Surface Matters - Prospects for Mechanistic Studies at Intermediate Energies

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Abstract
The phenomenology of nuclear (light-and heavy-ion) reactions is complex and suggests the presence of competing dissipative-dynamical nucleus-nucleus interactions and several mechanisms for the emission of nucleons and nuclear clusters. An operational decomposition of reaction phenomena and their understanding in context requires the development of an overall reaction scenario. This is possible to achieve in studies of surface interactions in peripheral collisions that lead to statistical and non-statistical particle and cluster emission. Exploring nuclear decay promotes a better understanding of surface structure and interactions. Suggestions are made for a comprehensive new research strategy.

I. Introduction and task definition
The past two decades have seen vigorous experimental and theoretical research in the realm of heavy-ion (HI) and spallation reactions at Fermi and intermediate bombarding energies, in which nuclear systems are produced close to the limits of (meta-) stability [Lot92, Mon94, Tok95, Mor98, Tra98, Dje01, Sch01, Bor02, Ago02, Hud05, Def05, Gol04]. Much of this activity has been inspired by the opportunity to study the equation of state (EOS) of finite nuclei and nuclear matter and its "isospin" (neutron-proton asymmetry) dependence [Dan73, Ber83, LiK98, LiS01, Bar02, Cho05]. More generally, research has focused on the thermodynamics of critically hot finite nuclei and a postulated nuclear liquid-gas phase transition.

The production of such systems in nuclear reactions has been modeled mostly in terms of classical or semi-classical transport theory such as the Boltzmann-Uehling-Uhlenbeck (BUU) or similar approaches [Col94, LiK98, Dan99, DiT99, Bon00, LiS01], in molecular dynamics [Aic93, Luk93], or intra-nuclear cascade concepts [Cug97, Bou04]. Attempts at quantal nuclear transport descriptions [Hor91, Fel97] have remained incomplete. Theoretical models [Gro93, Bon95, Bon00, Lop00, Nor00, Shl05, Cho05] for the internal reorganization of initially highly disturbed nuclear systems assume intrinsic degrees of freedom to equilibrate within the boundaries of the nuclear surface or a hypothetical "freeze-out volume".

In spite of impressive theoretical developments, a comprehensive explanation of experimental reaction and decay data has not yet been achieved. Still lacking is a consistent understanding of the interplay of dynamics and induced nuclear relaxation processes, the approach to equilibrium and the emergence of multi-particle saddle shapes, which determine the subsequent disintegration of reaction primaries and the population of the space of final reaction products. Clearly, phenomena encountered in intermediate-energy nuclear reactions have turned out to be more complex and interesting than previously imagined. To meet these challenges, new concepts and research strategies ("thinking out-of-the box") are needed.

Consolidation of present knowledge and planning of future research both require elucidation of the

1. Microscopic basis for the dynamic response of nuclei in energetic collisions,
2. Transport and relaxation phenomena induced in complex nuclear reactions,
3. Interdependencies between nuclear structure and reactions, e.g., the influence of the nuclear surface and the effects of mechanical and chemical instabilities.

Developing a comprehensive understanding of nuclear behavior requires compliance with accepted general principles of nuclear structure and nuclear phenomena. For example, the facts that nuclei are dominantly quantal entities with very diffuse surfaces and that generally collective degrees of freedom, however defined, interact with intrinsic motion (viscosity) should not be ignored. Ideally, a satisfactory understanding of nuclear processes also entails a relation of microscopic theory to models of macroscopic experience while avoiding over-simplification.

From future nuclear reaction studies, one hopes to glean answers to question concerning the shapes and density profiles of interacting nuclei, the magnitude of in-medium nucleonic correlations (clusters and effective masses \(m_n^*, m_p^*\)) and scattering, the effects of isospin asymmetry on equilibrium and non-equilibrium transport and on collective motion. Structure and dy-
namics of the surface of hot nuclei represent an interesting new challenge, for example, the evolution and decay of neck-like matter bridges between projectile and target nuclei and the "melting" of the surface in multi-fragment decay. A priority exploration of the nuclear surface is important, feasible, and timely.

To derive a realistic reaction scenario, in which to place specific phenomena, a plausible strategy first addresses peripheral (surface) nuclear interactions of different inelasticity, following their evolution with decreasing impact parameter and increasing bombarding energy. In cases where projectile/target fusion in its degree of completeness (momentum transfer) can be characterized, study of compound nuclear fusion, from sub-barrier to high-energy fusion, presents a viable alternative. Specific surface properties, such as promotion of cluster correlations, are probed in transfer reactions of particles and clusters, their prompt non-statistical emission, as well as in measurements of neck breakup particles. Finally, the influence of the surface and its thermodynamic fluctuations on nuclear stability and decay modes can be studied through sequential evaporation of nucleons and clusters from well characterized reaction primaries, such as fast-moving projectile-like fragments (PLFs).

The initial projectile/target isospin asymmetry provides an important new tool in the study of transport processes, whose thorough understanding is a prerequisite for the deduction of the nuclear EOS. In this context, the importance of studies employing secondary beam projectiles cannot be over emphasized. The following section provides some illustrations of how pieces of experimental evidence conflicting with popular expectations can help in generating a viable overall reaction scenario. Examples are then given of prospects of surface reaction and decay studies. Conclusions and outlook in Section IV represent an appeal to construct a more competent microscopic reaction and transport theory.

II. Experiment and illustration of current model understanding

A common feature of intermediate-energy reactions induced by heavy or light ions consists in the fact that large amounts of kinetic energy (~1 GeV) of relative motion can be transferred within short times (~10^{-22} - 10^{-21}s) into intrinsic nuclear excitation (typically ΔE^* = ΔE/A ~ 5 MeV). Depending on density (ρ) and temperature (T), thermal equilibration occurs on even faster time scales (t_rel), e.g. [Abu93],

\[ t_{rel}(T, ρ) = \frac{310}{T^2} \left( \frac{ρ}{ρ_0} \right)^{0.4} \left\{ 1 + 0.17 \left( \frac{ρ}{ρ_0} \right)^{0.5} \right\} \frac{57T^{-12}}{1 + 160/T^2} \left( \frac{ρ}{ρ_0} \right) \]

In Fig. 1, relaxation times given by Eqn. (1) for various relative densities ρ/ρ_0 and compound-nucleus particle evaporation times (t_{evap}) are compared to typical heavy-ion reaction times (t_{rxn}) [Sch87] based on the one-body nucleon exchange model NEM [Ran87]. It suggests that nuclear systems produced in energetic collisions equilibrate and disintegrate promptly, i.e., before projectile-like (PLF) and target-like (TLF) reaction partners can reseparate in the exit channel.

