საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 11, №3, 2017
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 11, no. 3, 2017

Physics

Differential Transverse Flow in He(Li, C) and (p, d, He, C)(C, Ta) Collisions at 4.2, 4.5 and 10 AGeV/c Momenta

Lidia Chkhaidze[*], Guram Chlachidze[**], Tamar Djobava[*], Lali Kharkhelauri[*]

[*]*High Energy Physics Institute, Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[**]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*

(Presented by Academy Member Alexander Kvinikhidze)

ABSTRACT. Differential transverse flow of protons and pions in HeLi and (p, d, He, C)-(C,Ta) (4.2, 4.5 and 10 AGeV/c) collisions was measured as a function of transverse momentum. The pC system is the lightest studied one, and the pTa is extremely asymmetrical system in which differential transverse flow of protons and pions have ever been detected for these particles. In agreement with predictions of a transversely moving thermal model, the strength of proton differential transverse flow is found to first increase gradually and then saturate with the increasing transverse momentum in all systems. In the whole range of transverse momentum studied pions are preferentially emitted to the opposite direction of the proton transverse flow (i.e. anti-flow) due to stronger shadowing effects. The differential flow data for both protons and pions, a dependence of the the temperatures and flow velocity b on mass numbers of projectile A_P and target A_T provide a more stringent testing ground for relativistic heavy-ion reaction theories. Detailed comparisons with predictions of relativistic transport models on the differential flow will be useful to extract more reliable information about the nuclear EOS. The data obtained from film detectors (SKM-200—GIBS - the two meter streamer chamber and PBC-500 - the propane bubble chamber), utilized at JINR. The quark gluon string and the ultrarelativistic quantum molecular dynamics models (QGSM, UrQMD) satisfactorily describe the experimental results. *© 2017 Bull. Georg. Natl. Acad. Sci.*

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

The ultimate goal of high energy heavy-ion studies is to investigate nuclear matter under extreme conditions of high density and temperature [1]. In particular, extensive experimental and theoretical efforts have been devoted to probe the nuclear Equation of State (EOS), to identify the Quantum Chromodynamics (QCD) phase transition and to study properties of the Guark-Gluon Plasma (QGP) which is a novel form of matter. New information extracted from these studies is critical to many interesting questions in both nuclear physics and astrophysics. It is thus fundamentally important to find sensitive experimental probes of hot and dense nuclear matter. The collective phenomena found in heavy-ion collisions [2, 3], such as the transverse (sideward directed) and elliptic flow of nuclear matter, have been shown to be among the most sensitive probes of the nuclear EOS. The transverse flow is the sideward deflection of nuclear matter moving forward and backward in the reaction plane. The transverse flow has been observed for nucleons, nuclear fragments and newly produced particles [4-9]. Collective flow constitutes in important observable [10] 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 [11, 12].

The collective flow of charged particles has been first observed at the Bevalac by the Plastic Ball and Streamer Chamber Collaborations. The flow continued to be explored at Berkeley and at GSI, and further at AGS and at CERN/SPS accelerators. By now, the collective flow effects were investigated in nucleus-nucleus interactions over a wide range of energies, from hundreds of MeV up to 5.02TeV [13–15]. Especially, around 4 GeV/nucleon where a transition from ”squeeze-out” perpendicular to the reaction plane to the in-plane flow is expected, a number of flow measurements have been carried out at the AGS/BNL and the JINR/DUBNA [16-22].

In order to study the properties of nucleus-nucleus interactions, the collective flows of protons, pions and Λ-hyperons were previously investigated [18–22] by the authors of the present paper at beam energies of 3.4 and 3.7AGeV. According to the study, the flow parameters of protons and negative pions increase at an increase of the mass of projectile and target nuclei $((A_p + A_T)^{1/2})$ in ^{2}H+C, He+C, Li+C, C+C, C+Ne, ^{2}H+Ta, He+Ta, C+Cu, C+Ta collisions and in in nucleon-nucleus interactions also p+C and p+Ta (10 GeV/c). Clear evidence of the transverse and elliptic flow effects for protons and p^--mesons were obtained in all colliding systems, obtained within the SKM-200-GIBS set-up and within the 2 m Propane Bubble Chamber of JINR. From the transverse momentum and azimuthal distributions of protons and p^--mesons with respect to the reaction plane defined by participant protons, the flow F (a measure of the collective transverse momentum transfer in the reaction plane) and the parameter a_2 (a measure of the anisotropic emission strength) have been extracted. The flow effects increase with the mass of the particle and the mass number of target A_T. The scaled flow $F_s=F/(A_P^{1/3}+A_T^{1/3})$ were used for comparison of transverse flow results of SKM-200-GIBS with flow data for various energies and projectile/target configurations. The F_s demonstrates a common scaling behaviour of protons flow values for different energies (Bevalac, GSI/SIS, Dubna, AGS, SPS) and systems. Focusing on the total transverse flow, i.e., integrated over transverse momentum, these studies have revealed much interesting physics [23-26], thus the differential transverse flow of protons and pions in central C-Ne and C-Cu collisions at a beam energy of 3.7 Gev/nucleon were measured at the SKM-200-GIBS setup of JINR. The strength of proton differential transverse flow is found to first increase gradually and then saturate with the increasing transverse momentum [27]. In the present work, we report results of a differential transverse flow analysis as a function of transverse momentum for protons and pions in HeLi and (p, d, He, C)-(C,Ta) (4.2, 4.5 and 10 AGeV/c) collisions measured at the SKM-200-GIBS and PBC-500 setups of JINR. Moreover, characteristics of protons and pions, emitted from those collisions, were determined and provided for comparison at the different energies. The dependence of these correlations on the projectile (A_p) and target (A_T) nucleus were investigated.

