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AZIMUTHAL CORRELATIONS OF SECONDARY PARTICLES IN ^{32}S INDUCED INTERACTIONS WITH Ag(Br) NUCLEI AT 4.5 GeV/c/nucleon

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The results on the azimuthal correlations of the fragments of colliding nuclei and relativistic particles in the interactions of ^{32}S with Ag(Br) nuclei at 4.5 GeV/c/nucleon in the emulsion track detector are summarized in this work. Transverse momentum, principal vectors and azimuthal correlation function analyses have been performed. Evidence for the collective flow of the projectile fragments has been observed in the case of noncentral nuclear interactions together with the strong azimuthal correlation in the emission of projectile and target fragments. The obtained results have been compared with the results from the interactions of ^{22}Ne at 4.1 GeV/c/nucleon and ^{16}O, ^{28}Si at 4.5 GeV/c/nucleon.

The investigation has been performed at the Laboratory of High Energies, JINR.

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Азимутальные корреляции вторичных частиц во взаимодействиях ^{32}S с ядрами Ag(Br) при 4,5 ГэВ/c/нуклон

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В работе представлены результаты анализа азимутальных корреляций фрагментов сталкивающихся ядер и релятивистских частиц во взаимодействиях $^{32}\mathrm{S}+\mathrm{Ag(Br)}$ при 4,5 ГэВ/c/нуклон с помощью эмульсионного трекового детектора. Выполнен анализ поперечных импульсов, суммарных векторов и азимутальных корреляционных функций. Обнаружен коллективный поток фрагментов снаряда в нецентральных ядерных соударениях вместе с сильной азимутальной корреляцией в эмиссии фрагментов соударяющихся ядер. Проведено сравнение с результатами $^{22}\mathrm{Ne}$ и $^{16}\mathrm{O}$, $^{28}\mathrm{Si}$ взаимодействий с Ag(Br) при 4,1 и 4,5 ГэВ/c/нуклон соответственно.

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1. INTRODUCTION

Collective flow plays an important role in the expansion and decay of compressed and excited nuclear matter created in heavy ion collisions over a wide range of incident energies. Accurate measurements of collective flow provide the best possibility to learn about nuclear matter compressibility and, indirectly, the nuclear equation of state. The collective emission of nuclear matter was first predicted on the basis of the nuclear fluid dynamical model [1].

Flow was firstly observed in heavy-ion experiments around 1 GeV/c/nucleon at the Berkeley Bevalac [2].

Since this experiment the collective flow in heavy ion collisions was measured also at higher energies. For example, using unique emulsion method the bounce-off of the projectile spectator fragments was investigated in collisions of $^{22}\mathrm{Ne}$ [3] beam at 4.1 GeV/c/nucleon, ^{28}Si [4] at 4.5 and 14.6 GeV/c/nucleon and $^{84}\mathrm{Kr}$ [5] at 1.55 GeV/c/nucleon with Ag(Br) nuclei. The results of the systematic study of the collective flow in $^{197}\mathrm{Au}$+Ag(Br) interactions at 11.6 GeV/c/nucleon have been reported by the EMU01 Collaboration [6].

In this paper we demonstrate the possibilities of emulsion experiments to measure collective flow.

2. EXPERIMENT

Stacks of NIKFI (Moscow) BR-2 nuclear photoemulsions have been irradiated horizontally by ^{32}S beam at the Dubna synchrophasotron. The experimental detailes have been published in [7].

The secondary charged particles involved in the analysis are:

- projectile fragments (PF) with charges $Z_{PF} \geq 1$,
- target fragments (TF) — the so-called h particles, consisting of fast g particles, mainly recoil protons with kinetic energies $26 \leq T \leq 400$ MeV, and slow b particles, target fragments with energy $T < 26$ MeV/nucleon.

For all particles their polar (ϑ) and azimuthal (ψ) angles with respect to the direction of primary nucleus have been measured.

For the present analysis we selected events of inelastic interactions of the projectile nucleus with Ag(Br) target nuclei at medium impact parameter. The selected events are characterized by the number of target fragments $N_{TF} \geq 8$ (representing an Ag or Br target) and the number of projectile spectators $N_{PF} \geq 4$. Using these criteria we selected 247 $^{32}\mathrm{S} + \mathrm{Ag(Br)}$ interactions (36% of all inelastic interactions with Ag(Br) target nuclei).

