

## Comparisons of microscopic calculations with experimental heavy residue distributions and the sensitivity to the density dependence of the nuclear symmetry energy

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During the last several years we have undertaken a systematic study of heavy residues formed in quasi-elastic and deep-inelastic collisions near and below the Fermi energy. The original motivation of these studies was the understanding and the optimization of the production of very neutron-rich rare isotopes in these collisions [1,2,3]. In parallel, we became motivated to pursue these studies further in hopes of extracting information on the properties of the nuclear effective interaction as manifested in the mechanism of nucleon exchange and the course towards  $N/Z$  equilibration [4]. In addition, studying specifically those heavy residues produced near the nuclear multifragmentation threshold, we investigated the possibility of obtaining the symmetry energy coefficient of the binding energy of the hot fragments [5,6].

Recently, we focussed our interest on the possibility of extracting information on the dynamics and the nuclear equation of state (EOS) by comparing our heavy residue data to detailed calculations using microscopic models of heavy-ion collisions at these energies [7].

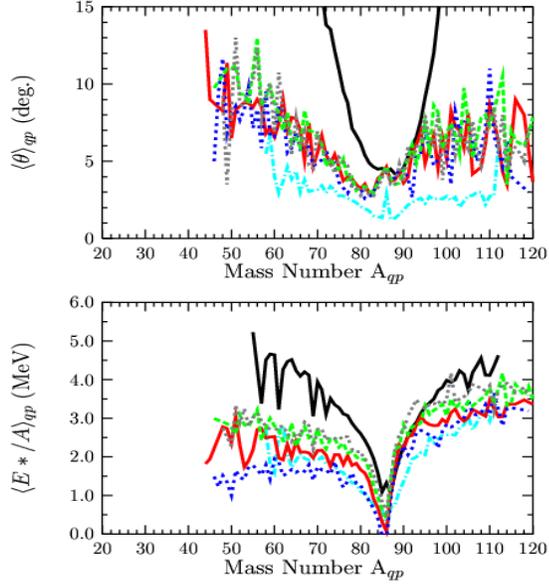
Our initial efforts with transport-type codes (BUU, BNV) have not been successful in describing the details of the heavy residue distributions. We believe that this may be due, in part, to the inability of these types of models to provide an accurate estimate of the primary fragment excitation energy in peripheral and semiperipheral collisions.

We subsequently turned our attention to the quantum molecular dynamics approach (QMD). At present, we are performing detailed calculations of the QMD type using a recent version of the constrained molecular dynamics code CoMD of M. Papa [8,9]. This QMD code is especially designed for reactions near and below the Fermi energy. It implements an effective interaction corresponding to a nuclear-matter compressibility of  $K=200$  (soft EOS) with several forms of the density dependence of the nucleon-nucleon symmetry potential. While not specifically using antisymmetrized  $N$ -body wave functions, CoMD imposes a constraint in the phase space occupation for each nucleon, thus effectively restoring the Pauli principle at each time step of the collision. This constraint preserves the fermionic nature of the interacting nuclei in a satisfactory manner [8]. The latest version (CoMD-II) also fully preserves the total angular momentum along with linear momentum and energy [9].

