Study of collective flow in p(C, Ta) and HeLi collisions at a momentum of 4.2 GeV/c/N

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Abstract. Collective flow of protons and pions has been studied in p(C, Ta) and HeLi (4.2 GeV/c/N) collisions has been studied of the most lights presented pC and HeLi systems for the first time. The data has been obtained by streamer (SKM-GIBS) and Propane Bubble (PBC-500) chamber Collaborations of JINR. The directed (in-plane) flow of protons have been observed in the above mentioned interactions, the elliptic (out-off-plane) flow of pions – in p(C, Ta) collisions. In pC interactions the directed flow of pions is in the same directions as for protons, while in pTa collisions pions show antiflow behaviour.
The dependence of the flow F on the projectile (A_P) and target (A_T) mass numbers have been studied. The magnitude of flow is increasing with the mass numbers.These results, as well as our old experimental F-data, complements the general regularities. From the azimuthal distributions of protons with respect to the reaction plane the anisotropy parameter a_2 have been extracted.

Introduction

Multiparticle azimuthal correlations are being investigated very intensively with the goal to study the dynamics of relativistic nucleus collisions. The study of this effect in terms of the collective flow variables with respect to the reaction plane has turned out to be especially fruitful. Study of collective flows in nucleus-nucleus interactions at high energies, such as the bounce-off [1] of compressed mater in the reaction plane (called the directed flow) and the squeeze-out [2] of the participant matter out of the reaction plane – the elliptic flow, is very important to learn more about the nuclear equation of state (EOS) [3, 4]. Many different methods were proposed for experimental studies of the flows in relativistic nuclear collisions, of which the most commonly used is the transverse momentum analysis technique proposed by P. Danielewicz and G. Odyniec [5].

The Collective Flow Effects (CFE) have been already observed for different species (protons, antiprotons, light nuclei, pions, kaons and lambdas) and at a wide energy range: (0.1 - 1.8) GeV/nucleon at LBL Bevalac and GSI/SIS, by the Plastic-Ball [6], Streamer Chamber, EOS-TPC, FOPI, LAND, TAPS and KAOS collaborations, (2 - 4) GeV/nucleon at JINR, Dubna by the SKM-200-GIBS and Propane Bubble Chamber (PBC) collaborations (our results), (2 - 14) GeV/nucleon at Brookhaven AGS [7], by the E877, E895, E917 [8] collaborations; 60 and 200 GeV/nucleon at CERN SPS[9, 10], by the WA98 and NA49 collaborations [11], by the STAR and PHENIX collaborations at RHIC BNL and, more recently, 2.76 TeV by the ALICE collaboration at CERN, LHC.

During last several years we have studied multiparticle azimuthal correlations of protons, pions and Λ-hyperons in central and inelastic collisions (4.2-4.5 GeV/c/nucleon) within two experiments [12-17]. The data obtained in different experiments (EOS, E895, SKM-GIBS, PBC, E877) show a transition from negative (out-of-plane) to positive (in-plane) elliptic flow at a beam energy of E_{tr} ~ 4 GeV/nucleon. According to the transport model the value of this transition energy E_{tr} directly is connected with the nuclear EOS. Therefore, further study of the above mentioned collective phenomena at energies near E_{tr} is very important for a better determination of the EOS.

The phase transition in this energy region can be evidenced through the excitation functions of the emission flow. It explains the importance of study of the collective flow effects at energy of 3.7 GeV/nucleon performed by our group.

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

We have studied directed flow of protons and negative pions and participant protons are using for the determination of the reaction plane [14]. We present collective flow results of protons and pions in p(C, Ta) and HeLi collisions at energy of 3.4 GeV/nucleon. These results, as well as our old experimental F-data, complements the general regularities Therefore, these results obtained by us at energy of 3.4 GeV/nucleon seem to be interesting from the viewpoint of the well enrichment of existing results in the above mentioned energy region ($2.0 \leq E_{beam} \leq 8.0$ GeV/nucleon). Also, our new results with the ould one, complements the general regularities.

EXPERIMENRAL DATA

The data combine results obtained within the SKM-200 set-up and within the 2 m Propane Bubble Chamber (PBC-500) of JINR.