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 [28] 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, ^{2}HC, HeC collisions in propane (C_3H_8) and the processing of the data including particle identification and corrections are described in detail in Refs. [29, 30]. The analysis produced 4581 events of ^{2}HC, 1424 of ^{2}HTa, 9737 of HeC, 1532 of HeTa (at an energy of 3.4 GeV/nucleon), 5882 and 16509 events of pC interactions at the momenta of 4.2 and 10 GeV/c, respectively, and 2342 events of pTa (at 10 GeV/c) collisions.

The protons with momentum p < 150MeV/c were not detected within the PBC-500 as far as their track lengths are less than 2mm (p+C interactions), and protons with p < 200MeV/c were absorbed in the Ta target plate (the detector biases). Thus, the protons with momentum larger than 150MeV/c were registered in p+C interactions, and the protons with p ≥ 250MeV/c in p+Ta 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 $N_{particles} \geq 3$ were required for the reliable determination of the correlation coefficients.

Differential Flow of Nucleons and Pions

Several different methods were utilized for analyzing flow effects in relativistic nuclear collisions, among them the transverse momentum analysis [3] and Fourier expansion of particle azimuthal angle distributions [31, 32] were most widely used. It is known that, the differential analysis of the flow strength as a function of transverse momentum is more useful in revealing detailed properties of the hot and dense matter, see, e.g. [9, 23–26]. In [27] we adopted the method of differential flow analysis first used by the E877 collaboration in ref. [33]. Let N+(N–) be the number of particles emitted in the same (opposite) direction of the transverse flow near projectile rapidity, then the ratio $R(p_t) = (dN^+/dp_t)/(dN^-/dp_t)$ as a function of p_t is a direct measure of the strength of differential flow near the projectile rapidity. It was shown experimentally that more detailed information about the collective flow can be obtained by studying this ratio [33]. The differential flow data also provides a much more stringent test ground for relativistic heavy-ion reaction theories. It was shown theoretically by Li et al in ref. [34] and Voloshin in ref. [35] that the ratio R(pt) at high p_t is particularly useful for studying the EOS of dense and hot matter formed in relativistic heavy-ion collisions.

Several theoretical models are proposed for nucleus-nucleus collisions at high energy. We used the Quark Gluon String Model (QGSM) [36, 37] and Ultra-relativistic Quantum Molecular Dynamics Model (UrQMDM) [38-40] for comparison with experimental data. The QGSM is based on the Regge and string phenomenology of particle production in inelastic binary hadron collisions. The UrQMD model is now widely applied for simulations of particle production and flow effects in various nucleus-nucleus interactions [41, 42], although its original design was directed towards high energies. We generated CC (2.65 fm) and CTa (6.53 fm) interactions by QGSM and dC (2.79 fm), HeC (2.79 fm), dTa (5.31 fm) and HeTa (5.46 fm) interactions by UrQMDM, as well as 50000 events for dC, HeC, CC, CTa and 1000 events for dTa, HeTa collisions.

The data were analysed event by event using the transverse momentum technique of P.Danielewicz and G.Odyniec [3]. The reaction plane was defined for the paricipant.Within the transverse momentum method, the direction of **b** is estimated event-by-event in terms of the vector constructed from particle transverse momenta:

$$\mathbf{Q_j} = \sum_{\substack{i=1 \\ i \neq j}}^{n} \mu_i \mathbf{P_i}^{\perp} , \tag{1}$$

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 [43]. Projection of the transverse momentum of each particle onto the estimated reaction plane is:

$$P_X{'}_j = \frac{\mathbf{P}_j^{\perp} \cdot \mathbf{Q}_j}{\left|\mathbf{Q}_j\right|} . \tag{2}$$

The dependence of the projection on the rapidity y was constructed for each interacting nuclear pair. For the further analysis, the average transverse momentum in the reaction plane, $\langle P_{x\,j}^{r}(y)\rangle$, is obtained by averaging over all events in the corresponding intervals of rapidity. Due to the finite number of particles used in the construction of the vector Q in (1), the estimated reaction plane fluctuates in the azimuth around the direction of the true reaction plane. Because of those fluctuations, the component P_x of a particle momentum in the true reaction plane is systematically larger than the component $P_X{'}$ in the estimated plane,

$$\langle \cos \Phi \rangle = \frac{\langle \mu P_X{'} \rangle}{\langle \mu P_X \rangle} , \tag{3}$$

where Φ is the angle between the true and estimated reaction planes. The overall correction factor $k=1/\langle\cos \Phi\rangle$ is a subject of a large uncertainty [3, 20], especially for low multiplicity events. In [4] the method for the definition of the correction factor was proposed. Each event is randomly divided into two almost equal sub-events and the vectors Q_1 and Q_2 are constructed. Then the distribution of the azimuthal angle F between these two vectors was obtained, and the average $\langle\cos \Phi\rangle$ was determined.