However, experimental observations of massive reaction fragments and intermediate mass clusters clearly disagree with such expectations. Several HI reactions, including the systems 209Bi + 136Xe (E_{Lab} = 7-62 MeV) and 197Au + 86Kr (E_{Lab} = 35 - 54 MeV) demonstrate unexpected resilience of dissipative, reaction features for essentially the entire reaction cross section and the entire range of bombarding energies. This feature is illustrated in Fig. 2 for the reaction 209Bi + 136Xe [Gaw05] at two bombarding energies. Experiments quoted here and below were
performed at the MSU/NSCL cyclotron laboratory with a 4π setup consisting of position-sensitive Si telescopes for the sampling of PLF fragments, the DwarfBall/ Wall charged-particle detector, and the SuperBall 4π neutron calorimeter.

The greatest surprise of the experiments was that massive PLFs (and TLFs) are observed at all. Furthermore, the measured PLF lab energies (relative to the beam energy), plotted in Fig. 2 vs. lab angle, demonstrate a classical dissipative orbiting pattern (Wilczyński plot). The superimposed solid lines represent average trajectories predicted by the above NEM simulation calculations. Decays of hot reaction primaries have been simulated with the statistical code GEMINI [Cha99]. Since dissipative orbiting prevails up to the highest energies measured so far, one is led to conclude that mean-field conservative and dissipative forces change only in a gradual fashion from near-barrier to intermediate bombarding energies.

Good agreement between data and NEM predictions has also been obtained for other correlations, such as between PLF energy and mean atomic number. A high-efficiency 4π measurement of the joint multiplicities of neutrons and light charged particles (LCP) provides an opportunity to reconstruct the total "thermal" excitation energy $E^*$ carried by evaporated neutrons and LCPs. The correlation is one between functionals $P$, i.e.,

$$P(E^*) = P(E_{\text{keV}}, m_n, m_{\text{LCP}}) f(E_{\text{keV}}, m_n, m_{\text{LCP}})$$

rather than a one-to-one function $f$. In Fig. 3, the joint multiplicity distribution $P(m_n, m_{\text{LCP}})$ observed for the $^{209}\text{Bi} + ^{136}\text{Xe}$ reaction at $E_{\text{lab}} = 62$ MeV is shown as a scatter plot of neutron multiplicity vs. LCP multiplicity. The dotted curves mark the positions of the ridge lines of the respective most probable multiplicities for three bombarding energies, corrected for differences in detection efficiencies [Gaw05]. The overlap of these lines demonstrates independence of bombarding energy and a dominantly statistical origin of the particles. By sorting data corresponding to joint multiplicity bins defined by segments (Fig. 5) cut perpendicular to the ridge line, one

**Figure 2:** Scatter plot of experimental PLF lab energy ($E_{\text{lab}}$)/angle ($\theta_{\text{lab}}$) correlations from the reactions $^{209}\text{Bi} + ^{136}\text{Xe}$ at $E_{\text{lab}} = 28$ and 62 MeV. [Gaw06]

**Figure 3:** Scatter plot of the multiplicity of neutrons vs. that of light charged particles. The dots mark the ridge line of the most probable multiplicities for three bombarding energies. [Gaw05]
obtains an approximate rendering of the data with respect to dissipated energy or impact parameter.

Primary PLF reconstruction [Gaw05] from the measured remnants and associated neutrons and light charged particles in the same $^{208}$Bi+$^{136}$Xe reactions provides information on the mean energy sharing between PLF and TLF as a function of total energy loss. It turns out that, like at low energies [Sch84], so also for the intermediate bombarding energy range, the excitation energy division evolves gradually with decreasing impact parameter, from $E^*_{PLF} = E^*_{TLF}$ toward the equal-temperature limit ($\varepsilon_{PLF}^* = \varepsilon_{TLF}^*$). This behavior is another hallmark of the dissipative reaction mechanism.

Very different model predictions for the overall joint $m_n/m_{LCP}$ multiplicity distribution are illustrated in Fig. 4. Primary fragments predicted by the NEM [Sch87] have been assumed in the simulation shown in the top two panels. Their sequential decay has been modeled using the statistical code GEMINI (top) or the multi-fragmentation code SMM [Bon95] (middle), respectively. The bottom panel of Fig. 4 represents results obtained for QMD calculations [Luk93], using again GEMINI for modeling of fragment decay.

The comparatively best agreement with the experimental data is obtained with the NEM/GEMINI calculations (Fig. 4, top), even though these calculations over predict both neutron and LCP multiplicities for high dissipated energies. This discrepancy can be traced back to an under estimation of the emission of relatively stable, neutron rich clusters. Both SMM and QMD fragmentation calculations yield characteristic multiplicity patterns at variance with experimental data. For example, a prominent peak in the QMD calculations at low joint multiplicities not seen in the data suggests that QMD fragments are largely too cold.

Similar comparisons of other experimental and simulation data demonstrate that presently no model performs satisfactorily and in a consistent fashion for the entire experimental data set. NEM calculations (CLAT, [Sch87]) describe rather well the dissipative PLF dynamics but do not treat direct or sequential PLF or TLF emission of intermediate-mass clusters (IMF, defined by $3 \leq Z_{IMF} \leq 15$). Such observations emphasize the limited utility of comparisons of theoretical predictions to only subsets of reaction data. Furthermore, measurements [Dje01, Gaw05] of the marginal joint multiplicity distributions for events with different cluster multiplicities have indicated an unexpected and strong dominance of clusters in the statistical competition of nuclear decay channels, for medium to high excitations [Tok05]. Failures to explain the large cluster/LCP branching ratios within traditional statistical theory suggest new statistical decay phenomena.

While no quantitative reaction model is available, the experimental cluster data are similar to the emission patterns of nucleons and LCPs (p, d, t, He) and support a generally dissipative reaction scenario with an additional source of non-statistical particles. The Galilei-invariant velocity plots of Fig. 5 show that, with increasing beam projectile velocity (left vs. right panel), the IMF velocity distributions stretch with increasing projectile velocity. Simulations of detector response reveal IMF cluster sources tracing kinematically with reconstructed PLF and TLF velocity vectors. These components are naturally assigned to sequential cluster evaporation from the respective hot PLF and TLF primaries. Their presence does not contradict a basically dissipative reaction environment.

However, a purely sequential two-emitter model is unable to describe experimental IMF (or LCP) emission patterns. The bulging contour lines seen in Fig. 5 between the PLF and TLF cluster components represent an additional component of clusters associated with the kinematical center of an intermediate velocity source (IVS), reported first [Lot92] in very peripheral $^{208}$Bi+$^{136}$Xe collisions associated with relatively cold PLFs and TLFs. This observation is taken as an indication of a non-statistical origin of IVS clusters, resulting possibly from fragmentation of a neck formed between emerging PLF and TLF. Corresponding observations for other systems
have been made with LCPs and neutrons [Que93], which also suggest IVS sources of high-energy particles. The curved lines in Fig. 5 trisecting the velocity distributions of clusters \((3 \leq Z_{\text{IMF}} \leq 15)\) for the \(^{209}\text{Bi}+^{136}\text{Xe}\) reaction [Gaw05] attempt to separate a transversal component of IVS clusters from those emitted sequentially from PLF (forward sector) or TLF (backward sector).

