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Physics

Experimental Study of Azimuthal Correlations in P(C, Ta) and He(Li, C) Collisions at a Momentum of 4.2, 4.5 and 10 AGeV/c

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ABSTRACT. Azimuthal correlations between protons and between pions were studied in pC (4.2, 10 GeV/c), He(Li, C) (4.5 AGeV/c) and pTa (10 GeV/c) interactions. The data were obtained from the SKM-200-GIBS streamer chamber and from Propane Bubble Chamber (PBL-500) systems utilized at JINR. Study of multiparticle azimuthal correlations offers unique information about space-time evolution of the interactions. Azimuthal correlations were investigated by using correlation function $C(\Delta\varphi)=dN/d(\Delta\varphi)$, where $\Delta\varphi$ represents the angle between the sums of transverse momenta vectors for particles emitted in the forward and backward hemispheres. For protons a "back-to back" ("negative") azimuthal correlations were observed in these interactions. The correlation coefficient $|\xi|$ decreases with the increase of momenta per nucleon and the mass numbers of the projectile (A_P). For pions a back-to-back correlation was obtained for light targets (Li, C) and a "side-by-side" ("positive") correlation — for a heavy target (Ta). Also, for pions $|\xi|$ insignificantly increases with the increase of the momenta per nucleon and almost does not change with the increase of the mass numbers of projectile A_P and target A_T nuclei. *© 2016 Bull. Georg. Natl. Acad. Sci.*

Key words: multiparticle azimuthal correlations, collision, nucleus, proton, pion

Studies of multi-particle correlations provided crucial insight into the underlying mechanism of particle production in relativistic heavy-ion collisions [1]. The primary goal of current relativistic heavy ion research is the creation and study of nuclear matter at high energy densities [2-4]. Open questions include the detailed properties of such excited matter, as well as the existence of a transition to the quark-gluon plasma (QGP) phase. Such a phase of deconfined quarks and gluons were predicted to survive for ~3-10 fm/c in Au-Au collisions at the Relativistic Heavy Ion Collider (RHIC) [5] and several experimental probes are proposed for its possible detection and study [2]. The most prominent feature of multi-particle correlations in AA collisions is due to collective flow (elliptic flow) [6, 7], an azimuthal anisotropy in momentum space induced by strong expansion of the initial almond-shaped overlap area of two nuclei [6]. Collective flow constitutes in important observable [8] because it is thought to be driven by pressure built up early in the collision, and therefore can reflect conditions exciting in the first few fm/c. Collective flow leads to an anisotropy in the azimuthal distribution of emitted particles. Studies of elliptic flow were carried out over a wide range of energies and systems at both RHIC and the LHC [9-11]. Study of multiparticle azimuthal correlations offers unique information about space-time evolution of the collective system [12-14]. One of the interesting methods is the conventional division of phase space into forward and backward moving particles according to the rapidity and emission angle and into slow and fast particles according to energy [13-15].

During last years we studied experimental data using the collective variables depending on the transverse momentum of all secondary charged particles in the azimuthal plane, to reveal a nontrivial effects in nucleus-nucleus collisions [16-23]. We investigated multiparticle azimuthal correlations of protons and pions in central and inelastic collisions (4.2, 4.5 GeV/c/nucleon) within two experiments with 2 m streamer chamber placed in a magnetic field (SKM-200-GIBS) and 2m Propane Bubble Chamber (PBC-500) of JINR. In order to investigate the mechanism of nucleus—nucleus interactions we studied the correlations of the particles with respect to the reaction plane (direct and elliptic flows) [16-21], as well as with respect to the opening angle between particles emitted in the forward and backward hemispheres [22, 23].

In this paper, we present results of the analysis of multiparticle correlations in pC (4.2, 10 GeV/c), He(Li, C) (4.5 AGeV/c) and pTa (10 GeV/c) collisions between protons or pions. Moreover, characteristics of protons and pions, emitted from those collisions, were determined and provided for comparison at the different energies. The dependence of the correlations on the projectile (A_P) and target (A_T) nucleus were investigated.

