Flow and Stopping in Asymmetric Collisions

O.N. Hartmann[1], A. Andronic[1], N. Herrmann[2,1], K.D. Hildenbrand[1], Y.J. Kim[1,3], M. Kirejczyk[1],
P. Koczon[1], Y. Leifels[1], W. Reisdorf[1], A. Schüttauf[1], Z. Tyminski[1,4], and Z.G. Xiao[1]
[1]GSI; [2]Heidelberg University; [3]Korea University; [4]Warsaw University - for the FOPI collaboration

Introduction

In the first asymmetric heavy ion collision studied by the FOPI collaboration the reaction ^{40}Ca on ^{197}Au was investigated both in normal and inverse kinematics, at a projectile energy of 1.5A GeV [1]. The experiment shows the suitability of the FOPI detector system in measuring asymmetric collisions and the physics potential of this reaction type in the SIS energy regime. The physics observables reported here are the sidewards flow, the squeeze-out and the nuclear stopping.

Flow

Flow in asymmetric collisions is a key observable for investigating the reaction dynamics. Looking at the sidewards flow, one can deduce the effective system center of mass. In contrast to symmetric collisions, where the c.o.m. is the one of two nucleons, this quantity is not known a priori; it is expected to be between the full system c.o.m. (i.e. the nucleus-nucleus system) and the participants c.o.m. (i.e. the overlap of the two nuclei [2, 1]). In Fig. 1 the mean transverse momentum of protons, projected into the reaction plane, and divided by the mass ($\langle p_x/m \rangle$), is plotted as a function of the scaled rapidity Y^0 ($Y^0 = -1$ corresponds to target rapidity and $Y^0 = 1$ to projectile rapidity, respectively). The mentioned limits are indicated by the full and dashed vertical lines, as well as the nucleon-nucleon c.o.m., defining the point of origin. The points of $\langle p_x \rangle / m = 0$ correspond to the effective c.o.m. rapidity.

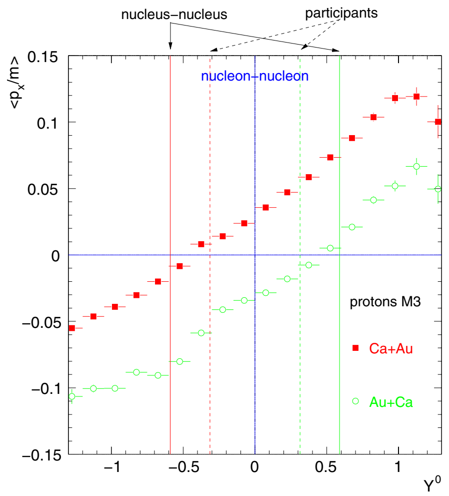

Figure 1: Mean transverse momentum of protons projected into the reaction plane as function of scaled rapidity.

The data from non-central collisions (multiplicity bin M3) shown in Fig. 1 appear to cross the zero line in between the values of rapidity indicated by the vertical lines, which means that there is a sizeable interaction of the reaction zone with the nominal spectators. The symmetry condition between the two reaction kinematics with respect to the point of origin is fulfilled satisfactorily.

Squeeze-out is investigated by analyzing the complete azimuthal distributions of the emitted particles. As an example, Fig. 2 shows the azimuthal angular distributions for protons from semicentral collisions (M4). These distributions are fitted with a Fourier function up to second order. The emission perpendicular to the reaction plane is measured by the expansion coefficient v_2. A rapidity window of 0.3Y^0 around the effective c.o.m. rapidity is selected, where the effective c.o.m. rapidity is taken from the sidewards flow analysis, the lower limit in $p_\perp/m$ is 0.4. The vertical lines indicate an angle of ±90° relative to the reaction plane.

