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Test of the Coherent Tube Model Approach to Relativistic Nucleus-Nucleus Interactions

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Abstract. Coherent Tube Model predictions concerning secondary pion multiplicities and transverse momenta were compared with the experimental data. It was shown that the discrepancies between the model and our experimental data could not be removed by taking into account fragmentation processes.

Recently published data on π^- meson production in relativistic nucleus-nucleus collisions [1] contain new information on the momentum structure of the final states. These data can be used for testing phenomenological models of high energy hadron-nucleus interactions. It seems valuable to carry out a generalization of these models for the case of nucleus-nucleus collisions (which is a rather straightforward procedure), since an increased number of nucleons participating in the interaction yields a possibility of testing model assumptions in the domain inaccessible in the hadron-nucleus collision.

In this work the Coherent Tube-Model, CTM [2], is considered and model predictions concerning pion multiplicities and transverse momenta are compared with the experimental data.

In recent SKM-200 Collaboration experiments [1] carried out with the use of the 2 m streamer chamber, inelastic interactions of ^{4}He nuclei (4.5 GeV/c incident momentum per nucleon) with several target nuclei (Li, C, Al, Cu and Pb) were studied. In particular multiplicities and transverse momenta of secondary π^- mesons [3] were determined. In Figs. 1 and 2 the average multiplicity $\langle n \rangle$ and transverse momentum $\langle p_T \rangle$ values are plotted against the target thickness $A_T^{1/3}$. One can see a marked increase of $\langle n \rangle$ and a tendency of $\langle p_T \rangle$ to decrease with increasing $A_T^{1/3}$.

A distinctive feature of the CTM model is the "universality" assumption. It states that in a tube-tube collision all final state characteristics, independent of target and projectile quantum numbers, depend on the available energy Q only and they are identical with those observed in elementary proton-proton collisions at the corresponding energy. This assumption, based on the simple estimate of the space-time dimensions of the interaction region, is valid when $E \gtrsim A^{1/3}$ GeV [4]. For momentum 4.5 GeV/c per nucleon Pb nucleus does not follow this condition, and some admixture of pions from the leading particle cascading is possible.

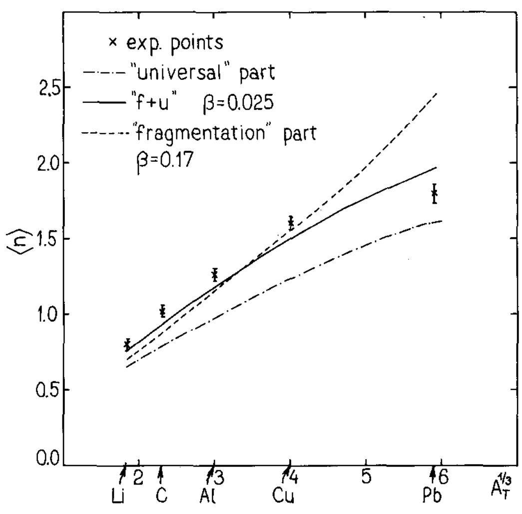

Fig. 1. Dependence of the average multiplicities of negative pions on the target thickness

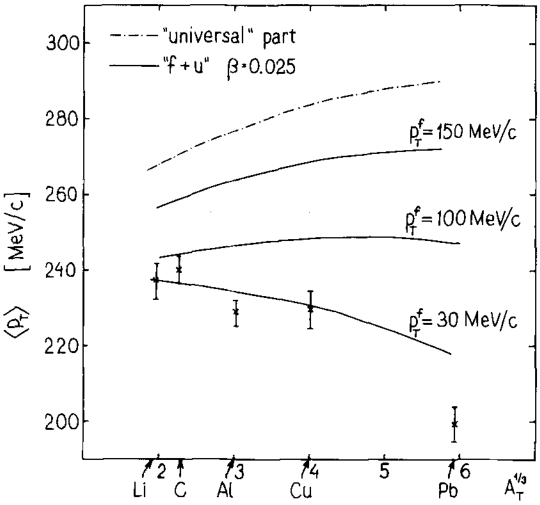

Fig. 2. Dependence of the average transverse momentum of negative pions on the target thickness

The following analysis is based however on the assumption that collective effects are dominant.