![Figure 5: Galilei-invariant velocity plots of IMF clusters from the \(^{209}\text{Bi}+^{136}\text{Xe}\) reaction, vs. velocity components parallel and transversal to the beam. The curved lines provide an arbitrary separation of PLF and TLF sources from an intermediate-velocity (IVS) source of clusters. [Gaw05]](image)

Differential sorting of data according to dissipated energy illustrates the evolution of the different identified IMF sources of clusters with impact parameter. Unlike PLF and TLF cluster components, IVS clusters are present essentially at all impact parameters. Mean IVS cluster multiplicities increase with decreasing impact parameter more strongly than the former components such that IVS cluster emission is emphasized among events selected according to high overall cluster multiplicities. IVS cluster particles also have a harder energy spectrum, in the respective emitter c.m. rest frames, than those evaporated from PLF or TLF. Typical logarithmic slope parameters for the IVS cluster energy spectra range from \(T_{\text{IVS}} = 15\) to \(T_{\text{IVS}} = 25\) MeV, for events where sequentially emitted LCPs suggest nuclear temperatures of only \(T_{\text{PLF}} = 5 - 8\) MeV. The fact that IVS cluster multiplicity, atomic number and energy distributions all depend on bombarding energy points to a dynamical production mechanism. Even so, with decreasing impact parameter the distinction between different emitters becomes more difficult and ambiguous. Higher resolution and statistical accuracy are required to perform a more specific analysis of the different cluster components.

While the above (hypothetical) IVS sources of neutrons, LCPs, and IMF clusters represent “prompt” non-equilibrium emission mechanism(s), it is not known at which stage of reaction these particles are emitted and whether light-particle and cluster mechanisms are identical. Pre-equilibrium transport theory applicable to intermediate-energy heavy-ion, or light-ion spallation, reactions has not advanced significantly beyond model parameterizations [You94, Bou04]. However, important in-medium NN interactions render bulk emission unlikely. Consequently, such emission processes can be used to probe surface structure and dynamics, e.g., the presence of nucleonic correlations in the nuclear surface. It turns out that surface modes are largely responsible also for equilibrium evaporation of clusters from hot, expanded nuclei.

Equilibrium and non-statistical cluster processes are cause and/or effect of a transformation of the dissipative reaction mechanism at intermediate energies, which otherwise describes the overall reaction scenario. They are important in an arsenal of tools available to study the physics of the nuclear surface. Examples of nuclear surface studies will be discussed next.

**III. Surface interactions and phenomena**

The nuclear surface plays an important role in a large range of nuclear phenomena, from elastic scattering to fusion reactions, as well as in compound nuclear decay. The specific density profile of the nuclear surface is a consequence, and therefore a measure, of the effective forces and mean field interactions [Sey61]. The surface is also the domain where multi-nucleon correlations (clustering) and scattering occur, influencing structure and nucleus-nucleus interactions. The “neutron skin” [Mye90] is an example of statistical multi-nucleon correlations related
to the nuclear symmetry energy and the iso-EOS. Few-nucleon correlations in the surface are important [Jon04] for the stability of exotic (halo) nuclei. There is also reason to anticipate important new insights into nuclear dynamics from a study of surface phenomena of hot nuclei and their transmutation. For example, the long-standing puzzle of nuclear multi-fragmentation may well be explained by the role played by the surface of a hot nucleus in its disintegration.

In order to develop a consistent picture, establishing a plausible, holistic picture and scenario of nuclear reactions of interest here is prerequisite to a deduction of specific physical parameters such as those of the iso-EOS. In comparisons to theoretical calculations, good reproduction of observed gross trends in projectile/target reaction dynamics with respect to changes in bombarding energy and dissipated energy or other measures of impact parameter are requisite for more detailed comparisons. Reaction codes available so far for such comparisons are based on essentially classical BUU-type, MD-type and INC cascade models.

1. Conservative surface interactions

In peripheral collisions and during the approach phase, nuclei interact dominantly via their surfaces. Detailed surface profiles for nuclear charge and mass density distributions are predicted by microscopic Thomas-Fermi, Hartree-Fock and relativistic mean field calculations, based on specific sets of effective in-medium (contact or finite-range) forces [Sey61, Blo78, Mye91, Chr95, Ala96, Sch84]. Calculations predict a "neutron skin," a neutron-rich surface layer that has so far eluded detailed experimental study. They also estimate the effective mean field, fusion and fission barriers and model a host of dissipative proximity effects [Sch84].

The conservative nucleus-nucleus interaction can be tested in more detail in elastic and inelastic scattering, transfer, knock-out and, for light systems, also in fusion [Sch84, Ala96]. These methods are sensitive to strong-absorption and critical fusion radii, $R_{SA}$ and $R_{FM}$, respectively, providing measures of matter density radii of exotic nuclei near the neutron and proton drip lines [She01, Tan95, Han03] and even their surface density profile. It is obvious that elastic scattering and direct reactions will continue to be used in the explorations of new domains of exotic nuclei far off stability.

Strong energy and isospin dependencies of the NN cross sections ($\sigma_{nn}$, $\sigma_{np}$) in the intermediate energy range indicate similar behavior of nucleus-nucleus surface interactions. In addition to the normal, iso-scalar interaction, the proximity potential acquires an iso-vector component. The potential can be cast [Pom80] into a familiar separable "proximity" form,

$$V_{\tau_1 \tau_2}(s) = \frac{R_1 R_2}{\bar{R}_1 \bar{R}_2} I_1 I_2 \cdot \mathcal{J}_{\tau_1 \tau_2}(s)$$

(3)

where the terms denote the surface separation ($s$), the radii ($R$), the average (bulk) neutron excesses ($I_i = (N_i - Z_i)/A_i$) and isospins $I_i$ of the interacting nuclei, respectively. $\mathcal{J}_{\tau_1 \tau_2}(s)$ is the form factor. Even though the form factor in Eq. (3) has significant magnitude, the iso-vector potential is expected to contribute only app. 5% to the total interaction [Chr95], if neutron and proton surface density profiles are similar as for most beta-stable nuclei.

Systematics of reaction cross sections [Kox87] feature bulk and surface contributions to the effective strong-absorption distance. Due to the decrease of the NN cross sections ($\sigma_{nn}$, $\sigma_{np}$) the energy dependent surface transparency term should increase in magnitude for bombarding energies approaching $\varepsilon \approx 100$ MeV. To establish experimentally the surface transparency is important because of its relation to the optical potential and its effect on for elastic and inelastic cross sections, in particular for transfer and knock-out processes [Fuc94, Per99, Han03, Jon04].

