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Meson Formation in Pb, Cu and C Nuclei by Cosmic Rays in the Stratosphere

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We have studied the cross section for meson formation in varoius nuclei. It was found that, the cross section increases differently at high and low energies.

INTRODUCTION

THE cross section for meson production by low energy protons (~ 400 mev) in various nuclei has been studied in the laboratory[1,2]. These experiments showed that the nuclear cross section for meson formation in various nuclei is proportional to $A^{2/3}$, while the cross section per nucleon decreases with increasing atomic weight of the target nucleus. This behavior of the cross section shows that, at a given energy, not all the nucleons in the nucleus are effective in forming mesons, but only those on the surface of the target nucleus. The decrease in "meson-producing effectiveness" with increasing atomic weight was explained by assuming that the energy of the incident proton is rapidly dissipated in nuclear matter, so that mesons are formed in only the first few collisions with the nucleons of the nucleus. It turns out that this picture does, indeed, lead, at low energies, to the observed dependence of the cross section on atomic weight[3].

At heights in the stratosphere of 25-28 km, we deal with particle energies of order 10^9 ev and higher. When the incident particles have such high energies, one would expect the cross section for formation of slow mesons to be approximately proportional to A, the atomic weight of the target nucleus. Hence it would appear that an investigation of the cross section for meson production in various nuclei at different heights in the stratosphere would lead to the dependence of this cross section both on A and on the energy of the incident particles. This dependence can also be obtained by comparing the cross sections for meson production by cosmic rays at mountain heights in the stratosphere.

Up to now, the cross section for meson production by cosmic rays at mountain altitudes has been studied using thick absorbers[4]. The chief disadvantage of thick (5-17 cm) targets is that, through decay and electromagnetic or nuclear interactions, the mesons formed can again be absorbed in the target, and this must be corrected for in computing the cross section for meson production. This correction is difficult to make because the spectrum of the emitted mesons, for various absorbers at a definite height, is not well known. Some experimental data[5,6] seem to indicate that the spectrum of the emitted mesons depends on height. These difficulties can be bypassed by using thin targets. For sufficiently thin targets, the corrections for decay and for electromagnetic and nuclear interactions can, presumably, be neglected. There is, of course, another difficulty – the incident cosmic rays will produce only a small number of mesons in a thin target. However, the statistical weight of the result can be increased by repeating the experiment.

On the basis of the preceding, we used thin absorbers to investigate the production of mesons in various nuclei.

EXPERIMENTAL METHOD AND RESULTS

In the present work we report our experimental results on the production of mesons by cosmic rays in Pb, Cu and C at heights of 24-28 km. Electron-sensitive photo-emulsions 300 and 340μ thick were exposed to cosmic rays at heights of 24-28 km during two flights in 1953 and one in 1954. The apparatus used in the first two flights is shown in Fig. 1; Fig. 2 shows the height as a function of time for the flights.

The photo-emulsions were surrounded by thin layers of lead, copper, graphite and paraffin; the thickness of the layers is shown in Table 1.

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[1] M. Block, S. Passman and W. Havens, Phys. Rev. 88, 1239 (1952).

[2] R. Sagane and W. Dudziak, Phys. Rev. 92, 212 (1953).

[3] S. Gasiarowicz, Phys. Rev. 93, 843 (1954).

[4] N. Dallaporta, M. Merlin, O. Pieruccie and A. Rostagni, Nuovo Cimento 9, 202 (1952).

[5] V. Kamalian and A. Alikhanian, Dokl. Akad. Nauk SSSR 47, 425 (1954).

[6] U. Camerini, P. Fowler, W. Lock and H. Muirhead, Phil. Mag. 41, 413 (1950).

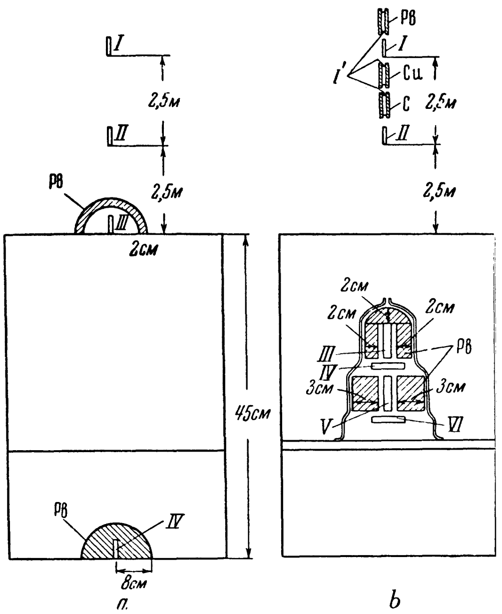

FIG. 1.