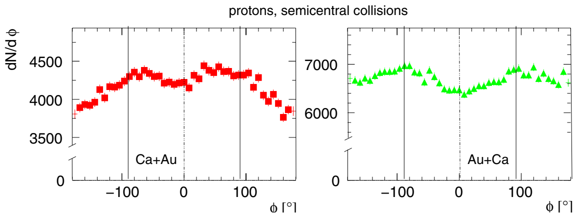

Figure 2: Azimuthal angular distributions of protons at effective c.o.m. rapidity.

The distributions in Fig. 2 show a clear squeeze-out signal at ±90°. The distributions still have a sizeable v_1-component which reflects the different collision geometries. The spectator nucleons are distributed quite asymmetrically around the azimuth. At effective c.o.m. rapidity the yield in Ca+Au has its maximum at 0° and becomes minimal at ±180°, where the symmetric collision shows the maximum at ±90° and equal yields at 0 and ±180° [3, 1]. By varying the position of the rapidity window a situation with a vanishing v_1 is found. Note that for the asymmetric systems the magnitude of v_2 is larger than in the symmetric reaction Au+Au [3], which points also to a spectator contribution rather than to a pure expansion effect. Comparing the results with the microscopic transport calculation IQMD [4], the model gives a somewhat larger signal if it is used with its standard parameters. As the following table shows, the data prefer a nuclear equation of state with smaller compression module (soft EOS). The sum of protons, deuterons and tritons is less affected by the model problems concerning the clusterization (the model gives a smaller number of fragments) and therefore is used for quantitative comparisions.

particles	v_2 (data)	IQMD (hard)	IQMD (soft)
protons	-0.096±0.011	-0.151±0.009	-0.129±0.008
p,d,t	-0.128±0.010	-0.154±0.009	-0.134±0.008

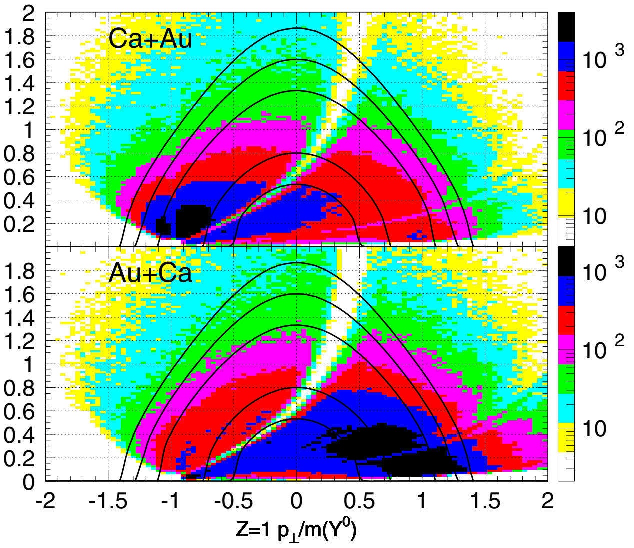

Figure 3: Phase space distributions of $Z = 1$ particles.

Nuclear Stopping

Rapidity distributions of asymmetric reactions reveal an unambigous signal of the degree of stopping. The phase space distributions for the two kinematics are shown in Fig. 3. The fact that one distribution is not a perfect mirror image of the other is due to the detector acceptance and slightly different efficiencies. The different phase space populations in the asymmetric collisions can easily be seen, the lines show constant c.o.m.-energies in the NN-system. Thus, the rapidity distributions are less difficult to interprete compared to symmetric reactions where a longitudinal expansion scenario cannot be ruled out.

