A STUDY OF GENERAL PROPERTIES OF THE PARTICLE INCLUSIVE SPECTRUM IN HADRON COLLECTIVE INTERACTION

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A new variant is proposed for the space-time model of cumulative processes in which the hypothesis of scale invariance is changed to the hypothesis of identity of the invariant inclusive cross sections in hadron-hadron and hadron collective interactions at equal mass of the intermediate system. Experiments are discussed which would prove that assumption.

1. Introduction

In papers [1–3] a space-time model has been formulated for the cumulative production of particles on nuclei. It is based on ideas used earlier for the space-time description of multi-hadron production [4, 5] and on the hypothesis of scale-invariance of the inclusive spectrum applied in the early analysis of processes of the cumulative type in collective interactions [6]. Briefly, this model was called "gathering" model since the process of formation of the intermediate hadron compound system in this limiting case consists in a successive accumulation of mass in inelastic collisions accompanied by the nucleon capture.

The process of gathering can be initiated both by hadrons and by other particles, e.g., by γ-quanta and even by neutrinos. In this case, a "startup" compound system results from the deep inelastic interaction, and its subsequent evolution proceeds via the same scheme. At present, it is clear that the exact fulfilment of scale invariance is not necessary for the model. It is enough to assume a considerably more weak condition that the invariant inclusive cross section, both in hadron-hadron and in hadron collective interactions, is almost the same in the case of equal masses of the intermediate compound system. In what follows, the assumption to fulfil this condition will be called the hypothesis of identity of hadron inclusive spectra or briefly the identity hypothesis.

The model of cumulative processes based on the identity hypothesis has certain advantages: First, the validity of the model does not depend on whether the scale invariance

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holds or not (this is very essential at low energies where scale invariance does not hold [7, 9]). Second, it makes the model of cumulative processes [1–3] even more close to the space-time formulation of the process of multi-hadron production [4–5].

The model also assumes that the decay of the intermediate system, the cluster, produced and developed in the nucleus, proceeds in the same way as the decay of the cluster produced in p−p interaction. The difference is that both the production of the intermediate system and its decay in the cumulative scheme proceed under limiting conditions very much different from the average conditions. A unique compound system is generated with the cross section $\sigma_c^{in} \ll \sigma_{tot}^{in}$, and its decay with emission of a cumulative particle occurs much faster than the development of the pionization system in a typical act which results in the multi-particle production. Also, it should be stressed again that the model does not require the prepared object existence in the nucleus, with double, triple, etc., nucleon mass. It simply deduces the necessary appearance of such an object from the clear fact that any physical process to be realized requires the finite space-time interval. According to Ref. [1], the effective length of the "gathering" region $\overline{\Delta z} \simeq 2.5-3.0$ fm. The latter circumstance for the dense nuclear matter, when the collection region contains more than one nucleon, leads to the formation of intermediate states with masses much larger than the maximum admissible mass in p−p interaction at the same initial energy. In other words, it would be surprising if such a mechanism does not contribute to the cumulative processes.

The space-time model was successfully applied to the cumulative pion production [1], to the subthreshold production of antiprotons on nuclei [2] and to the backward elastic p−d scattering [3]. In these papers, we calculated the model parameters: σ_c, the production cross section of a compound system, and τ_0 its life-time with respect to that of emission of an energetic particle. Values of these parameters seem reasonable from the data and arguments [1] available. In what follows, these parameters will be considered to be known. To test the generality of the model ideas and, in particular, of the identity hypothesis, it is necessary to extend the range of its comparison with experiment both in the set of described characteristics (sort of produced particles, collision energies) and in the class of processes in which the cumulative phenomena dominate.

In this connection, in view of the progress and perspectives in the study of cumulative processes, it seems reasonable to discuss the following problems: angular distributions of cumulative particles, yield of heavier mesons, $K^{\pm}$, vector ones, ϱ^0, ω and antiprotons and hyperons. For some of these the data are already available, for others the measurements are in progress. This and subsequent papers will discuss them briefly.

2. *Angular distributions of cumulative pions*

The invariant cross section of cumulative particle production is defined as follows:

$$R_A^{(i)} = \sum_n \varrho_i(s, x_n, p_\perp) \cdot W_A^{(n)}, \tag{1}$$

where $W^{(n)}$ are functions of the "gathering" model given in Ref. [1], n is the cumulative order, i.e., the number of collected nucleons of the nucleus with mass number A.

