Morphing of the Dissipative Reaction Mechanism

Department of Chemistry, University of Rochester, Rochester, NY 14627, USA
* Corresponding author, e-mail: Schroeder@chem.rochester.edu

Abstract

Important trends in the evolution of heavy-ion reaction mechanisms with bombarding energy and impact parameter are reviewed. Essential features of dissipative reactions appear preserved at $E/A = 50-62$ MeV, such as dissipative orbiting and multi-nucleon exchange. The relaxation of the $A/Z$ asymmetry with impact parameter is slow. Non-equilibrium emission of light particles and clusters is an important process accompanying the evolution of the mechanism. Evidence is presented for a new mechanism of statistical cluster emission from hot, metastable primary reaction products, driven by surface entropy. These results suggest a plausible reinterpretation of multi-fragmentation.

1 INTRODUCTION

The evolution of the heavy-ion reaction mechanisms with bombarding energy from the dissipative regime [1] towards higher energies ($E/A \sim 20$ MeV $\rightarrow$ 100 MeV) is characterized by the phenomenon of copious emission [2] of intermediate-mass nuclear cluster fragments (IMF). Such clusters are defined by atomic numbers approximately in the range $4 = Z \lesssim 20$ for heavy-ion reactions such as $^{197}$Au+$^{36}$Ar, $^{197}$Au+$^{86}$Kr, or $^{209}$Bi+$^{136}$Xe. Conventional statistical models of nuclear decay predict [3] negligible probabilities for the evaporation of IMF clusters from projectile-like (PLF), target-like (TLF), or composite-nucleus (CN) type reaction products. The absence of this decay channel is understood to be due to the high Coulomb barriers ($V_\text{nl} \sim 50-60$ MeV) for emission of clusters from a heavy nucleus, estimated to exceed even the maximum observed nuclear temperatures ($T \lesssim 6$ MeV) by an order of magnitude. So-called multi-fragmentation, central-collision events with several substantial clusters in the exit channel (up to 12 observed) seem therefore far beyond the realm of traditional statistical nuclear decay models.

As an interesting alternative, the above cluster emission process is often attributed to a hypothetical nuclear phase transformation occurring in a new domain of mechanical instability of hot nuclear matter. Observations of limits to nuclear temperatures [4-6] have been taken as supporting evidence for such a nuclear (liquid-gas) phase transition. Its demonstration would be of interest far beyond nuclear science, because nuclei are finite quantal systems produced in heavy-ion reactions in metastable nonequilibrium states [1] decaying into vacuum.

Attempting to justify equilibrium-statistical treatment of cluster decay, theories [7-9] modeling multi-fragmentation in terms of a phase transition typically concentrate on a small cross section associated with the most central collision events, potentially leading to a hot CN. Unfortunately, such events belong to those experimentally most difficult to reconstruct. Circumventing difficulties associated with high cluster emission barriers mentioned previously, these models ascribe the observed product distributions to statistical population of hypothetical “freeze-out” volumes, in which particles and clusters interact only via Coulomb forces. However, since actual transition states for cluster emission are strongly influenced by the nuclear interaction [10, 11], the implications of data comparisons with models neglecting it are not obvious.

In view of the difficulties faced by experimental and theoretical research of multi-fragmentation, now since some two decades, it appears necessary to take a fresh look at the entire heavy-ion reaction environment and its evolution with bombarding energy and impact parameter. For some heavy systems, data are now available for a dynamic range of $>50:1$ in bombarding energies over the interaction barrier. As will be illustrated below, this evolution turns out to be smooth, resembling a morphing of the
well-known dissipative mechanism. Previously enigmatic phenomena such as cluster emission and limitations of thermal energy sustained by a nucleus emerge as natural expressions of nuclear response at higher energies.

