Studies of the Nuclear Landscape and the Nuclear Equation of State using Peripheral Collisions near the Fermi Energy

George A. Souliotis
Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, Athens, Greece, and Cyclotron Institute, Texas A&M University, College Station, Texas, USA
E-mail: soulioti@comp.tamu.edu

Abstract.

Studies of peripheral (quasi-elastic and deep-inelastic) collisions near the Fermi energy are presented with a two-fold goal: first, to produce very neutron-rich nuclei towards the neutron drip line and, second, to obtain insight into the underlying dynamics and the nuclear equation of state (EOS). Towards the first goal, our studies indicated an enhanced production of neutron-rich nuclides suggesting that peripheral reactions at Fermi energies offer a novel way to access very neutron-rich rare isotopes in unexplored regions of the nuclear chart. Towards the second goal, we have made comparisons of our experimental data to detailed calculations using the semiclassical microscopic model CoMD (Constrained Molecular Dynamics). 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 phase space constraint to restore the Pauli principle during the collision. Present results from these comparisons are consistent with a soft equation of state (K=200) with a rather stiff density dependence of the symmetry potential (symmetry energy).

1. Introduction

The exploration of the nuclear landscape, as well as the elucidation of 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, 3] and references therein).

2. Neutron-rich rare-isotope production at Fermi energies

We have undertaken a systematic study of projectile-like fragment distributions from peripheral (quasi-elastic and deep-inelastic) collisions near the Fermi energy. The motivation of our studies was the understanding and optimization of the production of very neutron-rich rare isotopes in these collisions. The experimental procedures are described in detail in our recent articles [4, 5, 6, 7, 8].

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The use of the high-resolution recoil separator MARS in combination with standard $B{\rho} - \Delta E$–$E$ (magnetic rigidity, energy-loss, residual-energy) and time-of-flight techniques provided high-resolution information on the atomic number $Z$, the ionic charge $q$, the mass number $A$ and the velocity distributions of the projectile fragments. Summation over $q$ provided the yield distributions with respect to $Z$, $A$ and velocity from which production cross sections were extracted. The measurements were performed inside the grazing angles of the corresponding reactions at 25 MeV/nucleon and in a wide $B{\rho}$ window that enabled efficient collection of heavy projectile residues produced in a broad range of energy damping, from quasielastic to deep-inelastic collisions.

As representative results, the mass distributions (cross sections) of germanium (Ge) isotopes from the reactions of 25 MeV/nucleon $^{86}$Kr with $^{64}$Ni, and $^{124}$Sn are shown in Fig. 1 and compared with calculations. The simulations involve the deep-inelastic transfer (DIT) code of Tassan-Got [9] for the dynamic stage followed by the de-excitation code GEMINI [10, 11]. The calculations are shown by the thick solid lines. The dotted lines are predictions of the EPAX parameterization [12] of fragmentation cross sections. In high energy fragmentation (see, e.g., [13]) nucleon-pickup products are highly suppressed, compared to lower-energy peripheral collisions. As seen in Fig. 1, neutron-rich nuclides are produced with substantial yields. For near-projectile elements (e.g. Ge in Fig. 1), a large enhancement is observed that cannot be described by the DIT/GEMINI simulations. We found that this enhancement can be described by an extension of DIT in which realistic density distributions of the nuclei are employed. Thus, we infer that the neutron skin of the neutron-rich targets plays an important role [5, 7].

The present data show the production of nuclides with up to 4–5 neutrons picked-up from the target, along with usual proton removal products [5, 6, 7] demonstrating the important role of the target in the production mechanism. This point can be clearly seen in Fig. 2 which provides an overall representation of the measured production cross sections of projectile fragments from the reaction $^{86}$Kr (25 MeV/nucleon) + $^{64}$Ni on the $Z$–$N$ plane. In this figure, the cross section ranges are shown by open circles according to the key. The closed squares show the stable isotopes. The solid line indicates the astrophysical r-process path, whereas the dashed line denotes the location of the neutron drip-line according to [14]. In closing, we conclude that peripheral reactions around or below the Fermi energy offer a novel way to access very neutron-rich rare isotopes towards the r-process path and the neutron drip-line.

3. Studies related to the nuclear effective interaction and the nuclear EOS

In parallel to the rare isotope production studies, we employed the experimental results on residue distributions from peripheral reactions in efforts to extract information on the properties of the nuclear effective interaction as manifested in the mechanism of nucleon exchange taking place in these reactions and the course towards $N/Z$ equilibration [15]. We focussed our interest on the possibility of extracting information on the isospin part of the nuclear equation of state by comparing our experimental data on heavy residues to detailed calculations using microscopic models of heavy-ion collisions at these energies [16]. After some initial efforts with one-body transport-type codes (BUU, BNV) [17], we turned our attention to the N-body quantum molecular dynamics approach (QMD) [18]. We have performed detailed calculations using the recent version of the Constrained Molecular Dynamics (CoMD) code of A. Bonasera and M. Papa [19, 20].