The protons with momentum p<150 MeV/c were not detected within the PBC-500 (as far as their track lengths l <2 mm) and protons with p<200 MeV/c were absorbed in Ta target plate (the detector biases).

Experimental Data

The data were obtained from the SKM-200-GIBS streamer chamber and from Propane Bubble Chamber systems (PBC-500) utilized at JINR.

The SKM-200-GIBS setup is based on a 2 m streamer chamber placed in the magnetic field of 0.8 T and on a triggering system. An inelastic trigger was used to select the events. The streamer chamber [24, 25] was exposed to a beam of He nuclei accelerated in the JINR synchrophasotron to the momentum of 4.5 AGeV/c. The thickness of Li and C solid targets (in the form of a disc), were 1.5 and 0.2 g/cm^2, correspondingly. The analysis produced 4020 events of HeLi and 2127 of HeC collisions.

The 2 meter long Propane Bubble Chamber (PBC-500) was placed in the magnetic field of 1.5 T. The procedures for separating out the pC collisions in propane (C_3H_8) and the processing of the data including particle identification and corrections were described in detail in [26]. The analysis produced 5882 (10775 events in C_3H_8) and 16509 (28703 events in C_3H_8) events of pC at the momentum of 4.2 and 10 GeV/c, correspondingly and 2342 of pTa (10 GeV/c) collisions. In the experiment, the projectile fragmentation products were identified as those characterized by the momentum p > 3.5 GeV/c (4.2, 4.5 GeV/c/N) or p > 7 GeV/c (10 GeV/c/N) and angle $\Theta < 3.5°$, and the target fragmentation products - by the momentum p < 0.25 GeV/c in the target rest frame. The latter ones are mainly evaporated protons. After these selection criterions, the remaining protons are the participant protons. For the analysis minimum three particles $N_{\text{particles}}{}^{3}3$ were required for the reliable determination of the correlation coefficients.

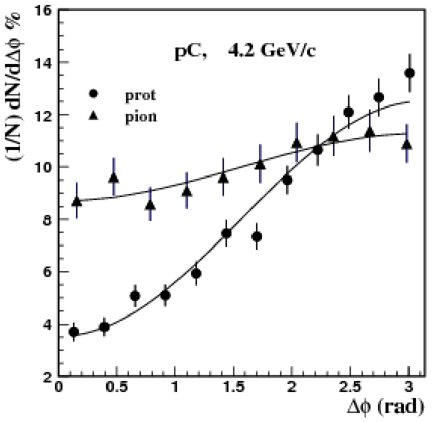

Fig.1. The dependence of the correlation function C(Δφ) on the Δφ from pC collision (4.2 GeV/c) for protons (●) and pions (▲), correspondingly. The curves are the results of the approximation of the data (see text).

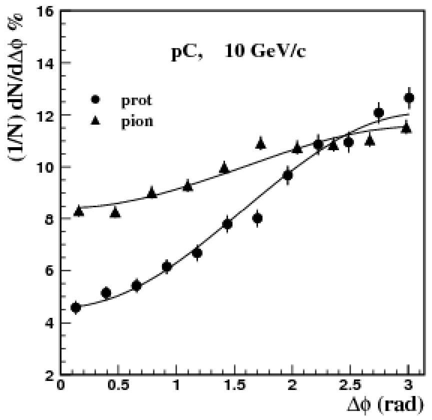

Fig. 2. The dependence of the correlation function C(Δφ)on the Δφ from pC collision (10 GeV/c) for protons (●) and pions (▲), correspondingly.

Azimuthal Correlations Between Protons or Pions

In [13-15] the method for studying the correlation between groups of particles was developed. The azimuthal orrelation function was defined by the relative opening angle between the transverse momentum vector sums of particles emitted forward and backward with respect to the rest frame of the target nucleus (a rapidity of y_0=0.2). The data were obtained at 4.9, 60 and 200 GeV (BEVALAC, CERN/SPS).

