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INTERACTIONS OF 60 GeV π^- MESONS WITH PROTONS AND NUCLEI

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Abstract: Interactions of 60 GeV/c π^- mesons with nucleons, light (C, O) and heavy (Ag, Br) nuclei have been investigated using emulsions of two types: the usual (Br–2) emulsion in which about $\frac{1}{3}$ of the interactions occur on light nuclei and emulsion enriched by (CH_2OH). In the latter type the fraction of interactions with free protons increases to 0.12 and with light nuclei to 0.5.

It is shown that the mean multiplicity of charged particles in inelastic collisions as a function of energy follows the $E^{0.36 \pm 0.04}$ law.

The characteristics of the interactions on C, O and Ag, Br have been studied, and also the coherent interactions of pions with the emulsion nuclei.

1. INTRODUCTION

General characteristics of inelastic pion-nucleon collisions and coherent production of pions using standard nuclear emulsions (denoted by I) with 60 GeV/c π^- mesons have been described in earlier papers [1,2]. In this paper investigations in nuclear emulsions enriched by CH_2OH (denoted by II) using the method of ref. [3] are presented.

Table 1
Composition of the emulsions.

	Number of nuclei/cm^3	
	I	II
H	3.148×10^{22}	5.157×10^{22}
C	1.412	1.853
O	0.956	1.675
N	0.395	0.148
Ag	1.036	0.387
Br	1.031	0.385

The nuclear composition of these emulsions is given in Table 1.

The photo emulsions were exposed to 60 ± 2 GeV/c π^- mesons at the Serpukhov accelerator. The admixture of electrons, μ mesons and K^- mesons was less than 5%. Starting close to the primary π^- meson entrance into the emulsion an along-the-track scanning for inelastic interactions was performed and 424 events were found along a length of 356 m.

2. INELASTIC π^--p INTERACTIONS

Inelastic π^--p interactions have been selected by application of the usual criteria. The average multiplicities of charged particles $\langle n_\pm \rangle$ and of shower particles $\langle n_s \rangle$ are shown in Table 2. The Table also presents the calculated (Cal) and experimentally obtained (Exp) values for the fraction of π^--p interactions. When determining the values of $\langle n_\pm \rangle$ and $\langle n_s \rangle$ we corrected for the decay of π^0 meson into electron and positron (Dalitz pairs). This correction was −0.16. Events were divided into three equal random groups, and errors were calculated by considering the deviation of each mean value from the mean value of the entire sample.

Table 2
Average multiplicities.

	II	I	from ref. [2]
No. of π^--p int.	45	59	566
$\langle n_\pm \rangle$	6.7 ± 0.2	6.3 ± 0.2	6.56 ± 0.16
$\langle n_s \rangle$	6.4 ± 0.2	6.04 ± 0.2	6.25 ± 0.16
fraction of π^--p int. (Cal)	0.10	0.04	0.04
(Exp)	0.1 ± 0.015	0.075	0.08

The difference between the calculated and experimentally obtained values Δ is due to interactions with quasi-free protons. For emulsion I $\Delta_I = 0.04$, for emulsion II $\Delta_{II} = 0 \pm 0.015$, a result which indicates that interactions with quasi-free protons mainly occur on Ag, Br nuclei. It is advantageous that in emulsion II the fraction of interactions with quasi-free protons is small and the fraction of inelastic interactions with free protons increases to 0.1. Consequently, one can speak of the unbiassed estimate of $\langle n_\pm \rangle$ in emulsion II (as far as emulsion I is concerned, this value could be overestimated, as shown in ref. [2]).

Using $\langle n_\pm \rangle = 6.7 \pm 0.2$ and $\langle n_\pm \rangle = 4.2 \pm 0.1$ obtained from a hydrogen bubble chamber experiment [5] at 16 GeV/c, we get

$$\langle n_\pm \rangle = cE^{(0.36 \pm 0.04)}$$

where E is the energy in the lab. system. Statistical and hydrodynamic models pre-