2 EXPERIMENTAL SYSTEMATICS

2.1 Cross Sections

It is interesting to note that, for heavy reaction systems and the bombarding energy range of interest here (E/A=30-60 MeV), the reaction cross section remains almost constant at \( \sigma_E = (5-6)b \) [12-14], tracing experimental systematics [15], even though free NN scattering cross sections decrease by factors 2-3, leading to corresponding increases in surface transparency. These figures are obtained from an analysis of the Coulomb dominated elastic-scattering angular distributions, which for reactions such as \(^{197}\text{Au} + ^{86}\text{Kr}\) and \(^{209}\text{Bi} + ^{136}\text{Xe}\) are of the Fresnel type still at E/A = 50-60 MeV. Within their (8-10)% experimental uncertainties, these cross sections are found consistent with direct integration of reaction events, with a PLF or its remnant as a distinctive leading particle at forward angles.

2.2 Experimental Methods

Because of the potentially high excitations, reconstruction of the main experimental observables requires an efficient measurement of the emission patterns of secondary decay products.

In the experiments reported here, neutrons, light charged particles (LCP), and IMF clusters have been measured with \( 4\pi \) coverage, using Rochester SuperBall [16] and St. Louis Dwarf [17] or MicroBall detector arrays. More massive PLF and/or TLF remnants are sampled with position-sensitive Si-strip detector telescopes. More details on experimental setup and performance can be found in Refs. [12-14].

Under certain conditions, an efficient \( 4\pi \) measurement of neutrons and LCPs allows one to reconstruct the massive primary reaction products, even if they disintegrate completely in the exit channel. Crucial is a (meta-) stability of the primary fragments that is sufficiently high, allowing acceleration to approximately asymptotic velocities to occur prior to disintegration.

Of particular interest is of course the total excitation energy E* generated in a reaction, one of the fundamental observables. As long as particle kinetic energies are relatively well known, or small compared to their binding energies in the parent nuclei, this information can be obtained already from an analysis of the particle multiplicities.

Experimental joint multiplicity distributions \( P(m_p, m_{LCP}) \) of neutrons and LCPs, resp., are illustrated in Fig. 1, for the \(^{209}\text{Bi} + ^{136}\text{Xe}\) reaction and energies between E/A = 28 and 62 MeV. These distributions virtually overlap, hence only the 62 MeV data are depicted in detail. The characteristic shape is due to the Coulomb barriers for LCP evaporation from PLF and TLF, which introduce strong non-linearities in all LCP-E* correlations, e.g., the popular \( m_{LCP}(E^*) \) relations. Here, neutron measurements resolve ambiguities.

![Figure 1: Contour diagram (log) of the measured joint multiplicity distributions of neutrons and LCPs, for the \(^{209}\text{Bi} + ^{136}\text{Xe}\) reaction at E/A=62 MeV. Average correlations for E/A=28 and 40 MeV are indicated by dotted curves.](image-url)
Detailed modeling [18], verified by calibration measurements, shows that the joint multiplicity distribution \( P(m_s, m_{\text{LCP}}) \) is a functional of the thermal excitation energy distribution \( P(E^*) \),

\[
P(m_s, m_{\text{LCP}}) = \bar{P}[P(E^*)]
\]

The direction of increasing average excitation energy is indicated by the solid curve (\( E^* \)) in Fig. 1. Regions in \( \{m_s, m_{\text{LCP}}\} \) space correspond in non-linear fashion to intervals in total excitation of primary massive fragments, rather independently of their multiplicity and mass splits, as long as cluster emission is not significant. Qualitatively, a cluster emission degree of freedom adds a third dimension [19] to the plot of Fig. 1, but the functional equivalent to Equ. 1 has not yet been obtained quantitatively.

The data shown in Fig. 1, together with the experimental efficiency filter, can already be used for benchmark testing of statistical decay models. As shown elsewhere [18], the statistical model MMMC [7] fails this test, due to its significant neglect of neutron phase space, while the competing SMM [8] is consistent with data.

