ANALYSIS OF ANGULAR DISTRIBUTION OF SECONDARY PARTICLES IN ULTRA HIGH ENERGY NUCLEON-NUCLEON COLLISIONS

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Formulation. In this paper we give an alternative explanation of the phenomena appearing in the nucleon-nucleon collision in the energy interval 10^{12} eV $< E < 10^{14}$ eV. We start from stressing that the criteria used by experimentalists [1—3] $n_s < 20$, $N_h \leqslant 5$, $\sigma > 0{,}6$ select those jets which correspond to peripheral collisions. According to the experimental data we shall assume that in the peripheral nucleon-nucleon collision two «leading particles» can be distinguished in the final state. These particles carry off the most part of the initial energy and angular momentum.

To take into account the peripherality of collisions we shall work in the angular momentum representation. The convenient representation for relativistic many particle system, which can be devided into two distinct subsystems was recently found by Werle [4].

The exact form of the transition probability amplitude from the initial proton-proton state to the final N-particle [4, 5] state has in the considered representation the following form:

$$\langle \mathbf{P}, \Omega, M, r, m, \varkappa, \lambda, \omega, m', \lambda', | \hat{S}\hat{P}_s | \mathbf{P}=0;$$
$$M_0, \lambda_a\lambda_b\rangle = \lambda/2\,(2\pi)^{3/2} M_0 \delta_3(\mathbf{P})\,\delta(M-M_0)\times$$
$$\times \sum_{\substack{J,\,s,\,s'\\ \mu,\,\Lambda,\,\mu'}} N_J^2 N_s N_{s'} \overline{D}^J_{\zeta,\,\sigma}(\Omega)\,\overline{D}^s_{\mu,\,\Lambda}(r)\,D^{s'}_{\mu',\,\nu'}\times$$
$$\times \langle \mu, \nu, s, m, \varkappa, \lambda, \mu', s', m', \lambda' | S_J(M_0)\times$$
$$\times [\,| J, \zeta, \lambda_a, \lambda_b\rangle + (-\lambda)^J\,| J, \zeta, \lambda_a, \lambda_b\rangle], \quad (1)$$
$$\hat{P}_s = \frac{1}{2}[1+(-1)^{2s}_i \hat{P}_{ab}]; \quad \tau \equiv (\alpha, \beta, \gamma).$$

If we define the generalized helicity $\hat{\Lambda} = \hat{\mathbf{P}}_x \hat{\mathbf{J}}^\sigma$ it follows that the angles α and β represent the polar angles φ and ϑ of some arbitrarily choosen but fixed particles x in the c. m. s. of the $N-2$ particle system.

We obtain the angular distribution of a definite particle by performing the summation of the square of the amplitude (I) over the final helicities λ and λ' and by integrating over the following continuous variables: Φ, θ, φ, γ, m, χ, φ', v', and m'. Thus we get:

$$W(\vartheta) = {}^1/_2\pi^3 M_0^2 \sum_{\substack{\lambda,\,\lambda'\\ \lambda_a,\,\lambda_b}} \int d\Phi\, d\theta\, d\varphi\, d\gamma\, d\varphi'\, d\vartheta' \times$$
$$\times\, dm\, dm'\, d\varkappa\, |\tilde{f}|^2. \quad (2)$$

The function $\tilde{f}$ represents here the sum of the right-hand side of the expression (I). In the formula (2) we can exactly perform the integration over angles Φ, θ, φ, γ', φ' and v' using the well known orthogonality properties of the $D^J_{MM'}$, (α, β, γ) functions.

As a consequence of the peripherality we can restrict the summation over the quantum numbers I, s, μ and Λ to some rather narrow intervals [5]. Assuming that the matrix elements $\langle \mu_1 \Lambda, s, m, \varkappa, \lambda, \mu', s', m', \lambda' / S_J(M_0) / i_{ab}\rangle$ are in the considered intervals practically constant with respect to the variables J, s, μ and Λ, we get the following expression for the angular distribution of secondary particles:

$$W(\vartheta) = A \sum_{\substack{J,\,s,\,\tilde{s}\\ \mu,\,\Lambda}} N_J^2\,[2+(-1)^J]\,N_s N_{\tilde{s}} \times$$
$$\times [1+(-1)^{s+\tilde{s}}]\,\tilde{d}^s_{\mu,\,\Lambda}(\vartheta)\,d^s_{\mu,\,\Lambda}(\vartheta), \quad (3)$$

where

$$A = {}^1/_2\pi^3 M_0^2 \sum_{\substack{\lambda,\,\lambda',\,\lambda_a,\,\lambda_b\\ \mu',\,s'}} \int dm\cdot dm'\cdot d\varkappa \times$$
$$\times |\langle \bar{\mu}, \bar{\Lambda}, \bar{s}, m, \varkappa, \lambda, \mu', s', m', \lambda' | \times$$
$$\times S_{\bar{J}}(M_0) | i_{ab}\rangle|^2.$$