On the other hand, matter density distributions featuring halos or other structure associated with the presence of surface clusters should be more readily detectable in elastic scattering. As an example, the experimental (solid squares) angular distribution for elastic scattering of $^6$He on $^{12}$C [Alk96] is compared in Fig. 6 to theoretical predictions based on few-body eikonal (solid curve) and folding (dashed) models. Such comparisons have been used to determine the 3-body $^6$He wave function.

The studies mentioned above can serve as illustrations of a broad domain of interplay between structure and mechanistic understanding required in investigations of exotic light nuclei. The main goals of reaction studies in this domain are a determination of parameters and trends in effective nucleus-nucleus interactions, more specifically of the optical model potential and the
corresponding transmission coefficients for particles and for fusion. There are obvious connections between the forces at work in the domains of elastic scattering and direct reactions and those responsible for substantially inelastic and strongly damped processes.

2. Prompt particle emission in dissipative surface interactions

Nucleon-nucleon (NN) interactions in the surface are responsible for the attractive nucleus-nucleus potentials, as well as a host of dissipative phenomena. The latter are observable in inelastic nucleus-nucleus scattering and via the prompt emission of non-statistical particles. In a one-body (mean-field) NEM picture [Blo78, Ran87], dissipative forces are generated through the exchange of independent nucleons between projectile and target, by collisions of nucleons with moving walls of the mean field ($U$), or through inelastic excitations. It is always due to randomizing in-medium NN collisions that irreversibility arises. In a short mean-free path, two-body scenario, dissipation arises entirely [Alb77, Ayi87]. The scenario assumed in the, essentially classical, BUU and BNV-type transport calculations invokes both aspects. In these approaches, the Boltzmann transport equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \nabla \cdot \nabla f - \nabla_t U \cdot \nabla f = \left( \frac{df}{dt} \right)_{\text{coll}}$$

(4)

for the phase space (Wigner) distribution functions $f(\vec{r}, \vec{p})$ is solved for each nucleon. The mean field $U(\rho, p, \delta)$ is generally density ($\rho$), momentum ($p$), and isospin ($\delta$) dependent. It is often derived independently from an energy density functional based on effective zero-range Skyrme interactions, e.g. [Nor00].

$$U(\rho_n, \rho_p) = U_v(\rho_n, \rho_p) + U_w(\vec{\nu}_p, \vec{\nu}_p) + U_{\text{coul}}(\rho_p)$$

(5)

Even though the Skyrme force has zero range, the effective mean field has an inhomogeneous Weizsäcker term $U_v$, which also induces a specific surface layer interaction that is different from the mean interaction in the bulk. The field (Eq. (5)) can also be expressed as a sum of an isoscalar term, $U_v(\rho)$, and an isovector term depending on the $n/p$ asymmetry energy approximately as $U_\delta \propto \delta^2 \left( \delta := (\rho_n - \rho_p)/(\rho_n + \rho_p) \right)$. The r.h.s. of Eq. (4) describes independent NN collisions $(1,2 \rightarrow 1',2')$ in the approximation

$$\left( \frac{df}{dt} \right)_{\text{coll}} = -\frac{d\vec{p}_1 d\vec{p}_2 d\vec{p}'_1 d\vec{p}'_2}{(2\pi)^6} \sigma_{12} v_{12} \left[ \frac{f_{12} f_{12}^* - f_{12} f_{12}^*}{f_{12} f_{12}^*} \right] \delta \left( \vec{p}_1 + \vec{p}_2 - \vec{p}'_1 - \vec{p}'_2 \right)$$

(6)

They depend mainly on in-medium cross section $\sigma_{12}$ and relative NN velocity $v_{12}$. Pauli blocking factors for the scattering are abbreviated as $\vec{f}$. The in-medium cross section $\sigma_{12}$ is itself a function of the relative velocity, $v_{12}$, and hence of the bombarding energy. Quite characteristically, the cross section decreases with increasing bombarding energy and increasing medium density.

As an example, the density contours in Fig. 7 show a snapshot of a mid-peripheral $^{16}\text{C}$ on $^{112}\text{Sn}$ collision modeled in BUU [code: LiK98] with an isospin dependent mean field equivalent to a soft equation of state ($K\approx200$ MeV). Seen in Fig. 7 is a projectile-like fragment (PLF) trailing a “neck” connecting it to the target-like fragment (TLF). The neck matter reflects substantial mixing of projectile and target nucleon fluids earlier in the collision. Neck and surfaces of both PLF

\[\text{Figure 6: Experimental (squares) elastic-scattering angular distribution for } ^6\text{He on } ^{15}\text{C and several model predictions. [AlK96]}\]
and TLF are rather diffuse. At the time (t=105 fm/c) of the snapshot, the neck is seen to be on the verge of disintegrating, breaking up into two or three small fragments (clusters) and a number of individual nucleons. Depending on duration of attachment of neck clusters to either PLF or TLF and their transversal motion, correlations of the final cluster velocities with those of PLF or TLF are expected [Col03, Hud05, DeF05]. In BUU approximation, extent and cohesion of neck matter are affected only by isospin dependent mean-field and NN collisions. Resulting correlations between the n/p (N/Z) ratios of prompt nucleons and clusters can be tested experimentally. The emergence of other nucleons seen in Fig. 7 during the reaction justifies the qualification “prompt”, even though they may have been emitted only after the approach phase of the collision. Because of the absence of NN correlations from the BUU model true nucleation into clusters does not take place, clusters form temporarily due to density fluctuations, but particles can easily rearrange subsequently. Specific surface interactions and the restricted quantal level density in the neck [Tok02] are neglected.

The basic concepts of classical mean field dynamics and two-body NN collisions are ubiquitous, underlying also QMD, INC, and hydro dynamical models, which differ mostly in technical detail. The extreme two-body scenario forms the basis of intra-nuclear cascade (INC) models for nucleon-induced spallation reactions [Cug97]. It also underlies eikonal, multiple (Glauber) scattering models of heavy-ion fragmentation reactions [Ber88, Shu03] with weak absorption. These concepts have also been employed in exciton models [Bla75, Kal77, You94] of pre-equilibrium cascades and associated emission of pre-equilibrium nucleons.

Figure 8 renders results of a hydro-dynamical calculation [Nix88] showing a rarefaction wave and the beginning (non-equilibrium) decay of a $^{196}$Pt nucleus following absorption and annihilation of an antiproton by a $^{197}$Au target nucleus. Close to the impact zone (on the r.h.s.), the surface of the expanding nucleus has frayed already and is ready to eject several pieces of matter of different sizes, nucleons and nuclear clusters, while the bulk remains basically intact.

This picture is plausible also for reactions induced by massive projectiles, as suggested by (the few) existing pertinent experiments. For example, in a study [Hil88] of 32 A-MeV $^{32}$S induced fusion reactions with $^{144}$Sm and $^{154}$Sm targets, non-equilibrium (NE) neutrons and protons are observed with relatively hard energy spectra and emission patterns similar to those associated with the IVS source introduced in Sect. II (cf. Fig.5). Their multiplicities are not consistent with average bulk abundances and contradict one-body model [Bon80, Ran87] predictions of “prompt” particle emission.