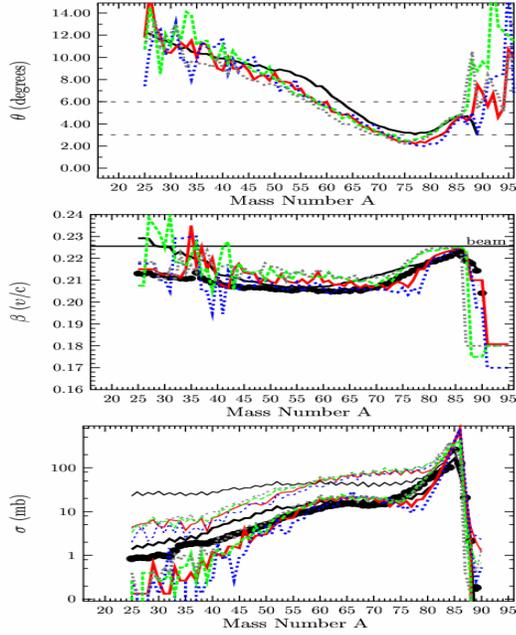
Preliminary results of the calculations and comparisons with our residue data are shown in Figs. 1-4. Fig. 1 shows the calculated average quasiprojectile angle (upper panel) and excitation energy per nucleon (lower panel) as a function of the mass of the (primary) quasiprojectiles. The black line corresponds to the prediction of the deep-inelastic transfer (DIT) code of Tassan-Got that has been extensively used in our studies of quasiprojectile formation near the Fermi energy [10]. The light blue curve shows the prediction of the heavy-ion phase-space exploration (HIPSE) model [11]. The remaining four lines are the results of CoMD calculations with four symmetry potential options referred to as: “a-soft” (blue line), “linear” (red line), “a-stiff” (green line) and “no-symm” (grey line). The above characterizations refer to the form of the density dependence of the nucleon-nucleon symmetry potential

$V_{\text{symm}}$ , whereas, in the last case (“no-symm”) this potential is set to zero (thus, only the kinetic part of the symmetry energy plays a role in this case). The CoMD calculation was stopped at  $t=300$  fm/c. We observe differences between the predictions of DIT, HIPSE and CoMD that we will try to further investigate and understand in the near future. Regarding CoMD, despite the observed fluctuations of the mean values, we may tentatively conclude that the mean quasiprojectile angle is not sensitive to the choice of the symmetry potential. However, the mean excitation energy shows some sensitivity in the choice that deserves further exploration.

In Fig. 2, the distributions of the mean angle, mean velocity and yield as a function of the mass of the (final) observable fragments are shown. The deexcitation of the primary fragments was done with the sequential decay code GEMINI. The meaning of the curves is as before: black line: DIT, coloured lines: CoMD. The top panel shows, along with the calculations, the angular acceptance of the MARS separator  $\Delta\theta=3^\circ\text{-}6^\circ$  for our measurements (dashed horizontal lines). In the middle and lower panels, the MARS data [1] are shown with solid symbols. The calculations in both cases are filtered with the angular acceptance of the separator. Additionally, in the lower panel, the thin lines show the calculations of the total residue yields. We observe an overall satisfactory agreement of the CoMD calculations



**Figure 1.** Mean quasiprojectile angle (upper panel) and excitation energy per nucleon (lower panel) as a function of quasiprojectile mass for the reaction  $^{86}\text{Kr}(25\text{MeV/nucleon}) + ^{124}\text{Sn}$ . Black line: DIT. Light-blue line: HIPSE. Blue (a-soft), red (linear), green (a-stiff) and grey (no-symm): CoMD calculations (see text).



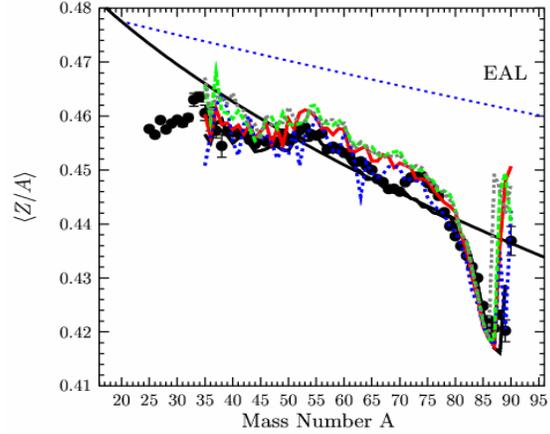
**Figure 2.** Mean angle (upper panel), mean velocity (middle panel) and yield (lower panel) as a function of projectile residue mass for the reaction  $^{86}\text{Kr}(25\text{MeV/nucleon}) + ^{124}\text{Sn}$ . Black line: DIT. Blue (a-soft), red (linear), green (a-stiff) and grey (no-symm): CoMD calculations (see text). Black points: MARS data [1]

with the data and again, in the CoMD calculations, an insensitivity to the choice of the symmetry potential. The situation is similar for the comparison of the mean  $Z/A$  values of the observed residues with the CoMD calculations shown in Fig. 3.