The functions $\varrho_i(s, x_n, p_\perp)$ are invariant inclusive densities for production of particles of the i-th sort in p−p interaction

$$\varrho_i(s, x_n, p_\perp) = \frac{E}{\sigma^{\text{in}}} \frac{d^3\sigma}{dp^3}, \tag{2}$$

$$x_n = p_{\parallel,(i)}/p^{\max}_{\parallel,(i)}(n) \tag{3}$$

where $p^{\max}_{\parallel,(i)}(n)$ is the maximum longitudinal momentum of the i-th particle at given $p_\perp$. Its value is defined by the kinematics of the n-th order cumulative process. At $p_\perp = 0$ equations (1)—(3) turn into the corresponding invariant cross sections of particles emitted at 180° with respect to the direction of motion of the incident particle [1].

To define the function $\varrho_i(s, x_n, p_\perp)$ we use a widely accepted approximation, factorization of the dependence on longitudinal and transverse momenta

$$\varrho_i(s, x, p_\perp) = F_i(s, x) \exp(-a_i p_\perp^2). \tag{4}$$

For pions $a_\pi \approx 4.24$ [8]. It is not difficult to establish approximately the energy at which it is necessary to exploit the data on the dependence of the invariant inclusive spectrum on logitudinal momentum, $F(x)$. It is calculated by equating the masses of intermediate systems in the case of p−p collisions and cumulative process

$$s = 2m(\tilde{E}+m) = (n^2+1)m^2+2nmE_{\text{p}}^{\text{in}}, \tag{5}$$

i.e.,

$$\tilde{E} = \frac{1}{2m}[(n^2+1)m^2+2nmE_{\text{p}}^{\text{in}}]-m. \tag{6}$$

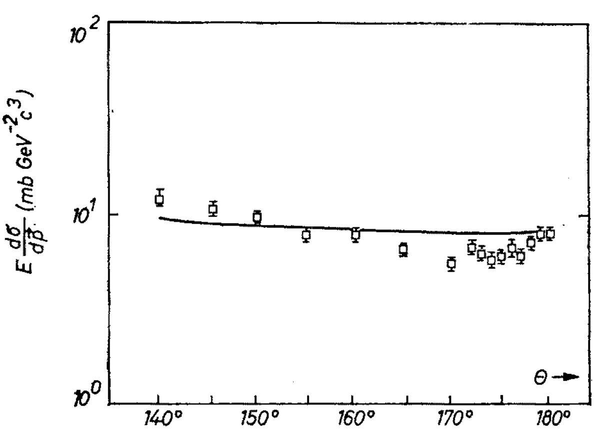

Fig. 1. R_{Pb} (0.5 GeV/c) as a function of the pion emission angle

For $E_{\text{p}}^{\text{in}} = 8.6$ GeV at $n = 2, 3$, it follows from (6) that $\tilde{E} \approx 19$—30 GeV. Data of this type can be found in Refs. [9, 10]. The results of calculations of the π^+ angular distribution with momentum 0.5 GeV/c for p−Pb interactions at $E_{\text{p}} = 8.6$ GeV are presented in Fig. 1, together with experimental data [11]. The comparison shows that the model satisfactorily reproduces both the magnitude of the invariant cross section and its angular dependence in the considered interval, $140° \leqslant \theta \leqslant 180°$.

Our calculation of the cumulative pion angular distribution, as before, neglects a possible influence of the nucleus on the emitted particle. An analysis given in paper [1] shows that this approximation is valid for calculation of the invariant cross section of energetic pions emitted at 180° since in the process of gathering a channel is open with very low density on their path through the nucleus. By estimations [1], the existence time of the channel is sufficient for the yield of the relativistic meson from the nucleus. However, the travel of pions through the channel surrounded by the dense absorbing matter can influence their angular distribution because of the diffraction effects. The diffraction picture is specified by the following parameters: wave length, distance from the emitter to the channel exit, and number of the Fresnel zones in the exit opening hole, i.e., pion momentum, length of the collection region and diameter of the exit hole. Since the two latter characteristics have substantial fluctuations, the diffraction picture cannot be clear.

Nevertheless, it may be supposed that the observed minimum in angular distributions of cumulative particles produced on heavy nuclei in the range 150°—170° is due to the diffraction effect. Indeed, it is not difficult to show that the angle, at which the destructive influence of the two first Fresnel zones can arise, is defined by the expression:

$$\theta \approx \pi - \mathrm{arctg}\left[\frac{\lambda}{\Delta z}\right]^{1/2} \approx \pi - \mathrm{arctg}\left(\frac{h}{p_\pi \Delta z}\right)^{1/2}, \tag{7}$$

where λ is the pion wave length, and $\Delta z \approx 2.5$—3 fm is the effective length of the gathering region. For cumulative pions ($p_\pi \geqslant 0.4$ GeV/c) $\theta \approx 150°$—170°. The sharpness of the diffraction picture may be different at different $\lambda_i = h/p_i$, depending on the energy and type of observed cumulative particles, and can increase at their certain combination.