The experimental selection criteria were applied to the generated events and the protons with deep angles greater than 60~grad were excluded, because in the experiment the registration efficiency of such vertical tracks is low. From the generated events, events with two protons were selected for C-target p>150 MeV/c and for Ta-target p > 200 MeV/c . First, in these collisions we examine the transverse momentum spectra of protons detected on the same dN^+/dp_t and opposite dN^-/dp_t side of the transverse flow (reaction plane) in these interactions, respectively. The chosen rapidity ranges are around the projectile rapidity of Y_{proj}=2.28. In these rapidity ranges particles with high transverse momenta must have suffered very violent collisions and thus originate most likely from the very hot and dense articipant region. On the other hand, particles with low transverse momenta are mostly from cold spectators. It is seen that there is a clear excess of protons emitted to the same side of the directed flow for all our systems. In these collisions the spectra show typical exponential behaviour for $p_t \geq 0.2$ GeV/c. The spectra for particles in the same and opposite directions of the transverse flow are approximately parallel to each other at p_t larger than about 0.7 GeV/c. These findings are similar to those observed by the E877 collaboration for protons in central Au-Au collisions at a beam energy of 10.8 GeV/nucleon [33].

The above observations can be understood qualitatively within the transversely moving thermal model of Li et al. [34]. Assuming that all or a fraction of particles in a small rapidity bin around Y_{proj} are in local thermal

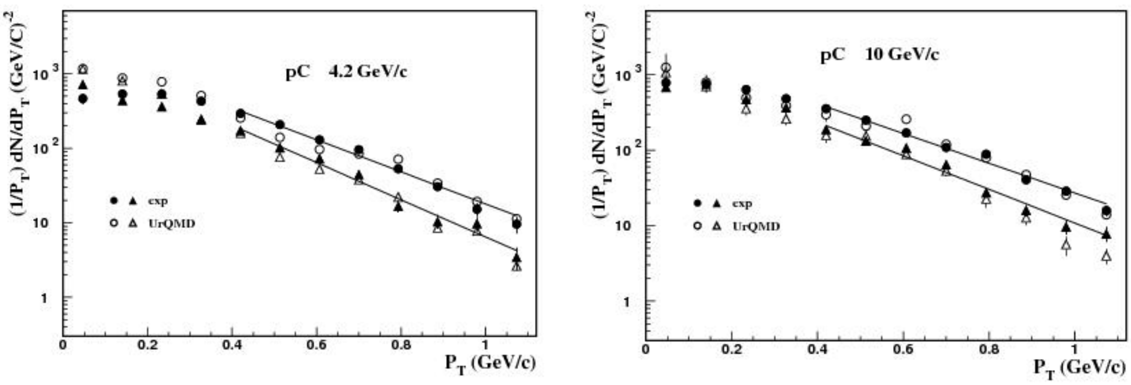

Fig. 1. The transverse momentum distributions of protons emitted in the reaction plane to the same and opposite side in experimental (Õl:▲) and UrQMD generated (**o,** △**)** pC (4.2 and 10 GeV/c) collisions. The lines are results of fitting by Eq. (5) at high *pt* (see text).

equilibrium at a local temperature T, and the center of mass of these particles are moving with a velocity β along the transverse flow direction +x in the reaction plane, then the transverse momentum spectrum of these particles can be written as

$$\frac{d^3N}{p_t dp_t d\phi dy} = c_\gamma (E - \beta p_t \cos(\phi)) e^{-\gamma(E-\beta p_t \cos(\phi))/T} \tag{4}$$

where c_γ is a normalization constant, $\gamma = \sqrt{1-\beta^2}$ and ϕ is the azimuthal angle with respect to the reaction plane. The transverse momentum spectra for particles emitted in the same $dN^+/P_t dP_t$ and opposite $dN^-/P_t dP_t$ directions of the transverse flow are then

$$\frac{dN_\pm}{p_t dp_t} = C_\pm e^{-\gamma E/T} \left(\gamma E \mp T\alpha\right) e^{\pm\alpha} \tag{5}$$

Where $\alpha = \gamma\beta p_t / T$. These distributions reduce to simple exponents:

$$\frac{dN_\pm}{p_t dp_t} = e^{(-p_t/T^\pm_{efff})} \tag{6}$$

at high transverse momenta p_t. In the above equation, the inverse slopes or effective temperatures T_{eff} in the semilogarithmic plot of the spectra at high p_t are

$$\frac{1}{T^\pm_{eff}} = -\lim_{p_t \to \infty} \left[\frac{d}{dp_t} \ln\left(\frac{dN_\pm}{p_t dp_t}\right) \right] = \frac{\gamma}{T}(\cosh(y) \mp \beta) \,. \tag{7}$$