The SKM-200 setup consists of a 2 m streamer chamber placed in the magnetic field of 0.8T and of a triggering system. The streamer chamber based spectrometers SKM-200 are electronic track detectors and allow to detect the nucleus-nucleus interactions in the fiducial volume of the chamber in "4π" geometry.The streamer chamber has been exposed to a beam of He nuclei accelerated in the JINR synchrophasotron to the momentum of 4.2 A GeV/c [18]. The data on He-Li (4020) interactions have been obtained using the SKM-200.

PBC-500 has been 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 have been described in detail in Ref. [19]. The analysis produced 7150 events of pC and 2342 of pTa collisions. Three Ta-plates (140x70x1) mm^3 in size and mounted into the fiducial volume of the chamber at a distance of 93 mm from each other, served as a nuclear target (PBC-500). The final results of events scanning and measurements are recorded as Data Summary Tapes in the computers.

The reaction plane have been defined by participant protons, because the protons with momentum p<150 MeV/c have not been detected within the PBC-500 (as far as their track lengths l <2 mm) and protons with p<200 MeV/c are absorbed in Ta target plate (the detector biases). In the experiment, the projectile fragmentation products have been identified as those characterized by the momentum p > 3.5 GeV/c and angle $\Theta < 3°$ and the target fragmentation products -- by the momentum p < 0.25 GeV/c in the target rest frame. The last ones are mainly evaporated protons. The participants are protons with p > 0.25 GeV/c different from the projectile fragments.

Event by event analysis in studies of collective flow effects it is necessary to perform an identification of secondary charged particles. For this purpose the method of π^+ meson identification has been developed in our group analyzing pairs of nuclei. The identification has been carried out on the statistical basis assuming the similarity of π^- and π^+ mesons multiplicity, transverse momentum P_T and longitudinal momentum P_L spectra. After this identification the admixture of π^+ was reduced from (20-25) % to (5÷7) % for HeLi collisions, which made possible the exclusive analysis of the events [14].

THE DIRECTED FLOW OF PROTONS AND PIONS

We have investigated the directed flow of protons and pions in pC, pTa and HeLi collisions at energy of 3.4 GeV/nucleon using the transverse momentum analysis technique developed by P. Danielewicz and G. Odyniec [5]. The participant protons of the reaction plane definition have been applied for the flow effects study.

The analysis has been carried out in the laboratory system. To eliminate the correlation of the particle with itself (autocorrelations) for each particle we estimated the reaction plane, with contribution of that particle removed from the definition of the reaction plane.

In the transverse momentum analysis the collective effects are studied with respect of the reaction plane, which is defined (constructed) by the impact parameter vector **b** and the beam direction. In experiment the measurement of the **b** is not possible, therefore the vector sum of transverse momenta of the participant protons **Q** was introduced instead. In order to remove the autocorrelations, the reaction plane is estimated for each particle j, which is constructed from the transverse momenta of the other particles in the same event:

$$\mathbf{Q_j} = \sum_{\substack{i=1 \\ i \neq j}}^{n} \omega_i \mathbf{P_i}^{\perp}, \qquad (1)$$

where i is the particle index and ω_i the weight factor. The weight factor ω_i depends on the rapidity of the emitted particle i, $\omega_i = y_c - y_i$, where y_i is i-th particle rapidity, y_c is the middle rapidity of the presented nuclear systems [20]. Projection of the transverse momentum of each particle onto the estimated reaction plane is:

$$P_X{}'_j = \frac{\mathbf{P}_j^{\perp} \cdot \mathbf{Q}_j}{|\mathbf{Q}_j|} \qquad (2)$$

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, $<P'_{x\,j}(y)>$, is obtained by averaging over all events in the corresponding intervals of rapidity. From the mean transverse momentum dependence on rapidity, the so-called flow parameter, the slope of the momentum distribution at the middle rapidity, $F=d<P_x>/d(y)$, will be extracted (see Table 1). The flow parameter is a measure of the collective transverse momentum transfer in the reaction. Fig. 1-3 show the dependence of the $<P_{xj}(y)>$ on y. The data exhibits S-shape behaviour, which may be identified as collective flow of particles.

