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SPECTRUM OF TRANSVERSE ENERGY IN CENTRAL REGION OF $\alpha\alpha$-INTERACTIONS - CALCULATIONS WITHIN THE FRAMEWORK OF VARIOUS MODELS

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At present one has not yet obtained quantitative description of production of particles with high transverse momenta (p_T) in hadron-nucleus and especially in nucleus-nucleus interactions and abnormally strong A-dependence of their cross sections. Numerous discussions about the role of hard quark rescatterings are still at the qualitative level and do not allow a detailed experimental check. As opposed to this, the situation in explaining transverse energy (E_T) distributions is more promising *). The paper [1] provides arguments in favour of the E_T-spectrum formation due to soft interactions. Calculations in the "wounded nucleons" approximation [2] are in qualitative agreement with observation of $\alpha\alpha$ collisions [3]. It was shown in the experimental investigation [4] that for reproducing E_T-distribution in nucleus-nucleus ($\alpha\alpha$) interactions it is sufficient to have information about particle multiplicity in the central region and p_T-distribution of the particles. Therefore one can hope that the models, satisfactorily describing multiplicity and transverse momenta distributions will be able to describe satisfactorily E_T distributions. This paper deals with the testing of this assumption.

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*) Here and below the transverse energy is defined as the sum of transverse energies over the particles of any type produced in a given rapidity region.

Note that the calculation of these characteristics within the framework of the existing models /5,6/ is a rather complicated problem, requiring a lot of computer time or picking out various subprocesses in nucleus-nucleus interactions. To solve the latter problem, we have used the Glauber approximation and its Regge interpretation.

As is known /7/, the amplitude of elastic scattering in the impact parameter representation is given by the expression:

$$\Gamma(b) = \langle \Psi_A ; \Psi_B | 1 - \prod_{i=1}^{A} \prod_{j=1}^{B} (1-\gamma_{ij}) | \Psi_B ; \Psi_A \rangle, \quad (1)$$

where Ψ_A and Ψ_B are the wave functions of the nuclear ground states; $\gamma_{ij} = \gamma(b - s_i + \tau_j)$ is the amplitude of elastic nucleon-nucleon scattering in the impact parameter representation;

$$\{s_i\} = \{s_1, s_2, \ldots, s_A\}, \quad \{\tau_j\} = \{\tau_1, \tau_2, \ldots, \tau_B\}$$

are the sets of impact coordinates of the nucleons of colliding nuclei with the mass numbers A and B. Neglecting dependence of γ on spin and isospin variables at high energies and assuming noncorrelated nucleon distribution in the nuclei, one can rewrite (1) in the form:

$$\Gamma(b) = \sum_{\mu} C_\mu g_\mu(\gamma) =$$

$$= \sum_{i=1}^{A} \sum_{j=1}^{B} \int d^2 s_i \, d^2 \tau_j \, \rho_A(s_i) \rho_B(\tau_j) \gamma_{ij} - \quad (2)$$

$$- \frac{1}{2} \sum_{i=1}^{A} \sum_{\substack{j,k=1 \\ j \neq k}}^{B} \int d^2 s_i \, d^2 \tau_j \, d^2 \tau_k \, \rho_A(s_i) \rho_B(\tau_j) \rho_B(\tau_k) \gamma_{ij} \gamma_{ik} + \ldots$$

Here ρ_A and ρ_B are the one-particle densities of nuclei A and B, respectively, integrated over longitudinal nucleon coordinates. As in papers /8,9/ one can put each term of series (2) in correspondence with bipartite or bicoloured graph or net diagram /10/ and consider each term of

the series as a graph function ($g_\mu(\gamma)$) entering into (2) with its combinatorical coefficient C_μ due to graph isomorphism.

