Z. Phys. A 350, 263–267 (1994)

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The dependence of proton correlations on integral characteristics of eA interactions

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Received: 5 July 1992 / Revised version: 24 March 1994

Abstract. We report the results of analysis of correlations of the product protons from inelastic eA collisions at small Q^2. The experimental data were measured by the ARGUS detector. The correlation effect at small relative momenta q (interference and final state interaction) is closely associated with the angular correlations due to momentum conservation. The examined correlations in eA collisions also show features similar to correlations in hA collisions.

PACS: 25.40

1. Introduction

It is often thought, that "cumulative" particles [1, 2] (emitted beyond the kinematical region of the free projectile-nucleon interaction) result from collision of the projectile with so-called fluctons inside the nucleus. These fluctons are dense fluctuations of nuclear matter considered to be short-range correlations, multiquark bags, etc. [3, 4].

The intrinsic features of cumulative particle production can be better understood if correlated pair products of the inelastic collision are investigated. By studying such reactions one has to bear in mind that the projectile may collide multiply with fluctons inside the nucleus. Thus, both single and multiple scattering of the incident particle with fluctons inside the nucleus can contribute to the experimentally observed correlated proton pairs. One must somehow learn to differentiate between events associated with the two principly different contributions.

Earlier studies of the proton correlations from hA reactions [5, 6] included scattering of negative pions and protons from a number of nuclei at different primary energies E_0. To determine the size of the interaction region r the correlations between the protons at small relative momenta were studied [7, 8]. We estimated the number of intranuclear interactions n applying the 4-momentum conservation law by analysing the angular correlations. It was found that r and n follow a simple relation: $nr^{-3} \approx$ const. This relation implies a constant density of fluctons inside the interaction region. Another way to assign a number of interactions n to the observed event is to find those general characteristics of the reaction, say, multiplicity, having a steady relation to n. It is better to perform such studies with experimental facilities with a large acceptance angle (about 4π). We performed an analysis of the data set obtained from the ARGUS detector [9].

The data set contained events identified as interaction of the primary e^+ and e^- beams of 5 GeV with residual gas (mainly H_2O) in the vacuum beam pipe of the storage ring DORIS-II a DESY. The analysed sample comprised 115 000 events. It significantly exceeds the statistics of events obtained so far by the experimental facilities of the largest acceptance angle, which has been used for studying cumulative particle production.

We previously reported [10] the data on inclusive production cross sections and the preliminary results of determining the size of an interaction region (interferometry measurements) derived from analysis of this data sample. In the present study, we have concentrated on how correlated proton pairs affect the general characteristics of the reaction, namely, multiplicity of the secondary protons N_p in the event and total deposited energy E_h. In particular, we would like to investigate the behaviour of the relation between r and n as a function of the selected general characteristics of the reaction.

2. Data analysis procedure

The procedure for selecting the beam-gas events was described in [10]. Here follow the criteria for selcting events where $e^{\pm}$ collide with ^{16}O nuclei:

1. The number of identified protons with momentum p in the range of 0.3–1.2 GeV/c and production angle $|\cos\theta| < 0.92$ is $N_p \geqq 1$;

2. The value of $W = (\Sigma E_{sh} - |\Sigma p_z|)/2E_0 < 0.07$. Here summing is performed over all measured charged particles and photons, E_{sh} is the energy deposited in the shower calorimeter, E_0, the primary beam energy, p_z [GeV/c], the z-component (along the beam direction) of the product particle;
3. The total deposited energy $E_h = \Sigma E - N_p \cdot m_p < 3$ GeV, where E is the total product particle energy, and m_p, the proton mass;
4. The distance of the event vertex from the beam axis is 2 cm and along the z-axis within $|z| < 6$ cm.

It has been shown [10] that such criteria reduce the contribution of events from e^+e^- annihilation in the studied sample to 7%. In this case the first criterion changes to $N_p \geqq 2$, which suppresses the background from e^+e^- annihilation.

The event accumulation trigger did not include the requirement to detect the scattered primary-beam particles. Therefore, practically all events in the analysed sample do not have beam particles detected. For this reason, the selected events can be considered as reactions of the beam particles with ^{16}O nuclei at small Q^2.