In general, the inverse slope $1/T^\pm_{eff}$ reflects combined effects of the temperature T and the transverse flow velocity β. For the special case of considering particles at midrapidity, β is zero and the effective temperatures are equal to the local temperature T of the thermal source. Otherwise, one normally expects $T^+_{eff} > T^-_{eff}$. For high energy heavy ion collisions in the region of 1 to 10 GeV/nucleon, b is much smaller than cosh(y) around the projectile rapidity, thus one again expects $T^+_{eff} \approx T^-_{eff}$ at high transverse momenta, i.e two approximately parallel spectra $dN^+/P_t dP_t$ and $dN^-/P_t dP_t$ at high p_t. The distributions dN^+/dP_t and dN^-/dP_t were fitted by eq.(5)

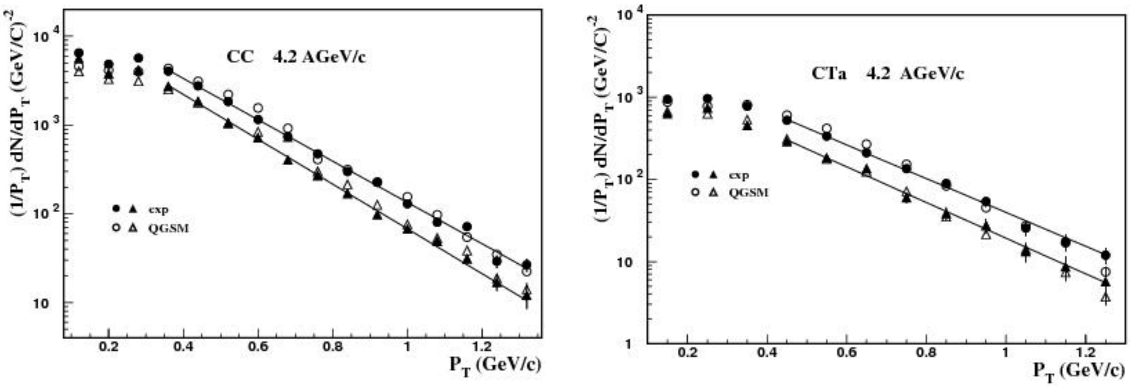

Fig. 2. The transverse momentum distributions of protons emitted in the reaction plane to the same and opposite side in experimental (Õl:▲) and QGSM generated (**o,** △**)** C(C, Ta) (4.2 AGeV/c) collisions. The lines are results of fitting (see text).

in the corresponding rapidity intervals of systems and from the dN^+/dP_t spectra at high p_t (p_t >0.6 GeV/c) the temperature T and flow velocity were obtained (Table 1.) The results of fitting are superimposed on spectra in Figs. 1, 2. There is a fairly good agreement between the experimental and the theoretical distributions.

To study the strength of differential transverse flow, we compare in Fig. 3 the ratios $R(p_t)$ as a function of p_t for the discussed here collisions. It is seen that the ratios increase gradually at low p_t and reach a limiting value. The values of $R(p_t)$ are greater than one in the whole transverse momentum range, indicating that protons are emitted preferentially in the flow direction at all transverse momenta. It is an unambiguous signature of the sideward collective flow. Similar results have also been obtained by the E877 collaboration for protons in Au-Au collisions at 10.8 GeV/nucleon where the ratio $R(p_t)$ increases with p_t and finally saturates at about 2. The saturation of $R(p_t)$ at high p_t is also what one expects within the transversely moving thermal model. From Eq. (5) one obtains readily

$$R\left(p_t\right)=\frac{dN^{+}/p_t dp_t}{dN^{-}/p_t dp_t}=\frac{C_+}{C_-}\frac{1-\beta p_t/E}{1+\beta p_t/E}e^{2p_t\gamma\beta/T}. \quad (8)$$

This ratio normally increases with p_t for any given values of T and β, but it becomes almost a constant at high p_t for very small b/T ratios. In relativistic heavy-ion collisions, particles are emitted continuously at different freeze-out temperatures during the whole reaction process. In particular, particles with high p_t are mostly emitted in the early stage of the reaction from the most violent regions where the local temperatures are high. Since the ratio $R(p_t)$ varies very slowly with p_t for low β/T ratios, one thus expects an approximately constant value of $R(p_t)$ at high p_t. At low transverse momenta, however, $R(p_t)$ is affected mostly by particles from the cold spectators, and the ratio $R(p_t)$ approaches one as p_t goes to zero.