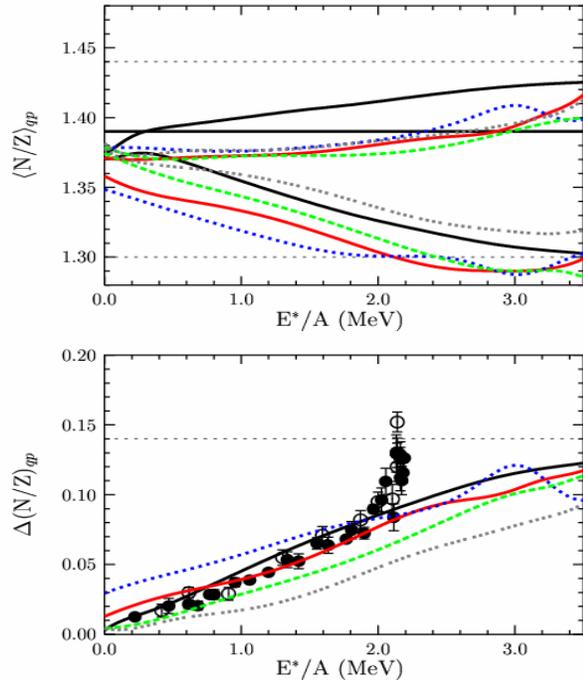
Finally, in Fig. 4, upper panel, we show the calculated mean  $N/Z$  of the primary quasiprojectiles as a function of the excitation energy per nucleon. The meaning of the curves is as in Fig. 1. The upper set of curves is for the  $^{86}\text{Kr}(25\text{MeV/nucleon}) + ^{124}\text{Sn}$  reaction and the lower set is for the  $^{86}\text{Kr}(25\text{MeV/nucleon}) + ^{112}\text{Sn}$  reaction. The solid horizontal line corresponds to the  $N/Z$

of the projectile, whereas the upper and lower dashed lines give the  $N/Z$  of the fully equilibrated systems in the two cases. In the lower panel of the figure we show the difference of the calculated mean  $N/Z$  values, along with our data (solid and open points) from the heavy-residue isoscaling analysis of [4]. It is interesting to note that the CoMD calculations show some sensitivity in the choice of the symmetry potential. However, this observation may be subject to the inherent uncertainty in the determination of the excitation energy of the quasiprojectiles. In the present calculations, the excitation energy has been determined from the difference of the binding energy of the (hot) quasiprojectiles as given by the CoMD code and the corresponding binding energy taken from mass tables. We plan to investigate the issues of the excitation energy determination in a systematic way.

Finally, we plan to explore the  $N/Z$  equilibration process (e.g. Fig. 4) in greater detail via comparisons of CoMD



**Figure 3.** Mean projectile residue  $Z/A$  as a function of residue mass for the reaction  $^{86}\text{Kr}$  (25MeV/nucleon) +  $^{124}\text{Sn}$ . Black line tracing the data: DIT. Blue (a-soft), red (linear), green (a-stiff) and grey (no-symm): CoMD calculations (see text). Black points: MARS data [1]. Black line: line of stability.



**Figure 4.** Upper panel: Mean  $N/Z$  of primary quasiprojectiles as a function of excitation energy per nucleon for the 25 MeV/nucleon reactions:  $^{86}\text{Kr} + ^{124}\text{Sn}$  (upper set of curves) and  $^{86}\text{Kr} + ^{112}\text{Sn}$  (lower set of curves). Black lines DIT. Blue (a-soft), red (linear), green (a-stiff) and grey (no-symm): CoMD calculations (see text). Lower panel: Difference in quasiprojectile mean  $N/Z$ . Lines as above. Black points: residue isoscaling data from [4].

calculations with our residue data from other reactions at 25 MeV/nucleon [5,6], as well as new experimental measurements at 15 MeV/nucleon that we plan to undertake in the near future.

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