The two-proton correlation function was calculated as the ratio

$$R_2^D = N_{12}/N_{\mathrm{mix}},$$

where N_{12} and N_{mix} were determined from distributions of pairs of protons in one $e\,^{16}$O collision and distribution of the proton pairs from different $e\,^{16}$O events, correspondingly. It is seen that the definition of R_2^D assumes cancellation of single-particle detection efficiency. It is worth noting, however, that triggers by accumulation of events and drift chambers contribute partly to the efficiency which is not cancelled out. Examples of such triggers are: the presence of at least one pair of charged tracks in the barrel region ($|\cos\theta| < 0.75$) with the azimuthal difference $\Delta\phi > 120°$, or the presence of at least one charged track in each z-hemisphere.

We calculated the detector efficiency using a generated sample of events with similar angular and momentum distributions. The Monte-Carlo generator is based on the phenomenological model [11]. The most essential features of the model are:

a) The energy lost by particles in excitation of the nuclear matter is proportional to the length of the path inside the nucleus.
b) The massless nuclear constituents along the primary trajectory heat up to 200 MeV.
c) The energy and momentum are conserved during the hadronization stage.
d) The total transverse momentum of all secondaries equals 0, and the longitudinal component of the momentum results from the energy lost by the primary particle.

Discussion of the model is not the task of this paper. For our purposes here, it is important only that we thus obtained an events sample which describes inclusive [11] and correlation (see next section) characteristics sufficiently well.

For generated events the correlation function R_2^G and the detector response were calculated. The correlation function R_2^{GD} was determined using the events from this sample which satisfied the trigger conditions. The detector efficiency was then determined from the ratio R_2^{GD}/R_2^G. We believe that this ratio provides a good estimate of efficiency, as the function R_2^{GD} is close to the function R_2^D. We calculated then the two-particle correlation function from the following equation:

$$R_2 = \frac{R_2^D}{R_2^{GD}/R_2^G}.$$

We tried different procedures for obtaining mixed-pair distributions to see what changes would result. Figure 1 shows the obtained distributions of mixed pairs as the cosine function of the angle between the two tracks: $\cos\psi = (\mathbf{p}_1\mathbf{p}_2)/(p_1 p_2)$. The distribution number 1 refers to the case when the protons of the pair were selected from different events, the set for distribution number 2 was assembled from protons from different events with the same multiplicity N_p. The protons for distribution 3 were selected from artificial events. Such events have protons from another event instead of real ones and satisfy the trigger conditions. The obtained distributions are very similar to each other. Data set 1 was used to calculate correlation functions.

The reliability of data analysis here is essentially dependent on the momentum resolution of the detector within the whole momentum range of the secondary protons $0.3 < p < 1.2$ GeV/c and production angle $|\cos\theta| < 0.75$. The momentum resolution changed from 5 MeV/c to 20 MeV/c for the collected sample of events over the whole accumulation period, which is sufficient for studies of correlations, including interferometry measurements, as has been established already.

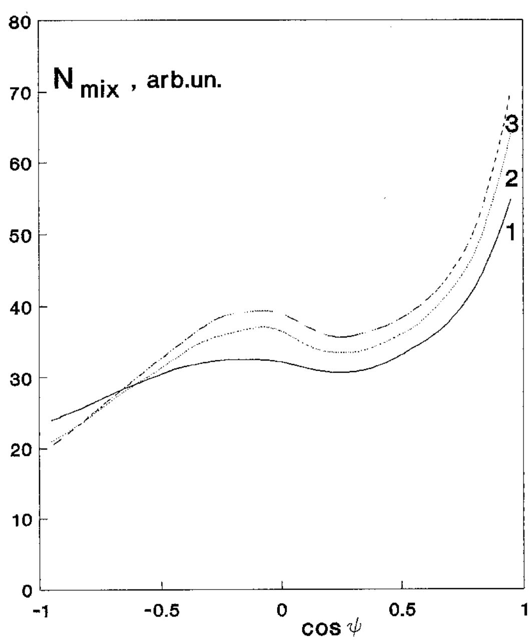

Fig. 1. The distributions of mixed pairs with different ways of mixing *(see text)*