Non-equilibrium, prompt emission of energetic nucleons has been studied experimentally [Sch01] for the pair of reactions $^{112}$Sn+$^{48}$Ca and $^{112}$Sn+$^{40}$Ca at E = 35 A MeV. Here, the transfer of neutrons and protons between projectile and target nuclei appears to follow initially the gradient of the underlying isospin driving potential. Gradually with decreasing impact parameter, the isospin-dependent nucleon diffusion mechanism leads to a net transfer of protons from $^{40}$Ca projectile to the $^{112}$Sn target, while the PLF and TLF in the $^{112}$Sn+$^{48}$Ca reaction preserve the initial N/Z asymmetry. The response of the diffusion mechanism to the N/Z asymmetry of the reaction partners is understood to result mainly from differences in avail-

![Figure 7: BUU simulation of the exit channel (t=105 fm/c) of $^{112}$Sn+$^{40}$Ca collision at E/A=50 MeV at b=6.5 fm.](image1)

![Figure 8: Illustration of the disintegration of $^{197}$Au after annihilation of an antiproton (impact from right). Snapshot of a hydro-dynamical calculation. [Nix88]](image2)
able, Pauli-restricted phase space, which should diminish with increasing bombarding energy.

In contrast, an impressive gradual process of "mixing" of the nucleon fluids of projectile and target is observed in the flow of high-energy, non-statistical nucleons from the 1VS source introduced earlier. Figure 9 illustrates the experimental multiplicity ratio $M_n/M_p$ for such nucleons as a function of total excitation or decreasing impact parameter. For $^{112}\text{Sn}+^{48}\text{Ca}$, this ratio starts from very large values $M_n/M_p$ values, approaching gradually the bulk value. For the neutron poorer system $^{112}\text{Sn}+^{40}\text{Ca}$, the ratio remains at $M_n/M_p \approx 1.6$ for all measured excitation energies.

High-sensitivity studies of the neutron-richness in non-statistical nucleon emission are highly desirable for a number of cross bombardments involving systems with different $N/Z$ asymmetries. Tentatively, the above large neutron enhancement observed for non-statistical nucleon emission is taken as evidence for a surface emission mechanism contradicting Fermi jet mechanisms [Bon76, Ran87] requiring a long mean free path. Such enhancement seems to be incompatible also with a rapid mixing of projectile and target nucleon fluids favored more by the BUU than the QMD approach. One is hence encouraged to search for other, presumably surface emission mechanisms. Fortunately, in peripheral collisions the complicating effects of different effective masses for neutrons and protons [LiC04], $m_n(\rho) \neq m_p(\rho)$ induced by the (quadratic) momentum dependence of the mean field are minimized since the effective masses approach their free values at low matter densities $\rho$.

Several conceptually different mechanisms can contribute to prompt, non-statistical emission of fast nucleons. In a one-body diabatic [Nor00] process, the moving walls of the mean field $U$ of a fast-approaching nucleus can transfer momentum to individual nucleons and cause their ejection. The spectrum of such non-statistical nucleons should depend on the geometrical overlap of projectile and target nuclei and show noticeable impact parameter dependence. Their kinematical center should coincide with the overall center-of-mass, and their mean kinetic energies should increase approximately in proportion to the relative nucleus-nucleus velocity. Increased ejection efficiency (particle multiplicity) of this process is expected at increased bombarding energies, in contrast to ejection induced in NN collisions. Because of a relatively weak isospin dependence expected for the mean field in peripheral collisions, neutrons and protons should be emitted with multiplicities reflecting the respective local abundances and show similar energy spectra. Combining the two features mentioned for diabatic nucleon emission, one should observe an anti-correlation between the neutron/proton multiplicity ratio and the average kinetic energy of these particles, for a given bombarding energy. No detailed theoretical calculations are available as yet to suggest a magnitude for the effect.

The second process contributing to the prompt, emission of fast NE nucleons is due to NN scattering in the overlap region of projectile and target mass density distributions (cf. Fig. 7) modeled by Boltzmann collision terms in Eqn. (6). The particles emitted in this process should display kinematical symmetry with respect to the NN center-of-mass. The dependence of NN scattering on relative energy and local matter density should induce a corresponding behavior of the average multiplicities for NE nucleons. At high nuclear temperatures, Pauli blocking becomes less effective, increasing slightly the NN scattering probability. This cancellation should therefore be less important in peripheral collisions.

The relative importance of NN scattering for NE nucleon ejection can be judged from the magnitude of the (two-body) surface viscosity with which the NE nucleon multiplicity should be directly correlated. A distinctive signature of this correlation is the strong iso-spin dependence of the NN scattering cross section and hence of viscosity. Calculations performed [Col98] in the

![Figure 7: Ratio of multiplicities of non-statistical neutrons and protons emitted in the two reactions 112Sn+48Ca and 112Sn+40Ca at $e$ = 35 MeV vs. total excitation energy. [Agn97, Sch01]](image)
framework of isospin dependent BNV transport have already demonstrated a dependence of relative probabilities for dissipative and fusion-type collisions on average neutron/proton densities, but attributed the effect to the iso-spin dependence of the mean field. NN collisions also contribute to the phenomenon, as shown [LiC98] for Sn+Sn reactions with large projectile/target isospin asymmetries.

Studies of NE surface cluster emission could help solve the puzzle. Very little is known about such processes in complex nuclear reactions at intermediate energies. In peripheral heavy-ion reactions, neutron-rich NE clusters have been observed [Lot92, Sch94, Mon94, Tok95, Sos01, Def05] with emission patterns characteristic of an IVS source. These clusters could come from the decay of a “neck zone” [Tok95] but could come from an earlier breakup phase. Correspondingly, the IVS cluster N and Z distributions should reflect either the mixed projectile/target matter in the neck region or indicate an angle-dependent strong memory of projectile and target N/Z ratios.

If NE nucleons and clusters are produced contemporaneously in similar mechanisms, their production yields should exhibit characteristic correlations (or anticorrelations) in multiplicity and energy spectra. In a simple classical random-coalescence approach, the momentum distribution of a cluster (N, Z) produced by a single effective source is estimated by simple expressions, e.g.

\[
\frac{d^3P(N, Z)}{dp^3_A} = \frac{S(N, Z, E, s)}{N!Z!} \left( \frac{4\pi p_0^3}{3} \right)^{N-1} \left( \frac{d^3P}{dp^3_n} \right)^N \left( \frac{d^3P}{dp^3_p} \right)^Z \cdot \delta \left( \sum_n \rho_n + \sum_p \rho_p - \rho_A \right)
\]

in terms of the probabilities for single nucleons, \(d^3P/dp^3\). Here, the volume \(V\), the N and Z values, as well as the neutron and proton densities, \(\rho_n\) and \(\rho_p\), are those of the effective source (e.g., the neck zone), and \(p_0\) is an adjustable parameter denoting a coalescence radius in momentum space. The kinetic factor \(S\) represents symbolically the successive pick-up/attachment probabilities of the involved nucleons. In principle, \(S\) should be a quantal transmission/attachment factor depending on Coulomb barrier and the internal cluster structure, in particular on the number of accessible states, but also on relative kinetic energies \(E\), Q values, and channel spins \(s\). For cluster formation in the diffuse nuclear surface, such terms should be crucial. Nevertheless, this important term is consistently ignored in coalescence analyses where the factor \(S\) is set to unity.