The emission patterns of light particles emitted in a heavy-ion reaction provide important clues on the reaction mechanism. In Fig. 2 [13], simulated events are shown where \( \alpha \) particles are evaporated from an accelerated TLF or PLF "source", produced in a dissipative \(^{197}\text{Au} + ^{86}\text{Kr} \) reaction at \( E/A = 39 \) MeV. The simulation used a dissipative reaction event generator [20] modeling the NEM one-body exchange mechanism [21], followed by statistical decay model GEMINI [22]. An emitter with established kinematics is recognizable by a "Coulomb ring" pattern centered at the emitter velocity, ideally like the distribution marked "TLF" in Fig. 2. The strong distortions of the expected circular patterns seen for PLF emission is due to limited granularity and stopping power of the detectors at forward angles sensitive to this latter source.

\[\text{Figure 2:} \text{Invariant cross sections for sequential evaporation of } \alpha \text{ particles from TLF, PLF (top and middle), and the combined distribution (bottom) vs. parallel and perpendicular } \alpha \text{ velocity.}\]

2.3 Dissipative Reaction Dynamics

Emission patterns of projectile-like fragments in the reaction \(^{209}\text{Bi} + ^{136}\text{Xe} \) at \( E/A = 28 \) and 62 MeV are shown in Fig. 3 as logarithmic contour plots of lab PLF kinetic energy vs. angle (top row) or fragment atomic number (bottom row). The solid and dotted lines in these plots represent simulation calculations [14] with the NEM [20, 21] correcting for sequential decay of the

\[\text{Figure 3:} \text{The } ^{209}\text{Bi} + ^{136}\text{Xe} \text{ reaction at 2 energies. Energy-angle correlations (top row), energy-Z correlations (bottom). Solid lines indicate average predictions by the NEM, arrows the direction favored by sequential decay. [14]}\]
primary fragments.

The fragment energy-angle correlations depicted in the top panels of Fig. 3 illustrate the presence of 3 cross section ridges. The ridge of elastically scattered events is visible as intense horizontal pattern, while a ridge of partially damped events outlines a correlation between dissipation and forward scattering. Finally, the distribution at lowest energies is attributed to negative-angle scattering.

The top panels of Fig. 3 demonstrate a well-known dissipative-orbiting phenomenon, a hallmark of the dissipative reaction mechanism. Clearly, dissipative forces are strong still at E/A = 62 MeV, and there is no direct evidence that the net conservative force has become repulsive. In fact, as illustrated by the solid lines superimposed on the cross section features, NEM simulation calculations provide a good representation of the data with the set of forces and adiabatic prescriptions that reproduce trends at much lower bombarding energies.

The same reaction model, based on a diffusion-like multi-nucleon exchange process, predicts average primary PLF charges to be close to that of the projectile, \( \langle Z_{PLF} \rangle \sim Z_{proj} = 54 \) (vertical lines “NEM” in bottom panels of Fig. 3). The characteristically narrow diagonal ridges in these \( E_{PLF} - Z_{PLF} \) plots are dominantly the result of evaporative decay of the primary reaction fragments proceeding in the general direction indicated by arrows in Fig. 3. This fact has been demonstrated for \(^{208}\text{Bi} + { }^{136}\text{Xe}\), as well as for the \(^{197}\text{Au} + { }^{86}\text{Kr}\) reaction, already at several bombarding energies, by direct reconstruction of the primary PLF-Z distributions. Unfortunately, due to significant uncertainties in the reconstruction procedure, no quantitative studies of the fluctuations in the fragment distributions are available as yet.

The reconstruction of the primary reaction fragments makes use of the fact that most particles are evaporated from these fragments in flight, revealing their origin in the corresponding invariant emission patterns (Fig. 2). In Fig. 4, some sample spectra are shown of protons (top row) and \( \alpha \) particles (bottom) emitted at the indicated angles from the \(^{197}\text{Au} + { }^{86}\text{Kr}\) reaction at E/A = 38.7 MeV. Solid dots represent data, while curves indicate contributions calculated with “moving-source” models assuming random evaporation from average PLF and TLF emitters, as well as app. isotropic emission of high-energy particles from a virtual intermediate-velocity source (“IVS”). Corresponding particle velocity \((v_p)\) spectra can be written in invariant form as,

\[
\frac{d\sigma}{d^3v_p} \approx \frac{M_p}{4\pi} \frac{m_p}{2} \sqrt{\frac{v_p^2 - V_{Coul}^2}{2T_s}} \exp \left\{ -\frac{m_p (\vec{v}_p - \vec{v}_e)^2}{2T_s} \right\}
\]