3. Experimental results

The values of the correlation function R_2 against the effective mass of the two protons M_{eff}, transverse momentum squared P_t^2, and cosine of the angle between the two protons $\cos\psi$ are shown in Fig. 2. R_2 is clearly dependent on these kinematical variables. The local maximum of R_2 at small M_{eff} is due to interference [7] caused mainly by proton interaction in the final state [8]. Function R_2^G is compared with experimental data in Fig. 2 . A qualitative agreement between R_2 and R_2^G is clearly seen. The dotted lines in Fig. 2 correspond to the detector efficiency. It rather weakly depends on $\cos\psi$ when compared with its dependences on other variables. We use the $\cos\psi$ variable in order to be able to compare the results of the present analysis of eA interactions with earlier analysis results of hA interactions [5]. Following [5], we fitted the function $R_2(\cos\psi)=C\cdot e^{-\beta\cos\psi}$ to the experimental data satisfying the condition: $-1.0<\cos\psi<0.9$. The value of the slope parameter β for the data presented in Fig. 2 equals 0.55 ± 0.01.

The analysis results reported in [5] show a dependence of the correlation function and, hence, β on momenta of the secondary protons. It is seen in Fig. 3 that β increases with the increase of p_1p_2. A similar behaviour for β is also observed in hA interactions. We fitted the func-

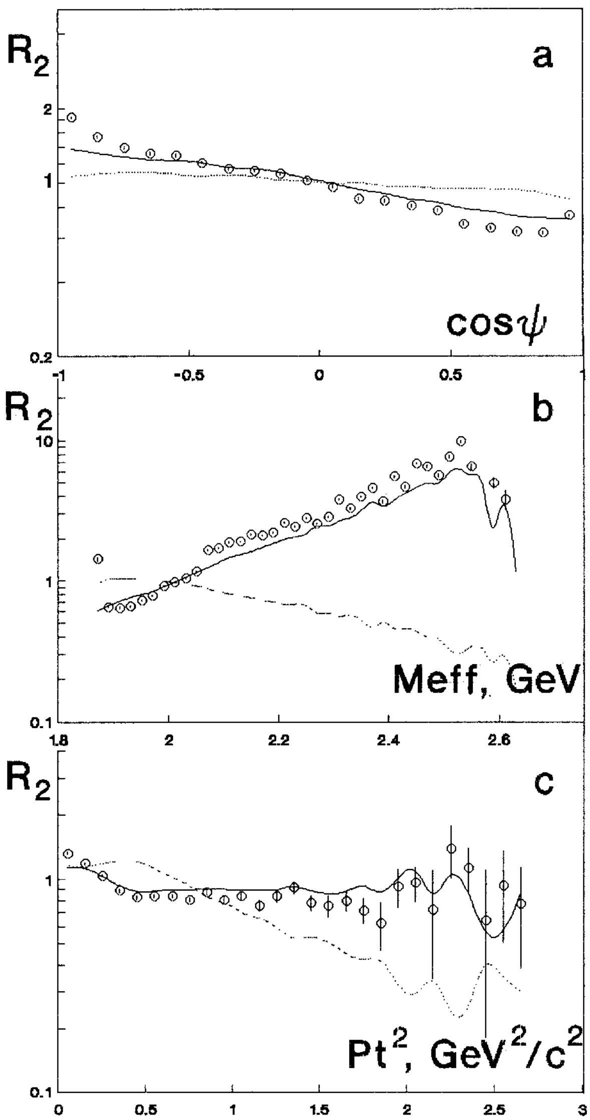

Fig. 2a–c. The dependence of two-proton correlation function R_2 on $\cos\psi$, M_{eff} and P_t^2. *Solid line*, R_2^G, *dotted line*, efficiency

