Elliptic Flow and Equation of State in Heavy Ion Collisions at SIS Energies

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A systematic study of the elliptic flow in Au+Au collisions at energies from 0.09 to 1.49 AGeV is presented. The experimental information allows us to extract information about the reaction dynamics and, by comparison with the IQMD transport model, the Equation of State (EoS) of nuclear matter.

1. INTRODUCTION

Ten years after its experimental discovery [1,2], the elliptic flow (commonly called squeeze-out [3] when the emission is preferentially out of the reaction plane) is still regarded as a relevant observable for studies of the EoS [4–6] and, lately, for the transition to the Quark Gluon Plasma (QGP) [7,6]. But despite the extensive experimental efforts [12–15], the question of the EoS remains still open. Whereas at higher energies this flow phenomenon is regarded as a messenger from the stage of the maximum compression [7], in our lower energy range the strong spectator shadowing makes its relevance to the EoS more difficult to assess.

2. EXPERIMENTAL SET-UP AND DATA ANALYSIS

The data presented here have been measured with the FOPI detector [8] at GSI Darmstadt.

The reaction products were identified by charge in the forward Plastic Wall (PW) at Θ_{lab} <30° using time-of-flight and specific energy loss and by mass in the Central Drift Chamber (CDC), covering $33° < \theta_{lab} < 150°$, using, besides the curvature of the particle tracks in a solenoidal magnetic field, the energy loss.

For the centrality selection we used the charged particles multiplicities, classified into five bins [9]. The two intermediate ones, denoted M3 and M4, correspond to geometrical impact parameter bins of 5.3-7.3 fm and 2.0-5.3 fm, respectively. At energies lower than 0.8 AGeV the variable $Erat = \sum_i E_{\perp,i} / \sum_i E_{\parallel,i}$ (the sums run over all the products detected in an event) has been additionally used for a better selection of the most central collisions.

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The reaction plane has been determined using the transverse momentum method [10].

For the present study we have selected a window at midrapidity by the condition $|y^{(0)}| < 0.1$, where $y^{(0)} = (y/y_P)^{cm}$. The azimuthal distributions with respect to the reaction plane were fitted using a truncated Fourier expansion:

$$\frac{dN}{d\phi} \sim [1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi)] \tag{1}$$

The second order coefficient $v_2 = \langle \cos(2\phi) \rangle$ characterizes the elliptic flow ($v_2 > 0$ for an in-plane emission and $v_2 < 0$ for out-of-plane). It has been corrected for the reaction plane resolution using the recipe of Ollitrault [11]. The correction factor is smaller than 2, except for the lowest incident energy, where it reaches almost 3.

3. RESULTS

The particle mass dependence of the v_2 coefficient is presented in Fig. 1 as function of the scaled transverse momentum per nucleon $p_t^{(0)} = (p_t/A)/(p_P^{cm}/A_P)$ for an incident energy of 0.4 AGeV. Consistent with previous findings [5,12], this result may be the natural consequence that the heavier particles are more sensitive to the collective part of the energy (proportional to the mass for a constant velocity field). It also can point to the different participation of the different species in the reaction dynamics. Wether clusterization and shadowing play a role in these dependences remains open for the moment.

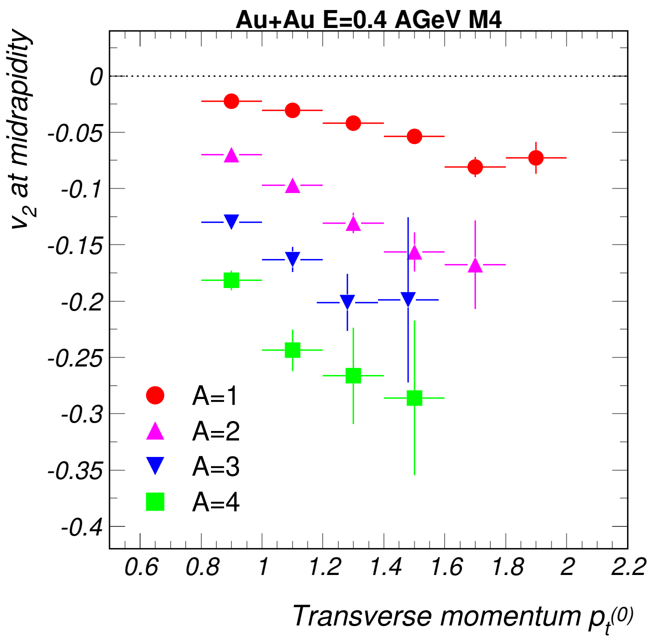

Figure 1. The dependence of the elliptic flow on the scaled transverse momentum (per nucleon) for different particles for the energy 0.4 AGeV, M4 centrality bin.