Considering the terms of series (2) as contributions of Regge nonplanar nonbranching graphs with pomeron exchanges and applying Abramovski-Gribov-Kanchely cutting rules /11/ one can find the production cross section to be given by the relationship

$$\sigma_{AB}^{prod} = \int d^2 b \sum_{\mu} C_\mu g_\mu(\sigma h), \quad (3)$$

$$\sigma h = \gamma(b) + \gamma^*(b) - \gamma(b)\gamma^*(b),$$

$$\int h(b) \, d^2 b = 1 .$$

σ_{AB}^{prod} can be represented in the form

$$\sigma_{AB}^{prod} = \sum_{\nu=1}^{A \cdot B} \sigma_\nu , \quad (4)$$

where σ_ν is the positively defined contribution of all graphs with ν cuts (roughly speaking with ν inelastic nucleon-nucleon interactions, with ν multiperipheral chains of particles, with $2 \cdot \nu$ strings)

$$\sigma_\nu = \frac{(-1)^{\nu+1}}{\nu!} \sigma^\nu \frac{d^\nu}{d\sigma^\nu} \sum_{\mu} C_\mu \int g_\mu(\sigma h) d^2 b . \quad (5)$$

In its turn σ_ν can be represented in the form of a sum of the graphs with various configurations of cuts ($\sigma_\nu = \sum_{\alpha}' \sigma_\alpha R_\alpha$). If configuration of cuts is represented by a graph R_α, one can write

$$\sigma_\alpha(R_\alpha) = \sum_{\mu}' (-1)^{\nu_{R_\alpha}+1} N_\mu^{R_\alpha} C_\mu \int g_\mu(\sigma h) d^2 b , \quad (6)$$

where ν_{R_α} is the number of cuts in the graph R_α and $N_\mu^{R_\alpha}$ is the number of subgraphs isomorphous to R_α in the initial elastic scattering graph.

Finally

$$\sigma^{prod}_{AB} = \sum_{\alpha}{}' \sigma_{\alpha}(R_{\alpha}) . \qquad (7)$$

To describe CERN ISR data on $\alpha\alpha$-interactions at $\sqrt{S_{NN}} =$ 31.2 GeV, we enumerated all the graphs with the aid of computer and found the coefficients C_{μ}, $N^{R_{\alpha}}_{\mu}$ and the graph function $g_{\mu}(\sigma h)$ at $\sigma = 33.4$ mb, $h(b) = \frac{a}{\pi} \exp(-ab^2)$, $a = 0.811$ fm^2. The results for $\sigma_{\alpha}(R_{\alpha})$ coincided with previously published ones [12].

Then characteristics of secondary particles were calculated within the framework of the leading hadron cascade model and the additive quark model.

According to the version of the leading hadron cascade model used in [6], each cut of a graph is treated as inelastic baryon-baryon interaction. Therefore a nucleus-nucleus interaction in this approximation is a set of baryon-baryon collisions sequenced in time. Note that according to this model baryons can acquire high values P_T because of multiple inelastic rescattering.

We also considered an alternative version of the model taking into account only interactions of the most rapid hadrons. Therefore we further will differ between the model of cascade baryons (MCB) and the model of cascade of energetic particles (MCEP).

In the additive quark model (AQM) the process of nucleus-nucleus interaction at the first stage is a set of "parallel" collisions of constituent quarks. After collisions constituent quarks "crumble" to point-like quarks-partons, which later formed hadrons taking part in further interactions (cascading of the secondary hadrons). Since each constituent quark interacts not more than once, the collision configuration of constituent quarks at a given cut graph R_{α} can be determined (simulated) with the help of MCB representations and the maximal cross section method [14] assuming that nucleons decrease their cross sections after each collision by 1/3. Considering the collision configuration of constituent quarks as a certain sequence of hadron-hadron interactions in accordance with [15] one can conclude that without allowance for cascading of secondary particles AQM is equivalent to the MCEP in which the leading/projecting hadrons can interact not more than three times.

So, from the point of view of these models the process of nucleus-nucleus interaction is a set of inelastic hadron-hadron collisions. Therefore, to determine characteristics of secondary particles it is sufficient to have a program of simulation of hadron-hadron interactions; in our case it was the Nikolaev-Levchenko model [16] modified for better description of the data at high energies.

