Physics

Study of the Collective Flows of Protons and Pions in p(C, Ta) and He(Li, C) Collisions at Momenta of (4.2, 4.5 and 10) AGeV/c

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ABSTRACT. Collective flow of protons and pions was studied at the momenta of 4.2, 4.5 and 10 AGeV/c for different projectile-target combinations, specifically, p(C, Ta) and He(Li, C). The data were obtained from the SKM-200-GIBS streamer chamber and from Propane Bubble Chamber systems utilized at JINR (PBC-500). The method of Danielewicz and Odyniec has been employed in determining the directed transverse flow of particles. The collective effects are studied with respect to the reaction plane, which is defined by the impact parameter vector and the beam direction. The values of the transverse flow parameter $F = d\langle P_X\rangle/d(y)$ and the strength a_2 of the anisotropic emission were defined for each interacting nuclear pair. The directed flow of protons and pions changes with increase of the energy and the mass numbers of colliding nucleus pairs. The elliptic proton flow points out of the reaction plane and also strengthens as system mass increases. The pion flow is in the reaction plane, as the proton one for the lighter (pC, He(Li, C)) systems, and in the opposite direction for the heavier (pTa) system. The pC system is the lightest studied one, and the pTa is extremely asymmetrical system in which collective flow effects (directed and elliptic) have ever been detected (for protons and pions). The information about them in interactions of light and medium projectile nuclei with various target nuclei is very limited and the results obtained in this paper will bring a new light on the nature of the flows. The obtained results provide very important information on the mechanism of nucleus-nucleus interactions at high energies, as well as on characteristics of the produced nuclear matter. *© 2015 Bull. Georg. Natl. Acad. Sci.*

Key words: *nucleus, collisions, protons, pions, collective flow.*

One of the central goals of the high-energy heavy-ion collision research was the determination of the properties of nuclear matter at densities high compared to that in the ground-state nuclei and at temperatures high compared to energies per nucleon in the ground-state nuclei. The flow produces asymmetries associated with the reaction plane, in the particle emission patterns. Theoretically, those asymmetries can be linked to the fundamental properties of nuclear matter and, in particular, to the equation of state (EOS) [1, 2]. Two types of asymmetries were identified. One was the directed flow [3] in the reaction plane, associated with the matter "bouncing-off" within the hot participant region of overlap between colliding nuclei. The other was the squeeze-out of the hot matter moving perpendicular to the reaction plane within the participant region. When energy increases into ultrarelativistic values the squeeze-out turns into an in-plane elliptic flow.

Regarding investigative strategy, the reaction plane is the plane within which the centers of initial nuclei lie, separated in transverse direction by the impact parameter **b**. Spatial asymmetry in the initial state, associated with the reaction plane, gives rise to asymmetries in the particle emission patterns. Within the method of analysis of those asymmetries, proposed by Danielewicz and Odyniec [5], those asymmetries are used to estimate the direction of the reaction plane and the asymmetries themselves are assessed in relation to the estimated reaction-plane direction. In an experiment, the determination of the impact parameter **b** is not possible and therefore instead of **b,** vector sum of transverse momenta of projectile and target nuclear fragments or participant protons are used. The fragmentation region of projectile and target nuclei is not acceptable for experimental set-ups in some experiments and therefore the reaction plane is defined by the second approach. The second approach is preferable also for the light nuclear systems, because the multiplicity of the participant protons is larger than the number of detected fragments.

By now, the collective flow effects were investigated over a wide range of energies, from tens of MeV/nucleon to 7 TeV/nucleon in the center of mass. Having determined the reaction plane it is possible to find quantitative properties of the flows. At low and intermediate energies the average projection of particles momentum on the reaction plane is used quite frequently, as well as a slope of its dependence on the particle rapidity. Coefficients of the Fourier decomposition of particle azimuthal distributions are very popular at high energies. For example, the elliptic flow was explored by many collaborations at AGS [6, 7], GSI [8], NA49 [9], CERN/SPS [10, 11] by means of the second harmonic coefficient of Fourier analysis of the azimuthal distributions - v_2.