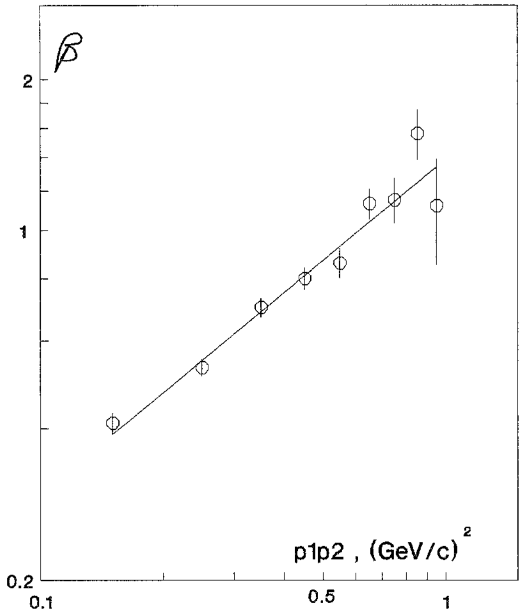

Fig. 3. The dependence of slopes β on p_1p_2. *Solid line* is the function $\beta=1.41\ (p_1p_2)^{0.68}$

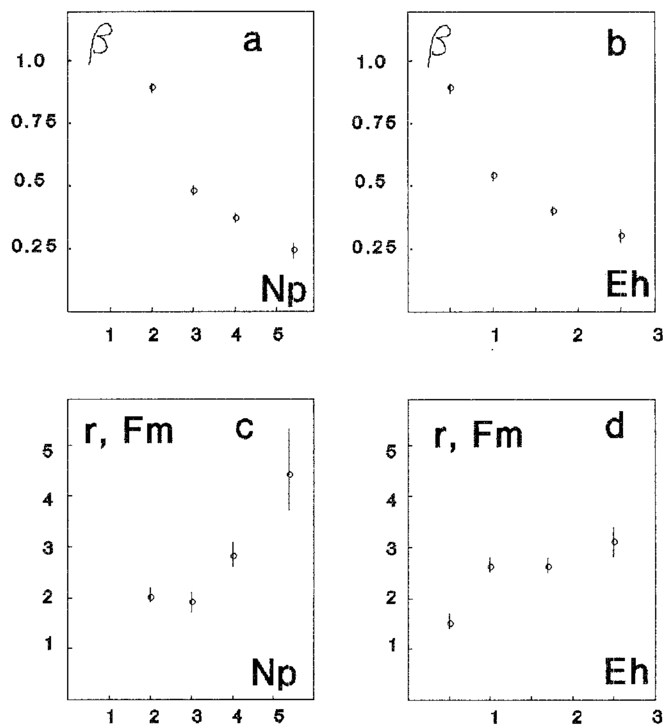

Fig. 4. The dependence of slopes β on **a** N_p or **b** E_h. The dependence of rms radii r on **c** N_p or **d** E_h

Table 1

E_h, GeV	0–0.7	0.7–1.4	1.4–2	2–3
$\bar{p}$, GeV/c	0.53	0.57	0.59	0.60
$\bar{p}$, GeV/c $q < 0.1$ GeV/c	0.45	0.45	0.49	0.46
N_p	2	3	4	$\geqq 5$
$\bar{p}$, GeV/c	0.58	0.57	0.56	0.54
$\bar{p}$, GeV/c $q < 0.1$ GeV/c	0.50	0.47	0.43	0.42

tion $\beta = a_1 (p_1 p_2)^{a_2}$ to the experimental data and obtained the following parameter values: $a_1 = 1.41 \pm 0.06$ and $a_2 = 0.68 \pm 0.04$.

Figures 4a, b show β as a function of E_h and N_p. β drops by a factor of 3 with the increase of E_h or N_p. The mean value of the proton momentum changes within 10% as E_h and N_p vary within the range selected for analysis (see Table 1). As follows from the fitted function for β, a 10% change of p causes a 15% change of β. This means that β is more sensitive to change in E_h and N_p. Thus, β dependence on E_h and N_p cannot be explained by its dependence on the product $p_1 p_2$. It is interesting to determine the value of β at small E_h and N_p. For $E_h < 1$ GeV (mean $E_h = 0.71$ GeV) and $N_p = 2$, β equals 1.81 ± 0.07, which is quite large. Indeed, the correlation function changes by a factor of 35 for $-1 < \cos\psi < 0.9$. As mentioned above, the maximum value of correlation function R_2 at small M_{eff} is due to the final-state interaction. It is convenient to perform the analysis of correlations at small relative momenta using the variable $q = |\mathbf{p}_1 - \mathbf{p}_2|$. The central drift chamber of the ARGUS detector becomes inefficient for paired tracks with small relative momenta below q equal to a tenth of the mean proton momentum. At $q < 0.1$ GeV/c, the mean proton momentum equals about 0.5 GeV/c and the lowest momentum which can be measured in the detector is about 0.05 GeV/c.

