Neutron-proton elliptic flow in Au + Au

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Abstract

The elliptic flow of neutrons, protons and light complex particles in reactions of neutron-rich systems at relativistic energies is proposed as an observable sensitive to the strength of the symmetry term in the equation of state at supra-normal densities. Preliminary results from a study of the existing FOPI/LAND data for $^{197}$Au + $^{197}$Au collisions at 400 A MeV with the UrQMD model favor a moderately soft symmetry term with a density dependence of the potential term proportional to $(\rho/\rho_0)^\gamma$ with $\gamma \approx 0.9 \pm 0.3$.

Considerable efforts are presently underway in order to determine the equation of state of asymmetric nuclear matter which is of fundamental importance to both nuclear physics and astrophysics [1]. While fairly consistent constraints for the symmetry energy near normal nuclear matter density have been deduced from recent data [1-3], much more work is still needed to probe its high-density behaviour. This requires reaction studies at sufficiently high energies and suitable probes sensitive to mean-field effects in the initial compressed stage of the reaction as, for example, the neutron-proton differential transverse and elliptic flows [4, 5].
In two experiments at GSI combining the LAND and FOPI (Phase 1) detectors, both neutron and hydrogen collective flow observables from $^{197}$Au + $^{197}$Au collisions at 400, 600 and 800 A MeV have been measured [6]. This data set is presently being reanalyzed in order to determine optimum conditions for a dedicated new experiment, but also with the aim to produce constraints for the symmetry energy by comparing with predictions of state-of-the-art transport models. Here, we report first results obtained with the UrQMD model which has recently been adapted to heavy ion reactions at intermediate energies [7].

The predictions obtained for the elliptic flow of neutrons, protons, and hydrogen yields for $^{197}$Au + $^{197}$Au at 400 A MeV are shown in Fig. 1. Two values are chosen for the power-law exponent describing the density dependence of the potential part of the symmetry energy, $\gamma = 1.5$ (asy-stiff) and $\gamma = 0.5$ (asy-soft). The UrQMD outputs have been filtered with the acceptance of the FOPI/LAND experiment which produces the asymmetry of $v_2$ with respect to mid-rapidity $y_{lab} = 0.448$. The neutron squeeze-out

![Figure 1: Elliptic flow parameter $v_2$ for mid-peripheral $^{197}$Au + $^{197}$Au collisions at 400 MeV per nucleon as calculated with the UrQMD model for protons (circles), neutrons (triangles), and the total hydrogen yield (stars) as a function of the laboratory rapidity $y_{lab}$. The results have been filtered to correspond to the geometrical acceptance of the LAND setup used in the joined experiment. The predictions obtained with a stiff and a soft density dependence of the symmetry term are given in the upper and lower panels, respectively.](image-url)
is significantly larger in the asy-stiff case (upper panel) than in the asy-soft case (lower panel) while the proton and hydrogen flows respond only weakly to the variation of $\gamma$ within the chosen interval.

![Figure 2: Differential elliptic flow parameters $v_2$ for neutrons (triangles) and hydrogens (stars, top panel) and their ratio (bottom panel) for central ($b < 7.5$ fm) collisions of $^{197}$Au + $^{197}$Au at 400 A MeV as a function of the transverse momentum per nucleon $p_t/A$. The symbols represent the experimental data, the UrQMD predictions for $\gamma = 1.5$ (a-stiff) and $\gamma = 0.5$ (a-soft) are given by the dashed lines.](image)

The comparison of the combined data set for central and mid-peripheral collisions with the corresponding UrQMD predictions for $b < 7.5$ fm shows that the overall $p_t$ dependence is well described (Fig. 2, upper panel). As expected from Fig. 1, the squeeze-out ratio is sensitive to the stiffness of the symmetry energy (lower panel). A linear interpolation between the predictions, averaged over $0.3 < p_t \leq 1.0$ GeV/c, yields $\gamma = 0.94 \pm 0.21$. A smaller but within errors consistent value $\gamma = 0.52 \pm 0.30$ is obtained if the comparison is restricted to mid-peripheral impact-parameters $5.5 \leq b < 7.5$ fm [9]. Other systematic uncertainties have been found to remain within $\Delta \gamma \approx 0.2$. Together with the kinetic term proportional to $(\rho/\rho_0)^{2/3}$, the squeeze-out data indicate a moderately soft behavior of the symmetry energy at supra-saturation densities.
This result can be considered as, within errors, consistent with the density dependence deduced from fragmentation experiments probing nuclear matter near or below saturation [3] and with the slightly softer density dependence resulting from the analysis of the pygmy dipole resonance in heavy nuclei [2]. It is, however, inconsistent with the super-soft behavior obtained from the IBUU analysis [10] of $\pi^-/\pi^+$ yield ratios reported by the FOPI collaboration for the same reaction $^{197}\text{Au} + ^{197}\text{Au}$ at 400 A MeV [11]. According to the arguments presented in the more recent paper [12], the pion ratios should be sensitive to the high-density region of the reaction. Preliminary studies with the UrQMD model indicate that also a considerably softer symmetry term will be needed if the same pion ratios are to be reproduced with that model. At present, therefore, it can only be concluded that more extended data sets and consistency checks in their analyses are needed in order to arrive at firm conclusions. In particular, it will have to be more precisely shown what densities have been probed, what signal modifications are to be expected during subsequent reaction stages, whether the deduced results are model invariant, and whether they are connected to the neutron richness of the studied systems.

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References

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