

Heavy ion collisions in the 1A GeV regime: how well can we join up to astrophysics?

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Abstract

The derivation of information useful for understanding the physics inside compact stars from HIC observations is a difficult task. Complications due to finite size, different chemistry, non-adiabatic compression, incomplete stopping and structural effects must be overcome. Using now available systematic FOPI data in the SIS energy range we try to trace the path to take.

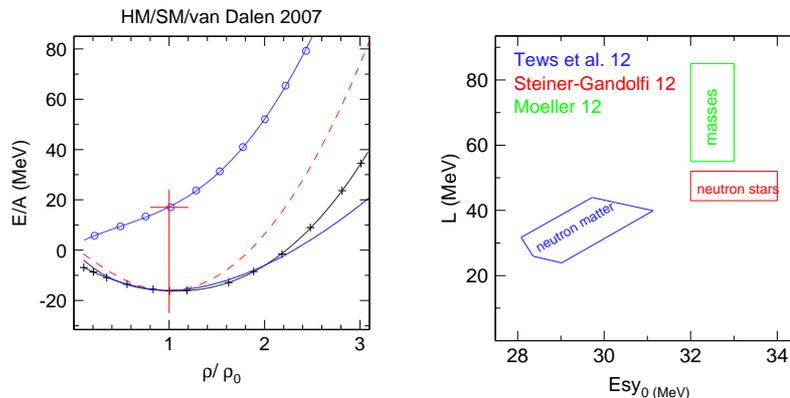


Figure 1: Various nuclear matter EoS (left) and constraints (right)

There now exists an extensive set of data on heavy ion reactions in the 1A GeV range [1]. In the sequel we confront the data with IQMD [2] simulations. The two options of purely phenomenological *cold* nuclear EoS that we use are plotted in Fig.1 and confronted with a 'microscopic' (Dirac-Brueckner-Hartree-Fock, DBHF) calculation [3] for symmetric matter. It is seen that in the density range relevant for SIS energies (up to $\rho/\rho_0 = 2.5$)

our 'soft' version, SM, is rather close to the theoretical calculation. We will see in the sequel that FOPI data are strongly favouring the SM version (full blue) over the stiff, HM, version (dashed).

Also included from the same theoretical work is the cold EoS for pure neutron matter. It is not possible in the laboratory to determine directly the neutron matter EoS. We have to rely on theoretical help. The adequacy of the theory, in turn, can be tested by confrontation with high quality experimental data constraining the symmetric matter EoS. Recent constraints on the EoS parameters L and $E_{\text{sym}0}$ from theoretical efforts [4], nuclear masses [5] and neutron star data [6] reflect incompatibilities associated with different physics sensitivities, see Fig.1 right.

In Fig.2 we show a sample of proton yield and flow data from our Collaboration (black dots with error bars) together with simulations using IQMD with the stiff version of the EOS (HM, red dashed) and the soft version (SM, blue full).

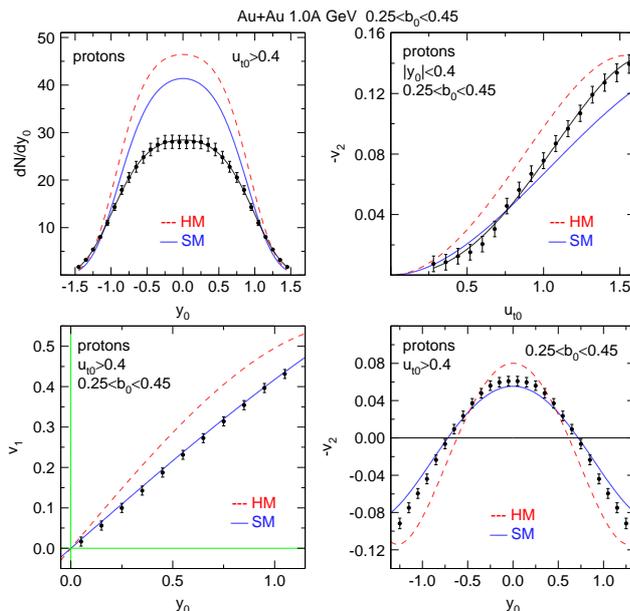


Figure 2: Proton rapidity and flow data and IQMD-SM/HM simulations

It can be seen that the three projections shown are best described by the SM version: see the rapidity (y) dependences of the directed, v_1 , and the elliptic ($-v_2$) flow in the two lower panels and the $p_t/m = u_t$ dependence of the elliptic flow in the upper right panel. As IQMD underestimates clus-

terization it overpredicts single nucleon (proton) yields (upper left panel). Notice a moderate, but still remarkable dependence on the EoS, however.

Taking a closer look at $-v_2(y_0)$ (we use the index 0 to indicate scaling with the beam parameters [1]) we see that the predicted shape is sensitive to the EoS *in the full rapidity range*. To take advantage of this feature we introduce a quantity dubbed v_{2n} defined by $v_{2n} = -v_{20} + |v_{22}|$ where the parameters are fixed by a fit to the flow data using $v_2(y_0) = v_{20} + v_{22} \cdot y_0^2$ in the scaled rapidity range $|y_0| < 0.8$.

The result for Au+Au between 0.4A and 1.5A GeV is shown in Fig.3 for protons (left) and deuterons (right).