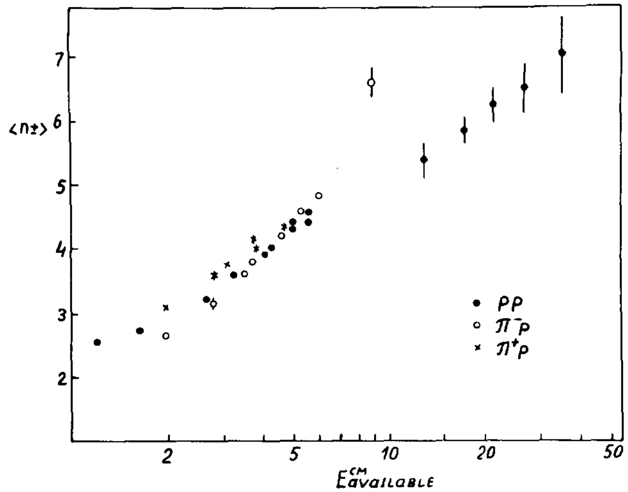

Fig. 1. The partial cross-sections in π^--p inelastic interactions depending on the energy in the c.m.s.

dict the $E^{1/4}$ law (if this law holds, then using $\langle n_\pm \rangle_{16}$ we obtain $\langle n_\pm \rangle_{60} = 5.84$). Pomeranchuk's model, on the other hand, predicts an $E^{0.5}$ behaviour for the average charge multiplicity. The value $\langle n \rangle = E^{1/3}$, obtained from Rotelli's work [7], agrees with the experimentally observed dependence. It should be noted that the logarithmic dependence $\langle n \rangle \sim \ln E$ obtained from many theoretical models cannot be excluded by the experimental data within the limits of the errors. It is interesting to compare the dependence of $\langle n \rangle$ on the available energy in the c.m.s., E_{av} for both π^--p and p-p collisions. In Fig. 1 the data from ref. [8] are presented, and the point for π^--p interactions at 60 GeV is added. As is seen from the figure, in experiments up to 30 GeV a steady increase of $\langle n \rangle$ as a function of E_{av} is observed for π^--p and p-p collisions. However, the point for π^--p at 60 GeV is markedly different from those obtained in cosmic ray experiments. Consequently, either at energies 30 GeV the curves for π^--p and p-p collisions diverge or there is an overestimate for the values of proton energies in cosmic ray experiments*.

Let us consider now the energy dependence of partial cross sections for different multiplicities of charged particles in inelastic collisions, which is essential for comparison with the hypothesis about the mechanism of hadron interactions.

Fig. 2 shows the dependence of partial cross sections on the total energy in the c.m.s. for inelastic π^--p collisions from ref. [5] up to 25 GeV and the present results at 60 GeV. The latter were calculated using the multiplicity distribution from ref.

* In the paper of Alam-Ata–Dubna–Krakow–Moscow–Tashkent–Ulan-Bator Collaboration presented at the Amsterdam Conf. in 1971, in which inelastic p-p interactions were investigated at 67 GeV, $\langle n_\pm \rangle = 6.6 \pm 0.2$. This coincides with the results of π^--p collisions at 60 GeV.

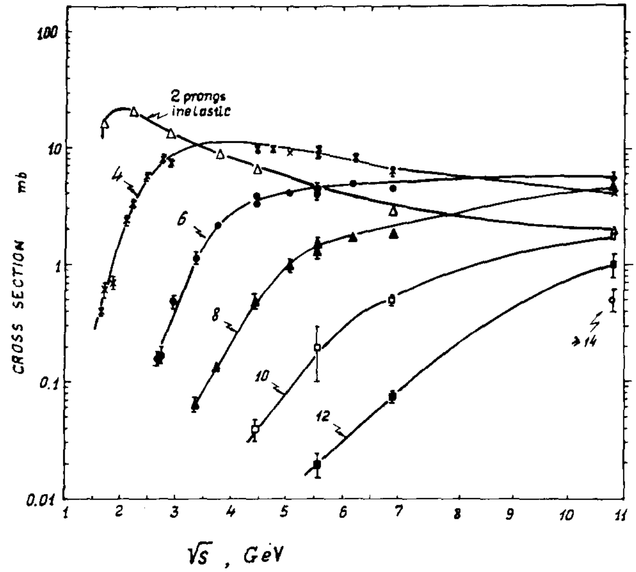

Fig. 2. The average number of charged particles depending on the free energy in the c.m.s.

[2], the total cross section (~ 24 mb) from ref. [9] and the elastic scattering cross-section (~ 4 mb) according to ref. [10]. As is seen in Fig. 2, the cross sections for smaller multiplicities as a function of energy after the maximum are not yet saturated.