In order to study the characteristics of nucleus-nucleus interactions, the collective flows of protons, pions and Λ hyperons have been previously investigated by the authors of the paper [12-15]. It is worth to mention, that the values of the elliptic flow excitation function v_2 obtained by us for protons correspond to quite interesting energy region. According to the investigations in Au-Au collisions at AGS [16], an evolution from negative ($v_2 < 0$) to positive ($v_2 > 0$) elliptic flow was observed in energy interval of $2.0 \leq E_{beam} \leq 8.0$ GeV/nucleon and an apparent transition energy $E_{tr} \sim 4$ GeV/nucleon was pointed. Therefore, the results obtained by us seem to be interesting from the viewpoint of enrichment of the existing results in the above mentioned energy region.

The collective flows are well established in collisions of heavy nuclei. The information about them in interactions of light and medium projectile nuclei with various target nuclei is very limited. We believe that the results obtained in the paper will bring a new light on the nature of the flows.

In this paper, we present collective flow results of protons and pions at the momenta of 4.2, 4.5 and 10 AGeV/c for different projectile-target combinations. The data were obtained from the Propane Bubble Chamber of JINR at Dubna. Moreover, characteristics of protons and pions, emitted from those collisions, were determined and provided for comparison at different energies.

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

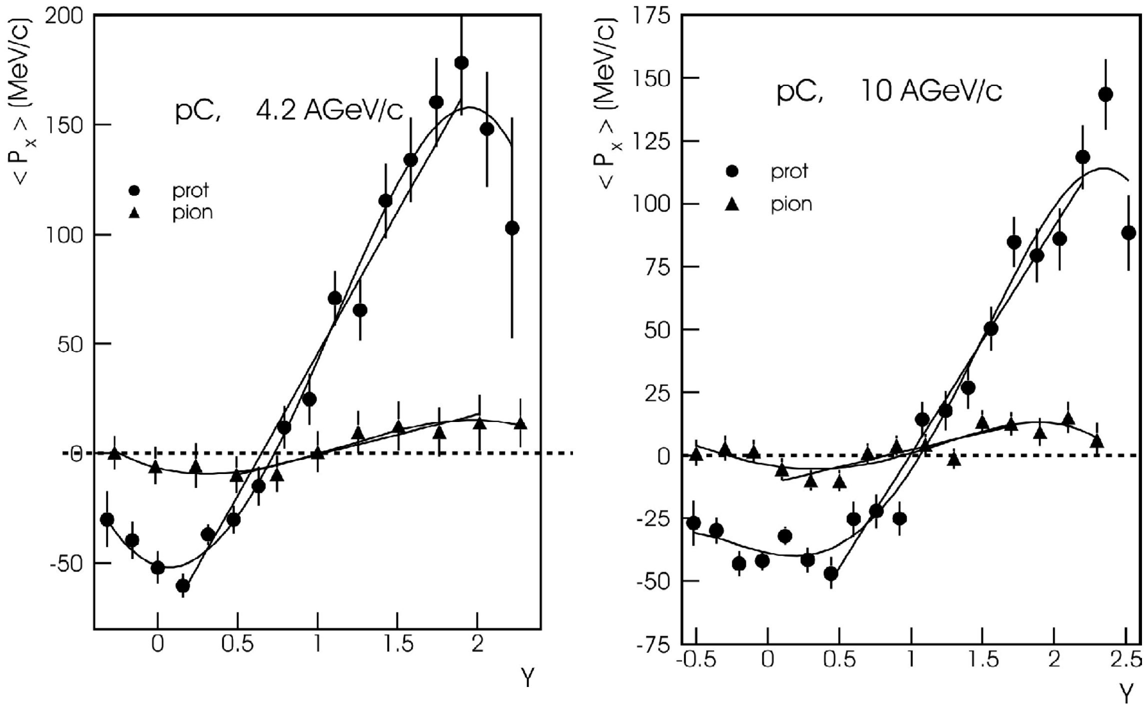

Fig. 1. The dependence of <P_X(Y)> on the rapidity Y for protons and pions in pC collisions at the momenta of 4.2 AGeV/c and of 10 AGeV/c: ● – protons and ▲ – pions. Straight lines stretches represent the slope of data at midrapidity, obtained by fitting the data with 1-st order polynomial within the intervals of the rapidity (see text). The curved lines guide the eye over data.

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 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 [17, 18]. 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 AGeV/c, correspondingly and 2342 of pTa (10 AGeV/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 Θ < 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 $N_{particles}$≥3 were required for the reliable determination of the reaction plane.