There have been few measurements [e.g., Hag00] of complex particle emission interpreted in terms of the simple one-source coalescence scenario. The considerably simpler \(p\)-induced spallation reaction may be more appropriate for applications of coalescence concept. However, systematic studies [Her06] of complex particle emission in \(p\)-induced reactions at \(E_p = 1-2.5\) GeV on a variety of targets have demonstrated an inadequacy of the coalescence model to account consistently for complex particle yields and spectra. Model fits require readjustment for each particle and each target. This deficiency exhibited by the coalescence model in relatively simple situations casts doubt on its viability for an interpretation of cluster emission in heavy-ion reactions.

The importance of the dissipative capture and attachment dynamics for the cluster emission probability is illustrated schematically in Fig. 10. Here the summed frequency of a cluster mass is plotted vs. mass number \(A\) for a given number of reaction events in \(^{12}\)C elastic (top) and inelastic (bottom) breakup induced by energetic protons. The process has been simulated in a schematic linear reaction model [Qui05] without (top) and with (bottom) dissipation. The results suggest that at zero surface viscosity there is
little propensity for $^{12}\text{C}$ to break up. The random breakup mass distribution is peaked at symmetric splits. In contrast, a high $^{12}\text{C}$ surface viscosity enables the projectile to drag out mass from the target nucleus, producing a U-shaped cluster mass distribution (bottom panel). In this schematic model, viscosity simulates the kinetics of nucleon capture and attachment to a cluster formed at the end of an intranuclear cascade. In surface emission modes probed in peripheral collisions, viscosity effects should be even more important. Here they are related to the internal structure (density of states) of the clusters, which have to be able to absorb collision energy. In this fashion, cluster formation depends on thermodynamic cluster properties as well as on the kinetics of the aggregation process.

The above qualitative discussion attributes to the internal structure of clusters an important role in fast aggregation and nucleation processes. Methods of identifying clusters in theoretical model simulations, e.g., in deriving BUU or QMD based predictions for cluster production, should consider the internal (quantal) structure of these light nuclei. Random proximity of nucleons in phase space may be a necessary but insufficient condition for cluster formation.

The mobility of nucleons exchanged between interaction partners trivially influences the makeup of clusters promptly emitted from the projectile/target overlap zone, e.g., from the neck. This mobility can be measured in isospin diffusion experiments monitoring the consistencies of PLF and TLF in peripheral collisions. Early experiments [Sch01] quoted above (cf. Fig. 9) suggest that interaction times in peripheral reactions vary sufficiently strongly with impact parameter to allow one to study the time dependent mixing process of projectile and target nucleons. This process should be observable in the changing A/Z distributions of clusters formed dynamically in surface interactions, suggesting a series of prompt cluster/PLF (TLF) coincidence experiments. The NE particle and cluster distributions obtained in exclusive coincidence experiments should provide important information on the neck dynamics in heavy-ion collisions. Quantal effects may play an important role in the formation and decay of the neck zone, which should receive attention.

3. Role of the surface in equilibrium nuclear decay

In addition to prompt cluster emission in peripheral (and probably central) collisions, sequential cluster emission has been observed experimentally [Lot92, Dje01, Sch03] in coincidence with projectile-like fragments. For example, Fig. 5 illustrates the kinematical tracking of cluster emission patterns with PLF velocity not anticipated by conventional statistical models, or by models developed for statistical multi-fragmentation. Traditional estimates of reaction and relaxation times (cf. Fig. 1) assert that reaction primaries are so unstable that they vaporize before significant acceleration in the Coulomb field could occur. This contradiction can be resolved by generalizing the view of the traditional compound nucleus (CN) to include surface structure, in particular its density of states [Tok81]. Increased overall CN stability results from expansion cooling, and unusual cluster/particle branching is produced by effects of surface entropy. This has been recognized in recent work [Tok05] modeling, largely analytically, the behavior of hot nuclei in terms of a harmonic interaction Fermi gas (HIFG) model. The decay patterns of such nuclei resemble those of a phase transition.

In statistical theory, the self-organization of an isolated system is modeled maximizing entropy $S$. Considering an excited nucleus as an interacting Fermi gas, this maximization is achieved through an expansion to equilibrium density $\rho_{eq}$ which can be significantly lower than the ground state matter density $\rho_0$. For nuclei, the quantum features of the diffuse surface play an important role, since here the number ($\omega$) of available states is comparatively large, making the surface entropy ($S = ln \omega$) a decisive factor in the quantal expansion process. Defining the nuclear temperature $T$ of the microcanonical nucleus in the usual fashion, the entropy $s$ (in units of the Boltzmann constant $k_B$) of a nucleon is given by

$$s(T, \rho) = \frac{\pi^2}{2} \frac{2m^*}{\hbar k_F^2(\rho)} T$$

(8)

Here, the density dependence of the Fermi momentum $k_F(\rho) = (3\pi^2 \rho)^{1/3}$ is responsible for the enhanced entropy per particle in diffuse density regions such as the nuclear surface, and the quantity $m^*$ is the effective nucleonic mass, accounting for momentum-dependent interactions. This relation leads to the free energy per nucleon [Sto79].
The quantity $\epsilon(0, \rho)$ is the total energy ("EOS") per nucleon (kinetic plus potential) in $T=0$ matter of density $\rho = \rho_0$. The thermal excitation energy per nucleon is given by the difference

$$\epsilon^*(T) = \epsilon(T, \rho(T)) - \epsilon(0, \rho(0)) \approx a(\rho(T), m') \cdot T^2$$

Equations (8)-(10) describe the essence of the expansion of a hot nucleus and its dependence on the isoEOS. Finally, the introduction of the level density parameter $a$ establishes a conceptual connection between the nuclear EOS, the parameters of nuclear expansion, and nuclear decay. Obviously, statistical branching in nuclear decay occurs according to entropy, i.e., the level densities of different daughter nuclei.