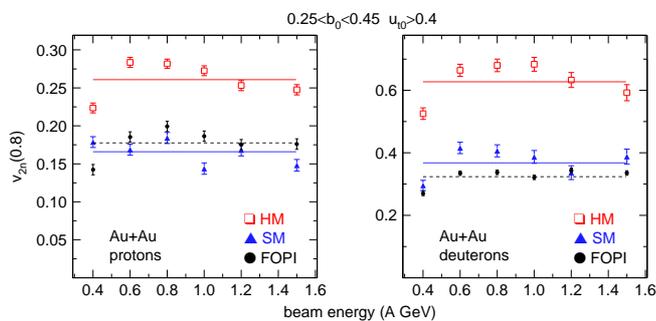


Figure 3: Elliptic flow v_{2n} for protons (left) and deuterons

As the beam energy dependences are rather weak, we indicate the average behaviour by straight lines. The comparison of the data for v_{2n} with the calculations shows a rather convincing preference for SM! The sensitivity is large: there is a factor 1.6 between HM and SM, a difference exceeding significantly the indicated experimental error bars. This strongly supports the Tübingen calculation (Fig.1).

Including mass three clusters (besides protons and deuterons) leads to the same conclusions. In view of high interests in isospin dependences it is worth looking in more detail at elliptic flow data of ^3H and ^3He : see the two upper panels in Fig.4 for Au+Au at $E/A = 0.4A$ (left) and 1.5A GeV (right). While there is no significant (within error bars) difference at the lower beam energy we see a remarkable effect at 1.5A GeV: the shape difference in $-v_2(y_0)$ is reminiscent of the SM/HM shape difference seen in Fig.2. We therefore use again v_{2n} to systematize this isotopic difference in terms of a single parameter: see the two lower panels showing the energy dependence for both isotopes (left) and, for the 1.5A GeV data, the centrality dependence in terms of the scaled impact parameter b_0 [1].

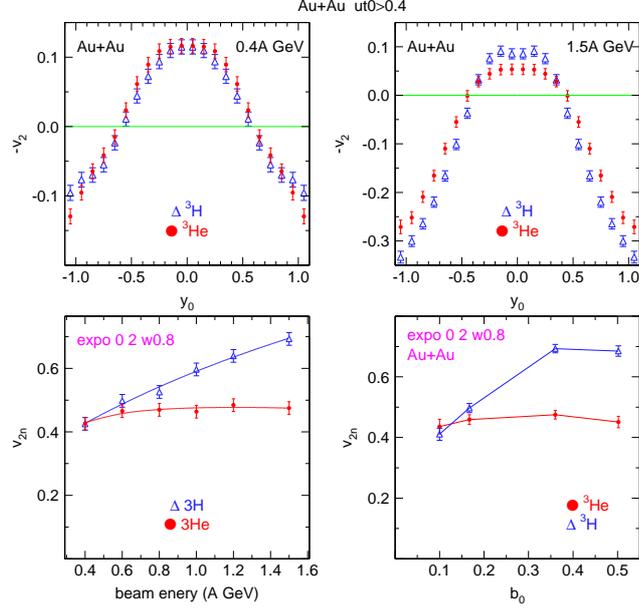


Figure 4: Studies of v_2 and v_{2n} for the two mass three isotopes

These observations, so far, are not reproduced by our IQMD version. Considering the limitation of the isotopic split to larger b_0 and higher E/A , we suggest unaccounted for momentum dependences and connection to Δ formation in an asymmetric medium. For future clarification of the latter we expect our pion yield and flow data [1] to be helpful.

Our conclusions concerning preference, in the SIS energy range, of a 'soft' EoS (see Fig.1) are in line with earlier findings using the comparison of K^+ yield data varying system size or centrality. A sample of such data [7] is shown in the right panel of Fig.5. Once cluster formation is better understood, there is some chance, that conclusions on the EoS can also be derived from system dependences (size and isospin) of various clusters, see the various panels in Fig.5. There is evidence for more efficient cooling (condensation) if the achieved density was higher, i.e. for more massive systems. For pions the increased production in softer, denser systems, is compensated out by the final cooling before freezeout. There is a loss of memory for the high density phase here.

To conclude, heavy ion data obtained at SIS, represent by now rather convincing constraints for the EoS of nuclear matter in the density range up to $\rho = 2.5\rho_0$.

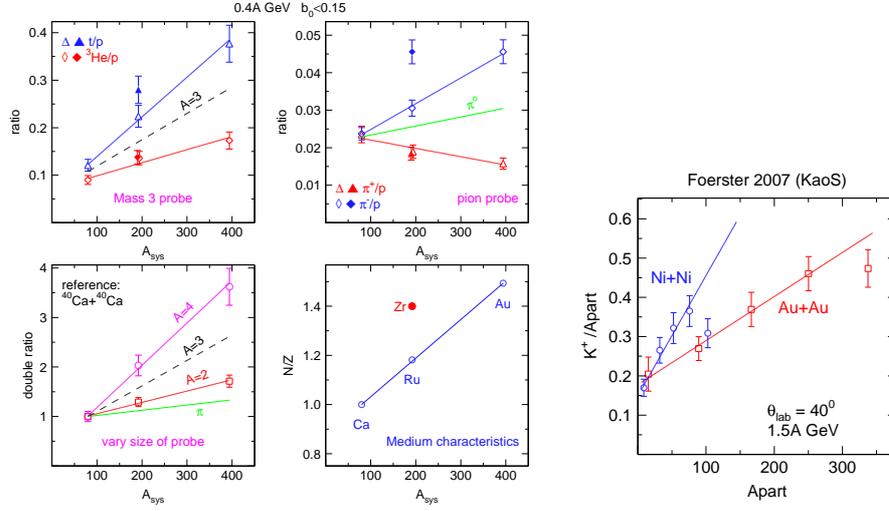


Figure 5: System size dependences of various indicated ejectiles

References

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