Directed Flow of Protons and Pions

We investigated the directed flow of protons and pions in various nucleus systems p(C, Ta) and He(Li, C). To determine the directed transverse flow of particles we employed the method of Danielewicz and Odyniec [5]. Most of the data below 4 AGeV in the literature were, in fact, analyzed by the following method. The advantage of that method is that it can be employed even at small statistics, which is typical for film detectors. The method relies on summation over transverse momenta of selected particles in the events. The participant protons of the reaction plane definition were applied for the flow effects study.

The analysis was carried out in the laboratory

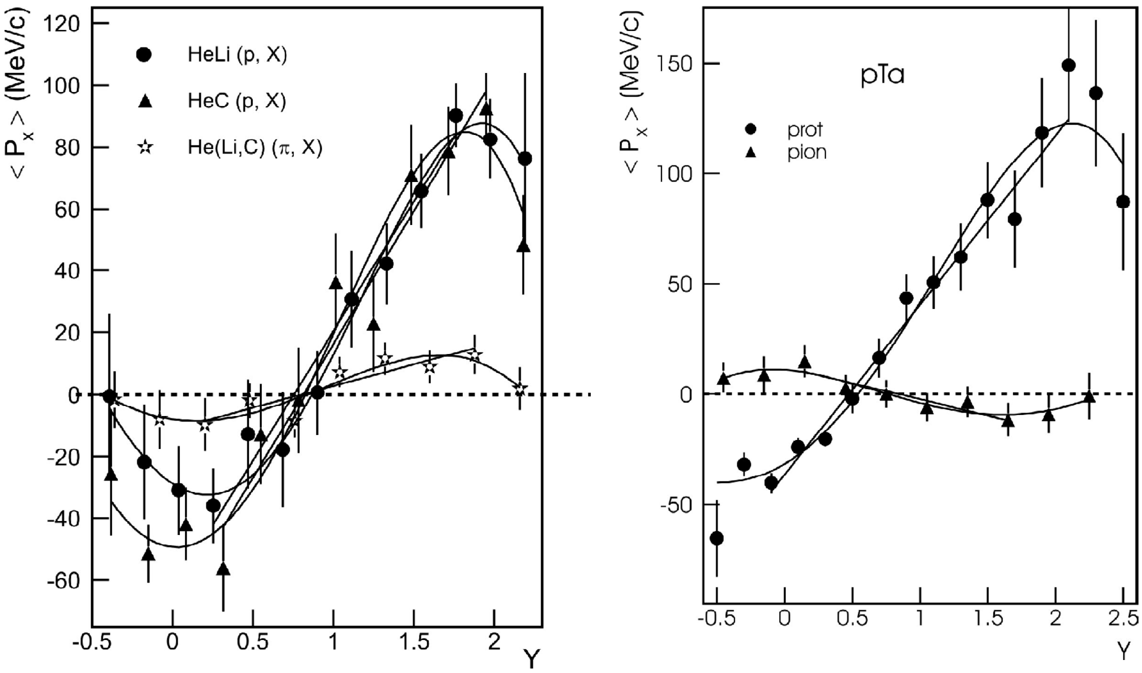

Fig. 2. The dependence of <P_X(Y)> on the rapidity Y for protons and pions in He(Li, C) (4.5 AGeV/c) and Ta (10 AGeV/c) collisions. Straight lines stretches represent the slope of data at midrapidity, obtained by fitting the data with 1-st order polynomial within the narrow intervals of the rapidity (see text). The curved lines guide the eye over data.

system. To eliminate the correlation of the particle with itself (autocorrelations), we estimated the reaction plane for each particle, with contribution of that particle removed from the definition of the reaction plane. The reaction plane is spanned by the impact parameter vector **b** and the beam axis. Within the transverse momentum method, the direction of **b** is estimated event-by-event in terms of the vector constructed from particle transverse momenta:

$$\mathbf{Q}_\mathrm{j} = \sum_{\substack{i=1\\ i\neq j}}^{n} \omega_i \mathbf{P}_\mathrm{i}^{\perp}, \tag{1}$$

where i is a particle index and ω_i is the weight factor, $\omega_i = y_i - y_c$, y_i is the rapidity of i-th particle, y_c is the average rapidity of the participant protons in each nucler systems [19]. Projection of the transverse momentum of each particle onto the estimated reaction plane is:

$$P'_{X\,j} = \frac{\mathbf{P}_\mathrm{j}^{\perp} \cdot \mathbf{Q}_\mathrm{j}}{|\mathbf{Q}_\mathrm{j}|} \tag{2}$$