where \( \vec{v}_e \) is the emitter velocity. Fit parameters include the emitter A, Z, Coulomb barrier \( V_{Coul} \), and average velocity, \( v_e \). For statistical emission, multiplicity \( M_p \) and spectral slope parameter \( T_s \) are related to emitter excitation energy \( E^* \) (\( T_s \sim T \)). Branching ratios \( (M_p) \) and spectra of these particles provide good constraints on the properties of the respective primary fragments. It is interesting to observe that, like at near-barrier bombarding energies, also at the upper boundary of the Fermi energy domain, reaction partners do not have sufficient contact time to relax to equilibrium, as far as excitation energy division \([12, 13, 23]\) or mass-density (A/Z) equilibration are concerned.

The hypothetical IVS emitter is used to represent non-equilibrium particle emission, a process that is expected \([1, 24, 25]\) to contribute significantly at the present bombarding energies.
The corresponding particle energy distribution can typically be described in terms of a random spectrum of higher-energy particles emerging from a kinematical center moving with an “intermediate velocity” \((v_c)\) of app. 50%-70% of the beam velocity \([24]\). The exponential energy spectra of these latter, non-equilibrium particles correspond to logarithmic slope parameters of the order of \(E_0 = 15-20\ MeV\). Presumably, these emission patterns are caused by couplings with the intrinsic Fermi motion of the nucleons.

In any case, these \(E_0\) parameters are so large that the associated emission process is well distinguished from slow, thermal evaporation \((E_0 = T = 6\ MeV)\). The non-equilibrium particle distributions contain important information on the dynamical evolution of multi-scattering cascades within the nuclear medium, which in turn is related to the equation of state of nuclear matter and its dissipative properties.

The comparison between data and model fits illustrated in Fig. 4 demonstrates that thermal evaporation of protons and \(\alpha\) particles from PLF or TLF dominates at far forward or far backward angles, respectively. The non-equilibrium component is best visible at intermediate angles, side-ways to the beam, in regions kinematically inaccessible to PLF or TLF evaporation. However, it is interesting to observe in Fig. 4 the non-equilibrium proton component exceeding the thermal spectrum also at angles as large as \(\theta = 138^\circ\).

The appearance of significant non-equilibrium emission complicates considerably the primary fragment reconstruction, unless the relative contributions from projectile and target to this process are well known. As illustrated below, utilizing projectile/target combinations with different A/Z asymmetries allows one to model the primary distributions in the presence of this complication.

As stated previously, a persistent disequilibrium of most degrees of freedom is a marked characteristic of the dissipative mechanism. This includes the relaxation of the A/Z (or N/Z) asymmetry brought in by projectile and target nuclei. There are very few detailed data yet on A/Z relaxation for the intermediate energy domain, owing to difficulties associated with event reconstruction, but this topic is gaining increased attention by the field \([26 - 28]\).

In Fig. 5, such A/Z relaxation is viewed through the ratio \(M_1/M_0\) of the multiplicities of neutrons and protons, respectively, evaporated from PLFs produced in peripheral reactions \(^{112}\text{Sn} + ^{40}\text{Ca}\) and \(^{112}\text{Sn} + ^{40}\text{Ca}\) at \(E/A = 35\ MeV\) \([23]\).

![Figure 5: Multiplicity ratio of neutrons and protons evaporated from PLFs from the \(^{112}\text{Sn} + ^{40}\text{Ca}\) reactions vs. total excitation energy. \([23]\)](image)

Here, the multiplicity ratio is plotted vs. the total reconstructed excitation energy, which is a measure of impact parameter. Indicated by dashed lines in this figure are the multiplicity ratios expected for “global” N/Z equilibration, defined in each case by the bulk N/Z of the combined system. The solid curves represent expectations based on an unchanged N/Z ratio of the PLF, given by the projectile N/Z.