Both the shielded photo-emulsions and the air plates were 5 m from the rest of the equipment to avoid side effects due to other dense absorbers. After the flight, all the emulsions were developed and fixed under identical conditions. The emulsions were scanned using a microscope with a 20x objective and 15 x eyepiece. The various events were identified by $\pi \rightarrow \mu$ decays, σ-capture and also by scattering and grain density measurements.

The experimental results are shown in Table 1. The same table also gives details of the flights and the emulsion thicknesses used. From Table 1, one can see the following:

1) In all three flights, the number of π mesons stopping per gm/cm^2 – hr increases as the atomic weight of the target nucleus increases.

2) The number of ρ mesons does not depend on the atomic weight of the absorber. A small increase in the number of ρ[*] mesons with increasing A could be due to negative π mesons which do not produce stars; it is known[7] that 27% of the total number of π^- mesons do not produce stars. In our method of analysis, such negative π mesons would be included in the number of ρ mesons.

FIG. 2. Arrows indicate the moment of release.

DISCUSSION

Formation of slow π mesons in air:

Surrounding the photoemulsions by a thin absorber increased the number of slow π mesons;

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[7] F. Adelman and S. Jones, Phys. Rev. 75, 1468 (1949).

[*] Translator's note: The original appears to be in error, having π instead of ρ.

this cannot be due to a slowing down in the absorber of π's formed in air, because π's with energy < 100 mev travel $\sim$ 6m, before decaying, while in 6m at 24-25 km in the stratosphere there is about 0.06 gm/cm^2 of matter. This is about 10 times less than the amount of matter in the packing around the plates and in the glass backing. Hence we can say that the π mesons observed in the plate which was suspended in air are formed in the packing material, and in the glass backing, while some of the stars were formed before the ascent to the stratosphere during storage in the laboratory.

Upon comparing the number of events in the control plate with that in the plate suspended in air, we see that almost no slow π mesons are formed in air (in the stratosphere). Hence to find the number of π mesons produced in matter one need only subtract the number of π mesons in the air plate from the number of π mesons underneath the absorber. The number of mesons produced per gm/cm^2 – hr is shown in Table 1.

TABLE 1

Flight number	Mean height above sea level in km.	length in min.		Time of drift in min.	Emulsion Thickness in μ	Area scanned in cm^2	Absorber	Absorber thickness in gm/cm^2	Number of events		Number of mesons produced per gm/cm^2 – hr.	Energy in mev of mesons produced in the absorber and stopping in the emulsion.
		ascent	descent						π	ρ		
I	26	110	67	123	300	21	air	—	8	60		
						21	paraffin	4	14	62	0,77±0,30	<28
						21	C	4	17	66	1,13±0,37	<28
						21	Cu	3,4	20	68	1,50+0.43	<19
						21	Pb	3.4	28	80	2.6 +0,5	<17
II	27	110	18	425	300	20	air	—	6	59		
						20	Cu	1,7	16	60	0,84+0,27	<12
						20	Pb	1,7	23	61	1,6 +0,30	<11
III	23,5	110	160	580	340	20	air	—	14	27		
						20	C	2,7	36	20	0,88±0,18	<21
						20	Pb	2,3	62	42	2,16+0,31	<13

THE CROSS SECTION FOR π MESON PRODUCTION

From Table 1 we easily obtain the relative cross sections for production of slow π mesons. The second and third columns of Table 2 show the relative cross sections for meson production per nucleon and per nucleus, as calculated from the experimental data.

Table 2 shows that the meson production cross section (relative to lead) increases with increasing atomic weight of the target nucleus; however, the increase differs from that observed at low energies with accelerators (column 4 of Table 2). We can calculate the relative meson production on the basis of various assumptions about the process by which mesons are formed when the incident particles interact with the nucleus. The number of mesons produced per gm/cm^2 – hr is

$$N_\pi = \sigma n S \overline{m}, \tag{1}$$

where $\sigma = kA^{2/3}$ is the nucleus-incident particle interaction cross section, n is the number of nuclei per gm/cm^2, $S = \int F(E)\,dE$ is the current of incident particles per cm^2 – hr, and $\overline{m}$ is the mean number of mesons produced per interaction.

According to (1), if we have two elements of atomic weights A_1 and A_2, the relative meson production cross section per nucleus will be

$$N_{1\pi} A_1 / N_{2\pi} A_2 = \sigma_1 \overline{m}_1 / \sigma_2 \overline{m}_2, \tag{2}$$

We can call $\sigma\overline{m}$ the meson production cross section

TABLE 2

Target nucleus	Meson production cross section relative to lead					
	per nucleon experimental	per nucleus				
		experimental	$A^{2/3}$ law	formula (3)	formula (3′)	formula (3″)
Paraffin	0,30±0,17					
C	0.42±0,12	0.024	0.15	0,06	0 027	0,07
Cu	0.55±0,18	0.16	0,46	0,3	0,18	0.34
Pb	1	1	1	1	1	1

$$\sigma_{1\text{prod}}/\sigma_{2\text{prod}} = \sigma_1 \overline{m}_1/\sigma_2 \overline{m}_2, \qquad (2')$$

$m_1/\overline{m}_2$ depends on the interaction between the incident particles and the nucleus. If we assume that, with a certain probability, mesons are produced only in collisions between the primary particle and individual nucleons in the nucleus, so that δ-nucleons do not take part in the formation of mesons, then the number of mesons produced will be proportional to the number of collisions of the primary particle with the nucleons of the nucleus.