The dependence of the projection on the rapidity y was constructed for each interacting nuclear pair. For further analysis, the average transverse momentum in the reaction plane, $<P'_{Xj}(y)>$, is obtained by averaging over all events in the corresponding intervals of rapidity (Figs. 1, 2). In Table 1 the values of flow parameter F are given, which are the slopes of

Table 1. The values of flow for protons and pions in the measured events, including event numbers before and after the multiplicity cut ($N_{event}/N_{ev.cut}$).

$A_P\ A_T$	pC 4.2 AGeV/c	pC 10 AGeV/c	HeLi 4.5 AGeV/c	HeC 4.5 AGeV/c	pTa 10 AGeV/c
$N_{event}/N_{ev.cut}$	5882 / 2258	16509 / 6553	4020 / 1136	2127 / 880	2342 / 1513
$F_{prot.}$ (MeV/c)	129.2 ± 6.2	90.2 ± 4.6	83.6 ± 8.9	88.7 ± 7.8	76.8 ± 4.9
$F_{pion.}$ (MeV/c)	18.2 ± 5.1	13.5 ± 2.8	14.0 ± 3.4*		-14.7 ± 4.5

* He-Li and He-C collision events are combined in order to increase statistics.

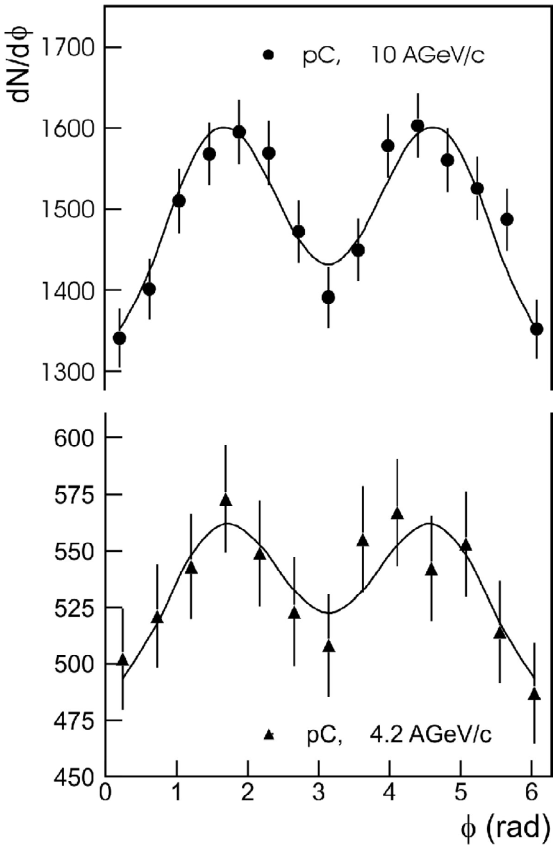

Fig. 3. The azimuthal distributions of the participant protons with respect to the reaction plane in pC collisions at two different momenta per nucleon: ▲ – 4.2 AGeV/c and ● – 10 AGeV/c. The curves are the result of the approximation by $dN/d\varphi = a_0(1+a_1\cos\varphi+a_2\cos2\varphi)$.

$<P_x(y)>$ at its midrapidity cross-over. The matter is that the component P_x of a particle in the true reaction plane is systematically larger than the component P_X' in the estimated plane. The angle Φ between the true and estimated reaction planes was defined. Thus, the correction factor $k = 1/<\cos\Phi>$, where $<\cos\Phi>$ is determined from the ratio [5, 20-24]:

$$\langle\cos\Phi\rangle = \frac{\langle\omega P_X'\rangle}{\langle\omega P_X\rangle} = \langle\frac{\omega \mathbf{P}_j^{\perp}\cdot\mathbf{Q}_j}{|\mathbf{Q}_j|}\rangle\sqrt{\frac{\langle Q^2-\sum_{i=1}^{n}(\omega P_i^j)^2\rangle}{\langle n^2-n\rangle}}, \quad (3)$$

where n is the particles, multiplicity in an event. It should be mentioned that corrections were made qualitatively differently in this case. Events with $k>10$ are not included in the analysis because they introduce significant distortions of the distributions.