3. INELASTIC COLLISIONS WITH C, O and Ag, Br NUCLEI

At accelerator and cosmic ray energies, ambiguous criteria have been used to select interactions with light nuclei and Ag, Br nuclei in different experiments. This leads to essential differences in dividing interactions into various nuclei groups. The selection of interactions with light nuclei was especially complicated, since their fraction in usual emulsions (I) is 0.3, and a significant fraction of Ag, Br nuclei have characteristics similar to those of light nuclei. The difficulty of separating interactions with light nuclei from Ag, Br is, to a great extent, reduced when dealing with emulsions II, as 0.12 of events correspond to interactions with protons, 0.5 with light nuclei, 0.38 with heavy nuclei (Ag, Br) and for Ag, Br interactions the number of heavy prongs very often exceeds the number of protons in light nuclei.

Using the nuclear composition of emulsions I and II, we have separated interactions with light and heavy nuclei by two methods. In the first method we use the distribution of stars in emulsion II as a function of n_h and in accordance with the nuclear composition from table 1 and the cross sections from data [4], we define events with $n_h \leqslant 3$ as due to C, O and $n_h > 3$ as due to Ag, Br interactions. This division is the first approximation. The extrapolation of the distribution of light nuclei to the region $n_h > 3$ and of Ag, Br nuclei interactions to the region $n_h < 3$ assuming that the ratio of the cross sections is conserved is the second approximation.

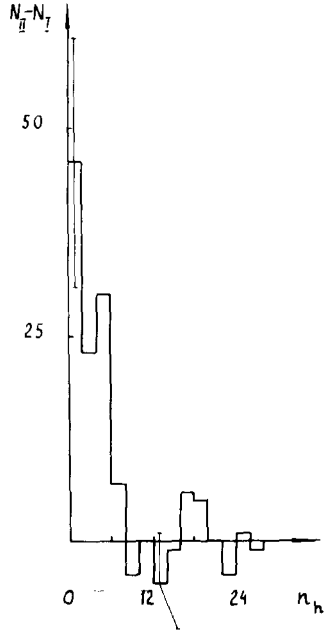

Fig. 3. The particle number n_h distribution on nuclei C, O obtained by method 2.

In the second method the distribution of stars (without interactions with free protons) in emulsion I after normalization was subtracted from the distribution of stars in emulsion II. This difference is the distribution of C, O interactions nuclei in CH_2OH (see fig. 3).

The characteristics of π^- meson interactions with C, O which were obtained by the second method are in agreement with the same characteristics from the first method. The results are shown in table 3. Fig. 4 shows the angular distribution of shower particles produced on light nuclei as well as on heavy ones.

Let us consider at once the question about the unbiassed estimate of $\langle n_\pm \rangle$ in emulsion II. If we look at $\langle n_s \rangle$ for C, O, as a function of n_h, we find that for $n_h = 0.1$, $\langle n_s \rangle = 6.7 \pm 0.6$, but for $n_h = 2$, $\langle n_s \rangle = 8.9 \pm 0.7$. Consequently, if we have even some admixture of interactions with nuclei in collisions with free protons, we do not have the biassed estimate of $\langle n_\pm \rangle$.

Table 3
Results.

	C, O			Ag, Br	
	Method 1 1st approx.	2nd approx.	Method 2	Method 1 1st approx.	2nd approx.
$\langle n_\pm \rangle$	9.7 ± 0.1	9.6 ± 0.1	10.7 ± 0.3	20.6 ± 0.5	20.6 ± 0.4
$\langle n_s \rangle$	7.4 ± 0.3	7.4 ± 0.3		9.9 ± 0.7	10.2 ± 0.3
$\theta_{s,1/2}$	8.8 ± 0.8			16.4 ± 0.6	
$\langle n_h \rangle$	1.79 ± 0.03	2.2 ± 0.03	2.7 ± 0.2	10.8 ± 0.5	10.3 ± 0.3

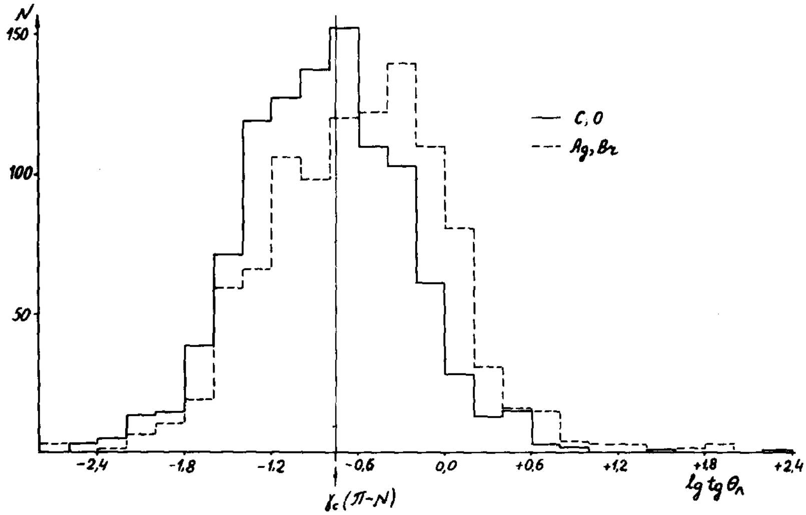

Fig. 4. The angular distribution of shower particles on nuclei C, O and Ag, Br.