Clearly, one observes a relaxation of the N/Z asymmetry with increasing \(E^{*}_{\text{tot}}\) or decreasing impact parameter, which depends on the initial conditions, the projectile-target N/Z asymmetry. Although the equilibrium N/Z ratios for the two systems are not dramatically different, the evolution is strikingly opposite for the two systems. While the n-poor \(^{40}\text{Ca}\) projectile tends to pick up a net number of neutrons, \(^{40}\text{Ca}\) does not appear to donate any net number of neutrons to the n-poorer \(^{112}\text{Sn}\) target nucleus.

From the evolution of the experimental multiplicity ratios seen in Fig. 5, one concludes that global equilibrium is not reached, except perhaps for the highest excitation energies measured in the experiment. An opposite behavior of the multiplicity ratio \(M_1/M_0\) with \(E^{*}_{\text{tot}}\) in the two reactions can be understood as a consequence of
the locations of the injection points relative to the local structure of potential energy surface (PES) driving nucleon exchange between the interacting nuclei. The \(^{112}\text{Sn}+^{40}\text{Ca}\) injection point is located on the steep slope of the PES, whereas this point is located in the PES minimum for \(^{112}\text{Sn}+^{40}\text{Ca}\) trapping this latter system, for all measured impact parameters (\(E^*_{\text{cm}}\)). This feature is completely equivalent to that observed [1] at low energies and demonstrates similarity to the dissipative reaction mechanism. It should be mentioned that, even at low bombarding energies of \(E/A\sim 30 - 40\) MeV, non-equilibrium particles are emitted still with relatively small multiplicities. These particles are identified by their characteristic energy and angular distributions, consistent with the hypothetical IVS emission patterns introduced earlier.

While the above data illustrate the fragment \(N/Z\) ratios at late times, derived from their slow statistical decay, it has recently become possible to study the dynamics of \(N/Z\) (“isospin”) relaxation at very early times, when presumably fast, non-equilibrium particles are emitted from the colliding system. For peripheral collisions and bombarding energies of \(E/A\sim 30 - 40\) MeV, non-equilibrium particles are emitted still with relatively small multiplicities. These particles are identified by their characteristic energy and angular distributions, consistent with the hypothetical IVS emission patterns introduced earlier.

In Fig. 6, the evolution with total excitation is displayed for the ratios \(M_n/M_p\) of the multiplicities of non-statistical neutrons and protons emitted in the two \(^{112}\text{Sn}+^{40}\text{Ca}\) reactions discussed already above [23]. In either case, significantly more neutrons are emitted than protons. In view of the bulk ratios of only \(N/Z\) \(\sim 1.2\) and 1.3 for \(^{112}\text{Sn}+^{40}\text{Ca}\) and \(^{112}\text{Sn}+^{48}\text{Ca}\), respectively, the relative magnitude of excess non-equilibrium neutron emission is surprising. Comparison between the two systems suggests that this discrepancy is probably not caused by the Coulomb barrier, which is not significantly different for these two systems.

In addition, one again observes a dramatically different behavior of the (non-equilibrium) \(M_n/M_p\) ratio with excitation energy for the two reactions. However now, the ratio is relatively stable for the \(^{112}\text{Sn}+^{48}\text{Ca}\) system \((M_n/M_p\sim 1.6)\), while it decreases from a large value of 7.6 down to a still significant \(M_n/M_p\sim 3\), for the more n-rich system. The bulk \(N/Z\) ratios are not reached by either system.

This observation demonstrates that non-equilibrium neutron and proton emission occurs mainly at times when projectile and target nucleons have not mixed. There is a clear memory of the entrance channel visible in the non-statistical \(M_n/M_p\) ratio, specifically of the projectile \(N/Z\). In fact, this mixing process, the relaxation of the mass-to-charge density (“isospin”) occurs significantly after the impact phase, which is thought responsible for the emission of fast nucleons.

In terms of macroscopic nuclear dynamics, the above process of non-equilibrium nucleon emission and its changes with impact parameter have to be attributed to the presence of a strong isospin dependence of the macroscopic nuclear equation of state (EOS). Overall matter compressibility must be significantly different for neutrons and protons. Qualitatively, such behavior is expected from theoretical models of isospin dynamics in heavy-ion reactions [26-28].