Figs. 1, 2 show the rapidity dependence of the average in-plane transverse-momentum component for protons and pions in p(C, Ta) and He(Li, C) collisions. In view of the strong coupling between the nucleon and pion, it is interesting to know, if pions also have collective flow behaviour in that presented nuclear systems and how the pion flow is related to the nucleon flow. As seen, the flow F parameter's value changes with the increase of the momentum and of the mass numbers of projectile A_P and target A_T nuclei (Table 1). Interestingly, proton and pion collective flow parameters in He-C collisions of SKM-200-GIBS with the clear, solid thin targets have been further compared to those collisions from C_3H_8 (PBC-500, our earlier results) [13, 15]. Both results are in good agreement within errors.

There are no auto-correlations for pions, because the reaction plane is determined by protons. It is apparent that the pions and protons flow in the same in-plane directions, in the forward and backward hemispheres of pC (4.2, 10 AGeV/c) and He(Li, C) (4.5 AGeV/c) collisions. As one can see from the Table 1 and Fig. 1, 2 the situation with the directed flow of pions is different than with the flow of protons. The maximum transverse momentum and the flow parameter are smaller for pions than for protons.

The reduced magnitude of average pion momentum component compared to protons was seen before at Bevalac [25, 26], GSI-SIS [27] and CERN-SPS [10, 11, 28]. Historically, the pattern of pion emission relative to the reaction plane has been first studied at the Bevalac by the Streamer Chamber Group [26] and later by the EOS collaboration [29] at Saturne by the Diogene group [30]. The Diogene group investigated, in particular, collisions similar to ours where one nucleus, in their case the projectile Ne, was fixed while the counterpart target nuclei were varied. In the investigations at Bevalac and Saturne, projection of pion transverse momentum onto the reaction plane was examined. The direction of pion flow opposite to proton flow, so called anti-flow, was seen before in either asymmetric [30] or symmetric [10, 11, 29, 31]

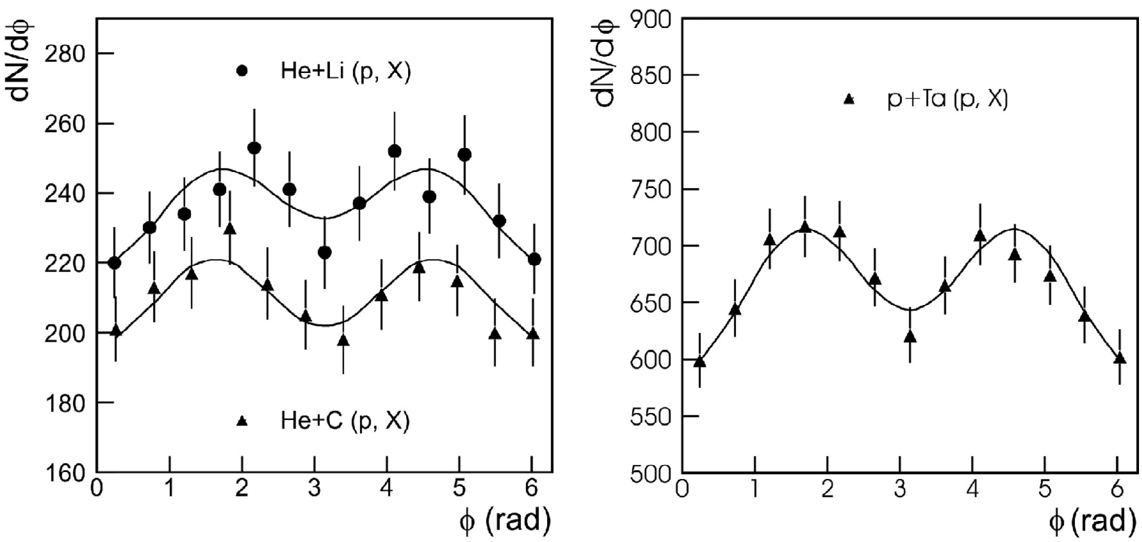

Fig. 4. The azimuthal distributions of the participant protons with respect to the reaction plane in He-Li, He-C and p-Ta collisions. The curves are the results of the approximation by $dN/d\varphi = a_0(1+a_1\cos\varphi+a_2\cos2\varphi)$.

systems. However, we are unaware of an observation of the pion anti-flow in strongly asymmetric system such as our p-Ta.