The first calculation gives reassuring results (see Fig. 1) - multiplicity distribution of negative particles and that one of particles produced in the central region of $\alpha\alpha$-interactions appeared in reazonable agreement with the experimental data [17,18], predictions of AQM and MCB appearing similar to each other.

The situation with P_T distribution is somewhat worse. In spite of the fact that calculations were carried out separately for all 316 graphs describing $\alpha\alpha$-collisions with rather good statistics for each one, we could not reach the region $P_T > 3$ GeV/c (see Fig. 2). It means that soft rescatterings of leading particles cannot explain observed picture production of particles with high P_T, since the contribution of leading hadrons becomes insignificant with increasing of secondary particle multiplicity. Therefore the hope formulated in paper [20] should be considered groundless and another

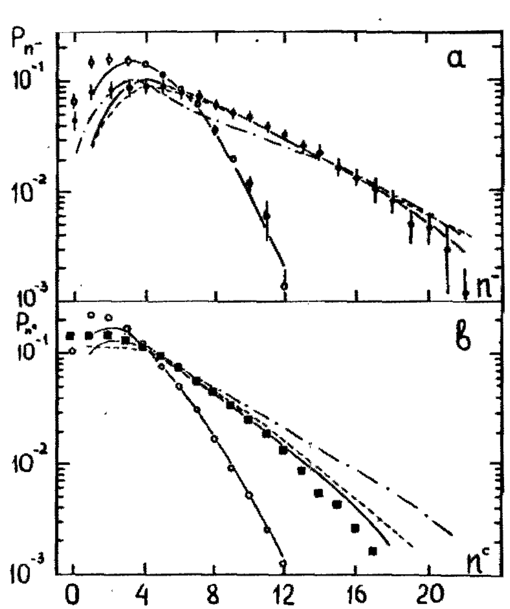

Fig. 1. a) Negative particle multiplicity distributions. The dark and light points are the experimental data [17] on $\alpha\alpha$- and pp-interactions at $\sqrt{S_{NN}}$ = 31.2 GeV, respectively. The solid, dashed and dashed-dotted curves are the calculations within the framework AQM, MCB and MCEP respectively.

b) Charged particle multiplicity distributions in the central region ($|y^*| \leq 0.8$). The dark and light points - the data [18] on $\alpha\alpha$- and pp-collisions respectively. Notations are identical to those in Fig. 1a (a fall down of the curves at low multiplicities is due to taking no account of diffractive dissociation processes).

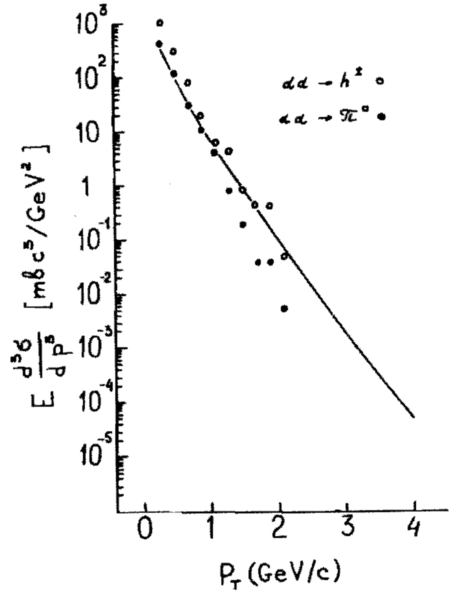

Fig. 2. Invariant inclusive cross sections of $\pi^{\pm 0}$ production in $\alpha\alpha$ -interactions at $y^* \sim 0$. The curve is a fit of the experimental data [19]. The light and dark points - the calculated cross sections of charged and neutral π -mesons. (Predictions of the three models differ insignificantly).