The number of collisions can be found from the following simple considerations. The primary particle cuts out a cylinder upon traversing the nucleus. If r is the radius of nuclear forces, and R_A the radius of a nucleus of atomic weight A, then the volume of the cylinder will be $V = 2\pi r^2 a$, where a is the path length of the primary particle in the nucleus. its value depends on how the primary particle traverses the nucleus ,but on the average will be $\overline{a} = k_0 A^{1/3}$, i.e., proportional to the nuclear radius. The number of collisions (interactions) on the average will be

$$N_{\text{coll}} = \overline{V}\rho = Cr^2 A^{1/3},$$

where ρ is the density of nucleons in the nucleus, and C is a constant, independent of A. Evidently in this case $\overline{m}_1/\overline{m}_2 = (A_1/A_2)^{1/3}$ and formula (2) becomes

$$\frac{\sigma_{1\text{prod}}}{\sigma_{2\text{prod}}} = \frac{\sigma_1}{\sigma_2}\left(\frac{A_1}{A_2}\right)^{1/3}. \qquad (3)$$

If we assume that mesons are formed not only by the primary particles, but also by δ-nucleons, produced in internal cascade processes, then similar considerations show

$$\frac{\sigma_{1\text{prod}}}{\sigma_{2\text{prod}}} = \frac{\sigma_1}{\sigma_2} 2^{-\left(A_2^{1/3} - A_1^{1/3}\right)/k_1}, \qquad (3\ )$$

where $k_1 = 1.5$ is a geometric factor.

It should be noted that in the above, the interaction of the primary particle with the nucleus was considered to be a succession of independent nucleon-primary interactions. As remarked in Ref, 8 such a picture is valid when the time between interactions is significantly larger than the duration of an interaction. The hydrodynamical theory of Landau[9] gives a different formula for the production cross section

$$\frac{\sigma_{1\text{prod}}}{\sigma_{2\text{prod}}} = \frac{\sigma_1}{\sigma_2}\left(\frac{A_1}{A_2}\right)^{1/4}. \qquad (3'')$$

Equations (3) and (3′) and (3′′) can be used to calculate the relative meson production cross sections, and the results compared with the experimental data.

Table 2 gives the results of calculations with Eqs. (3), (3′) and (3′′), and also, in column 4, the relative cross section according to the $A^{2/3}$ law. Comparison with the experimental data shows that formula (3′) agrees best with the data which indicates, apparently, that internal cascade processes are important in meson production. We note that our data refers to mesons with energies less than 28 mev, and hence should not be compared with the predictions of theories[9,10] applicable at high energies, as confirmed by Table 2.

Our data can be compared, to some extent, with the results of Refs ,11 and 12, in which a cloud

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[8] I. Rosental and D. Cherniavskii, Usp. Phys. Nauk 52, 185 (1954).

[9] L. D. Landau, Izv. Akad. Nauk SSSR, Ser Fiz. 17, 51 (1953).

[10] E. Fermi, Progr. Theor. Phys. 5, 570 (1950).

[11] B. Gregory and I. Tinlot, Phys. Rev. 81, 667 (1951).

[12] A. Lovati, A. Mura, G. Salvinia C. Tagliaferri, Phys. Rev. 77, 284 (1950).

chamber containing alternate plates of lead and light elements (carbon and aluminum) was used to investigate the dependence of the nuclear cross section on atomic weight. By subtracting out the number of nuclear events with 1,2 etc. end particles, the authors of Refs. 11 and 12 were able to show that the probability of a nuclear interaction (per g/cm^2 of material) with a large number of end products increases considerably with increasing atomic weight. As noted by Rossi[13] this is to be expected if the process goes essentially by successive collisions between the primary particle and the nucleons in the nucleus.

We can apparently draw the following conclusions from our data:

1) As A increases, the meson production cross section increases differently at high energies than it does at low energies (in accelerators).
2) When the primary particle has high energy, then not only the surface nucleons, but also the nucleons inside the nucleus play a role in the production of mesons.
3) At high energies, internal cascade processes are important in meson production.

In conclusion, it is our pleasant duty to thank S. N. Vernov and Prof. N. A. Dobrotin for useful discussions of the results, and our co-workers M. G. Antonov and P. A. Ysik for help in preparing the stratosphere flights.

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[13] B. Rossi, *High Energy Particles*, Moscow, 1955 p. 586 (Russian translation).

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