3. EXPERIMENTAL RESULTS

There are many methods which are ideally suited to study emission patterns and event shapes in relativistic nuclear reactions. We used the conventional transverse momentum approach [8]. In the transverse momentum analysis the reaction plane is defined by the direction of the incident nucleus and the plane vector $\vec{Q}_i$, which is constructed individually for each ith PF from the transverse momenta $\vec{P}_{t,j}$ of all remaining PFs in the same event as

$$\vec{Q}_i = \sum_{j=1, j\neq i}^{N_{PF}} A_j \vec{P}_{t,j}, \qquad i = 1, 2, ..., N_{PF}, \tag{1}$$

where A_j is the mass number of projectile fragment, and $\vec{P}_{t,j}$ is the transverse momentum of fragment j.

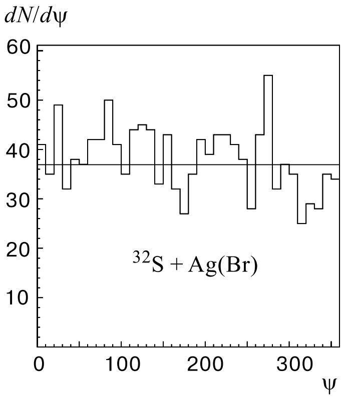

Fig. 1. The distribution of the azimuthal angle of the projectile fragments

In order to remove autocorrelations, $\vec{Q}_i$ is calculated from the transverse momenta $\vec{P}_{t,j}$ of all fragments in the event except the i one.

Assuming that each projectile fragment i has the same longitudinal momentum per nucleon, P_l, as the incident projectile nucleus, the transverse momentum per nucleon of the ith fragment is given by $P_{t,i} = P_l \tan\vartheta_i$.

The distribution of PFs in the azimuthal angle in Fig. 1 is uniform with $\chi^2/ndf = 1.24$.

To study the bounce-off of the projectile fragments the transverse momenta of the projectile fragments $\vec{P}_{t,i}$ were projected onto their reaction plane by

$$P_{Q,i} = \vec{P}_{t,i} \cdot \frac{\vec{Q}_i}{\mid \vec{Q}_i \mid}, \qquad i = 1, ..., N_{PF}. \tag{2}$$

The experimental P_Q distribution is presented in Fig. 2*a* (solid histogram). The average transverse momentum per nucleon in the reaction plane $< P_Q >$ would be equal to zero if $P_{t,i}$ is randomly distributed in the azimuthal plane and it will differ from zero if a directed flow deviates from the zero-angle direction. The measured value is $< P_Q >= 18.4 \pm$ ± 2.1 MeV/c/nucleon.

To investigate if the obtained value represents a significant flow of transverse momenta, the same procedure has been applied to mixed events. The mixed events have been generated from the original total sample of fragments randomly distributed in the new events [5]. Thus mixed events should possess no correlations in the reaction plane. The mixed events P_Q distribution is shown in Fig. 2*a* as the dashed histogram. The mean value is $< P_Q >_{ME} =$ $= 1.3 \pm 0.7$ MeV/c/nucleon.

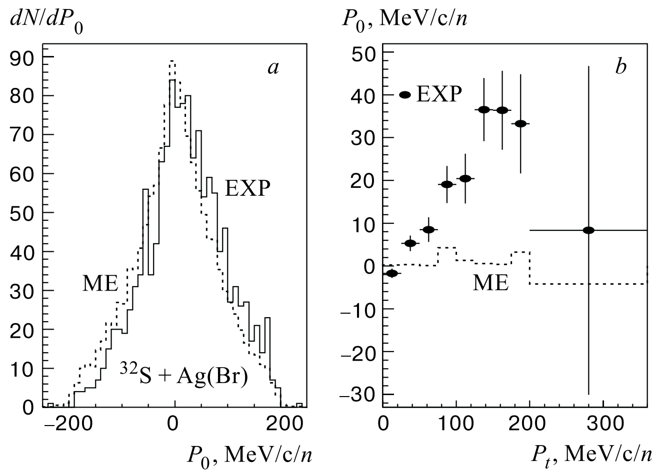

Fig. 2. (*a*) The transverse momenta of the projectile fragments projected onto the reaction plane, where EXP – this experiment and ME – mixed events, (*b*) the transverse momenta of the projectile fragments projected onto the reaction plane as a function of P_t

The dependence of $< P_Q >$ on P_t is shown in Fig. 2*b*. One observes that our data significantly differ from the zero and display the bounce-off of the projectile fragments as predicted by Stöcker [9]. The randomized events do not manifest this bounce-off effect.