The correlation function $R_2(q)$ is given in Fig. 5a. A clear maximum is seen below $q = 0.1$ GeV/c, and the function slowly increases at $q > 0.1$ GeV/c. This increase reflects the dependence of the correlation function on $\cos\psi$, which has already been discussed above, and was fitted by the function $1 + kq^2$, where k is a free parameter. The theoretical models [7, 8] account for interference and final-state interaction. However, they do not include correlations due to the momentum conservation law. We try to account for the effect of momentum conservation using the function $R_2'(q) = R_2(q)/(1 + kq^2)$ to determine the size of the interaction region. The correlation function $R_2'(q)$ is presented in Fig. 5b. Assuming a spherically symmetrical gaussian form of the proton source, we obtained an estimate of the emission region size equal to $r = 2.6 \pm 0.1 \pm 0.3$ fm. The value is given with both random and systematic error components. The estimate of the systematic error was obtained by analysing the results for the different distributions for N_{mix}. The systematic error estimate comes from comparing the integrals of the

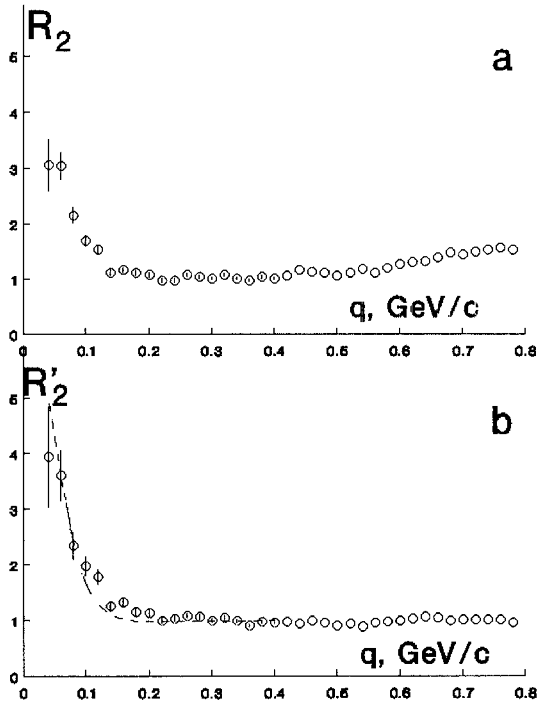

Fig. 5. **a** The dependence of R_2 on q. **b** The dependence of R_2' on q. The *curve* is the result of theoretical calculation for rms radius $r = 2.6$ fm

function $R_2' - 1$ and theoretical correlation function over $q < 0.1$ GeV/c. The latter method does not take into account the shape of the maximum of the correlation function at small q, but it is less sensitive to the momentum resolution of the detector. The dependence of r on E_h and N_p is illustrated in Fig. 4c, d. The value of r increases with the increase of E_h and N_p. For $E_h < 1$ GeV and $N_p = 2$ the value of $r = 1.9 \pm 0.2 \pm 0.3$ fm.

4. Discussion

At low Q^2, eA interactions are almost equivalent to interactions of real gamma with nuclei. Due to the vector dominance effect, one may assume that a virtual gamma quantum interacts with the nucleus in the same way as a hadron does. The validity of this assumption has already been confirmed by the results of earlier analysis of the same data sample to determine the inclusive production cross section for $e - O$ collisions [10]. Therefore, we continue the data analysis assuming an hA interaction scenario for the studied reaction. In this case, it is natural to think that N_p increases with the number of intranuclear interactions n (or number of fluctons involved into the collision). Bearing this in mind, one may interpret the dependence of β and r on E_h and N_p as equivalent to its dependence on n. Thus, the variables β and r show a close correlation.