The average number of "universal" mesons produced in the heavy ions collision with impact parameter **B** is given by [5]

$$n(\mathbf{B})=\int \frac{d^2b}{\sigma}\,\tilde{n}(Q(i_1,i_2)), \tag{1}$$

where $\tilde{n}(Q)$ is the average number of π^- mesons produced in the proton-proton interactions at an available energy Q (for later calculations the parametrization of the formula given in [5] was used). The quantity $Q(i_1,i_2)$ is the available energy in the CM system of tubes containing $i_1=\sigma\cdot T_1(\mathbf{b})$ and $i_2=\sigma\cdot T_2(\mathbf{B}-\mathbf{b})$ nucleons, $T_i(\mathbf{b})=\int dz\,\rho_i(\mathbf{b},z)$ [6]. σ denotes the geometrical tube-tube cross-section and it is assumed to be equal to total proton-proton cross-section $\sigma=39$ mb and $\int d^2b/\sigma$ corresponds to performing the summation over all colliding tubes.

Averaging expression (1) over **B** one obtains:

$$\langle n\rangle=\int d^2B\,P(\mathbf{B})\,n(\mathbf{B})/\int d^2B\,P(\mathbf{B}), \tag{2}$$

where $P(\mathbf{B})$ is the probability of an inelastic tube-tube interaction for a given impact parameter **B** [7]. Similar consideration leads to the formula:

$$\langle p_T\rangle=\int d^2B\,P(\mathbf{B})\,P_T(\mathbf{B})/\int d^2B\,P(\mathbf{B}), \tag{3}$$

where

$$P_T(\mathbf{B})=\int \frac{d^2b}{\sigma}\,\tilde{P}_T(Q)\,\tilde{n}(Q)/n(\mathbf{B})$$

and $\tilde{P}_T(Q)$ is the average transverse momentum in the proton-proton interactions [8].

Results of the calculations based on (2) and (3) are shown in Figs. 1 and 2 (curves denoted "universal"). The calculated average multiplicity is only about 20% smaller than experimental values. It can be argued that this discrepancy is due to uncertainties in the model assumptions. These results are in agreement with those obtained in [5]. However, in the case of $\langle p_T\rangle$ vs. $A_T^{1/3}$ dependence discrepancy is much more striking - even the trend of experimental and calculated points is different.

It has been shown in [9] that the "universality" assumption if applied to all produced pions leads to an inconsistency with experimental data. Considering a quantity dependent on the quantum numbers of the colliding tubes one has to take into account a tube fragmentation process. In the first stage the colliding tubes produce a "universal" pion component. The second stage, i.e. the decay of the tubes, consists in independent fragmentation processes of individual nucleons in the interacting tubes.

In the nucleus-nucleus interactions more nucleons are involved in the tube-tube collisions ("active" nucleons) than in the case of the hadron-nucleus interactions and consequently a rather large contribution of the "fragmentation" pion component is expected (in our energy region) as compared to that due to the "universal" pions. It seems, therefore, necessary to take into account the fragmentation processes in calculating such characteristics of secondary pions as $\langle n\rangle$ and $\langle p_T\rangle$. In order to test whether the discrepancies described above could be removed in this way, the following additional assumption [10] has been introduced into further considerations.

Each nucleon in a tube decays independantly of its energy and of the number of the surrounding nucleons. An immediate consequence of this assumption is the identity of the fragmentation processes of nucleons in elementary interactions with that in nuclear collisions.

Let us denote by β the average number of π^- mesons from a nucleon fragmentation. Since the numbers of π^- mesons from proton and neutron are different, β should be taken as their average. Adding fragmentation component to (1) we obtain:

$$n(\mathbf{B})=\int \frac{d^2b}{\sigma}\,\tilde{n}(Q)+N(\mathbf{B})\cdot\beta, \tag{4}$$

where $N(\mathbf{B})$ is the average number of "active" nucleons for an impact parameter **B**. $N(\mathbf{B})$ was calculated with the use of approximate formulae for intersection volume of cylinder and sphere given in [11].