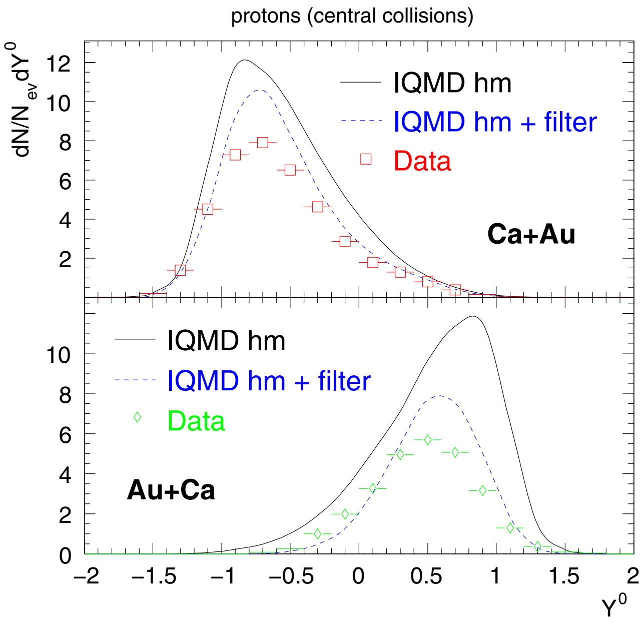

Figure 4: Proton rapidity distributions for central events.

Fig. 4 shows the rapidity distributions for central collisions (M5, corresponding to 2% of the reaction cross section) in the two kinematics. The prediction of the IQMD calculation (full line) is shown, and also the effect of the filter which takes into account the acceptance of the detector (dashed line). In the Ca+Au case the acceptance is more complete than in the Au+Ca case. The general tendency of the model to overpredict the proton yield is obvious. To derive quantitative information on the degree of stopping the nucleon-nucleon cross section is varied in the calculation. The standard value is the free one (as used in Fig 4), to simulate a larger stopping power the cross section is artificially increased (doubled), for a smaller stopping power it is decreased, respectively. A completely stopped scenario is reached when the shape of the rapidity distribution does not change any more even if the nucleon-nucleon cross section is increased further.

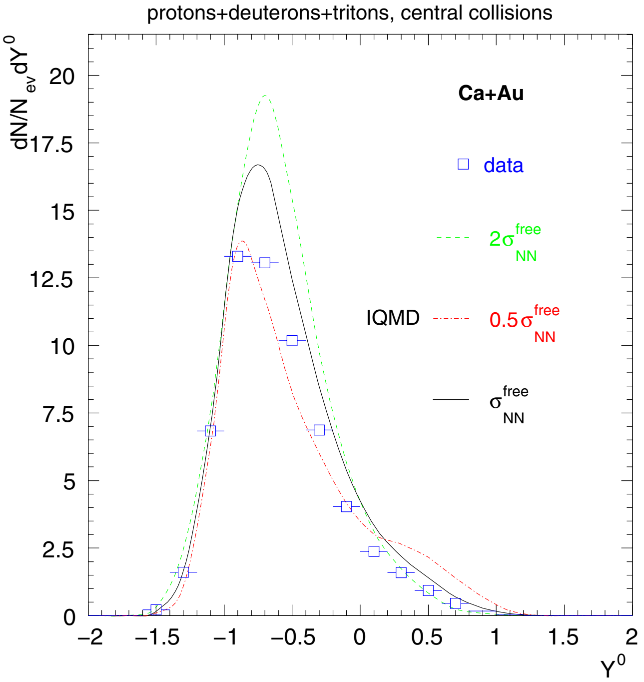

Figure 5: p,d,t rapidity distributions, data and transport calculation

In Fig. 5 the comparison of the rapidity distributions is shown for protons, deuterons and tritons from central Ca+Au collisions. The data are not described by the plotted model calculations. The free nucleon-nucleon cross section (full line) still overestimates the degree of stopping, and the doubled cross section (dashed line) can be ruled out. Hence, the data do not show a complete stopping of the projectile nucleus, they rather describe a partially transparent scenario.
In a continuation of these experiments the FOPI collaboration has investigated in 2003 the system ^{58}Ni and ^{208}Pb at 400A, 800A and 1160A MeV, again in normal and inverse kinematics.

References

[1] Hartmann, O., Dissertation, TU Darmstadt 2003
[2] Eskola, K.J., Nucl. Phys. B 323 (1989) 37
[3] Kreß, T., Dissertation, TU Darmstadt 2002
[4] Hartnack, C., EPJ A1 (1998) 151