The ASY-EOS Experiment at GSI: Constraining the Symmetry Energy at Supra-Saturation Densities

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Abstract - The elliptic-flow ratio of neutrons with respect to protons or light complex particles in reactions of heavy ions at pre-relativistic energies has been proposed as an observable sensitive to the strength of the symmetry term of the nuclear equation of state at supra-saturation densities. In the ASY-EOS experiment at the GSI laboratory, flows of neutrons and light charged particles were measured for \(^{197}\)Au+\(^{197}\)Au, \(^{96}\)Zr+\(^{96}\)Zr and \(^{96}\)Ru+\(^{96}\)Ru collisions at 400 MeV/nucleon. Flow results obtained for the Au+Au system have been compared with predictions of the UrQMD transport model to constrain the density dependence of the symmetry energy.

INTRODUCTION

The neutron-proton elliptic flow ratio and difference have been proposed as effective probes of the high-density behavior of the nuclear symmetry energy [1, 2, 3]. The comparison of existing data from the FOPI-LAND experiment [4] with calculations performed with the UrQMD transport model [5] suggests a moderately soft to linear symmetry term. The result suffers, however, from the considerable statistical uncertainty of the experimental data [1,3]. The same data set was also compared to calculations performed with the Tübingen QMD model and a constraint compatible with the UrQMD result was obtained [6]. At the same time, a thorough study of the parameter dependence of the model predictions was performed in order to devise a route towards a model independent constraint of the high-density symmetry energy [6]. It was, in particular, found that different parameterizations of the isovector part of the equation of state, the Gogny inspired (momentum dependent) vs. the power law (momentum independent) potential, lead to very similar results.

In order to improve the statistical accuracy of the experimental flow parameters for the Au+Au reaction and to extend the flow measurements to other systems, the symmetric collision systems \(^{197}\)Au+\(^{197}\)Au, \(^{96}\)Zr+\(^{96}\)Zr and \(^{96}\)Ru+\(^{96}\)Ru at 400 MeV/nucleon incident energies have been chosen for the ASY-EOS experiment, conducted at the GSI laboratory in May 2011 (S394 experiment). As in the previous experiment, the Large Area Neutron Detector LAND [7] was used for the detection and identification of neutrons and light charged particles. By including the KRATTA telescope array [8] in the setup, the study of isospin effects in these reactions was extended to additional observables as, e.g., the yield ratios of light isobar pairs \(^3\)H/\(^\text{He}\) and \(^3\)Li/\(^\text{Be}\).

ASY-EOS EXPERIMENT AT GSI

A schematic view of the experimental set-up is shown in Fig. 1. The Large Area Neutron Detector (LAND) [7] was positioned to cover laboratory angles around 45° with respect to the beam direction, at a distance of about 5 m from the target. A veto-wall of plastic scintillators in front of LAND allowed discriminating neutrons and charged particles. In this configuration, it was possible to measure the direct and elliptic flows of neutrons and charged particles at mid-rapidity with high precision in the same angular acceptance. In addition, the Krakow Triple Telescope Array, KRATTA [8], was installed to measure the energy, emission angles and isotopic composition of light charged reaction products. The 35 modules of KRATTA were placed opposite to LAND at a distance of 40 cm from the target at polar angles between 20° and 64° [9]. The determination of the impact parameter and the orientation of the reaction plane required the use of several devices: i) the ALADIN Time-of-Flight (AToF) wall [10] was used to detect charged particles at polar angles smaller than 7°; two walls (front and rear) of 2.5*100 cm\(^2\) plastic scintillators, read by two photomultipliers at both ends, gave information on emission angle, atomic number and velocity of forward-emitted ions; ii) 50 thin (between 3.6 and 5.6 mm) CsI(Tl) elements, read out by photo-diodes and arranged in 4 rings, of the Washington-University µBall array [11], surrounded the target at polar angles between 60° and 147° with the aim of measuring the multiplicity and angular distribution of backward emitted particles in order to discriminate against background reactions on non-target material; iii) 352 CsI(Tl) scintillators, 12 cm thick, of the CHIMERA multi-detector [12], arranged in 8 rings with
2π azimuthal coverage around the beam axis and covering polar angles between 7' and 20', were used to detect light charged particles from mid-rapidity emissions. With beam intensities of about $10^3$ pps and targets of 1-2% interaction probability, about $5\times10^6$ events were collected for each system. Special runs were performed with and without target, in order to measure the background from interaction of projectile ions with air, and with iron shadow bars in front of LAND or the neutron background measurement.

Elliptic neutron and charged-particle flows

Firstly we have rejected background reactions due to the interaction of Au projectiles with non-target material (mainly air), by using the correlation of the two reaction plane orientations given by CHIMERA and by the μBall detectors, and characterized collision centrality by using global variables [13]. Then, azimuthal distributions of neutrons and light charged particles measured with LAND with respect to the reaction plane given by CHIMERA have been extracted for Au+Au reactions from runs with and without the shadow bar. After subtracting the background, the obtained distributions have been fitted with formula (1) of Ref. [1] in order to determine the direct ($v_1$) and elliptic ($v_2$) flow coefficients. The results for neutrons and for all recorded charged particles (Ch) are here presented. The $v_1$ and $v_2$ parameters for Ch and neutrons as functions of the reduced rapidity $Y_{lab}/Y_{proj}$ are shown in the upper and lower panels of Fig. 2, respectively. In the same figure, also the UrQMD predictions for a soft ($\gamma=0.5$) and a stiff ($\gamma=1.5$) symmetry energy potential [1] are given. Constraints for the symmetry energy were determined as in Ref. [1] by comparing the ratios of the elliptic flows of neutrons and Ch, $v_2^{\text{neutron}}/v_2^{\text{Ch}}$, with the corresponding UrQMD predictions for the soft and stiff cases. The results obtained as functions of the reduced rapidity and of the transverse momentum $p_T$ are shown in Fig. 3. A preliminary value for the power-law coefficient $\gamma$, deduced by linearly interpolating between the predictions, is $\gamma = 0.76 \pm 0.12$. The new constraint is compatible with the previous one presented in Ref. [1] by using FOPI-LAND data and the same UrQMD model but the statistical error has been significantly reduced by a factor of ~ 2. The determination of systematic uncertainties is still on-going; a preliminary analysis indicates an overall final uncertainty of the order of $\gamma \approx 0.25$.

OUTLOOKS

Comparisons of the experimental data with other theoretical transport models will be useful in order to pursue the route towards a model-independent constraint of the high-density symmetry energy initiated in Ref. [6]. The promising preliminary results of the present experiment may also be seen as an encouragement for extending the measurement of neutron and charged particle flows to other reaction systems and energies. Future experiments may thereby benefit from the unique possibilities offered by the NeuLAND detector presently constructed as part of the R3B experimental set-up [14] and from the availability of radioactive ion beams for reaction studies at FAIR.

REFERENCES

[14] https://www.gsi.de/r3b