Table 1. Characteristics of the measured collision events, including event number **N** prior to multiplicity cut

	p-C	**He-Li**	**p-Ta**
$\mathbf{N_{event}}$	7150	4020	2342
$\mathbf{F^{prot}}$ **(MeV/c)**	76.8± 7.0	84.4 ± 10.8	106.9 ±9.0
$\mathbf{F^{pion}}$ **(MeV/c)**	15.6 ± 6.2	---------	16.8 ±6.8
$\mathbf{a_{2prot}}$	0.041±0.016	0.043±0.017	0.064±0.014

For the analysis minimum three particles $N_{particles} \geq 3$ are required for the reliable determination of the reaction plane. Figs. 1, 2 present the directed flow effects of protons and negative pions in pC and pTa collisions. Fig 3 shows the dependence of P_X (Y) on Y for protons in He-Li collisions for identification and no-identification data. For our systems, we have investigated the directed flow of pions. Pions with momentum p>50 MeV/c have been detected within the detector. There is no auto-correlations for pions, because the reaction plane are determined by protons.

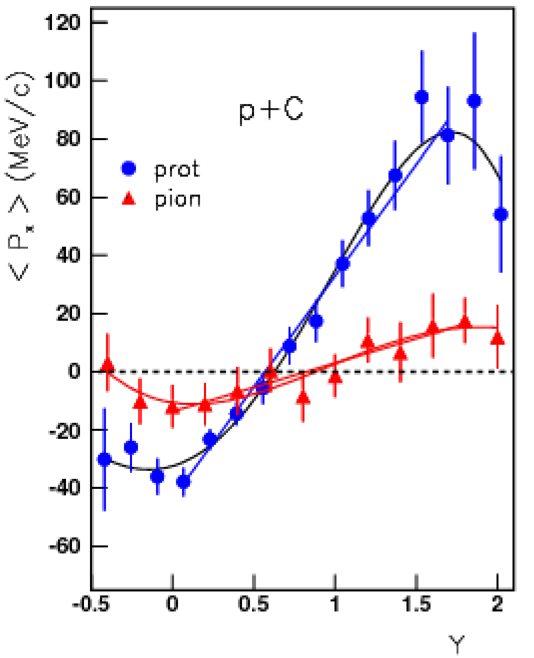

Fig. 1. The dependence of <P_X(Y)> on the rapidity Y_{LAB} for protons (●) and pions (▲) in pC collisions. Straight lines stretches represent the slope of data at midrapidity, obtained by fitting the data with 1-st order polynomial within the corresponding intervals of rapidity. The curved lines guide the eye over data.
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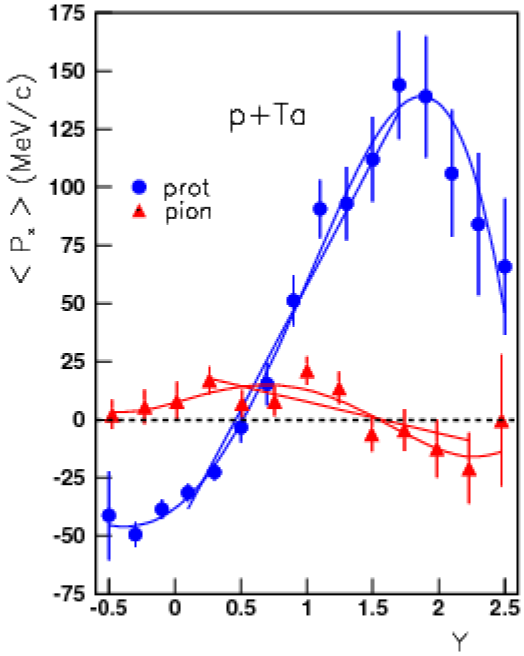

Fig. 1. The dependence of <P_X(Y)> on the rapidity Y_{LAB} for protons (●) and pions (▲) in pTa collisions. Straight lines stretches represent the slope of data at midrapidity, obtained by fitting the data with 1-st order polynomial within the corresponding intervals of rapidity.