Approximately, one can determine the contribution of the intrinsic, thermal energy $E_a$ to the total excitation energy, $E^*$, by subtracting a mean compression energy, $E^*_{\text{comp}}(\rho) = E_b(1 - \rho_{\text{comp}}/\rho_0)^2$, which is approximated here by a quadratic form involving the binding energy $E_b$. The equilibrium situation, i.e., the actual density $\rho$ of the nucleus, is defined by maximization of the entropy,

$$S(T, \rho) = 2\sqrt{a(\rho)E_a(\rho)} = 2\sqrt{a(\rho)(E^* - E^*_{\text{comp}}(\rho))}$$

of the expanded nucleus by varying the density $\rho$ for the fixed total excitation energy. For simplicity, a radial density profile corresponding to self-similar expansion of the ground state density distribution is employed. As suggested by experimental systematics [Tok81], the level density parameter has density dependent volume and surface terms. The relative importance of the surface term to the total level density increases with the surface area and is higher for lighter and expanded nuclei ($\rho < \rho_0$). Since the expansion against the EOS restoring force requires energy, the temperature $T$ of the expanded nucleus must decrease to

$$T = \frac{E_a}{a} \left( \frac{\rho_{\text{comp}}}{\rho_0} \right)^{1/2} \frac{1}{\sqrt{a}} \sqrt{E^* - E_b\left(1 - \frac{\rho_{\text{comp}}}{\rho_0}\right)^2}$$

The schematic model caloric curve (Equ.(12)) graphed in Fig. 11 demonstrates a striking non-monotonic behavior. The theoretical relation between temperature and excitation energy depends also on the effective nucleon masses, a dependence that flattens [Sob04] the caloric curve somewhat. The general dependence of the caloric curve in the HIFG model asserts that there is a maximum temperature that a nucleus can sustain. This is a unique model prediction that follows without reliance on hypothetical constructs of external gas pressures. Equation (12) further suggests that it is possible in principle to study the isoEOS by measuring the caloric curve $T(E^*)$ of finite nuclei. It is encouraging that the important feature of the caloric curve showing a plateau of constant temperature for a range of excitations is borne out by experimental caloric curve systematics [Nat02].

The decrease in thermal energy due to expansion cooling increases the overall lifetime of the nucleus against particle decay [Tok05], explaining qualitatively why it has been possible to observe sequential (PLF) cluster decay following heavy-ion reactions. Surface entropy also changes the statistical competition between evaporation of clusters and light particles [Dje01].

The fact that a hot nucleus can generate a dinuclear system with significantly increased surface area produces a new, prompt fission instability. It turns out that the several tens of MeV high barriers ($\psi_{\text{bar}}$) hindering the emission of massive clusters ($3 \leq Z_{\text{cl}} \leq 10$) from heavy nuclei do not change substantially when expansion is taken into account. However, at total excitation
energies of the order of $E^*/A = (4-5) \text{ MeV}$, the di-nuclear saddle-point configuration of a cluster ($A_{cl}$, $Z_{cl}$) and the residue ($A_{res}=A-A_{cl}$, $Z_{res}-Z_{cl}$) attains a higher entropy, $S_{\text{dim}}$, than that ($S_m$) of the parent mono-nucleus ($A$, $Z$),

$$S_{\text{dim}}(A_{cl}, Z_{cl}, A_{res}, Z_{res}, E^*) = S(A_{cl}, Z_{cl}, \rho(\frac{E^*-V_{int}}{A_{cl}})) + S(A_{res}, Z_{res}, \rho(\frac{E^*-V_{int}}{A_{res}}))$$

(13)

Therefore, the fission-like process can overcome unfavorable energetics ($V_{int} > T$), provided that there is a sufficiently large entropy gain. In a canonical description, this is due to the relation between the corresponding free energies $F$:

$$F_m = E_m - 2a_{int}T_m^2 > F_{\text{dim}} = E_{\text{dim}} + V_{\text{int}} - 2a_{\text{int}}T_{\text{dim}}^2$$

(14)

Here, $a_{int}$ and $a_{\text{dim}}$ are the corresponding level density parameters. The entropy gain in cluster formation is the larger, the lower the average density $\rho$ and the higher the surface diffuseness of the cluster are. Entropy associated with internal structure has to be added to that of the final state, amplifying the importance of the entropy contribution to the free energy (Equ. (14)). Formation of clusters with a higher level density is favored relative to nuclei with only a few excited levels and can dominate even the release of nucleons or alpha particles.

With increasing excitation the surface of a hot nucleus softens, with an HIFG surface tension vanishing as

$$\Lambda = \frac{\delta E}{\delta \sigma} \bigg|_{S=\text{const}} = \frac{1}{4\pi \sigma_0} \left( \varepsilon_\sigma - a_\sigma T^2 \right)$$

(15)

Here, $\sigma$ is the surface area and $a_\sigma$ is the surface level density parameter, $\varepsilon_\sigma$ is given relative to the liquid-drop surface energy $E_\sigma$,

$$\varepsilon_\sigma = \frac{E_\sigma}{A^{2/3}} = \frac{E_\sigma}{A^{2/3}} \cdot \frac{4\pi (r_n A^{(3)})^2}{\sigma}$$

(16)

and $F_2$ is the ratio of this area to the surface of the corresponding spherical nucleus [Tok81].

Equation (15) describes gradual softening of the surface with increasing temperature, where the surface tension vanishes at the critical temperature $T_\sigma$. Using liquid-drop model surface energy constants of $b_0=17-18 \text{ MeV}$, a radius parameter of $r_0=1.2 \text{fm}$, and $a_\sigma = 0.274 \text{ MeV}^{-1}$ for the nuclear ground state, one can derive an upper limit for this critical temperature,

$$T_\sigma \leq \sqrt{\frac{\varepsilon_\sigma}{a_\sigma}} \approx 8 \text{ MeV}$$

(17)

For an expanded nucleus, the specific surface energy should be smaller, and the level density parameter larger, than for its ground state density. A more precise value for $T_\sigma$ is presently not available, but the critical temperature predicted by the HIFG model is much smaller than the approximately 18-20 MeV predicted by standard matter calculations [Ban90].

A better theoretical determination of this critical temperature in a more detailed and rigorous theory is highly desirable. A body of theoretical work [Col94, LiK98, Nor00, Cho05] discusses critical temperatures for mechanical and chemical instabilities of nuclei or nuclear matter to develop. Instabilities of homogeneous nuclear droplets with sharp, structure-less surfaces have been studied [Nor00] based on effective (Skyrme-type) in-medium forces. Neglecting surface entropy, isentropic expansion modes of such nuclei are calculated. With these restrictions [Nor00], one predicts a temperature and isospin dependent surface tension of the form

$$\varepsilon_\sigma(\rho) = \frac{a_\sigma}{4\pi \sigma_0} \left( \frac{\rho}{\rho_0} \right)^3 \left( 1 - a_\sigma \delta^2 \right) \left( 1 + \beta T^2 \right)$$

(18)

Here, the constant $a_\sigma$ and the central nuclear density ($\rho_0 \approx 0.85 \rho_0$) are determined by the assumed Skyrme force. The parameter $\beta$ defines a soft ($\beta = 0.006 \text{ MeV}^2$) or stiff ($\beta = 0.008 \text{ MeV}^2$) EOS. The isospin term ($\delta^2$) in Equ. (18) ensures that the surface tension is smaller for more iso-asymmetric systems. According to this equation, the surface energy of a sharp-surface nucleus increases with temperature, opposite to what is expected for real nuclei. Assuming the same density dependence of the Skyrme forces for the entire range of densities and excitation
energies of interest, one simulates the neglected surface entropy effect by inserting into Eq. (18) the HIFG equilibrium density and temperature functions. The result depicted in Fig. 12 indicates that, for an $\Lambda = 200$ nucleus, the surface tension should vanish at $E^* \approx 1.7$ GeV ($T_c < 8$ MeV), in agreement with the critical temperature of Eq. (17). At this temperature the surface “melts” initiating complex nuclear disintegration, a process that has hallmarks of a phase transition.