Then we see that for peripheral collissions the dependence of (3) on the unknown matrix elements is reduced to an energy in dependent factor A. Thus as long as we are interested

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in the angular distribution there is no necessity for us to make any assumptions about dependence of the matrix element

$$\langle \mu, \Lambda, s, m, \varkappa, \lambda, \mu', s', m', \lambda' \,|\, S_J(M_0) \,|\, i_{ab} \rangle$$

on the remaining $4N - 4$ quantum numbers $M, m, \varkappa, \lambda_1, \mu_1 S_1', m', \lambda'$.

Results. Fig. 1 shows the angular distributions of secondary particles for $P - P$

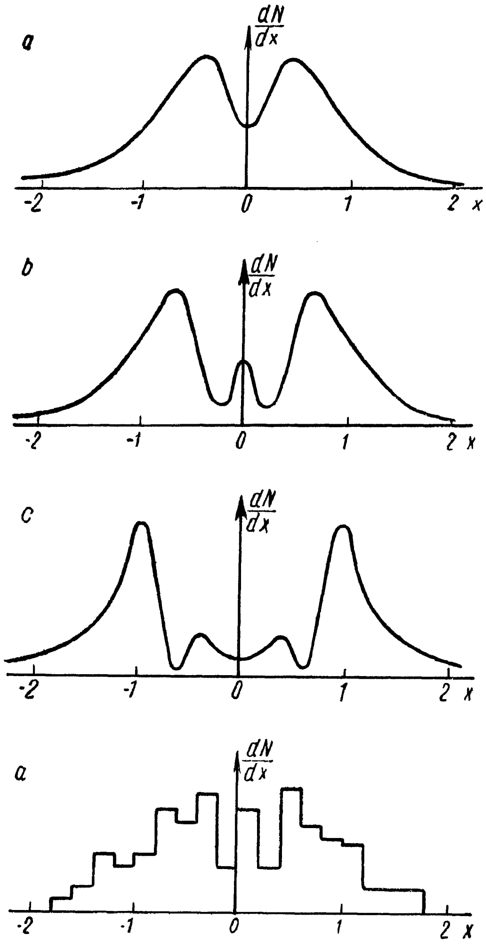

Fig. 1.

peripheral collisions at the energies 10^{12}, eV, 10^{13} eV and 10^{14} eV, respectively. Our results show that the minimum is getting deeper and the maxima are pushed more and more aside as the energy increases. This is an agreement with the experimental data [1, 6, 7]. For the sake of comparison we show in Fig. 1*d* the experimental angular distribution for nucleon-nucleon peripheral collision at energy $\sim 10^{13}$ eV obtained by Barkow et al. [6].

We can notice also on Fig. 1 the characteristic asymmetry of the distributions with respect to the position of the individual maxima, what does not appear in the angular distributions obtained by the fire-ball model. Such asymmetry was recently observed experimentally [7].

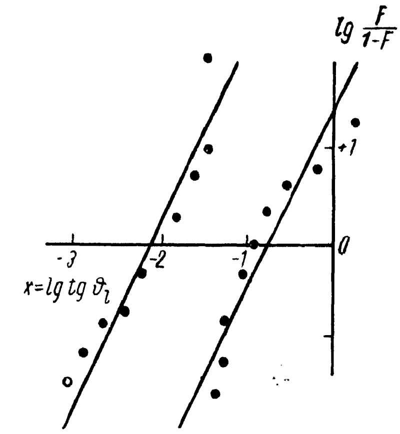

Fig. 2.

On Fig. 2 the theoretical integral angular distributions for separate maxima at energy $E_1 = 10^{12}$ eV are plotted. We see that the points of these distributions lie near the straight line with slope 2; however, they show

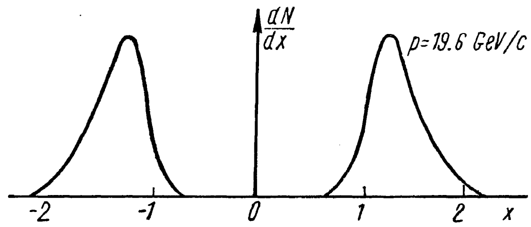

Fig. 3.

deviations from isotropic distribution. It seems that the experimental integral angular distributions also show the deviations in the same direction [2]. Let us remark that the equality of the average slope for the experimental distributions to 2,1 was regarded as a strong evidence for the reality of the fire-ball model [2,8].

