Probing the Nuclear Equation of State with Peripheral Heavy Ion Collisions at Fermi Energies

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Abstract

A systematic study of quasi-elastic and deep-inelastic collisions at Fermi energies is presented with the aim of obtaining insight into the underlying dynamics and the nuclear equation of state (EOS). Comparisons of experimental heavy-residue data to detailed calculations using the semiclassical microscopic model CoMD (Constrained Molecular Dynamics) are shown. The CoMD code implements an effective interaction with a nuclear-matter compressibility of K=200 (soft EOS) or K=380 (stiff EOS) with several forms of the density dependence of the nucleon-nucleon symmetry potential and imposes a constraint in the phase space occupation for each nucleon, restoring the Pauli principle during the collision. Preliminary results from these comparisons point to a soft equation of state (K=200) with a rather stiff density dependence of the isovector part (symmetry energy).

The nuclear equation of state (EOS) and, especially, its isospin part (symmetry energy) have recently received an exceptionally strong attention by the nuclear physics community. The EOS, being intimately connected to the underlying nucleon-nucleon effective interaction, plays a pivotal role in a broad range of phenomena in both nuclear physics, e.g. the structure and dynamics of exotic/drip-line nuclei and in astrophysics, e.g. the structure and evolution of neutron stars and the dynamics of supernova explosions (e.g. [1,2] and references therein).

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. One of the motivations of these studies was the understanding and the optimization of the production of very neutron-rich rare isotopes in these collisions [3–5]. 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 [6].
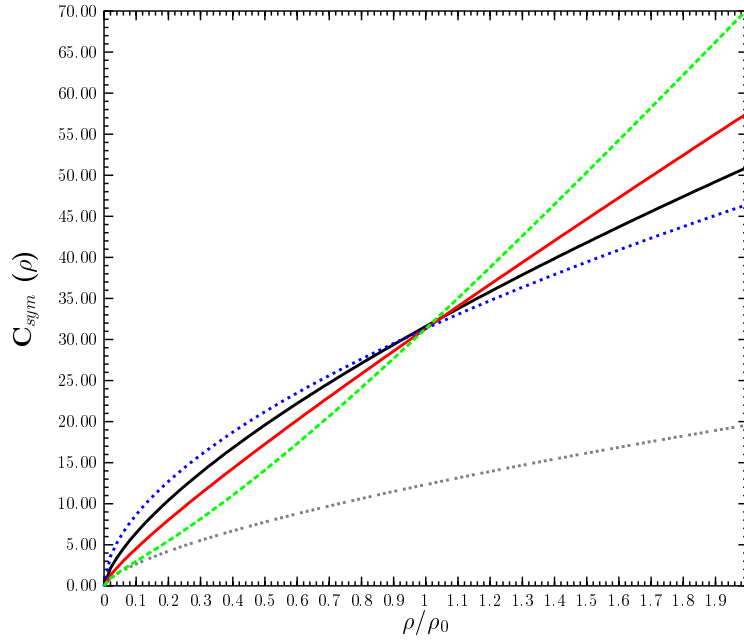
Fig. 1. (Color Online) Density dependence of the nuclear symmetry energy $C_{sym}(\rho)$ corresponding to the forms of the nucleon-nucleon symmetry potential in the CoMD code. Blue (dotted): asy-soft, red (solid): asy-stiff, green (dashed): super asy-stiff and grey (lower dotted) line: no symmetry potential. The black (solid) line represents the form $31.6(\rho/\rho_0)^{0.69}$ consistent with the isoscaling analysis of fragments from central heavy-ion collisions [2].

Recently, we focussed our interest on the possibility of extracting information on the isospin part of the nuclear equation of state by comparing our heavy residue data to detailed calculations using microscopic models of heavy-ion collisions at these energies [7]. After some initial efforts with one-body transport-type codes (BUU, BNV) [8], we turned our attention to the N-body quantum molecular dynamics approach (QMD) [9]. To date, we have performed detailed calculations using the recent version of the constrained molecular dynamics (CoMD) code of A. Bonasera and M. Papa [10,11].