Now we turn to the analysis of differential transverse flow for negative pions in these reactions. Shown in Fig. 4 are the $R(p_t)$ ratios for negative pions in the rapidity selected range of the systems. The solid lines are the linear fits to the experimental data to guide the eye. In the (d,He,C)C da CTa (4.2 A GeV/c) collisions the ratio $R(p_t)$ is less than one in the whole range of transverse momentum, indicating pions direction to the opposite side of protons (anti-flow). Moreover, the strength of the pion differential transverse flow decreases linearly with p_t and reaches about 0.4 ÷ 0.6 GeV/c. It is necessary to mention here that a similar target dependence of the pion preferential emission in asymmetric nucleus-nucleus collisions was first observed by the DIOGENE collaboration [44]. Our results are consistent with theirs. This target dependence of the appar-

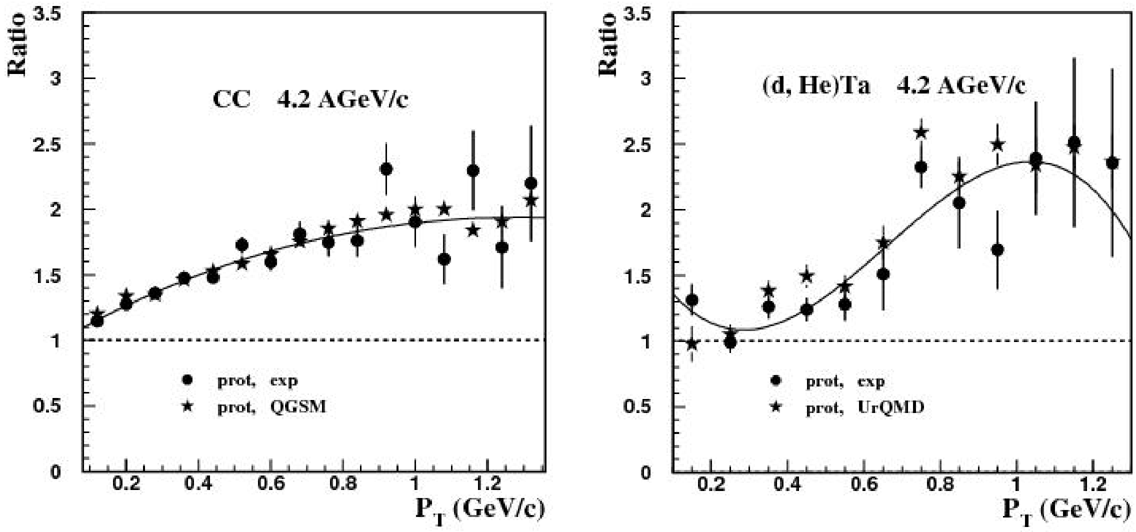

Fig. 3. Ratios of the yield of protons emitted to the same and opposite side of the transverse flow as a function of P_T in experimental (O) and generated (★) CC and (d, He)Ta (4.2 AGeV/c) collisions. The curves are logarithmic fits to the data to guide the eye.

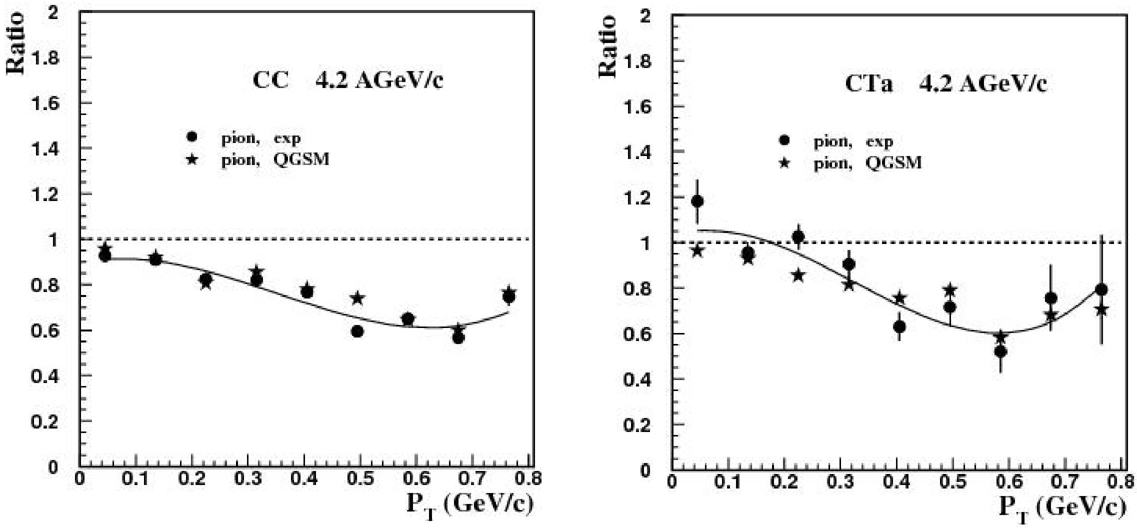

Fig. 4. Ratios of the yield of pions emitted to the same and opposite side of the transverse flow as a function of P_T in experimental (O) and QGSM generated (★) C(C, Ta) (4.2 AGeV/c) collisions. The curves are logarithmic fits to the data to guide the eye.

ent pion transverse flow was explained quantitatively by nuclear shadowing effects of the heavier target within nuclear transport models [45, 46]. Our results on the pion differential transverse flow and its dependence on the target are thus also understandable.