The mean values of $< P_Q >$ and $< P_Q >_{ME}$ for experiments with other projectiles at Dubna energy [10] [11] [12] are shown in Tabl. 1. (The original DST of the former Dubna Emulsion Collaboration was used for calculations.) Using the above selection criteria, 190 $^{16}\mathrm{O} + \mathrm{Ag(Br)}$ interactions, 441 $^{22}\mathrm{Ne} + \mathrm{Ag(Br)}$ interactions and 246 $^{28}\mathrm{Si} + \mathrm{Ag(Br)}$ interactions at medium impact parameters have been chosen for the present analysis.

To compare the results with data at higher energy we made the same analysis for ^{32}S+Ag(Br) interactions at 200 GeV/c/nucleon (EMU01 Data Pool used in calculations). The experimental details can be found in [7]. We obtained $< P_Q >= 25.9 \pm 2.9$ and $< P_Q >_{ME} = 2.8 \pm 0.9$.

The accuracy of the reaction plane determination method has been tested by the following procedure [13]. The projectile fragments in each event were randomly divided into two parts with equal numbers of fragments and the reaction planes have been estimated for these subevents.

The width of the distribution of the differences between the azimuthal angles $\delta\Psi$ of the two constructed reaction planes serves as a measure for the resolution of the reaction plane after division by factor 2, see [13]. Using this method, a reaction plane resolution of $24.6°$ was achieved. The resolution obtained in these studied emulsion experiments (Tab. 1) is about $25°$ which is comparable to the accuracy reported for other experiments [14], [6].

Table 1. The mean values of $< P_Q >$, $< P_Q >_{ME}$ and obtained resolutions of the reaction plane for studied experiments

Primary nucleus	^{16}O	^{22}Ne	^{28}Si	^{32}S	^{32}S
Momentum [GeV/c/n]	4.5	4.1	4.5	4.5	200
$\langle P_Q \rangle$ [MeV/c/n]	12.8 ±2.8	16.1 ±2.6	6.1 ±2.3	18.4 ±2.1	25.9 ±2.9
$\langle P_Q \rangle_{ME}$ [MeV/c/n]	−0.7 ±0.9	0.8 ±0.8	0.1 ±0.7	1.3 ±0.7	2.8 ±0.9
σ [°]	26.1	25.6	24.8	24.6	24.6

The azimuthal angle distributions $\delta\psi$ of projectile and target fragments relative to the reaction plane constructed from projectile fragments are shown in Figs. 3*a* and 3*b*.

The curves which overlay the histograms in the figure are fits with the function [15]

$$\frac{dN}{d\delta\psi} = A(1 + \lambda \cos \delta\psi), \tag{3}$$

where A is the normalization constant and λ is a measure of the strength of the collective flow. The values of the correlation constants λ_{PF} and λ_{TF} are given in Tabl. 2.

We observe the preferential emission of projectile fragments in the direction of the reaction plane and target fragments opposite to this direction.

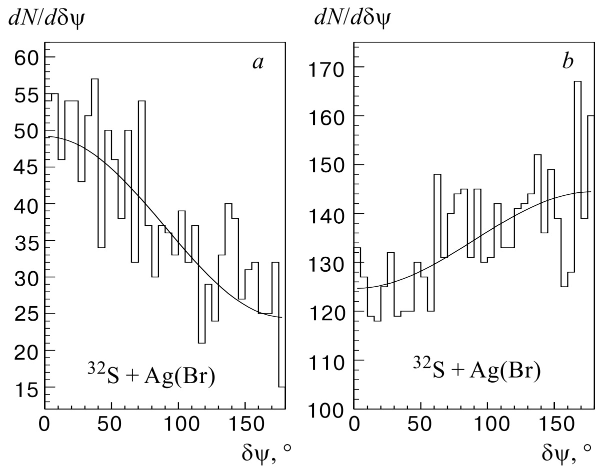

Fig. 3. (*a*) The distribution of the azimuthal angle of projectile fragments and (*b*) target fragments relative to the reaction plane