It is interesting that in the high energy elastic collision we have also two-maxima structure of the angular distribution in the coordinate $x = \lg \operatorname{tg} \vartheta/2$ and $y = dN/dx$ (see Fig. 3). On the other hand it is obvious that the elastic process has nothing to do with the creation of fire-balls. All these facts point out that we must be very careful when we relate the effect of two maxima in the angular distribution with the existence of fire-balls.

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DISCUSSION

Zh.S. Takibaev

In a series of experiments (see, for example, Vernov's paper) a large energy transfer of the electromagnetic component was observed for colliding nuclei in the range of very high energies. I would like to point out that large neutral pion energy transfer in discrete collision events does not exhibit a distinctive feature only in the range of very high energies ($>10^{11}$ eV). In a detailed study of inelastic nucleon-nucleon and pion-nucleon collisions at 20 GeV we showed that this was in fact the case. Actually, the reaction $p+n \to \pi^- + p + p + N\pi^0$, in which the energy of all the charged products could be measured, enables us to determine accurate coefficients of inelasticity. Apparently, these coefficients are very large, especially in the case of the development of colliding nucleons. Consequently, we are dealing with central or quasicentral collisions. However, various investigators differently interpret the distinction between central and peripheral collisions. How is this distinction made in the speaker's paper?

R. Ronchka

In order to separate peripheral nucleon-nucleon collisions we used the conditions $n_s < 20$. $N_h \leqslant 5$ and $\sigma > 0.6$. Consequently, showers with $\sigma < 0.36$ are not included in the class of peripheral collisions. It is our opinion that showers with $\sigma < 0.36$ constitute statistical fluctuations of central collisions.

E.L. Feinberg

Why, taking the sum over the angular momentum, do you impose such a strong constraint $\Delta J < J$ on the considered angular momenta? Surely, if this constraint is made in the sum over the harmonics, we can obtain particle escape in a strictly defined direction. However, in the experiment we observed the superposition of all impact parameters, i.e., a wide interval of J-values participates.

R. Ronchka

Double-humped distribution are observed only for showers, selected under the conditions $n_s < 20$, $N_h \leqslant 5$, $\sigma > 0.6$. This class contains 20–30% of all the showers. On the other hand, we selected the summation limits $\Delta J \equiv J_{max} - J_{min} = 0.1 J_{max}$. From geometrical considerations it follows that for this value of ΔJ we allow for 20% peripheral collisions, which fully agrees with the number of experimental peripheral showers.

Zh.S. Takibaev

As known, in a number of cases jets were observed in which the angular distribution of the shower particles is even narrower than the corresponding angular distribution in log tan θ representation for isotropic showers of particles in the center-of-mass system. When $\sigma < 0.36$ in the developed scheme, this distribution is apparently unexplained. It should be shown that the multiplicity in such jets, where the angular distribution is narrower than the isotropic distribution, is sufficiently small, so that it is impossible to refer to central collisions.

V.S. Barashenkov

Is it possible to formulate your point of view in such a way that with the aid of your theory all experimental data can be explained without studying the "fireball" model ?

R. Ronchka

In principle, yes. With the aid of our approach we found an explanation for most of the experimental facts pertaining to the set of showers responsible for the peripheral collisions.

D.S. Chernavskii

1. Analyzing the value of $W(\theta)$, we can only arrive at the character of the total distribution of a set of many stars. The problem of the angular distribution in each star cannot be solved. Consequently in the two different cases – when all the stars are double-humped and when all the stars are asymmetric but single-humped – the value of $W(\theta)$ may be the same. Accordingly, it seems to me that on the basis of the presented study it is impossible to say whether it explains fireball production or not.

2. An analysis of the narrow interval $\Delta J \ll J_{max}$ is equivalent to that of the narrow interval of impact parameter from ρ_{min} to ρ_{max}, where $\rho_{min} \sim \rho_{max}$. This agrees too much with the large "core" in the framework of the Weizsäcker–Williams method.

At the time the "core" in the Weizsäcker–Williams method gave rise to many problems and as a result this method had to be abandoned. It seems to me that in the development of Dr. Ronchka's scheme the same problems will arise sooner or later.