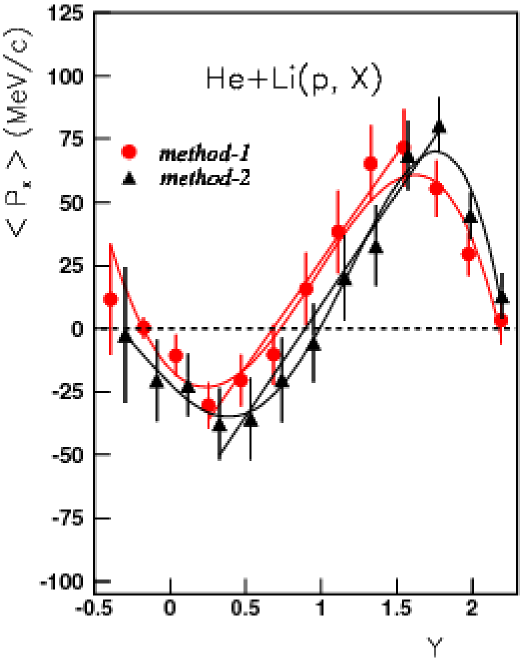

Fig. 3. The dependence of $\mathbf{P_X}$ **(Y)** on **Y** for protons in **He-Li** collisionsin: ● -- the identification data and ▲ -- the no-identification data.

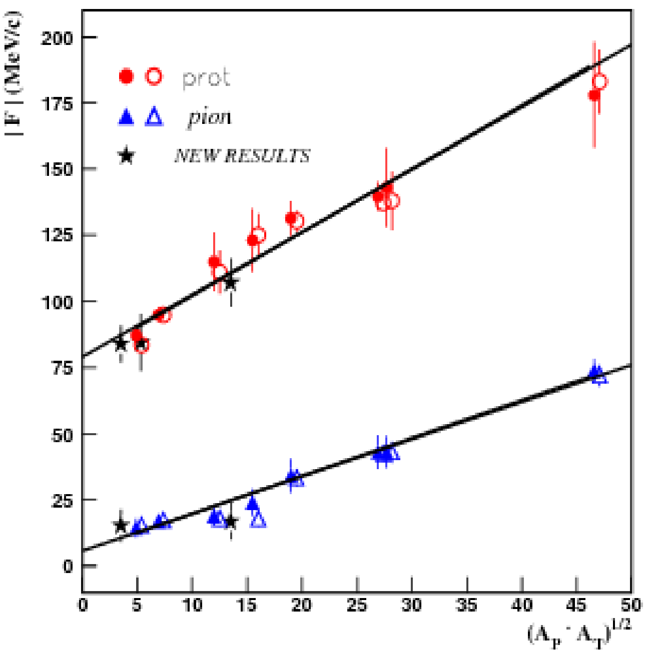

Fig. 4. The dependences of │F│-directed flow parameter on geometric mean of projectile and target masses $(A_P \cdot A_T)^{1/2}$ for protons (upper) and pions (down) in pC, ^{2}HC, HeLi, HeC, CC, pTa, CNe, ^{2}HTa, HeTa, CCu and CTa collisions (together with our earlier experimental data), closed symbols correspond to experimental data and open ones to the QGSM and UrQMD calculations [15].

As seen, the flow F parameter increases with the increase of the mass numbers of projectile A_P and target A_T nuclei (Table 1). The dependences of F - directed flow parameter on $(A_P*A_T)^{1/2}$ for protons in dC, HeC, CC, CNe, dTa, HeTa, CCu and CTa collisions are shown on Fig 3 together with our earlier results [15]. Our earlier experimental results from d(C, Ta) and He(C, Ta) collisions are compared with the predictions of the Ultra-relativistic Quantum Molecular Dynamics Model (UrQMDM) and CC, CNe, CCu and CTa systems -- with the predictions of the Quark-Gluon String Model (QGSM).

ELLIPTIC FLOW (SQUEEZE-OUT)

The azimuthal angular distributions (ϕ) of protons in pC, HeLi and pTa collisions have been studied. The angle ϕ is the angle of the transverse momentum of each particle in an event with respect to the reaction plane ($\cos\phi = p_X / p_T$). The azimuthal angular distributions show maxima at $\phi = 90^0$ and $\phi = 270^0$ (Fig.5, 6).