Anti-correlation of nucleons and pions was explained in [32] as due to the effect of multiple πN scattering. However, in Refs. [33-35] it was shown that the anti-correlation is a manifestation of the nuclear shadowing of the target and projectile-spectators through both pion re-scattering and re-absorptions. Quantitatively, the shadowing can produce in-plane transverse momentum components comparable to the momenta itself and, thus, much larger than components due to collective motion for pions [36]. In our opinion, our results indicate that the flow behaviour of pions in light systems is due to the flow of Δ resonances, whereas the anti-flow behaviour in a heavier system (pTa) is the result of the nuclear shadowing effect.

Proton Elliptic Flow

We have studied the proton elliptic flow in pC (4.2 AGeV/c, 10 AGeV/c), He(Li, C) (4.5 AGeV/c) and pTa (10 AGeV/c) collisions. The azimuthal φ distributions of the protons were obtained and presented in Figs 3, 4, where φ is the angle of the transverse momentum of each particle in the event with respect to the reaction plane ($\cos\varphi = P_X/P^{\perp}$). The azimuthal angular distributions show maxima at $\varphi = 90°$ and 270° with respect to the event plane. The maxima are associated with preferential particle emission perpendicular to the reaction plane (squeeze-out). To treat the data in a quantitative way, the azimuthal distributions were fitted with the Fourier cosine-expansion (given the system invariance under reflections with respect to the reaction plane)

$$dN/d\varphi = a_0(1 + a_1\cos\varphi + a_2\cos2\varphi). \qquad (4)$$

The squeeze-out signature is the negative value of the coefficient a_2 and this coefficient is the measure of the strength of the anisotropic emission.

The elliptic anisotropy, quantified in terms of the a_2 coefficient ($a_2 = 2v_2$) (Table 2) extracted from the azimuthal distributions of the protons with respect to the reaction plane at mid-rapidity (Table 2). According to the investigations in Au-Au collisions at AGS [16], the sign of the elliptic flow changed at an apparent transition energy of $E_{tr} \sim 4$ GeV/nucleon. It should be mentioned that, no change of the sign of the elliptic flow was observed in p-C and pTa collisions at 10 AGeV/c.

The elliptic flow was investigated by various groups for different systems. Comparison of the elliptic flow measurements of charged hadrons in CuCu

Table 2. Characteristics of proton elliptic flow for experimental events

A_P A_T	pC 4.2 AGeV/c	pC 10 AGeV/c	HeLi 4.5 AGeV/c	HeC 4.5 AGeV/c	pTa 10 AGeV/c
$N_{event}/N_{ev.cut}$	5882 / 2258	16509 / 6553	4020 / 1136	2127 / 880	2342 / 1513
a_2	-0.051 ± 0.017	-0.071 ± 0.009	-0.043 ± 0.018	-0.052 ± 0.019	-0.071 ± 0.015

and AuAu collisions at $\sqrt{S_{NN}}$ = 62.4 and 200 GeV by PHOBOS Collaboration did not exhibit any dependence on $(A_P \cdot A_T)^{1/2}$ [see Ref. [37] Fig. 2 a, c]. The ALICE group has found about a 30% increase in the magnitude of v_2 from $\sqrt{S_{NN}}$ = 200 Gev (AuAu) to 2.76 TeV (PbPb) (see Ref. [38] Fig. 4).

Conclusions

The directed transverse collective flows of protons and π^- mesons and elliptic flow of protons emitted from pC (4.2 AGeV/c, 10 AGeV/c), He(Li, C) (4.5 AGeV/c) and pTa (10 AGeV/c) collisions have been studied. It were observed:

1) The pC system is the lightest studied one, and the pTa is extremely asymmetrical system in which collective flow effects (directed and elliptic) have ever been detected for protons and pions. As shown, the pions exhibit directed flow consistent with that for protons in the (p, He)C and HeLi collisions. On the other hand, for the pTa interactions, the pion flows turn into anti-flow with the pion average in-plane momenta becoming opposite to those for protons.