3.1. Brief description of the CoMD model

The CoMD code is especially designed for reactions near and below the Fermi energy. Following the general philosophy of the QMD approach [18], in the CoMD model, nucleons are described as localized Gaussian wave packets. The wave function of the N-body nuclear system is assumed
Figure 1. (Color online) Comparison of the experimental mass distributions of Ge (Z=32) from $^{86}\text{Kr}$ (25 MeV/nucleon) on $^{64}\text{Ni}$ [4] and $^{124}\text{Sn}$ [5] with DIT/GEMINI calculations without and with (lower and upper solid lines, respectively, on the neutron-rich side) realistic neutron and proton density distributions. Dotted line: EPAX prediction [12].

Figure 2. (Color online) Representation of the production cross sections of projectile fragments from the reaction $^{86}\text{Kr}$ (25 MeV/nucleon) + $^{64}\text{Ni}$ on the Z–N plane [4]. The cross section ranges are shown by open circles according to the key. The closed squares show the stable isotopes. The solid line indicates the astrophysical r-process path, whereas the dashed line denotes the neutron drip-line according to [14].

to be the product of these single-particle wave functions. With the Gaussian description, the N-body time-dependent Schrödinger equation leads to (classical) Hamilton’s equations of motion
Figure 3. (Color Online) Density dependence of the nuclear symmetry energy $C_{\text{sym}}(\rho)$ 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].

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. 3 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 $V_{\text{sym}}$ 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 [19]. 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 [17]. The latest CoMD version (CoMD-II) fully preserves the total angular momentum (along with linear momentum and energy) [20], features which are critical for the accurate description of observables from heavy-ion collisions.

3.2. Comparisons of CoMD calculations to the experimental data

Results of the CoMD calculations (with compressibility $K=200$) and comparisons with our experimental data on heavy-residue distributions are shown in Figs. 4–7. Fig. 4 shows the calculated average quasiprojectile angle (upper panel) and excitation energy per nucleon
Figure 4. (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).
Figure 5. (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 (25 MeV/nucleon) + $^{124}$Sn. DIT calculations are given by the black (solid) line. CoMD calculations are given by the other three lines as in Fig. 4 (see text). Black points: MARS data [5].

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. 6.

In Fig. 7, 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. 4. 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 with our data (solid and open points) from the heavy-residue isoscaling analysis of [15]. 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 been determined from the difference of the binding energy of the (hot) quasiprojectiles 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. 7 suggests a rather stiff dependence of the symmetry energy on density (Fig. 3) in overall agreement with other studies, as presented in Ref. [2] (and references therein).

3.3. Calculation of ground state properties with CoMD
As part of our detailed studies with the CoMD model framework, we report in Fig. 8 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. 9 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 [21, 22]) and widths ~4 MeV in very good agreement.

Figure 6. (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. 4 (see text). Black points: MARS data [5]. Black near-diagonal (solid) line: stability line. EAL: evaporation attractor line [11].
Figure 7. (Color Online) Upper panel: Mean $(Z/A)^2$ of quasiprojectiles as a function of excitation energy per nucleon for the 25 MeV/nucleon reactions: \(^{86}\text{Kr} + {^{112}\text{Sn}}\) (upper set of curves) and \(^{86}\text{Kr} + {^{124}\text{Sn}}\) (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 [15].

with expectations for near ground-state nuclei [21].

4. Plans for future work
In regards to the production of rare isotopes and the studies of the nuclear EOS, in the near future we plan to extend our studies utilizing a broad set of recent experimental data with the MARS separator concerning the reactions of 15 MeV/nucleon \(^{40}\text{Ar}\) and \(^{86}\text{Kr}\) projectiles on \(^{64,58}\text{Ni}\) and \(^{124,112}\text{Sn}\) targets. The analysis of these data is approaching completion. Detailed calculations with the CoMD code will follow along the lines presented in this paper.
Figure 8. (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).

Figure 9. (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 [21, 22].
5. Summary and conclusions
Systematic studies of heavy residue distributions from quasi-elastic and deep-inelastic collisions near the Fermi energy were presented with a two-fold goal: first, to produce very neutron-rich nuclei towards the neutron drip line and, second, to obtain insight into the underlying dynamics and the nuclear equation of state (EOS). Towards the first goal, our studies indicated an enhanced production of neutron-rich nuclides in comparison with the traditional high-energy fragmentation mechanism which was attributed to the role of the N/Z and the nuclear periphery of the target. From a practical viewpoint, these reactions at Fermi energies offer a novel way to access very neutron-rich rare isotopes towards the r-process path and the neutron drip-line. Towards the second goal, we have made detailed comparisons of our experimental data to calculations with the semiclassical microscopic model CoMD (Constrained Molecular Dynamics). We believe that the CoMD model, being an N-body approach, offers an appropriate model framework to provide a unified description of a large body experimental data as the present heavy-residue data from peripheral collisions in the Fermi energy regime. The 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. [2] and references therein).

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