We applied this method for our data, but the analysis was carried out in the central rapidity region of laboratory system, instead of the target rapidity range of [13-15]. The analysis was performed event by event, in each event we denoted the vectors:

$$\vec{Q}_B = \sum_{y_i<y_c} \vec{P}_{\perp_i} \qquad (1)$$

and

$$\vec{Q}_F = \sum_{y_i\geq y_c} \vec{P}_{\perp_i} \qquad (2)$$

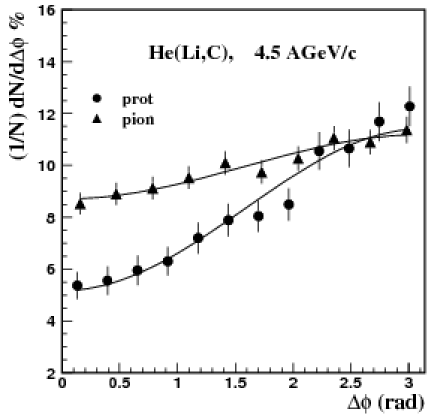

Fig.3. The dependence of the correlation function C(Δφ) on the Δφ from He(Li, C) collision (4.5 AGeV/c) for protons (●) and pions (▲), correspondingly.

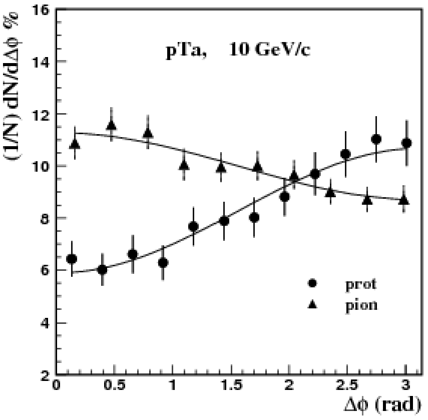

Fig.4. The dependence of the correlation function C(Δφ)on the Δφ from pTa collision (10 GeV/c) for protons (●) and pions (▲), correspondingly.

Table 1. The number of experimental events (N_{event}), the correlation coefficient (ξ) for protons and pions in pC (4.2 and 10 GeV/c), He(Li, C) (4.5 AGeV/c) and pTa (10 GeV/c) collisions.

A_P, A_T	N_{event}	ξ_{prot}	ξ_{pion}
pC 4.2 GeV/c	5882	-0.561±0.024	-0.129±0.032
pC 10 GeV/c	16509	-0.450±0.015	-0.158±0.010
HeLi 4.5 AGeV/c HeC	4020 2127	-0.375±0.030	-0.125±0.020
pTa 10 GeV/c	2342	-0.289±0.037	0.129±0.025

where y_c is an average rapidity of participant protons for each colliding pears of nuclei. The correlation function C(Δφ) was determined as:

$$C(\Delta\varphi) = dN/d\Delta\varphi \tag{3}$$

where Δφ is the angle between the vectors $\vec{Q}_B$ and $\vec{Q}_F$:

$$\Delta\varphi = \arccos\frac{(\vec{Q}_B \cdot \vec{Q}_F)}{(|\vec{Q}_B| \cdot |\vec{Q}_F|)} \tag{4}$$

Essentially, C(Δφ) measures whether the particles are preferentially emitted “back-to back” or “side-by-side” correlations. “Back-to back” means the “negative” correlations, where C(Δφ) increases with Δφ and reaches a maximum at Δφ = 180°; “Side-by-side “ means the “positive” correlations, where C(Δφ) decreases with Δφ and have a maximum at Δφ= 0°; or “” (“positive”, correlation decreases and have maximum Δφ=0°) [9].

In view of the strong coupling between the nucleons and pions, it is interesting to know the correlations between pions. Thus, we have studied correlations between protons and between pions. Fig. 1,4 show the experimental correlation function C(Δφ) for these particles from p(C, Ta) and He(Li, C) collisions. One can observe from Figures a clear correlation for protons and pions. To quantify these experimental results the data were fitted by the function:

$$C(\Delta\varphi) = 1 + \xi\cos(\Delta\varphi) \tag{5}$$

Results of the fitting are listed in Table 1. The strength of the correlation is defined as:

$$V = C(0^0) / C(180^0) = (1 + \xi)/(1 - \xi) \tag{6}$$

Apparently, the correlation coefficient $\xi<0$ and thus the strength of correlation $\varsigma< 1$ for protons in all interactions, meaning that protons are preferentially emitted back-to-back.