Similar results have been obtained using the other methods. In the flow angle analysis proposed by Heckman [16] the unit vectors in the direction of emission of PFs and TFs are summed to give their principal vectors $\vec{V}_{PF}$ and $\vec{V}_{TF}$, respectively. These vectors are assumed to be in the direction of their sources with respect to the beam direction.

Table 2. The values of λ_{PF}, λ_{TF}, $\langle\Theta_{PF}\rangle$, $\langle\Delta\Psi_{PF-TF}\rangle$ and Λ in the studied interactions

Primary nucleus	^{16}O	^{22}Ne	^{28}Si	^{32}S
Momentum $[GeV/c/n]$	4.5	4.1	4.5	4.5
λ_{PF}	0.21 ± 0.05	0.22 ± 0.03	0.15 ± 0.04	0.34 ± 0.04
λ_{TF}	-0.09 ± 0.03	-0.07 ± 0.02	-0.12 ± 0.02	-0.07 ± 0.02
$\langle\Theta_{PF}\rangle$ [°]	0.68 ± 0.03	0.91 ± 0.04	0.58 ± 0.02	0.64 ± 0.02
$\langle\Delta\Psi_{PF-TF}\rangle$ [°]	103 ± 4	96 ± 3	107 ± 3	103 ± 3
Λ (χ^2)	0.62 ± 0.09 (0.37)	0.53 ± 0.06 (1.39)	0.39 ± 0.10 (1.05)	0.54 ± 0.06 (0.23)

The distribution of the flow angle Θ_{PF} (polar angle of the vector $\vec{V}_{PF}$) from ^{32}S+Ag(Br) interactions is presented on Fig. 4*a* compared with the mixed events Θ_{PF} distribution. The corresponding mean values of Θ_{PF} for studied experiments are listed in Tabl. 2. One observes that Θ_{PF} significantly differs from zero in all experiments. The average angles $\langle\Theta_{PF}\rangle$ present in the studied experiments are higher in comparison with ^{197}Au induced collisions with Ag(Br) nuclei at 11.6 GeV/c/nucleon [6] and smaller than in $^{84}\text{Kr} + \text{Ag(Br)}$ interactions at 1.55 GeV/c/nucleon [5], where the values $\langle\Theta_{PF}\rangle = 0.31° \pm 0.02°$ and $\langle\Theta_{PF}\rangle = 1.89° \pm 0.07°$, respectively, have been measured. In [17] it was also shown that the mean value of Θ_{PF} decreases with increasing energy. On the other hand, the increase of the $\langle\Theta_{PF}\rangle$ with decreasing impact parameter was seen for different beam and energy combinations.

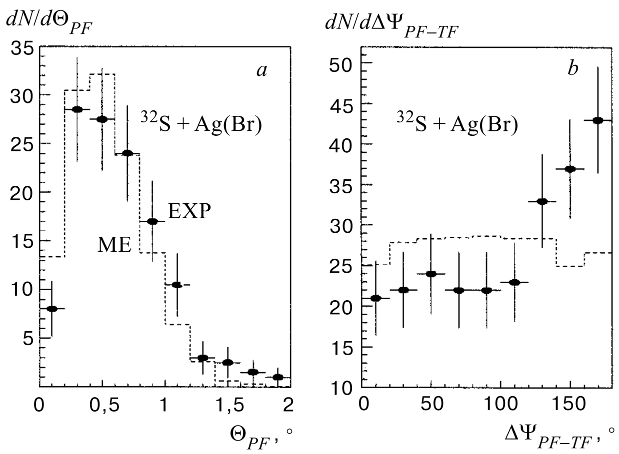

Fig. 4. (*a*) The distribution of the flow angle of projectile fragments, (*b*) the distribution of the difference of the azimuthal angles of the projectile and target plane vectors

Figure 4*b* presents the difference $\Delta\Psi_{PF-TF}$ of the azimuthal angles of the plane vectors constructed separately for projectile and target fragments in the same event compared with the difference resulting from the mixed events. The corresponding mean values are $\langle\Delta\Psi_{PF-TF}\rangle = 103° \pm 3°$ and $\langle\Delta\Psi_{PF-TF}\rangle_{ME} = 90° \pm 1°$.