Reactions at intermediate energies are quite complicated to analyze in terms of isospin \((N/Z\) asymmetry) relaxation effects or an “iso-EOS.” However, the fact that several reaction phenomena depend simultaneously, but in different
ways, on isospin removes ambiguity and provides constraints on theory.

Models of dissipative reaction dynamics have been developed [1] for heavy-ion reactions at near-barrier energies leading to small density overlap, where assumptions of perturbation theory are relatively well fulfilled. The success of these models also in domains, where their physical foundations are questionable, implies that these models have successfully captured the trends governing the dissipation of energy and angular momentum, the exchange of nucleons between the interaction partners and the evolution of their approximately distinct existence and incomplete communication. In particular, it is worthwhile to remember that the reaction systems are essentially in disequilibrium with respect to all degrees of freedom. The intrinsic transport mechanisms lead only slowly to a relaxation towards equilibrium. However, even highly excited, primary massive reaction products are stable enough to achieve internal equilibration, before decaying statistically on their asymptotic trajectories.

To the extent that heavy-ion reaction mechanisms at Fermi and intermediate bombarding energies follow these same trends, one recognizes the same underlying physical mechanism, a smooth transition to a new regime, and a gradual development of new phenomena. These latter phenomena concern mainly the mechanisms of cluster emission, which becomes important for E/A > 20 MeV, as discussed next.

2.4 Cluster Emission in Heavy-Ion Reactions

Emission of particles heavier than \( \alpha \)-particles or other He isotopes is rare in nuclear processes at low excitations, although spontaneous cluster radioactivity has been observed for actinides [29] generating keen interest in the structure of such nuclei. Challenges to the understanding the emission of massive clusters (carbon or oxygen, say) from a heavy nucleus relate to the difficulty to model multi-particle in-medium correlations associated with the “preformation” of such clusters, as well as the inhibition by 50-60-MeV high Coulomb barriers. Interesting new attempts at an understanding of the phenomena, both in nuclear structure and dynamics, involve therefore the nuclear surface.

Experimentally, there are at least two different and rather distinct mechanisms of cluster emission observed in reactions such as \(^{197}\text{Au}+^{40}\text{Kr}\) and \(^{209}\text{Bi}+^{136}\text{Xe}\) at bombarding energies between E/A = 20 and 60 MeV. In peripheral reactions leading to PLF and TLF products that are essentially cold, one observes [30-32] Be, B, and C clusters with IVS-type kinematical patterns and multiplicities of the order of \( M_{\text{IMF}} \sim 10^3 \). Both Z and energy distributions are exponential in character. The slope parameters \( T_0 \) of the cluster energy spectra are significantly larger than emission temperatures (T \( \leq 6 \) MeV) of PLF and TLF, measured via evaporated light particles.

The second observed type of cluster emission is sequential, statistical emission from primary PLF (or TLF). It is quite remarkable a) that sequential cluster emission is observed at all and b) that cluster decay is slow enough to allow the hot primary fragments to undergo Coulomb acceleration, requiring at least some \( \sim 10^{20} \) s to complete. Most data sets to date do not distinguish between these 2 cluster emission mechanisms [3].

A set of typical data is illustrated by Fig. 7 [14] for the dissipative \(^{209}\text{Bi}+^{136}\text{Xe}\) reaction at three bombarding energies. Shown are invariant
velocity contour diagrams for IMF clusters sorted according to centrality, as defined by the joined multiplicity of neutrons and LCPs. Events are plotted vs. velocity components parallel and perpendicular to the beam direction. Clusters are defined as having \( Z_{\text{IMF}} = 3 \), with oxygen serving as an average, typical cluster.

It is obvious from Fig. 7 that the cluster emission patterns follow to a large extent the essentially binary kinematics of PLF and TLF sources, as the bombarding energy is raised from 28 MeV to 62 MeV. The dashed Coulomb semi-circles, indicating qualitative expectations based on similar patterns for LCP emission, emphasize this trend.