Together with the EOS defining the bulk compressibility and the restoring force for bulk normal modes, the surface tension plays a crucial role in the development of nuclear instabilities. The liquid-drop model predicts [Boh96] for the stiffness of a surface mode of multipolarity $\lambda$ in a nucleus $(A, Z)$, in the usual notation for liquid-drop model parameters $b_s$ and $b_C = 3\varepsilon_0^2/5\hbar_0$,

$$C_i = (\lambda - 1)(\lambda + 2) \frac{b_s}{4\pi} A^{2/3} \frac{5}{2\pi} \frac{(\lambda - 1)}{2\lambda - 1} \frac{b_C}{A^{1/3}}$$

(19)

The energy of the $\lambda$ mode is related to stiffness $C_i$ and deformation parameter $\beta_i$ as $E_\lambda = C_i \beta_i^2$. The stiffness parameter $C_i$ is mainly determined by the first (surface) term in Eq. (19), which is proportional to the surface energy. For Fermi matter, surface and Coulomb parameters have temperature dependencies of the form [Kol04]

$$b_s(T) = 17.5 \text{MeV} \left( \frac{T_c^2 - T^2}{T_c^2 + T^2} \right)^{1/4}$$

$$b_C(T) = 0.7 \text{MeV} \left(1 - 7.6 \times 10^{-4} \left( \frac{T}{T_c} \right)^2 \right)$$

(20)

Taking for the critical temperature the value quoted in Eq. (17), i.e., $T_c = 8$ MeV, one obtains results shown in Fig. 13. A fission-like ($\lambda = 2$) instability arises for a $^{112}$Sn nucleus already at approximately $T_{\lambda=2} = 4.3$ MeV. Higher temperatures are predicted for the limiting temperatures for higher modes, $\lambda > 2$. However, as gathered from Fig. 13, the limiting temperature is non-linear in the multipolarity. As the multipolarity $\lambda$ increases, the limiting temperature $T_\lambda$ approaches the series limit, $\lim_{\lambda \to \infty} T_\lambda = T_c$. For temperatures approaching this limit, a large number of nearly degenerate surface modes can be excited, providing for a range of regular and irregular nuclear (surface) shapes.

The above considerations can be made more accurately within the HIFG model, which gives a consistent account of expansion cooling and surface melting effects. Here surface oscillations are driven by the corresponding free energy.
\[ F_\lambda = E_\lambda - 2a_\lambda T^2 = C_\lambda \left( 1 - \frac{2a_\lambda}{E_\lambda} T^2 \right) \beta_\lambda^2 \]  

(21)

defining effective stiffness and restoring force for the surface modes. Since the surface modes carry very little (free) energy, they are excited with high probabilities, thermally or through dynamically during a collision. It takes an excitation of approximately \( \varepsilon^* = 4 - 6 \) MeV to reach the low-excitation energy boundary of the instability domain, where a binary fission-like process dominates nuclear decay. Based on the liquid-drop energies and the corresponding HIFG surface entropies, one can generalize Equs. (15)-(17) to describe multi-cluster saddle configurations, associated limiting temperatures, as well as the \( \lambda \) series limit. One expects that the temperatures at which cluster saddle point configurations associated with different multiplicities begin to form freely increase relatively strongly at low multiplicities but saturate for large multiplicities. This behavior should be reflected in an experimentally observable dependence of probabilities for events with different cluster multiplicities as functions of nuclear excitation. The threshold for the effect should correspond to \( \lambda = I \), i.e., prompt fission.

While data are still scarce, the effects discussed above may cause the puzzling observation [Dje01, Gaw05] that the thermal excitation energy, measured via the multiplicities and spectra of associated light particles emitted in a heavy-ion collision at \( R_{\text{sim}} = 30-60 \) MeV, does not change very much with the multiplicity (\( m_{\text{sim}} \)) of emitted clusters, once \( m_{\text{sim}} > 2-3 \). Such explanation would fit well into the overall scenario of a basically dissipative reaction mechanism suggested by many other observables. At present, no other explanation for these data has been put forward.

IV. Summary and outlook

It seems important to develop a detailed theory of the surface of excited (or loosely bound) nuclei and their fundamental modes. Meta-stable surface modes form the doorways for surface cluster formation and decay. Establishing unambiguous properties of multiple cluster emission mechanisms outlined above requires systematic experimentation and theoretical analysis. Primary tasks consist in identification and isolation of sequential from prompt cluster emission processes and their correlations with emission of light particles. This can be achieved with \(^{\text{PLF/TLF spectroscopy,}}\) studying particle emission from (relatively) well prepared primary projectile-like (and/or target-like) fragments in peripheral and semi-peripheral collisions. Once systematic trends with decreasing impact parameter have been established, a study of central collisions, in particular of fusion processes, could prove feasible and informative.

Experimental requirements at this point are vast: Needed are comprehensive measurements of non-equilibrium and statistical cluster branching ratios, effective cluster emission barriers, energy spectra and angular distributions as functions of bombarding energy, thermal excitation energies and angular momenta carried by massive reaction primaries such as PLFs. The study of time dependent nucleon mixing processes and the origin of IVS clusters and light particles requires excellent experimental resolution and particle identification.

In these tasks, the role of isospin degrees of freedom is two-fold: On the one hand, one can exploit the isospin dependence of the nuclear EOS and of NN scattering processes as a useful tool in mechanistic study. On the other hand, by varying the isospin asymmetry of projectile, target, and ejectiles, one can investigate isoEOS and in-medium NN correlations.

Challenges to reaction theory are also substantial, as previous theories of nuclear reaction and decay mechanisms have been severely compromised by an enduring lack of a plausible reaction path to postulated final states. Development of comprehensive reaction scenarios includes modeling of quantal (transport) behavior of interacting nuclei. Obtaining a better understanding of the structure of the nuclear surface and its evolution in surface interactions and at high excitations is an important prerequisite. Rather than attempting to add to detail knowledge, the aim is at substantial improvement of our grasp of nuclear phenomenology.

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V. References

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