4. MECHANISM OF THE INTERACTION OF FAST π^- MESONS WITH NUCLEI

As is shown in refs. [11, 12], the cascade mechanism for the interaction of particles with nuclei takes place up to 10 GeV. Many authors, for example [13, 14], have considered the mechanism which can be called "trailing". Following the primary interaction, fast moving secondaries leave a region of less nucleonic matter density behind them. This fact has recently been confirmed by theoretical calculations [15].

The increase in energy makes it possible to realize the process when some secondaries, produced inside a nucleus in the primary collision, interact with one of its nucleons. This mechanism has been proposed in ref. [16] to explain experimental results in cosmic rays. Table 4 compares the data from table 3 with the many-particle model calculations [17]. The data from ref. [14] regarding the interactions of 17.2 GeV/c π^- mesons and their comparison with the calculations by the usual cascade model [18] are also presented. The predictions of the many-particle model and the observed value of $\langle n_s \rangle$, $\langle n_g \rangle$ and $\theta_{s,1/2}$ for Ag, Br nuclei at 60 GeV/c are in agreement.

Table 4
Comparison of data with theoretical predictions.

	60 GeV/c				17.2 GeV/c	
	C, O		Ag, Br			
	exp.	theory [17]	exp.	theory [17]	exp. [14]	theory [18]
$\langle n_s \rangle$	7.4 ± 0.3	5.1 ± 0.3	9.9 ± 0.7	9.3 ± 0.5	5.9 ± 0.3	7.1 ± 0.5
$\theta_{s,1/2}$	8.8 ± 0.8	9.6 ± 0.5	16.4 ± 0.6	15.4 ± 0.8	22.0 ± 1.1	24 ± 2
$\langle n_h \rangle$	2.2 ± 0.1		10.0 ± 0.5	14.5 ± 0.6		
$\langle n_g \rangle$		1.6 ± 0.1	4.11 ± 0.35	4.0 ± 0.2	2.3 ± 0.1	4.0 ± 0.4
$\langle n_6 \rangle$			6.54 ± 0.43	10.5 ± 0.5		

Note that the proposed many-particle mechanism describes the process of collective interactions of fast particles with nucleons inside the nucleus and is an inverse analogy of the coherent generation process. Its experimental proof is of great interest for nuclear and elementary particle physics. As a consequence, analogous investigations with larger variations of the nuclear composition of emulsions and energies of primary particles would be interesting.

5. COHERENT INTERACTIONS

Coherent interactions are inelastic interactions of fast particles with all or some nucleons of the nucleus in which the whole nucleus obtains a recoil momentum. This process was theoretically considered in [19].

In ref. [20] it was shown that at small angles without the absorption of partial amplitudes σ would be proportional to A^2.

Absorption effects which cannot be precisely calculated are very essential. Comparing the theory with the experiment, it was concluded that $\sigma \sim A^{2/3}$ [20]. In a number of works serious disagreements are observed.

In ref. [21] a comparison between the emulsion and bubble chamber results has been made and it is concluded that all the nuclei of photo emulsions participate in the coherent generation and the fast increase, i.e. A^2 due to the Coulomb generation is not valid. In ref. [22] a detailed comparison of methodic factors in emulsion and bubble chamber works has been made and it is concluded that "there are no good grounds against Good's and Walker's assumption [23] that the coherent process occurs predominantly in light nuclei".

The bulk of the data on coherent generation has been obtained using bubble chambers with different filling liquids.

In comparison with photo emulsions, chambers with heavy liquids achieving sufficient statistics have an essential advantage to detect π^- mesons. However, events characterized by the emission of low energy particles from the nuclear disintegration which are not detected in bubble chambers are reliably detected in emulsions.

In accordance with this fact investigations by means of photo emulsions with different nuclear compositions are of interest.