The dependence of r on β is shown in Fig. 6, where the results of the previous analysis of hA interactions are also presented. It is seen that the data follow a universal dependence $r(\beta)$. The function shows no correlation with

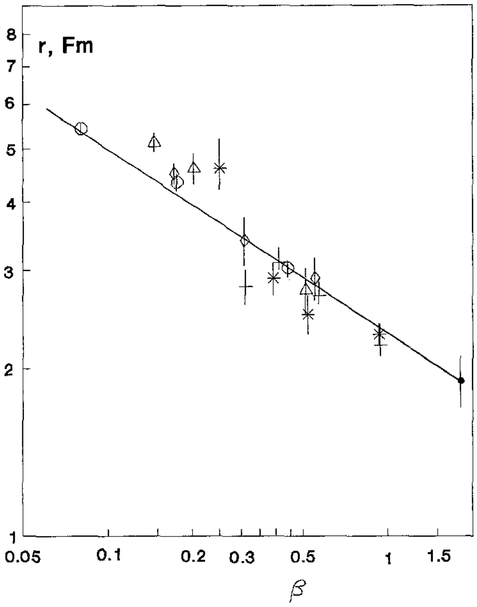

Fig. 6. The dependence of r on β. * - ARGUS data for various N_p; + - ARGUS data for various E_h; ● - ARGUS data for $N_p = 2$ and $E_h < 1$ GeV; ○ - p(7.5 GeV/c) A; ◇ - p(3 GeV/c) A; △ - π (3.0 GeV/c) A [10]. Line is the function $r \sim \beta^{-1/3}$

the mode of the change of n, which depends on E_h, N_p, E_0 and A. The fit of the function $r = b_1 \beta^{b_2}$ to the data in Fig. 6 provided the following parameter values: $b_1 = 2.22 \pm 0.05$ and $b_2 = -0.37 \pm 0.02$. The value of b_2 is very close to $-1/3$, which implies a constant density of fluctons in the interaction region.

For the product particles emitted from a single projectile-flucton interaction, one may consider $\beta = 1.81$ as a lower limit for the slope parameter of the correlation function and $r = 1.9$ fm as an upper limit for the size of the flucton. The estimate of the slope parameter for the case of a single projectile-flucton collision in an hA interaction was reported in [12]. That estimate was based on the assumption that $R_2 = R_2^* + R_2^{**}$, where R_2^* refers to the protons from a single projectile-flucton collision and R_2^{**} to protons from different collisions. The value of R_2^* depends on the angle ψ, whereas R_2^{**} does not depend on it. R_2^{**} has been estimated as R_2 at small ψ. The slope parameter of the function $R_2^*(\cos\psi)$ does not depend on the atomic mass of nucleus A and primary energy E_0. The mean value of the slope is 1.90 ± 0.26, which is in good agreement with the value obtained here for the events from eA interactions.

At polar angles of the emitted particle close to $\theta = 90°$ the slope β can be compared with the widely known azimuthal asymmetry α. The value of α can be calculated from $\alpha = \mathrm{th}(\beta/2)$, which is derived from the equation for R_2 introduced above: $R_2(\cos\psi) \sim e^{-\beta\cos\psi}$. The statistical model relates an azimuthal asymmetry with a number of secondary particles N by the following expression at $N \gg 1$: $\alpha \sim 1/(N-1)$. For $\beta = 1.81$ one obtains $N = 2.4$. One may interpret this value as the mean number of particles taking part in the compensation of the transverse momentum of cumulative protons generated from a single projectile-flucton collision.

5. Conclusion

1. The size of the interaction region is related to the number of fluctons involved in the reaction. This effect was first discussed in [5], when both these parameters were considered to be a function of the initial energy and A. It is also related, as we have shown here, to the general characteristics of the reaction, namely the multiplicity N_p and energy deposit E_h.
2. Quantitatively, this relation agrees well with the constant space density of fluctons in the interaction region.
3. The strength of the pairing correlations in the case of a single projectile-flucton collision estimated using two independent methods yields consistent results.

We would like to thank all members of the ARGUS team who made available to us the data set for beam-gas events analysis. This work was supported in part by a Soros Foundation Grant awarded by the American Physical Society.

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