mechanism of production of particles with high P_T is necessary. For our purpose - an analysis of E_T - distribution - it is, however, sufficient. Really, we reproduce multiplicity distribution of particles produced in the central region and the initial part of P_T -distribution which is in the light of paper [4] necessary for successfull description of E_T-distribution. Therefore the result given in Fig. 3a is not surprising. Noting, however, that the experimental data [3,4] over E_T-distributions for charged and neutral particles are similar in the region $E_T < 12$ GeV and supposing such behaviour to be valid in a broader region, one can compare our calculations over E_T^{ch} with the data /3/. The comparison in Fig. 3b shows that the spectra coincide up to $E_T \sim 20$ GeV when the value $\frac{1}{L}\frac{dN}{dE_T}$ varies within 7 orders of magnitude. But the theory does not describe E_T-distributions for neutral particles either in pp or in $\alpha\alpha$ -interactions.

Discrepancy between calculated E_T^{o}- and E_T^{ch}-distributions is a natural consequence of the Nikolaev-Levchenko model /16/ involving isotopic symmetry. According to the data /3,4/ isotopic relations are broken for the particles produced in the central region of pp- and $\alpha\alpha$ -interactions. In our opinion three reasons for the discrepancy between the theory and the experiment are possible: a drawback of theoretical models, incorrect operation of the experimental equipment or incorrect treatment of the experimental information.

As to the first assumption, the calculations given in Fig. 1,2 and (quite satisfactory) calculations of the rapidity distributions which are not given make us sure that at least AQM and MCB are close to the truth.*) Only the authors of Ref./5/ can draw a conclusion about the second one. As to the third one, we note that the paper /3/ claims that allowance for energy losses of particles in the shower calorimeter only shifts E_T-spectrum along the E_T-axis and changes the slope of the curve only by 1% (paper /3/ p. 143). In a similar investigation /21/ of pp-interactions at $\sqrt{S_{NN}}$ = 63 GeV it is stated that this correction increases the slope parameter (paper /21/ p. 133). In our opinion this statement is closer to reality.

*) We suppose that single particles and jets with high P_T ($P_T >$ 3 GeV) does not vary substantially E_T -distributions at low E_T -values.

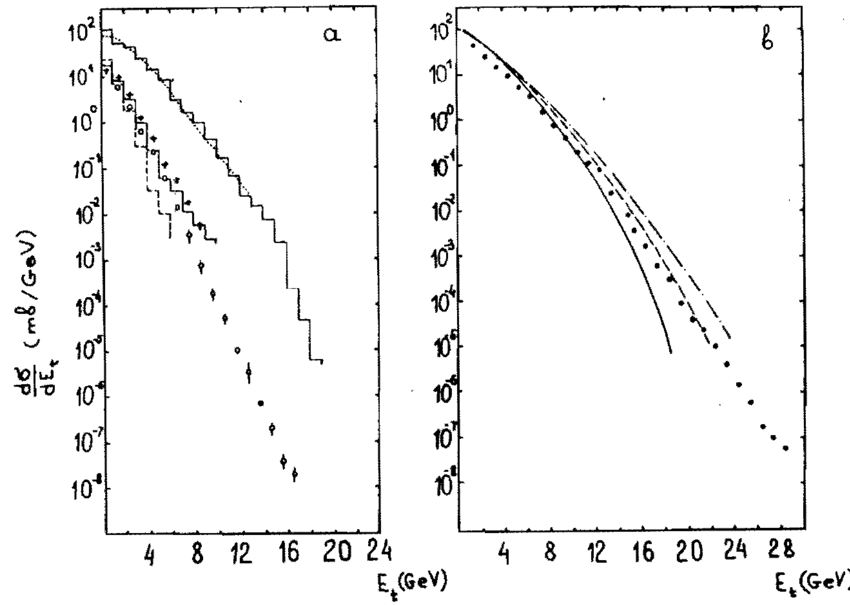

Fig. 3. Transverse spectra in the central region.