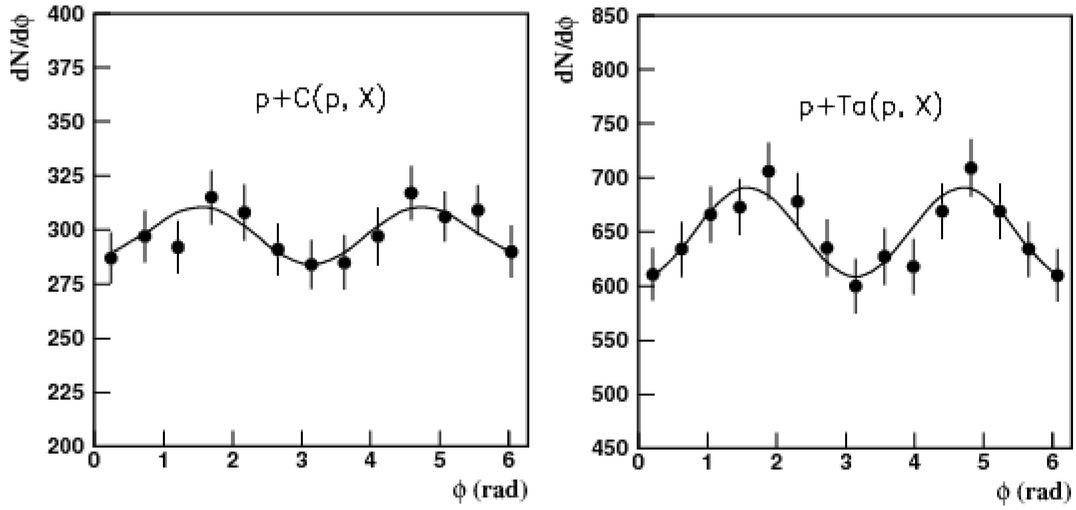

Fig. 5. The azimuthal distributions of the participant protons with respect to the estimated reaction plane. in pC and pTa collisions. The curve is the result of the approximation by $dN/d\phi = a_o(1+a_1\cos\phi + a_2\cos\phi)$.

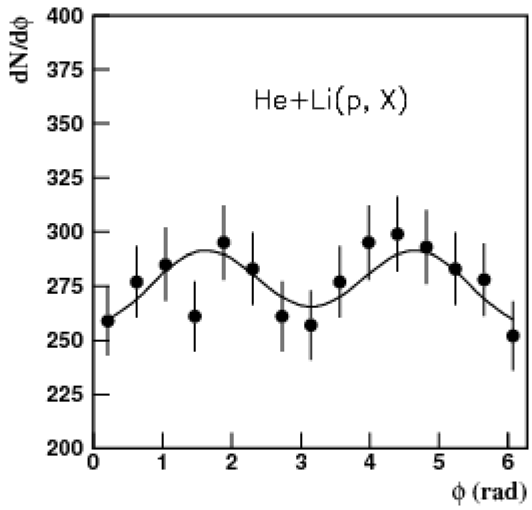

Fig. 6. The azimuthal distributions of the participant protons with respect to the estimated reaction plane in HeLi collisions.

The maxima are associated with preferential particle emission perpendicular to the reaction plane (squeeze-out). Thus a clear signature of an out-of-plane signal (elliptic flow) is evidenced. To treat the data in a quantitative way, the azimuthal distributions have been fitted with the Fourier cosine-expansion (given the system invariance under reflections with respect to the reaction plane)

$$dN/d\phi = a_0 (1 + a_1 \cos\phi + a_2 \cos 2\phi) \qquad (3)$$

The anisotropy factor a_2 is negative for out-of-plane enhancement (squeeze-out) and is the measure of the strength of the anisotropic emission with respect to the event plane (Table 1).

The dependences of a_2 -- anisotropy parameter on $(A_P*A_T)^{1/2}$ for protons in pC, dC, HeLi, HeC, CC, pTa, CNe, dTa, HeTa, CCu and CTa collisions are shown on Fig.7 together with our earlier results.

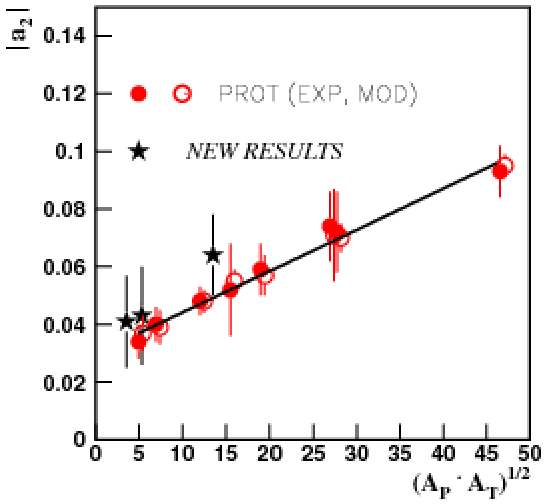

Fig. 7. The dependences of $|a_2|$-elliptic flow parameter on $(A_P*A_T)^{1/2}$ for protons in pC, ^{2}HC, HeLi, HeC, CC, pTa, CNe, ^{2}HTa, HeTa, CCu and CTa collisions (together with our earlier results: • -- the experimental data, o -- QGSM and UrQMD generated data (see text). The lines represent linear fits to the exp. data.