3. *Production of cumulative $K^\pm$ mesons and antiprotons in pA interactions*

The invariant cross sections for cumulative $K^\pm$ mesons and antiprotons were calculated by Eqs. (1)—(3) at $p_\perp = 0$ for initial momentum $p_p^{in} = 8.6$ GeV/c. For kaons in the considered kinetic energy range $0.2\ \mathrm{GeV} \leqslant T \leqslant 0.5\ \mathrm{GeV}$ the main contribution comes from the cumulative orders $n = 2, 3$. The energy of $p-p$ collision required for using the data on the invariant inclusive spectrum is defined by Eq. (7) and equals 19—30 GeV. Information on the behaviour of $F_i(x)$ approximately in that energy range can be found in Ref. [12].

Figure 2 shows the results of the calculation of R_A by model [1] for the cumulative production of $K^\pm, \bar{p}$ at angle 180° on nuclei C^{12}, Cu^{64}, Pb^{208}. The comparison with experiment can be made only for K^+ mesons produced on C^{12} [13]. Within experimental error (rather large) the calculation is consistent with experiment. Other curves are essentially predictions of the model.

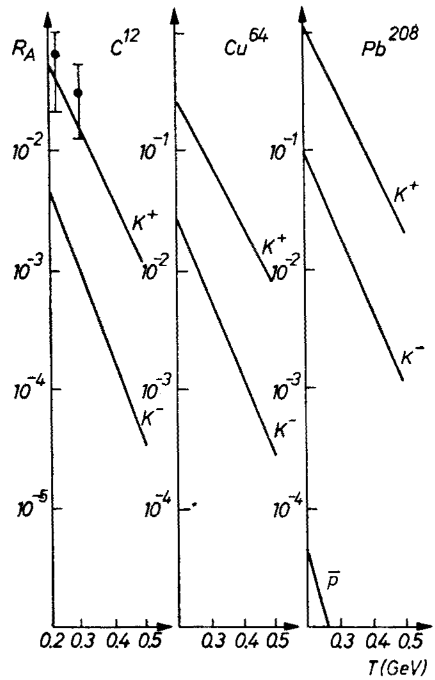

Fig 2. $R_A(T)$ for production of $K^{\pm}$ mesons and antiprotons on nuclei

4. *Cumulative vector mesons*

It is of special interest to find an estimate of the cross section of vector meson production in the cumulative range since the Laboratory of High Energies of JINR possesses an apparatus capable to detect these particles. Unfortunately, we have no data on the behaviour of the invariant inclusive cross section for ϱ^0 and ω mesons in p$-$p collisions in the corresponding energy interval. Therefore, we will use the function $F_{(i)}(s, x)$ constructed by assuming that it has the same form as for pions, i.e.,

$$F_i(s, x) = C_i F_\pi(x),$$

with the normalization constant C_i defined rigorously by the condition

$$C_i \int_0^\infty (p^2+m_i^2)^{-1/2} F_\pi(s, x) d^3p \Big[\int_0^\infty (p^2+m_\pi^2)^{-1/2} F(s, x) d^3p\Big]^{-1} = \sigma^{(i)}/\sigma^{(\pi)}. \qquad (8)$$

or

$$C_i = \frac{\langle E_i\rangle \sigma^{(i)}}{\langle E_\pi\rangle \sigma^{(\pi)}}. \qquad (9)$$

In the energy range of an order of several dozen GeV in p$-$p collisions the mean energy of pions in the c.m.s. is: $\langle E_\pi\rangle \approx 0.4$—$0.5$ GeV and the mean energy of particles with mass

$m_i \gg m_\pi$ equals approximately $\langle E_i \rangle \approx m_i + \frac{3}{2} m_\pi$. Therefore,

$$C_{\varrho^0} \approx (1.4-1.8)\, \frac{\sigma^{(\varrho^0)}}{\sigma^{(\pi)}}\,; \qquad C_\omega \approx (1.5-2.0)\, \frac{\sigma^{(\omega)}}{\sigma^{(\pi)}}\,.$$

The results of calculation of $R_A^{(\rho^0,\omega)}$ at $p_\perp = 0$ for the interaction of $p_p^{in} = 8.6$ GeV/c protons with nuclei C^{12}, Cu^{64}, Pb^{208} are shown in Fig. 3. The normalization constants

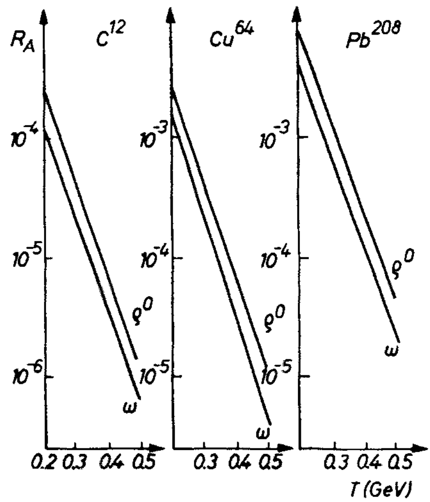

Fig. 3. $R_A(T)$ for production of ρ^0 and ω mesons on nuclei

were taken as follows: $C_{\rho^0} \approx 7.2 \cdot 10^{-3}$; $C_\omega \approx 4.54 \cdot 10^{-3}$. The data on $\sigma_{pp}^{(i)}$ are from Ref. [12]. A comparison with experiment would reveal whether some extra distinctive features appear in the vector meson production at collective interactions.