a) The dotted curve and crosses are the experimental data /4/ on E_T-spectrum of charged particles in $\alpha\alpha$- and pp-interactions at $\sqrt{S_{NN}}$ = 31 GeV in the region $|y^*| \leq 0.8$. The light points are the experimental data /3/ on E_T-spectrum of the neutral particles in pp-interactions at the same value $\sqrt{S_{NN}}$ in the region $|y^*| \leq 0.9$. The solid histograms are the calculations of E_T-spectra in AQM. The dashed curve is the calculation of the E_T-spectrum of neutral particles in pp-interactions.

b) The points are the experimental data /3/ on E_T-spectrum of neutral particles in $\alpha\alpha$ -interactions in the region $|y^*| \leq 0.9$. Curves are the calculations of E_T-spectra of charged particles in AQM, MCB and MCEP in the region $|y^*| \leq 0.8$. The notations are identical to those of Fig. 1.

Note another detail which is not clear to us. In all experimental papers /3,21/ dealing with this subject nothing is said about the accuracy of determination of longitudinal components of electromagnetic showers (along the device axis). We think that it is not high enough and, as consequence, the accuracy of E_T^o determination is low. Coincidence of the E_T^o- and E_T^{ch} spectra is probably due to peculiarities of the experimental device and the data treatment. Leaving aside the question about correctness of the experimental data considered, we return to the theoretical description.

Consider our calculations of the E_T^{ch}-spectra in pp-collisions as a fit of E_T^o-distribution.

Then, according to Fig. 3b, we reproduce the E_T^o-spectrum in $\alpha\alpha$ -interactions. A statement in paper /2/ that the Glauber theory does not describe events with $E_T^o > 8$ GeV is based on the rough "wounded nucleon model" which did not take into account a complicated structure of high multiplicity diagrams.

In conclusion, returning to the discussion about formation of the E_T-spectrum as a result of "parallel" nucleon-nucleon interactions /22/, we note that, according to our calculations within the framework of MCB, the main contribution to the E_T-distribution is made by the graphs with the number of cuts from 5 to 10 among which there are no graphs of parallel collisions. In AQM where a contribution of multiple collisions is suppressed because of cross sections for various processes of nucleus-nucleus interactions differ from the strict Glauber expression, a more rapid decrease of the E_T-spectrum with increasing E_T (at $E_T > 15$ GeV) is observed than in MCB. So, high E_T values are a good indicator of multiple collisions in nucleus-nucleus interactions, and presence of the accurate data on E_T-spectra will allow a "hard" discrimination of the theoretical model.

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Спектр поперечной энергии в центральной области $\alpha\alpha$-взаимодействий — расчеты в рамках различных моделей

С использованием точных глауберовских значений для сечений различных процессов в неупругих взаимодействиях α-частиц при $\sqrt{S_{NN}}$= 31,2 ГэВ рассчитаны в рамках модели каскада лидирующих адронов и в аддитивной кварковой модели спектры поперечной энергии (E_T) в центральной области. Расчеты хорошо согласуются с данными по спектру поперечной энергии, уносимой заряженными частицами, при $E_T \lesssim 12$ ГэВ. Отмечена близость экспериментальных спектров для нейтральных и заряженных частиц, послужившая основанием для проверки теории в более широкой области значений E_T.

Работа выполнена в Лаборатории вычислительной техники и автоматизации ОИЯИ.

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Spectrum of Transverse Energy in Central Region of $\alpha\alpha$-Interactions — Calculations within the Framework of Various Models

On the basis of Glauber expressions for various processes in inelastic interactions of α-particles transverse energy (E_T) spectra are calculated within the framework of the model of leading hadrons cascade and the additive quark model at $\sqrt{S_{NN}}$=31.2 GeV in the central region. The calculations are in good agreement with the data on spectra of transverse energy taken away with charged particles at $E_T < 12$ GeV. A similarity of experimental spectra of neutral and charged particles is noted, it was used for justification of the theory in a broader E_T region.

The investigation has been performed at the Laboratory of Computing Techniques and Automation, JINR.

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