The lower limit of β can be estimated from the difference of the average π^- mesons multiplicities in the $n-p$ and $p-p$ interactions. The difference, roughly constant with energy, is known from experimental data [12] as $\Delta n \cong 0.33$. Neglecting proton fragmentation into π^- mesons and assuming that the numbers of protons and neutrons in a nucleus are equal, we obtain:

$$\beta = \frac{\Delta n}{2}$$

If this value of β is used in calculations based on equation (4) the $A_T^{1/3}$ dependence of $\langle n \rangle$ for fragmentation pions is obtained (see Fig. 1). It is seen that the multiplicity values for the fragmentation component are comparable to $\langle n \rangle$ measured in our experiment. This result suggests the possibility that, at least in our energy range, fragmentation component is dominant and "universal" production should not be introduced at all. Instead of looking for such a mechanism we have accepted all general assumptions of CTM and have argued that efficiency of the nucleon fragmentation in the nucleus-nucleus collision is smaller than that in the nucleon-nucleon collision. Consequently, the β value cannot be taken from experimental data on elementary interactions, but it should be considered rather as a free parameter. A reasonable agreement with our $\langle n \rangle$ data is obtained for $\beta = 0.025$ (see Fig. 1). It should be stressed, however, that also twice as big efficiency is allowed by the data if we remember of all the uncertainties in the model assumptions. Nevertheless it does not change our qualitative conclusions and $\beta = 0.025$ have been further used for calculation of $\langle p_T \rangle$ values.

In order to take into account the fragmentation processes it is necessary to introduce into consideration the value of the average transverse momentum of the "fragmentation" mesons denoted by p_T^f. The $\langle p_T \rangle$ values to be compared with the experimental data were evaluated from the formula:

$$p_T(\mathbf{B}) = \left(\int \frac{d^2 b}{\sigma} \tilde{p}_T(Q)\, \tilde{n}(Q) + p_T^f N(\mathbf{B})\, \beta\right) / n(\mathbf{B}) \qquad (5)$$

The results of the calculations for three p_T^f values are shown in Fig. 2. It can be shown [13] that taking into account fragmentation pions of protons does not change the p_T^f value. For reasonable p_T^f values (expected to be of the order ~150–200 MeV/c) the calculated average transverse momenta of pions, $\langle p_T \rangle$, are incompatible with experimental data. The agreement can be achieved only for the value of $p_T^f \approx 30$ MeV/c which does not seem to be realistic.

The qualitative results presented in this work lead us to the conclusion that the average values of the pion multiplicities and transverse momenta calculated within the framework of the CTM model (with fragmentation processes taken into account) are inconsistent with the experimental data. The discrepancies could not be removed even with slightly modified assumptions concerning fragmentation processes. It seems, therefore, that the CTM model is unable to reproduce our experimental data unless some essentially new modifications of the model are introduced.

References

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6. In our simple analysis the distributions ρ_i of individual nucleons within the nuclear volume are assumed to be constant and not intercorrelated with the radius of nucleus $R = r \cdot A^{1/3}$, where $r = 1.27$ fm
7. According to [5] the following formula for $P(\mathbf{B})$ was used: $P(\mathbf{B}) = 1 - \exp(-\sigma \int d^2 b\, T_2(\mathbf{b}) \cdot T_1(\mathbf{B} - \mathbf{b}))$
8. The following parametrization was taken for calculating the $\tilde{p}_T$ values: $\tilde{P}_T(Q) = 235 + 69.5 \ln Q - 12.2 (\ln Q)^2$ MeV/c
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13. The "universal" component of the multiplicity of π^- mesons in the tube-tube collision includes the fragmentation of two protons which is the consequence of using $\tilde{n}(Q)$ taken from $p-p$ data. The following calculation shows that taking into account proton fragmentation in the fragmentation part of formulae 5 does not change p_T^f value. Average $\langle p_T \rangle$ can be expressed as:

$$\langle p_T \rangle = \frac{n^u p_T^u + n^f p_T^f}{n^u + n^f},$$

where n^u is the number of "universal" pions, p_T^u is the average p_T of the "universal" part (both taken from the pp data) and n^f, p_T^f are corresponding quantities for fragmentation part. After taking into account proton fragmentation we have:

$$\langle p_T \rangle = \frac{n^{u'} p_T^{u'} + n^{f'} p_T^{f'}}{n^{u'} + n^{f'}},$$

where

$$n^{u'} = n^u - \Delta, \qquad n^{f'} = n^f + \Delta$$

$$n^{u'} p_T^{u'} = n^u p_T^u - \Delta p_T^{f'}$$

Comparing these two expressions we get

$$p_T^f = p_T^{f'}$$

Exact calculation (i.e. based on the formulae (4) and (5)) gives the same result