The CoMD code is especially designed for reactions near and below the Fermi energy. Following the general philosophy of the QMD approach [9], in the CoMD model, nucleons are described as localized Gaussian wave packets. The wave function of the N-body nuclear system is assumed to be the product of these single-particle wave functions. With the Gaussian description, the N-body time-dependent Schöndinger equation leads to (classical) Hamilton's equations of motion for the centroids of the nucleon wavepackets. The potential part of the Hamiltonian consists of a Skyrme-like effective interaction. The isoscalar part of this effective interaction corresponds to a nuclear-matter compressibility of K=200 (soft EOS) or K=380 (stiff EOS). For the isovector part,

several forms of the density dependence of the nucleon-nucleon symmetry potential are implemented. The corresponding symmetry energy functionals are shown in Fig. 1 and referred to as: "asy-soft": blue (dotted) line; "asy-stiff": red (solid) line; "super asy-stiff": green (dashed) line; and, "no symmetry potential": grey (dotted) line. The first three forms correspond to a dependence of the symmetry potential V_{sym} on the 1/2, 1 and 2 power of the density, respectively, whereas in the last case, the nucleon-nucleon symmetry potential is set to zero – thus, only the kinetic part of the symmetry energy plays a role in this case.

In the CoMD model, while not explicitly implementing antisymmetrization of the N-body wavefunction, a constraint in the phase space occupation for each nucleon is imposed, effectively restoring the Pauli principle at each time step of the (classical) evolution of the system. This constraint restores in an approximate way the fermionic nature of the nucleon motion in the interacting nuclei [10]. The short range (repulsive) nucleon-nucleon interactions are described as individual nucleon-nucleon collisions governed by the nucleon-nucleon scattering cross section, the available phase space and the Pauli principle, as usually implemented in transport codes [8]. The latest CoMD version (CoMD-II) fully preserves the total angular momentum (along with linear momentum and energy) [11], features which are critical for the accurate description of observables from heavy-ion collisions.

Results of the CoMD calculations (with compressibility K=200) and comparisons with our experimental data on heavy-residue distributions are shown in Figs. 2–5. Fig. 2 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 (solid) 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 [12]. The remaining three lines are the results of CoMD calculations with symmetry potential options: "asy-soft": blue (dotted) line; "asy-stiff": red (solid) line; "super asy-stiff": green (dashed) line (see, also Fig. 1). The CoMD calculation was stopped at t=300 fm/c. We observe differences between the predictions of DIT 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. 3, 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 [13]. The meaning of the curves is as before: black (solid) line: DIT,
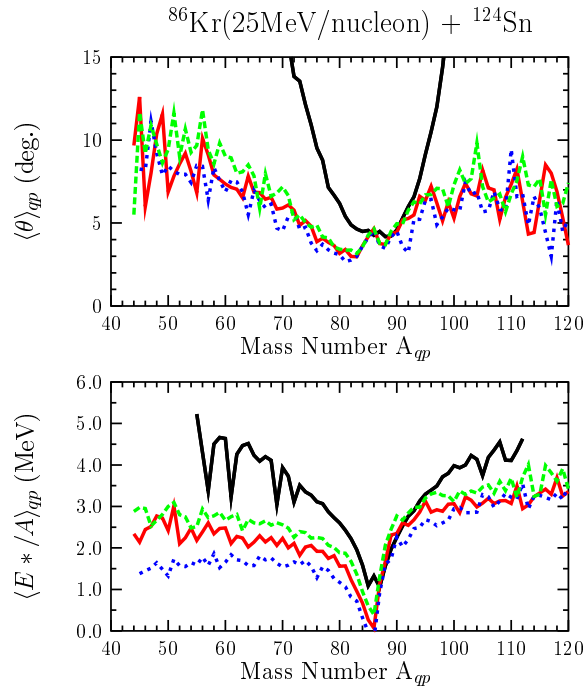
^{86}Kr(25MeV/nucleon) + ^{124}Sn

Fig. 2. (Color Online) Mean quasiprojectile angle (upper panel) and excitation energy per nucleon (lower panel) as a function of quasiprojectile mass for the reaction ^{86}Kr(25MeV/nucleon) + ^{124}Sn. The black (solid) line represents DIT calculations. CoMD calculations are given by the following lines: blue (dotted): asy-soft, red (solid): asy-stiff, and green (dashed): super asy-stiff (see text).

colored lines: CoMD. The top panel shows, along with the calculations, the angular acceptance of the MARS separator $\Delta\theta=3^o$–6° for our measurements (dashed horizontal lines). In the middle and lower panels, the MARS data [3] 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 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 (atomic number over mass number, or proton fraction) values of the observed residues with the CoMD calculations shown in Fig. 4.