Detailed simulations of sequential cluster emission from accelerated PLF and TLF are not able to reproduce the experimental patterns with satisfactory accuracy. As is necessary in the description of LCP emission patterns, an intermediate IVS source is also required for an adequate description of experimental cluster emission

![Figure 8: Logarithmic slope parameters (apparent temperatures) of LCP and cluster spectra for emission from PLF and IVS sources. The triplets indicate the variation with bombarding energy (28, 40, 62 MeV), [14].](image)

patterns. The presence of the IVS source is particularly obvious in the distributions at lower bombarding energies (Fig. 7, left column) and at angles sideways to the beam. Here, the contours change less rapidly than at forward angles, indicating a harder energy spectrum for IVS clusters.

Results of a preliminary analysis of LCP and Li-like cluster spectra are shown in Fig. 8 for the reaction \(^{209}\text{Bi} + ^{136}\text{Xe}\) at \(E/A = 28\) MeV (green), 40 MeV (red), and 62 MeV (black).

Spectral slope parameters for H and He particles emitted sequentially from the PLF have values of the order of \(T_\alpha = 5 - 7.5\) MeV. Such events are collected at forward angles. As expected, the highest \(T_\alpha\) values appear for central collisions (Fig. 8, right panel) and for the highest bombarding energy. Such particles emitted from the IVS source, presumably non-statistical particles, have energy spectra with slope parameters of the order of 12-14 MeV. For these particles, the deduced \(T_\alpha\) values are lower for the higher bombarding energies, a fact that has yet to be understood.

Finally, spectra of Li clusters evaporated from PLFs show slightly higher slope parameters than the corresponding H and He distributions. Most remarkable, however, are the high slope parameters obtained for the non-statistical Li clusters associated with the IVS source. These latter values range from \(T_\alpha = 15\) MeV for peripheral collisions to \(T_\alpha = 25\) MeV, for more central events.

For the heavy systems studied here both average cluster multiplicity \(\langle \text{M}_{\text{IMF}} \rangle\) and width of the multiplicity distribution \(P(\text{M}_{\text{IMF}})\) increase with increasing dissipation (decreasing impact parameter). At the same time, the balance between statistical and non-statistical cluster probability shifts somewhat in favor of the latter. For example, in mid-peripheral \(^{209}\text{Bi} + ^{136}\text{Xe}\) collisions, the 3 sources, PLF, TLF, and IVS, each contribute approximately similarly to the total cluster multiplicity \(\text{M}_{\text{IMF}}\). At central collisions, on the other hand, non-statistical cluster emission clearly dominates.

This competition between production mechanisms has an unexpected effect on the correlation between the cluster multiplicity \(\text{m}_{\text{IMF}}\) and the joint neutron–LCP multiplicity distribution. As explained earlier, the latter signifies a range in thermal excitation energy of the entire system.

The above correlation effect is demonstrated in Fig. 9 for the \(^{197}\text{Au} + ^{86}\text{Kr}\) reaction at 35 MeV,
which is representative for other reactions studied in this bombarding energy regime. As expected, one observes that a region of small multiplicities or small excitations is associated with the absence of clusters (m_{IMF}=0) and that the emission of one cluster requires already a significant amount of excitation acquired by the system in semi-peripheral collisions. Less expected is the fact that always the same \{m, m_{LCP}\} region appears “illuminated,” regardless of how many clusters are measured in coincidence. This may indicate an irregular pattern of competition between the emission of clusters and that of light particles. However, at present, correlations of the type shown in Fig. 9 are not available separately for the sequential, statistical cluster component.

In characterizing the cluster production mechanism, it is interesting to explore its dependence on bombarding energy and excitation. As it turns out, the statistical cluster multiplicity distribution for fixed thermal excitation changes very little with bombarding energy, while the non-statistical process becomes more dominant at higher bombarding energies.