One can observe from Fig. 1,3, a clear back-to-back ($\xi< 0$, $\varsigma< 1$) correlations for pions for light systems of pC (4.2 and 10 GeV/c) and He(Li, C) (4.5 AGeV/c). For heavy, asymmetric pairs of pTa (10 GeV/c) the side-by-side ($\xi> 0$ and $\varsigma> 1$) correlations of pions can be seen from Fig. 4 (Table 1).

We also studied a dependence of the correlation coefficient (ξ) on mass numbers of projectile A_P and target A_T for protons and pions. The absolute values of ξ for protons decreases linearly with the increase of projectile momenta per nucleon and mass numbers of projectile of A_T nuclei from **0.561 ± 0.024** for pC (**4.2 GeV/c)** up to **0.450±0.015** for pC (10 **GeV/c),** and up to **0.289±0.037** for pTa (10 **GeV/c),** respectively. For pions $|\xi|$ insignificantly increases with the increase of the momenta per nucleon and almost does not change with the increase of the mass numbers of projectile A_P and target A_T nuclei from **0.129±0.032** for pC (**4.2 GeV/c)** up to **0.158±0.010** for pC (10 **GeV/c),** and up to **0.129±0.025** for pTa (10 **GeV/c),** respectively (Table 1).

Back-to-back correlations were observed between protons with the Plastic-Ball detector in p + Au collisions at energy of 4.9, 200 GeV/c and in (O, S)Au reactions at 200 GeV/c [14, 15, 27]. Because, the azimuthal correlation function was defined in the target fragmentation region, the correlation parameters in the wide range of energy increases inappreciable. Previously, in CC (4.2 GeV/c/N, PBC-500) inelastic interactions for small statistic data samples (2500 events) [12] the back-to-back azimuthal correlations were obtained between protons emitted in the forward and backward hemispheres in the c.m.s. ($-0.5 < y < 0.5$). They obtained the absolute value of asymmetry coefficient 0.26 ± 0.01 for protons. Later, we analysed [19] the same data samples of CC inelastic collisions (PBC-500), but contained 15962 events and obtained for protons $|\xi| = 0.24 \pm 0.01$ ($-0.5 < y < 0.5$, $N_{prot} \geq 2$). One can see that our result obtained in [23] agrees with the result of [12] obtained for small statistic data samples.

The back-to back emission of protons can be understood as the results of (local) transverse momentum conservation [14, 15]. This behavior is in a good agreement with collective nuclear matter flow concept [28,29].

Back-to-back ($\xi < 0$, $\varsigma < 1$) pion correlation for light systems of pC (4.2 and 10 GeV/c) and He(Li, C) (4.5 AGeV/c) and the side-by-side ($\xi > 0$, $\varsigma > 1$) pion azimuthal correlations for heavy, asymmetric pairs of pTa (10 GeV/c) are obtained in this paper, as well as for asymmetric pairs of nuclei (d,He)Ta and CTa (4.2 AGeV/c) in our work [16, 17]. Similar, side-by-side correlations of pions were observed in p+Au collisions at Bevalac (4.9 GeV/nucleon) and CERN-SPS (60 and 200 GeV/nucleon) energies [14, 15]. Another investigatios of large angle two-particle correlations, carried out at the 3.6 AGeV C-beam in Dubna [12] showed a back-to-back pion correlation for a light target (Al) and a side-by-side correlation for a heavy target (Pb). For protons a back-to-back correlation was observed for all targets. Again, these results appear to be consistent with our observed proton and pion azimuthal correlations and with the variation of the pion correlation when going from C to a Ta.