We turn now to the excitation function of the elliptic flow, presented in Fig. 2a for the multiplicity bin M3 in the case of protons alone and for an integral over A=1,2,3 particles, for a momentum cut $p_t^{(0)} > 0.8$. At lower energies we observe a transition from in-plane to out-of-plane emission; the squeeze-out exhibits a maximum around 0.6 AGeV and then it decreases again towards higher energies. The characteristic time of the out-of-plane expansion, which is a measure of the achieved pressure, and hence of the EoS, and the passage time of the spectators lead to a logarithmic decrease of the elliptic flow [6]. Note that the inelastic n-n channel, leading to pion production, starts also in this region. One can also see that the contribution of the composites to the v_2 values gradually decreases towards higher energies, a consequence of their reduced yield.

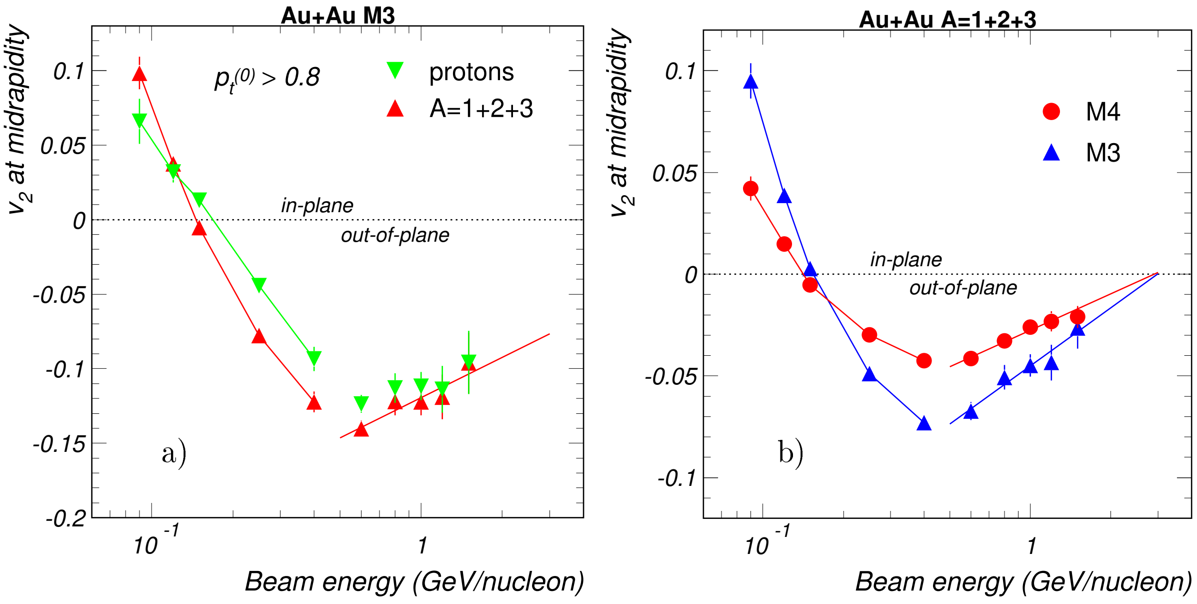

Figure 2. Excitation function of the elliptic flow: a) for various particles for the centrality bin M3 and $p_t^{(0)} > 0.8$ and b) for two centrality bins (integrated over the full p_t range).

Fig. 2b shows the v_2 excitation function for two centrality bins, integrated over momentum and particle masses A=1, 2 and 3. Higher values of the squeeze-out for larger impact parameters is a clear effect of the shadowing by spectator matter, the size of the fireball leading to stronger expansion for more central collisions [17].

We note that the energy and centrality dependence of the elliptic flow is affected by the sidewards flow angle (Θ_{flow}), which is quite sizeable in our energy range [16], and one can study it in a rotated reference frame [1]. However, the reaction plane correction is not straightforward in this case.