The absolute value of the directed flow parameter |F| for the protons decreases with the increase of momenta per nucleon and the mass numbers of projectile A_P and target A_T nuclei, while almost no changes were observed for pions:

protons:

129.2 ± 6.2, 90.2 ± 4.6 (pC, 4.2 AGeV/c, 10 AGeV/c) and 76.8 ± 4.9 (pTa, 10 AGeV/c)

pions:

18.2 ± 5.1, 13.5 ± 2.8 (pC, 4.2 AGeV/c, 10 AGeV/c) and 14.7 ± 4.5 (pTa, 10 AGeV/c)

2) It should be mentioned that, there is no change of the sign of the elliptic flow in p(C, Ta) collisions at 10 AGeV/c. The absolute value of the proton elliptic flow parameter a_2 increases with momenta per nucleon and almost does not change with the increase of mass numbers of projectile A_P and target A_T nuclei: 0.051 ± 0.017, 0.071 ± 0.009 (pC, 4.2 AGeV/c, 10 AGeV/c) and 0.071 ± 0.015 (pTa, 10 AGeV/c)

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ფიზიკა

პროტონებისა და პიონების კოლექტიური ეფექტების შესწავლა p(C, Ta) და He(Li, C) დაჯახებებში 4,2; 4,5 და 10 AGeV/c იმპულსის დროს

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(წარმოდგენილია აკადემიის წევრის ა. ხელაშვილის მიერ)

შესწავლილ იქნა პროტონებისა და პიონების კოლექტიური გამოდინების ეფექტები p(C, Ta) და He(Li, C) სხვადასხვა დამცემი-სამიზნე ბირთვული წყვილებისათვის 4,2; 4,5 და 10 AGeV/c იმპულსის დროს. გამოყენებული ექსპერიმენტული მასალა მიღებულია ქ. დუბნის ბირთვული კვლევების გაერთიანებული ინსტიტუტის მაღალი ენერგიების ლაბორატორიაში ფილმური დეტექტორების (მაგნიტური სპექტრომეტრები SKM-200-GIBS და პროპანის ორმეტრიანი ბუშტოვანი კამერა PBC-500) საშუალებით. მიმართული განივი გამოდინებები (მგგ) და ელიფსური გამოდინებები (ეგ), აღნიშნულ დაჯახებებში შესწავლილ იქნა პ. დანიელევიჩისა და გ. ოდინიეცის განივი იმპულსების მეთოდით (გიმ). ამ მეთოდის მიხედვით კოლექტიური ეფექტები შეისწავლება რეაქციის სიბრტყის მიმართ, რომელიც აიგება ორი ვექტორის საშუალებით დაჯახების პარამეტრითა და ნაკადის მიმართულებით. ყოველი ბირთვული წყვილისათვის დადგინდა $F=d<P_X>/d(y)$ – გამოდინების პარამეტრისა და a_2 – ანიზოტროპიული გამოსხივების სიძლიერის საზომის რაოდენობრივი მნიშვნელობები. პროტონებისა და პიონების მიმართული განივი და ელიფსური გამოდინებები იცვლება ენერგიისა და დამცემი-სამიზნე ბირთვული წყვილების მასური რიცხვების ზრდასთან ერთად. პიონების გამოდინებები რეაქციის სიბრტყეში თანხვდება პროტონების გამოდინებებს მსუბუქი ბირთვული სისტემებისათვის (pC, He(Li, C)) და საწინააღმდეგო მიმართულებისაა შედარებით მძიმე ბირთვული (pTa) სისტემისთვის. ნაშრომში კოლექტიური ეფექტები შესწავლილია სადღეისოდ არსებულ ყველაზე მსუბუქ pC და ყველაზე ასიმეტრიულ pTa დამჯახებელ წყვილებში. დადგინდა გამოდინების F და a_2 პარამეტრების დამოკიდებულება

დამჯახებელი ბირთვების (A_P, A_T)-სა და ენერგიაზე. მიღებული შედეგები იძლევა საინტერესო ინფორმაციას ბირთვული მატერიის მახასიათებლების, კერძოდ ბირთვ-ბირთვული ურთიერთქმედების მექანიზმის შესახებ.

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