Conclusion

The study of differential transverse flow of protons and pions in experimental and generated **(QGSM, UrQMD)** HeLi and (p, d, He, C)-(C,Ta) (4.2, 4.5 and 10 AGeV/c) collisions have been carried out. The pC system is the lightest studied one, and the pTa is extremely asymmetrical system in which differential transverse flow of protons and pions have ever been detected for these particles.

1. From the transverse momentum distributions of protons emitted in the reaction plane to the same and opposite side of the transverse flow the temperatures and flow velocity b have been extracted in all these

Table 1. Differential transverse flow and T parameters of protons emitted in the reaction plane to the same and opposite side in HeLi and (p, d, He, C)-(C,Ta) (4.2, 4.5 and 10 AGeV/c) collisions. (the result of the approximation of cosn^* distributions using equation (1), see text)

	N_{even}	:	T
pC 4.2 GeV/c	5882	0.0156±0.0044 0.0185±0.0045	82.1±3.4 88.6±3.5
pC 10 GeV/c	16509	0.0214±0.0061 0.0244±0.0062	126.7±3.7 129.5±3.7
dC	4581	0.0182±0.0047 0.0220±0.0050	86.7±3.4 99.3±3.5
HeC	9739	0.0197±0.0041 0.0224±0.0042	110.7±2.4 117.3±2.5
He(Li, C)	4020 2127	0.0217±0.0049 0.0247±0.0051	110.4±4.1 112.2±4.2
CC	15962	0.0207±0.0032 0.0239±0.0033	113.7±1.8 124.2±1.9
pTa	2342	0.0236±0.0069 0.0200±0.0065	134.4±4.5 126.9±4.4
(d,He)Ta	1424 1532	0.0257 0.0054 0.0223 0.0052	125.1± 3.2 123.0 ±3.1
CTa	2469	0.0319± 0.0048 0.0281± 0.0045	171.5 5.5 158.1 5.3

interactions. The observations are in qualitative agreement with predictions of a transversely moving thermal model.

2. In the whole range of transverse momentum studied, pions are found to be preferentially emitted to the opposite direction of the proton transverse flow (i.e. anti-flow), which was explained by nuclear shadowing effects only of the heavier target (**Ta).** The results on the pion differential transverse flow and its dependence on the light targets (Li, C), are thus also understandable.

3. The differential flow data for both protons and pions, a dependence of the the temperatures and flow velocity b on mass numbers of projectile A_P and target A_T provide a more stringent testing ground for relativistic heavy-ion reaction theories. Detailed comparisons with predictions of relativistic transport models on the differential flow will be useful to extract more reliable information about the nuclear EOS.

4. The QGSM and UrQMDM satisfactorily describe the distributions of protons and pions differential flows for all systems.

Acknowledgements

The authors express their deep gratitude to A. Galoyan and V. Uzhinsky for modeling of all the collisions by UrQMD model and very fruitful remarks. One of us (L. Ch) would like to thank the board of directors of the Laboratory of Information Technologies of JINR for the warm hospitality.

This work was partially supported by the Georgian Shota Rustaveli National Science Foundation under Grant DI/38/6-200/13.

ფიზიკა

დიფერენციალური განივი გამოდინებები He(Li, C) და (p, d, He, C)(C, Ta) დაჯახებებში 4,2; 4,5 და 10 AGeV/c იმპულსის დროს

ლ. ჩხაიძე*, გ. ჩლაჩიძე, თ. ჯობავა*, ლ. ხარხელაური***

** ივანე ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტი, მაღალი ენერგიების ფიზიკის ინსტიტუტი, თბილისი საქართველო*
*** ფერმის ნაციონალური ამაჩქარებლის ლაბორატორია, ბატავია, ილინოისი, აშშ*

(წარმოდგენილია აკადემიის წევრის ა. კვინიხიძის მიერ)