The results made with the help of emulsion I are given in [1,2]. Coherent interactions in emulsion II were selected according to the same criteria as in [1,2]. The data on three-prong coherent events $\pi^- + A \rightarrow \pi^- + \pi^+ + \pi^- + A$ showing an essential decrease in emulsion II are presented in table 5.

Table 5
Data on three-prong coherent events.

	I	II
Nuclei number C, O, N	2.76×10^{22}	3.68×10^{22}
1 cm^3 Ag, Br	2.07×10^{22}	0.77×10^{22}
Length of tracks (m)	3147	364
Number of events	197	11
$\langle \Lambda_{coh} \rangle$ (m)	16 ± 1.4	33 ± 10
$\langle \Sigma_i^3 \sin \theta_i \rangle$	0.067	0.071

As is seen in table 5, the relative increase $\langle \Lambda_{coh} \rangle$ for emulsion II corresponds to the relative decrease of the Ag, Br nuclei number in emulsion II in comparison with I. This result reflects the fact that coherent integrations are mainly due to Ag, Br nuclei. An analogous conclusion was obtained from the theoretical work [24] where the results on the coherent generation in photo emulsions and bubble chambers were compared.

The assumption that a main role is played by light nuclei in such interactions is unlikely, since in this case $\langle \Lambda_{coh} \rangle$ in emulsion II should be decreased to 10.7 m.

Preliminary results of the present work were given in ref. [25].

REFERENCES

[1] Alma-Ata – Budapest – Cracow – Dubna – Moscow – Sofia – Tashkent – Ulan-Bator collaboration, Phys. Lett. 31B (1970) 237, 241.
[2] Z.V. Anzon, G. Bozoki, N. Dalkhazhav et al., preprint JINR PI-5072 (1970).
[3] N. Dalkhazhav, T.A. Kalinkina, L.G. Kriventsova, K.D. Tolstov, V.M. Uvarova, Yad. Phot. p. 171, Moscow, 1962.
[4] V.S. Barashenkov, K.K. Gudina et al., preprint JINR P2-4520 (1969).
[5] H. Honeker, J. Klugow, H. Böttcher et al., Nucl. Phys. B13 (1969) 571.
[6] I.L. Pomeranchuk, reports AN 78 (1951) 889.
[7] P. Rotelly, Phys. Rev. 182 (1969) 1622.
[8] A. Vrublevsky, Rapporteur report at the 15th. Int. Conf. on high energy phys., Kiev, 1970.
[9] L.M. Vasiliev, Yu.D. Prokoshkin et al., 15th. Int. Conf. on high energy phys., Kiev, 1970.
[10] G. Giakomelli et al., CERN-HE A 69-1 (1969).
[11] V.S. Barashenkov, V.V. Glagolev, N. Dalkhazhav et al., Nucl. Phys. 14 (1959) 522.
[12] K.D. Tolstov, Nucl. Phys. 47 (1963) 11.
[13] V.S. Barashenkov, K.K. Gudina, V.D. Toneev, Yad. Fiz. 10 (1969) 755.
[14] J. Kohli, Nucl. Phys. B14 (1969) 500.
[15] V.S. Barashenkov, A.S. Il'inov, V.D. Toneev, preprint JINR P2-5211 (1970).
[16] I.Z. Artykov, V.S. Barashenkov, S.M. Eliseev, Nucl. Phys. 87 (1966) 241; Nucl. Phys. B6 (1968) 11; preprint JINR P2-4510 (1969).
[17] I.Z. Artykov, V.S. Barashenkov, preprint JINR P2-4510 (1969).
[18] I.Z. Artykov, V.S. Barashenkov, S.M. Eliseev, Nucl. Phys. 87 (1966) 89.
[19] I.Ya. Pomeranchuk, E.L. Feinberg, AN 93 (1959) 438.
[20] I.I. Veillet, Topical Conf. on high energy coll. hadrons, CERN N67-7 I (1968) 537.
[21] A. Caforio, D. Ferraro et al., Nuovo Cim. 32 (1964) 1471.
[22] A.A. Camal, I.V. Rao, Rukmini Rao, Proc. of the Indian Academy of Sciences, VLXIX (1969) 218.
[23] M.L. Good, W.D. Walker, Phys. Rev. 120 (1960) 1855 and 1857.
[24] H. Lesniak, L. Lesniak, preprint CERN TH, 1269 (1970).
[25] N. Dalkhazhav, K.D. Tolstov, G.S. Shabratova, preprint JINR PI-5326 (1970); Report at the Int. Conf. on high energy phys., Kiev (1970).