5. *Production of cumulative hyperons*

It is an important task to compare the model predictions concerning the production of cumulative hyperons with experiment. A distinctive feature of the hyperon production is that their invariant cross section in p–p interactions differs greatly from the meson cross section rapidly decreasing with increasing x and, instead, is similar to the proton one.

This fact indicates an essential difference in the production mechanism for hyperons and mesons. A study of the cumulative hyperons would provide an answer to whether the identity hypothesis is valid for their production in the collective interaction. We have calculated the functions R_A for Λ_0 hyperons emitted at 180° in the interaction of 8.6 GeV/c protons with nuclei C^{12}, Cu^{64}, Pb^{208} by using the data of paper [14] on the invariant cross section of Λ_0 production in p–p collisions at equivalent energies (8). For Σ^+ hyperons we assumed that their spectra in p–p collisions are similar to Λ_0 spectra, $\sigma^{(\Lambda_0)}/\sigma^{(\Sigma)} = 2.5$ [13]. The results of calculations are given in Fig. 4.

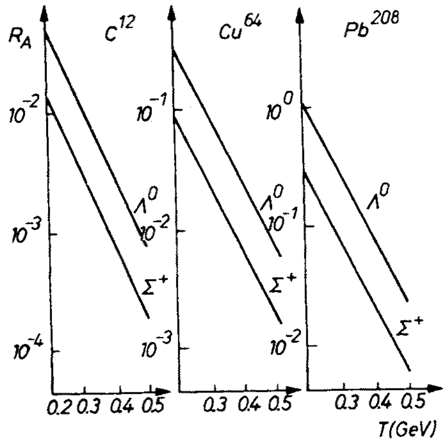

Fig. 4. $R_A(T)$ for production of Λ_0 and $\Sigma^\pm$ hyperons on nuclei

6. *Conclusion*

A refined formulation has been given for the model of cumulative processes proposed earlier. It allows one to extend substantially the class of effects studied in the hadron collective interaction. On the basis of the hypothesis of identity of inclusive spectra in hadron collisions and collective interactions of hadrons at equal masses of the intermediate system, predictions have been made on the invariant cross sections for different-type particles produced in cumulative processes. Relevant experiments could test whether the above hypothesis is an additional principle that the hadron interaction models should obey.

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REFERENCES

[1] B. N. Kalinkin, A. V. Cherbu, V. L. Shmonin, *Acta Phys. Pol.* **B9**, 375 (1978).
[2] B. N. Kalinkin, A. V. Cherbu, V. L. Shmonin, *Acta Phys. Pol.* **B9**, 385 (1978).
[3] B. N. Kalinkin, A. V. Cherbu, V. L. Shmonin, *Acta Phys. Pol.* **B9**, 393 (1978).
[4] B. N. Kalinkin, V. L. Shmonin, Preprint JINR P2–7869, 7870, 7871, Dubna 1974; *Yad. Fiz.* **21**, 628 (1975).
[5] B. N. Kalinkin, V. L. Shmonin, IV Int. Seminar on High Energy Physics, D1, 2–9224, 258, Dubna 1975; Preprint JINR E2–9137, Dubna 1975.
[6] A. M. Baldin, *Comm. on Physics* No. 1, USSR, p. 35, 1971.
[7] B. M. Abramov et al., *JETP Lett.* **26**, 403 (1977).
[8] S. B. Gerasimov, N. Ghiordanescu, Preprint JINR P2–7687, Dubna 1974.
[9] I. A. Radkevich, ITEP "*Elementary Particles*", III, p. 104–124 (1973).
[10] J. V. Allaby et al., Proc. of IV Int. Conf. on High Energy Collisions, Oxford 1972.
[11] A. M. Baldin et al., Contribution to the European Conf. on Particle Physics, Budapest 1977.
[12] V. Blobel et al., *Nucl. Phys.* **B69**, 237 (1974).
[13] A. M. Baldin et. al., JINR E1-8054, Dubna 1974.
[14] H. Bøggild et al., *Nucl. Phys.* **B57**, 77 (1973).