pC (4,2 GeV/c, 10 GeV/c), (d, He)C, CC, (d, He)Ta (4,2 AGeV/c), He(Li, C) (4,5 AGeV/c) და pTa (10 GeV/c) დაჯახებებში პროტონებისა და პიონების დიფერენციალური განივი გამოდინებები დამზერილ იქნა განივი იმპულსის ფუნქციის სახით. pC სისტემა არის ყველაზე მსუბუქი და pTa კი ექსტრემალურად ასიმეტრიული იმ წყვილებს შორის, რომლებშიც დღემდე შესწავლილა დიფერენციალური განივი გამოდინებები პროტონებისა და პიონებისათვის. განივად მოძრავი თერმული მოდელის წინასწარმეტყველების თანახმად, განივი იმპულსის ზრდისას პროტონების დიფერენ-ციალური განივი გამოდინება თავდაპირველად თანდათან იზრდება, შემდეგ კი თითქოს გაჯერებაზე გადის ყველა განხილული სისტემისთვის. შესწავლილი განივი იმპულსების არეში პიონები გამო-სხივდებიან უპირატესად პროტონების გამოდინების საწინააღმდეგო მიმართულებით, რაც აიხსნება ძლიერი ეკრანირების ეფექტებით. პროტონებისა და პიონებისათვის დიფერენციალური გამოდინებები და მათი დამახასიათებელი პარამეტრების ტემპერატურისა და გამოდინების =სიჩქარის დამოკი-დებულება A_P-დამცემისა და A_T-სამიზნის მასური რიცხვებისაგან იძლევა რელატივისტური თეორიების შემოწმების უფრო მყარ საფუძველს. დიფერენციალური გამოდინებების დეტალური ანალიზი და შედარება რელატივისტური გადატანითი მოდელის წინასწარმეტყველებასთან უფრო დამაჯერებელ ინფორმაციას მოგვცემს ბირთვული მატერიის განტოლების (EOS) შესახებ. ექსპერიმენტული მასალა მიღებულია ბირთვული კვლევების გაერთიანებული ინსტიტუტის (JINR) მაღალი ენერგიების ლაბორატორიაში ფილმური დეტექტორების (SKM-200-GIBS - ორმეტრიანი სტრიმერული კამერა და PPBC-500 - პროპანის ორმეტრიანი ბუშტოვანი კამერა) საშუალებით. კვარკ გლუონური სიმური და ულტრა რელატივისტური კვანტურ მოლეკულურ დინამიკური მოდელები (QGSM და UrQMD) ცდომილების ფარგლებში დამაკმაყოფილებლად აღწერს ექსპერიმენტულ შედეგებს.

REFERENCES

1. Dusling K., Li W. and Schenke B. (2016) Novel collective phenomena in high-energy proton–proton and proton–nucleus collisions. *Int. J. Mod. Phys.*, **25E:** 1630002.
2. Ollitrault J.-Y. (1992) Anisotropy as a signature of transverse collective flow. *Phys. Rev.*, **46D**: 229.
3. Danielewicz P. and Odyniec G. (1985) Transverse momentum analysis of collective motion in relativistic nuclear collisions. *Phys. Lett.*, **157B**: 146.
4. Westfall G. D. (1998) The impact parameter and isospin dependence of the disappearance of flow. *Nucl. Phys.*, **630A**: 27.
5. Gutbrod H. H., Poskanzer A. M. and Ritter H. G. (1989) Plastic Ball Experiments. *Rep. Prog. Phys.*, **52**: 1267.
6. Reisdorf W and Ritter H. G. (1997) Collective flow in heavy-ion collisions. *Ann. Rev. Nucl. Part. Sci.*, **47**: 663.
7. Ogilvie C. et al. (1998) Au + Au reactions at the AGS: Experiments E866 and E917. *Nucl. Phys.*, **638A**: 57.
8. Rai G. (2001) Hadronic flow in 2-A-GeV to 8-A-GeV Au + Au collisions. *Nucl. Phys.*, **681A**: 181.
9. Ackermann K. et al. (2001) Elliptic flow in Au + Au collisions at (S(NN))**(1/2) = 130 GeV. *Phys. Rev. Lett.*, 86, 402.
10. Pinkenburg C. et al. (2002) Production and collective behavior of strange particles in Au + Au collisions at 2-AGeV - 8-AGeV. *Nucl. Phys.*, **698A**: 495.
11. Agakishiev G. et al. (2012) Directed and elliptic flow of charged particles in Cu+Cu collisions at “sNN = 22.4 GeV. *Phys. Rev.*, **85C**: 014901.
12. Aamodt K. et al. (2010) Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV. *Phys. Rev. Lett.*, **105**: 252302.
13. Herrmann N., Wessels J.P., Wienold T. (1999) Collective flow in heavy ion collisions. *Ann. Rev. Nucl. Part. Sci.*, 49, 581.
14. Reisdorf W. et al. (2007) Collective flow in heavy ion collisions. *Nucl. Phys.*, **781A**, 459.
15. Abelev B. B. et al. (2014) Multiparticle azimuthal correlations in p -Pb and Pb-Pb collisions at the CERN Large Hadron Collider. *Phys. Rev.*, **90C**, 054901.
16. Adamovich M. et al. (1999) Flow effects in Kr-84 induced collisions in emulsion at 0.95-GeV per nucleon. *Eur. Phys. J.*, **6A**: 427.
17. Simic Lj. and Milosevic J. (2001) Event anisotropy in 4.2-GeV/A/c C+C collisions. *J. Phys.*, **27G**: 183.
18. Chkhaidze L. et al. (1997) Study of collective matter flow in central C - Ne and C - Cu collisions at energy of 3.7-GeV per nucleon. *Phys. Lett.*, **411B**: 26.
19. Chkhaidze L. et al. (2004) Study of collective flow effects in CC collisions at a momentum of 4.2-GeV/c per nucleon. *Phys. Atom. Nucl.*, **67**, 693.
20. Chkhaidze L. et al. (2007) Collective Flow of Protons and Negative Pions in Nucleus-Nucleus Collisions at Momentum of 4.2 / 4.5-10/c. *Nucl. Phys.*, **794A**: 115.
21. Chkhaidze L. et al. (2011) Collective flows of protons and pi-mesons in H-2 + C, Ta and He + C, Ta collisions at 3.4 GeV/nucleon. *Phys. Rev.*, **84C**: 064915.
22. Chkhaidze L. et al. (2016) Study of collective flows of protons and A” -mesons in p(C, Ta) and He(Li, C) collisions at momenta of 4.2, 4.5 and 10 AGeV/c. *Eur. Phys. J.*, **52A**: 351.
23. Li B. A. and Sustich A.T. (1999) Differential flow in heavy ion collisions at balance energies. *Phys. Rev. Lett.*, **82**: 5004.
24. Li B. A., Sustich A. T. and Zhang B. (2001) Proton differential elliptic flow and the isospin dependence of the nuclear equation of state. *Phys. Rev.*, **64C**, 054604.
25. Gyulassy M., Vitev I., Wang X.-N. (2001) High p(T) azimuthal asymmetry in noncentral A+A at RHIC. *Phys. Rev. Lett.*, **86**: 2537.
26. Andronic A. et al. (2001) Differential directed flow in Au+Au collisions. *Phys. Rev.*, **64C**: 041604.
27. Chkhaidze L. et al. (2002) Differential transverse flow in central C-Ne and C-Cu collisions at 3.7 GeV/ nucleon. *Phys. Rev.*, **65C**: 054903.
28. Anikina M. et al. (1986) Pion production in inelastic and central nuclear collisions at high-energy. *Phys. Rev.*, **33C**: 895.
29. Agakishiev G.N. et al. (1986) Λ and K^0 production in Cp and CC interactions at 4.2-GeV/c per nucleon (in Russian). *Yad. Fiz.*, **43**: 366.
30. Armutlijski D. et al., (1987) Multiplicity, momentum and angular distributions of protons in the interactions of light nuclei with carbon nuclei at 4.2-GeV/c per nucleon (in Russian)*Yad. Fiz.*, **45**: 1047.
31. Ollitrault J.-Y. (1992) Anisotropy as a signature of transverse collective flow. *Phys. Rev.*, **46D**: 229.
32. Voloshin S. and Zhang Y. (1996) Flow study in relativistic nuclear collisions by Fourier expansion of Azimuthal particle distributions. *Z. Phys.*, **70C**: 665.