In order to get information about the EoS, comparisons with the IQMD model (Isospin Quantum Molecular Dynamics) [5] have been performed. The model events were centrality selected in the same way as the data and the reaction plane has been reconstructed and corrected for, also in the same manner. Two parametrizations of the EoS have been studied, soft (compressibility K=200 MeV) and hard (K=380 MeV), both using momentum dependent interactions, labeled SM and HM, respectively.

The results are presented in Fig. 3 for the energy 0.6 AGeV, for protons of centrality bin M4. Both parametrizations overpredict the experimental values, which seem to call for an EoS even softer than 200 MeV. The exclusion of the momentum dependent interactions leads also to a significant reduction of the squeeze-out [6,14].

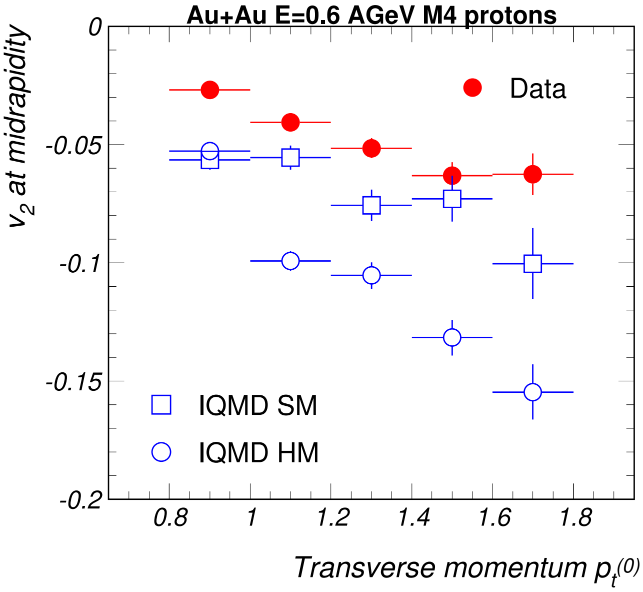

Figure 3. Comparison of data with IQMD model calculations for two parametrizations of the EoS.

4. CONCLUSIONS

The presented experimental results reveal detailed information on the various dependences of the elliptic flow observable at intermediate energies. Its excitation function shows that a maximum is reached at about 0.6 AGeV and then a gradual decrease towards higher energies is seen. Our study shows that, within IQMD, a soft EoS is better suited to explain the data.

REFERENCES

1. H.H. Gutbrod et al., Phys. Lett. B 216 (1989) 267.
2. M. Demoulins et al., Phys. Lett. B 241 (1990) 476.
3. H. Stöcker et al., Phys. Rev. C 25 (1982) 1873.
4. G.M. Welke et al., Phys. Rev. C 38 (1988) 2101.
5. C. Hartnack et al., Phys. Lett. B 336 (1994) 131 ; Mod. Phys. Lett. A 9 (1994) 1151.
6. P. Danielewicz et al., Phys. Rev. Lett. 81 (1998) 2438 ; also these proceedings.
7. H. Sorge, Phys. Rev. Lett. 78 (1997) 2309.
8. A. Gobbi, FOPI Collaboration, Nucl. Instr. and Meth. in Phys. Res. A 324 (1993) 156; J. Ritman, FOPI Collaboration, Nucl. Phys. B (Proc. Suppl.) 44 (1995) 708.
9. N. Herrmann, FOPI Collaboration, Nucl. Phys. A 553 (1993) 739c.
10. P. Danielewicz and G. Odyniec, Phys. Lett. B 157 (1985) 146.
11. J.-Y. Ollitrault, nucl-ex/9711003, Nucl. Phys. A 638 (1998) 195.
12. D. Brill et al., Z. Phys. A 355 (1996) 61.
13. M.B. Tsang et al., Phys. Rev. C 53 (1996) 1959.
14. P. Crochet, FOPI Collaboration, Nucl. Phys. A 627 (1997) 522.
15. C. Pinkenburg, nucl-ex/9903010.
16. F. Rami, FOPI Collaboration, Nucl. Phys. A 646 (1999) 367.
17. A. Andronic, FOPI Collaboration, Prog. Part. Nucl. Phys. 42 (1999) 161.