The elliptic flow has been investigated by various groups for different systems. In comparison to the elliptic flow measurements of charged hadrons in CuCu and AuAu collisions at $\sqrt{S_{NN}}$= 62.4 and 200 GeV PHOBOS Collaboration do not show any dependence on $(A_P*A_T)^{1/2}$ [see Ref. [21] 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. [22] fig 4).

7. Conclusions

The directed transverse collective flows of protons and pions and elliptic flow of protons emitted from pC, HeLi and pTa reactions at energy 3.4 GeV/nucleon have been studied. It has been observed:

1. The pC system is the lightest studied one, and the pTa -- fully (extremely) asymmetrical system in which collective flow effects (directed and elliptic) have been ever detected (for protons and pions).

2. As shown, the pions exhibit directed flow consistent with that for protons in the pC collisions. On the other hand, for pTa interactions, the pion flows turn into anti-flow with the pion average in-plane momenta becoming opposite to those for protons.

3. The directed flow parameter F increases with increase of the mass numbers of projectile A_P and target A_T nuclei for the protons from 76.8±7.0 (pC) to 106.9±9.0 (pTa) (MeV/c) and from 15.3±6.2 MeV/c for pC-interactions to 16.8±6.8 MeV/c for pTa ones, correspondingly.

4. The proton elliptic flow parameter $| a_2 |$ increases with increase of the mass numbers of projectile A_P and target A_T nuclei from 0.041 ± 0.016 for pC-interactions to 0.064±0.014 for pTa ones.

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References

[1] H. Stocker, J.A. Marhuhn and W. Greiner, Phys. Rev. Lett. Vol. **44**, 725 (1980).
[2] H. Stocker et al., Phys. Rev. C **25**, 1873 (1982).
[3] C. Hartnack et al., Nucl. Phys. A **538**, 53 (1992).
[4] C. Hartnack et al., Mod. Phys. Lett. A **9**, 1151 (1994).
[5] P. Danielewicz and G. Odyniec, Phys. Lett. B **157**, 146 (1985).
[6] P. Chung et al., Phys. Rev. Lett. **86**, 2533 (2001).
[7] C. Pinkenburg et al., Nucl. Phys. A **698**, 495 (2002).
[8] J. L. Ritman et al., Z. Phys. A **352**, 355 (1995).
[9] M. Aggarwal et al., Nucl. Phys. A **638**, 459 (1998).
[10] M. Aggarwal et al., Nucl. Phys. A **638**, 147 (1998).
[11] H. Appelshauser et al., Phys. Rev. Lett. **80**, 4136 (1998).
[12] L. Chkhaidze et al., Phys. Lett. B411, 26 (1997); B **479**, 21 (2000).
L. Chkhaidze et al., Eur. Phys. J. A**1**,299 (1998).
[13] L. Chkhaidze et al., Phys. Rev. C**65**, 054903;
[14] L. Chkhaidze et al., Phys. Part. Nucl. Vol. **2**, 393 (2002).
[15] L. Chkhaidze et al., Nucl. Phys. A **794**, 115 (2007).
L. Chkhaidze et al., Nucl. Phys. A **831**, 22 (2009).
[16] L. Chkhaidze et al., Phys. Rev. C**84**, 064915 (2011).
[17] L. Chkhaidze et al., Phys. of Atom. Nucl., v. **75**, 811(2012).
[18] A. Bondarenko et al., JINR Report E1-84-785, Dubna, 1984;
Phys. Rev. C**33**, 895 (1986).
[19] A. Bondarenko et al., JINR Preprint P1-98-292, Dubna, 1998.
G. N. Agakishiev et al., Yad. Fiz. **43**, 366 (1986).
[20] Beavis et al., Phys. Rev. C **45**, 299 (1992).
[21] B. Alver et al., e-Print arXiv:0707.4424 [nucl-ex].
[22] A. Aamodt et al., e-Print arXiv:1011.3914 [nucl-ex].