33. Barrette J. et al. (1995) Directed flow and particle production in Au + Au collisions from experiment E877 at the AGS. *Nucl. Phys.*, **590A**: 259.
34. Li B. A., Ko C. M. and Li G. Q. (1996) P(t) dependence of transverse flow in relativistic heavy ion Collisions. *Phys. Rev.*, **54C**: 844.
35. Voloshin S.A. (1997) Transverse radial expansion and directed flow. *Phys. Rev.*, **55C**: R1630.
36 Amelin N.S., Staubo E.F., Csernai L.P. et al. (1991) Strangeness production in proton and heavy ion collisions at 14.6-A/GeV. *Phys. Rev.*, 44C: 1541.
37. Amelin N. S. (1986) Colli - Monte Carlo generator of soft hadronic, hadron nucleus and nucleus nucleus collisions at high-energies (in Russian). JINR P2-86-837, Dubna.
38. Bass S. A., Belkacem M., Bleicher M. et al. (1998) Microscopic models for ultrarelativistic heavy ion collisions. *Prog. Part. Nucl. Phys.*, **41**: 225.
39. Bravina L.V., Brandstetter M., Gorenstein M. I. et al. (1999) Local thermal and chemical equilibration and the equation of state in relativistic heavy ion collisions. *J. Phys.*, **25G**: 351.
40. Botvina A. S., Iljinov A. S., Mishustin I. N. et al. (1987) Statistical simulation of the breakup of highly excited nuclei. *Nucl. Phys.*, **475A**: 663.
41. Nasim Md., Kumar L., Netrakanti P.K., Mohanty B. (2010) Energy dependence of elliptic flow from heavy-ion collision models. *Phys. Rev.*, **82C**: 054908.
42. Li Q., Li Z., Soff S., Bleicher M., Stoecker H. (2006) Probing the equation of state with pions. *J. Phys.*, **32G**: 151.
43. Beavis O. (1992) Collective motion in Ar + Pb collisions at beam energies between 400-MeV/nucleon and 1800-MeV/nucleon. *Phys. Rev.*, **45C**: 299.
44. Gosset J. et al. (1989) Nuclear collective flow and charged pion emission in Ne - nucleus collisions at ee/a = 800-MeV. *Phys. Rev. Lett.*, **62**:1251.
45. Li B. A., Bauer W. and Bertsch G. F. (1991) Preferential emission of pions in asymmetric nucleus-nucleus collisions. *Phys. Rev.*, **44C**: 2095.
46. Li B. A., (1994) Nuclear shadowing effect in relativistic heavy ion collisions. *Nucl. Phys.*, **570A**, 797.

Received May, 2017