically distributed and not distinguishable in their direction from evaporation prongs.

The authors wish to express their thanks to Dr. G. Bernardini for exposing the plates to the neutron and meson beam, to Dr. S. Lindenbaum for exposing one set of plates to the meson beam and for many interesting and stimulating discussions. Many thanks are due Mrs. E. Medd for her accurate and exacting work in scanning the plates and to Mrs. E. Schwarzer for her careful work in developing the plates.

APPENDIX

In problems connected with measurements of cross section an accurate knowledge of the mass of the exposed emulsion is necessary.

Mass determination of unprocessed emulsions can be performed by weighing the plate before and after processing and by ascribing the difference in weight to the quantity of silver halides and water soluble constituents removed during processing. Another method consists in micrometric measurement of the emulsion thickness before and after development. In both cases the operations have to be performed in the darkroom, and it is necessary to condition the emulsion to the darkroom humidity since both weight and emulsion thickness depend on the water content of the emulsion.

We therefore investigated another possibility for mass determination based on x-ray transmission, especially useful for the experiments on stratified emulsions. ·

The x-ray beam used for this purpose should be monochromatic or at least not change its quality within the range of the absorption measurements which generally comprises plates with 50 to 600μ emulsion thickness. Furthermore it is important that the penetrating power of the x-radiation should be appropriate in order to obtain appreciable changes in transmission for only small changes in emulsion thickness. As silver and bromine are the main constituents (per weight) of the emulsion, it is advisable to work near the short-wave edge of the K line of silver.

In the experiments a Norelco x-ray diffraction unit and an x-ray tube with Cu or Fe cathode was used and operated at 40 kev and 20 ma. The unit has four symmetrically located exit windows; two of these windows were used, one for the actual measurement and the other for monitoring the beam. In front of both windows diaphragms were placed with $\frac{1}{3}$-mm opening diameter in order to limit the size of the x-ray spot in the emulsion. The measurements were made with ionization chambers and the actual measurement always related to the monitoring beam and a carefully weighed standard emulsion and standard glass.

Figure 9 shows the transmission curve for a series of pellicles (NTB Eastman-Kodak emulsion) measured individually and then in groups of 2, 3, and 4 together. In this semilogarithmic curve, the weights of the emulsions per cm^2 (weighed at the same relative humidity) is plotted *versus* the transmitted radiation. The linearity of this curve proves the applicability of the method. The method is sensitive, since the radiation is dimished by a factor 30 while the weight per cm^2 of the combined emulsions varies only by a factor of 4.75.

Figure 10 gives the results obtained with Ilford $G5$ emulsions of about 200, 300, 400, and 600 microns. The abscissas are the weights of the plates per cm^2 after subtracting the weights of the corresponding glass slides. The ordinates correspond to the product $\mu_{em}d$ calculated from the expression

$$l^{-\mu_{em}d-\mu_{ge}}/l^{-\mu_{ge}}.$$

It was found that the attenuation of glass slides (same batch) does not vary more than ± 3 percent. Since in a 300-micron emulsion five times more radiation is absorbed in the emulsion than in the corresponding glass slide, the error introduced is negligible. This fact has an advantage over the weighing method, where the weight of the glass slide—in the case of the 300μ emulsion—is about 3 times greater than the emulsion weight.

The point of the curve 2a with the letter L refers to the laminated emulsion plate having alternate layers of about 7μ and emulsion layers of about 35μ. These emulsions were weighed before development, after soaking in cold water and after processing. After each step the emulsion was conditioned to the same value of humidity. The thickness of emulsion and gelatin layers after processing was measured microscopically at various degrees of humidity before and after incorporating glycerin. Finally the emulsion was dissolved and weight and x-ray transmission of the glass slide were determined. From these measurements and the known composition of the emulsion and gelatin, we obtained the weight of the gelatin layers. The point L, weight of laminated emulsion minus weight of the gelatin layers, fits the transmission curve quite well. In the case of the stratified emulsions used in the neutron experiment and in one set of meson exposures, the ratio of light elements in emulsion to light elements in the gelatin layers in the dry plate (the emulsions were kept in the refrigerator before exposure) was determined to 2.95×0.3.

PHYSICAL REVIEW VOLUME 91, NUMBER 4 AUGUST 15, 1953

The Cosmic-Ray Albedo*

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(Received May 12, 1953)

The fraction of splash albedo radiation leaving the earth which goes into (bound) orbits leading back to the earth is discussed in the Stoermer approximation. It is shown that the returning particles arrive at latitudes very close to the latitudes from which they leave the earth. A qualitative argument indicates that the returning radiation should be roughly isotropic.

I. INTRODUCTION

Rocket[1,2] and balloon[3] measurements carried out in recent years suggest that at the top of the atmosphere an appreciable flux of cosmic radiation is directed toward the upper hemisphere. This *albedo* radiation presumably consists of secondary particles produced in the interactions initiated in the atmosphere by primary cosmic radiation; and as would be expected on the basis of such an interpretation, the albedo appears to be most intense at large zenith angles.[1]

Some of the albedo particles which emerge from the atmosphere can be expected to escape the earth's magnetic field; but some of them may be trapped in bound orbits, in which case they must eventually return to the earth in the "primary" radiation. We shall distinguish between two kinds of albedo radiation at the top of the atmosphere: *splash albedo* (particles whose direction of motion lies in the upper hemisphere); and *albedo primaries* (returning albedo particles, whose direction of motion lies in the lower hemisphere). This distinction is based only on direction of motion at the top of the atmosphere. A third class of particles at the top of the atmosphere consists of true primary radiation. The splash albedo can be distinguished experimentally by means of Cerenkov counters, for example.[4]

* Supported by the joint program of the U. S. Atomic Energy Commission and the U. S. Office of Naval Research.
[1] J. A. Van Allen and A. V. Ganges, Phys. Rev. **78**, 50 (1950); **79**, 51 (1950).
[2] S. F. Singer, Phys. Rev. **77**, 729 (1950); **80**, 47 (1950).
[3] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).
[4] J. R. Winckler, Phys. Rev. **85**, 1053–1054 (1952).