In Fig. 5, upper panel, we show the calculated mean $(Z/A)^2$ of the primary quasiprojectiles as a function of the excitation energy per nucleon. The meaning of the curves is as in Fig. 2. The upper set of curves is for the ^{86}Kr (25 MeV/nucleon) + ^{112}Sn reaction and the lower set is for the ^{86}Kr (25MeV/nucleon) + ^{124}Sn reaction. The solid horizontal line corresponds to the $(Z/A)^2$ of the projectile, whereas the upper and lower dashed lines give the $(Z/A)^2$ of the fully equilibrated systems in the two cases. In the lower panel of the figure we show the difference of the calculated mean $(Z/A)^2$ values, along
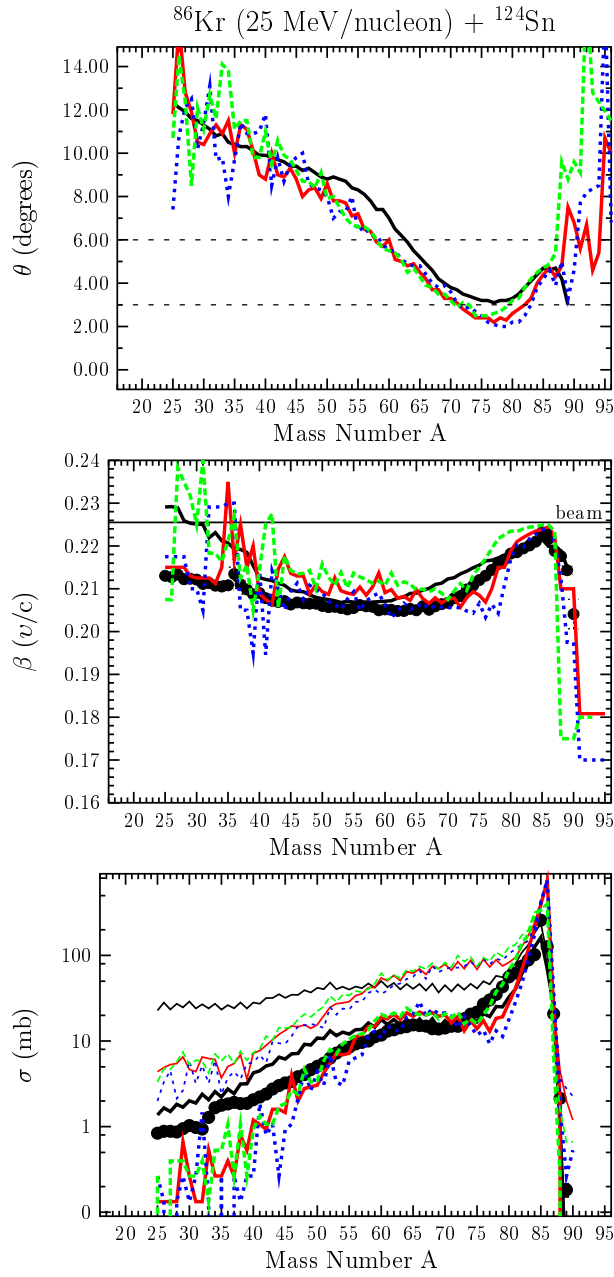
Fig. 3. (Color Online) Mean angle (upper panel), mean velocity (middle panel) and yield (lower panel) as a function of projectile residue mass for the reaction ^{86}Kr (25MeV/nucleon) + ^{124}Sn. DIT calculations are given by the black (solid) line. CoMD calculations are given by the other three lines as in Fig. 2 (see text). Black points: MARS data [3].

with our data (solid and open points) from the heavy-residue isoscaling analysis of [6]. It is interesting to note that the CoMD calculations show 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
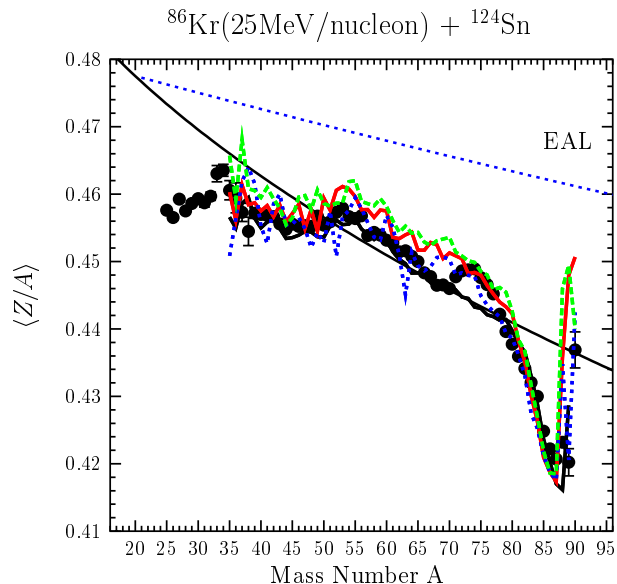
Fig. 4. (Color Online) Mean projectile residue Z/A as a function of residue mass for the reaction ^{86}Kr(25MeV/nucleon)+^{124}Sn. DIT calculations are given by the black (solid) line that traces the data. CoMD calculations are given by the other three lines as in Fig. 2 (see text). Black points: MARS data [3]. Black near-diagonal (solid) line: stability line. EAL: evaporation attractor line [14].