The mean values $\langle\Delta\Psi_{PF-TF}\rangle$ in the studied interactions are given in Tabl. 2. A strong correlation is present here, favoring the opposite directions of the projectile and target plane vectors. These results confirm our previous conclusion about bounce-off detection. The mean values of $\langle \Delta\Psi_{PF-TF} \rangle$ obtained in collisions of $^{84}\mathrm{Kr} + \mathrm{Ag(Br)}$ at 2.1 GeV/c/nucleon [18], $^{139}\mathrm{La} + \mathrm{Ag(Br)}$ at 1.8 GeV/c/nucleon [19], and $^{197}\mathrm{Au} + \mathrm{Ag(Br)}$ at 11.6 GeV/c/nucleon [6] are $106° \pm 4°$, $115° \pm 5°$, and $107° \pm 3°$, respectively.

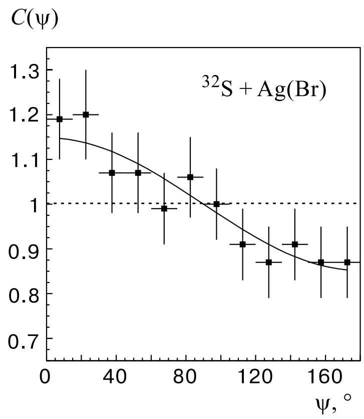

Fig. 5. The dependence of azimuthal correlation function on the azimuthal angle between the transverse momenta of two fragments

To avoid event-by-event estimate of the reaction plane we also tried an azimuthal correlation function analysis. Then the collective flow can be parametrized in terms of azimuthal angle distributions of projectile fragment pairs. Following [15], let us assume that the probability distribution $P(\psi)$ of the angle ψ between the transverse momenta of two correlated fragments is $P(\psi) = A^2(1 + 0.5\Lambda^2 \cos\psi)$, where A is a normalization constant. The azimuthal correlation function $C(\psi)$ is defined by $C(\psi) = P_{\mathrm{corr}}(\psi)/P_{\mathrm{uncorr}}(\psi)$, where $P_{\mathrm{corr}}(\psi)$ represents the distribution of the angle ψ for correlated fragment pairs occuring in the same event and $P_{\mathrm{uncorr}}(\psi)$ is obtained from the distribution of the uncorrelated fragment pairs generated by event mixing. If $C(\psi) > 1$ at small values of ψ and $C(\psi) < 1$ at large ψ, then it is an indication of collective flow. The magnitude of the observed flow can be characterized by the value of Λ obtained from a fit of $A^2(1 + 0.5\Lambda^2 \cos\psi)$ to $C(\psi)$ with $A = 1$.

The fitted values of Λ for all studied experiments given in Tabl. 2 indicate the presence of the collective flow of nuclear matter. In ^{84}Kr collisions at 1.55 GeV/c/nucleon and ^{197}Au at 11.6 GeV/c/nucleon with Ag(Br) the values $0.48 \pm 0.04 (\chi^2 = 0.58)$ and $0.41 \pm 0.02 (\chi^2 = 1.20)$, respectively, have been obtained for the same event selection criteria. Within the errors the values of Λ seem to be independent of the projectile mass and momentum.

4. CONCLUSION

The investigation of ^{32}S induced nuclear interactions and comparison with ^{16}O, ^{22}Ne and ^{28}Si induced interactions at (4.1–4.5) GeV/c/n have been made using the unique emulsion track detector.

The methods of transverse momenta, principal vectors and azimuthal correlation functions have been applied.

The bounce-off effect of the fragments of the projectile nuclei in their collisions with Ag(Br) target nuclei at middle impact parameters has been observed. The back-to-back correlation of the projectile and target fragments in the azimuthal plane has been obtained.

The mixed events which do not comprise collective effects did not reproduce the observed effects. It shows that the nucleus-nucleus collision cannot be represented as a superposition of the individual nucleon-nucleon collisions.

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