The reason for the observed difference between protons and pions is that the pions are absorbed in the excited target matter ($\pi + N \rightarrow \Delta$ and $\Delta + N \rightarrow N + N$) [13-15]. While the back-to-back emission of protons can be understood as a result of the transverse momentum conservation. The side-by-side correlation of pions can be naturally explained on the base that pions, which are created in collision suffer at $b \neq 0$ fm (b is the impact parameter) either rescattering or even complete absorption in the target spectator matter. Both processes will result in a relative depletion of pions in the geometrical direction of the target spectator matter and hence will cause an azimuthal side-by-side correlation as observed in the experimental data.

Conclusion

The study of multiparticle azimuthal correlations between protons or between pions in pC (4.2 and 10 GeV/c), He(Li, C) (4.5 AGeV/c) and pTa (10 GeV/c) collisions were carried out:

1. The pC system is the lightest studied one, and the pTa is extremely asymmetrical system in which azimuthal correlations between protons and between pions in the “backward” and “forward” hemispheres have ever been detected for these particles. As shown, the pions exhibit “back-to back” (negative) correlations consistent with that for protons in these collisions.

2. For protons a back-to-back correlation was observed for all interactions. The absolute values of correlation coefficient ξ decreases with increase of momenta per nucleon and the mass numbers of the projectile A_P.

3. For pions a back-to-back correlation obtained for a light targets (Li, C) and a side-by-side correlation for a heavy target (Ta). the correlation coefficient ($|\xi|$) insignificantly increases with the increase of the momenta per nucleon and almost does not change with the increase of the mass numbers of projectile A_P and target A_T nuclei.

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ფიზიკა

აზიმუტალური კორელაციების ექსპერიმენტული შესწავლა პროტონების ან პიონების ჯგუფებს შორის p(C, Ta) და He(Li, C) დაჯახებებში 4,2; 4,5 და 10 GeV/c ნუკლონზე იმპულსის დროს

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გამოკვლეულ იქნა მრავალნაწილაკოვანი აზიმუტალური კორელაციები pC (4,2 GeV/c, 10 GeV/c), He(Li, C) (4,5 AGeV/c) და pTa (10 GeV/c) დაჯახებებში ერთი და იმავე ტიპის ნაწილაკების (პროტონები/პიონები) ჯგუფებს შორის. ექსპერიმენტული მასალა მიღებულია ბირთვული კვლევების გაერთიანებული ინსტიტუტის (JINR) მაღალი ენერგიების ლაბორატორიაში ფილმური დეტექტორის (SÊM-200-GIBS) და პროპანის ორმეტრიანი ბუშტოვანი კამერა P(PBC-500) საშუალებით. მრავალნაწილაკოვანი აზიმუტალური კორელაციების შესწავლა იძლევა ინფორმაციას ურთიერთქმედების პროცესის განვითარებაზე დროსა და სივრცეში. მრავალნაწილაკოვანი აზიმუტალური კორელაციები შეისწავლება $C(\Delta\varphi)=dN/d(\Delta\varphi)$ კორელაციის ფუნქციის მეშვეობით, სადაც $\Delta\varphi$ არის კუთხე წინა და უკანა ნახევარსფეროებში გამოდინებული ნაწილაკების განივი იმპულსების ჯამურ ვექტორებს შორის. განხილულ დაჯახებებში პროტონებისათვის დამზერილ იქნა ე.წ. "back-to-back" (უარყოფითი) კორელაციები. პროტონებისათვის კორელაციის კოეფიციენტი $|\xi|$ მცირდება იმპულსისა და დამცემი ბირთვის მასური რიცხვის ზრდასთან ერთად. პიონებისათვის მიიღება უარყოფითი ("back-to-back") აზიმუტალური კორელაციები შედარებით მსუბუქი სამიზნეებისათვის (Li, C) და დადებითი („side-by-side") აზიმუტალური კორელაციები შედარებით მძიმე სამიზნეზე (Ta) გადასვლის დროს. ამასთან, პიონებისათვის $|\xi|$ უმნიშვნელოდ იზრდება იმპულსის ზრდისას და თითქმის არ იცვლება A_P დამცემი და A_T სამიზნე ბირთვის მასური რიცხვების ზრდასთან ერთად.

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