been determined from the difference of the binding energy of the (hot) quasi-projectiles as given by the CoMD code at t=300 fm/c and the corresponding binding energies of cold nuclei taken from mass tables. We have investigated the issues of the excitation energy determination and we believe that, except from very peripheral collisions (essentially corresponding to direct reactions) the CoMD code provides a reliable estimate of the excitation energies of the quasiprojectiles. The comparison presented in Fig. 5 suggests a rather stiff dependence of the symmetry energy on density (Fig. 1) in overall agreement with other studies, as presented in Ref. [11] (and references therein).

As part of our detailed studies with the CoMD model framework, we report in Fig. 6 the predicted neutron skin of the ^{86}Kr nucleus using the four options of the symmetry potential. The values of the skin show a small sensitivity to the density dependence of the symmetry potentials and are in agreement with expectations from microscopic SHF or Thomas-Fermi calculations. In the same vein, Fig. 7 presents the giant dipole resonance (GDR) spectrum of the ^{86}Kr nucleus obtained from the Fourier transform of the spatial oscillation of the neutron vs proton spheres within the CoMD model. The symmetry potentials employed seem to give reasonable values for the GDR energy centroids (although somewhat lower that the value 16.8 MeV expected from empirical systematics [15,16]) and widths ∼4 MeV in very good agreement with expectations for near ground-state nuclei [15].
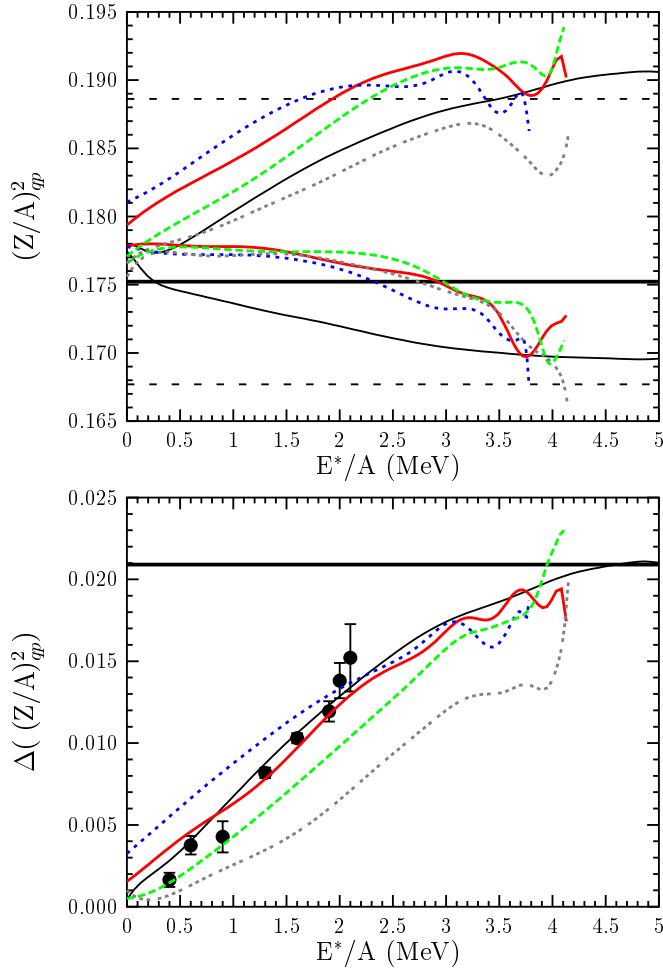
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^{86}Kr(25MeV/nucleon) + ^{124,112}Sn

Fig. 5. (Color Online) Upper panel: Mean $(Z/A)^2$ of quasiprojectiles as a function of excitation energy per nucleon for the 25 MeV/nucleon reactions: ^{86}Kr+ ^{112}Sn (upper set of curves) and ^{86}Kr+ ^{124}Sn (lower set of curves). Lower panel: Difference in quasiprojectile mean $(Z/A)^2$. Black (solid) lines represent DIT calculations. CoMD calculations are given by the following lines (as in the previous figures): blue (dotted): asy-soft, red (solid): asy-stiff, green (dashed): super asy-stiff and grey (dotted): no symmetry potential (see text). Black points: residue isoscaling data from [6].

Finally, we plan to explore the N/Z equilibration process (e.g., Fig. 5) in greater detail via comparisons of CoMD calculations with a broader set of experimental data including our recent data from 15 MeV/nucleon ^{40}Ar and ^{86}Kr projectiles on ^{64,58}Ni and ^{124,112}Sn targets that are presently under analysis.

In summary, we presented comparisons of experimental heavy-residue data to calculations with the semiclassical microscopic model CoMD (Constrained Molecular Dynamics). We believe that the model framework, being an N-body approach, is an appropriate model framework to provide a unified description
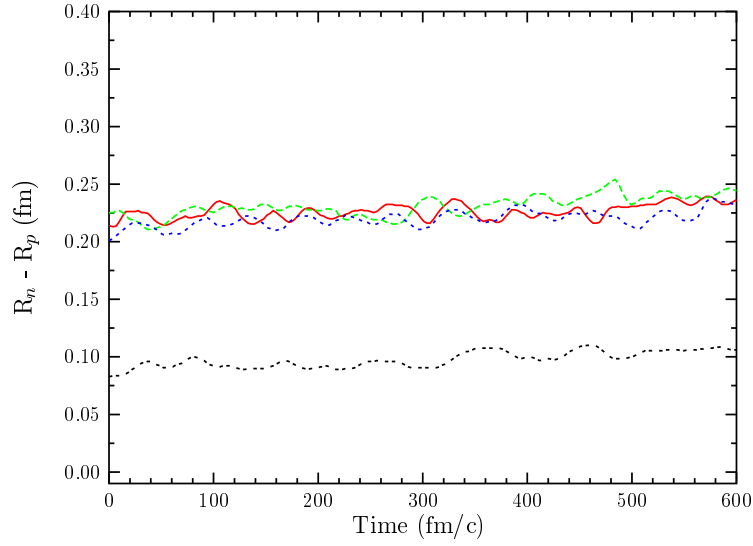
Fig. 6. (Color Online) Time evolution of the neutron skin of an isolated ^{86}Kr nucleus predicted by CoMD. The various lines correspond to the choices of the nucleon symmetry potential as follows: blue (dotted): asy-soft, red (solid): asy-stiff, green (dashed): super asy-stiff and gray (lower dotted): no symmetry potential (see text).
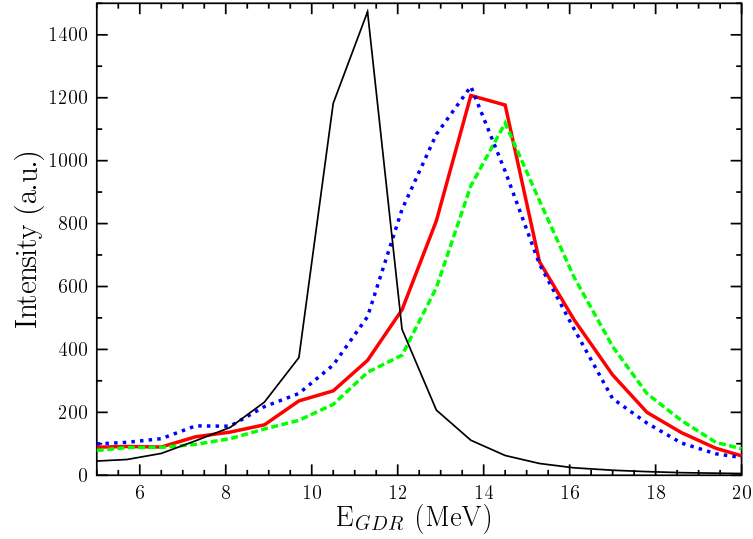

Fig. 7. (Color Online) Giant dipole resonance (GDR) response of an isolated ^{86}Kr nucleus predicted by CoMD. The various lines correspond to the choices of the nucleon symmetry potential as follows: blue (dotted): asy-soft, red (solid): asy-stiff, green (dashed): super asy-stiff, and black (left solid): no symmetry potential. The expected value of the energy according to the empirical GRD systematics is 16.8 MeV [15,16].

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of a large body experimental data as the present heavy-residue data from peripheral and semiperipheral collisions in the Fermi energy regime. Our preliminary results from the present comparisons point to a soft equation of state (K=200) with a rather stiff density dependence of the symmetry energy part of the nucleon-nucleon effective interaction, in overall agreement with other heavy-ion studies (e.g. [11] and references therein).

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