Clearly, statistical and non-statistical cluster components (PLF/TLF vs. IVS) are produced by different mechanisms. Experimental data have already generated constraints on possible candidates for theoretical models of dynamic, non-statistical cluster production, which is observed to occur at all impact parameters. Elastic or inelastic projectile/target breakup on impact is an obvious candidate for the production of the latter, highly energetic IVS-type clusters. Establishing their origin unambiguously requires highly specific cluster correlation measurements, which are not yet available. Using projectile/target combinations with significantly different N/Z asymmetries would facilitate identification of the non-equilibrium mechanism. In addition, experimental data of cluster emission in hadron-induced reactions [34, 35] could be used to complement observations in heavy-ion reactions.

3 MODEL OF STATISTICAL CLUSTER EMISSION

In the following, a new model [36] is briefly described for previously unexplained sequential cluster emission from excited primary fragments from dissipative heavy-ion collisions. This model hence concerns just one of the two observed cluster processes.

It is based on the well known principle of reaction kinetics that a reaction that is energetically disfavored can nevertheless take place, if the associated entropy gain is sufficiently high. The model further utilizes the fact that the density of nucleonic states in dilute nuclear matter such as found in nuclear surface is greater than in dense bulk matter. This property is illustrated by the level density parameter systematics [37] with mass number A,

\[
a(\rho) = a_v + a_s = \left( A \alpha_v + A^{\frac{2}{3}} \alpha_s \right) \left( \rho / \rho_0 \right)^{-2/3} \tag{3}
\]

The level density parameter \(a\) in Eqn. 3 contains a volume and a surface term, \(a_v\) and \(a_s\), respectively. In order to be able to treat nuclei that have densities \(\rho\) different from the normal nuclear matter density \(\rho_0\), an overall scaling factor \(\left( \rho / \rho_0 \right)^{-2/3}\) has been incorporated in the definition of \(a\), as suggested by the Fermi gas model for self-similar expansion or contraction.
The level density parameter determines the magnitude of the nuclear entropy, $S$, for a given thermal excitation energy $E_{\text{therm}}$:

$$S = 2\sqrt{a \cdot E_{\text{therm}}}$$  \hspace{1cm} (4)

Nuclei with temperatures $T$ of the order of several MeV do not retain normal matter density but expand to an equilibrium density, $\rho_{\text{eq}} < \rho_0$, defined by maximum entropy. Using a harmonic approximation of the mean field [38], the density can be expressed analytically

$$\frac{\rho_{\text{eq}}}{\rho_0} = \frac{1}{4} \left(1 + \sqrt{9 - \frac{8E_{\text{total}}}{E_{\text{binding}}}} \right)$$  \hspace{1cm} (5)

in terms of the total excitation energy

$$E_{\text{total}} = E_{\text{therm}} + E_{\text{comp}}$$  \hspace{1cm} (6)

The total excitation energy is a sum of thermal and compression energies. Since the nuclear compressibility is a function of the nuclear asymmetry energy, the second term in Equ. 6 establishes interesting contact to the isospin dependent nuclear equation of state.

As a consequence of the energy consumed for expansion of the nucleus, to densities of $\rho_{\text{eq}} / \rho_0 \sim 1/3$, for $E_{\text{total}}/A > 8 \text{ MeV}$, the nucleus cools. The excitation energy dependence of the nuclear temperature becomes nonlinear, as illustrated in Fig. 10 for an $A=208$ nucleus. The temperature rises up to a maximum of $T \sim 6 \text{ MeV}$, in this example, and decreases at higher excitations leading to negative nuclear heat capacities. The maximum temperature shown in Fig. 10 is the limit an $A=208$ nucleus can sustain, before disintegrating into nucleons. Entropy driven nuclear expansion is hence seen as the ultimate reason for experimentally observed [4-6] limits of thermal stability. Due to the reduction in nuclear temperature caused by expansion, nuclear stability is actually increased, as compared to the same nucleus at normal density. In addition, negative heat capacities have also been reported in the literature [39, 40]. For the first time, the present harmonic interaction Fermi gas model (HIFGM) gives a consistent explanation for both these effects, suggesting a host of interesting studies, e.g., of the isospin dependence of thermal stability and heat capacity.

Furthermore, it is a natural consequence of the HIFGM that a hot, expanded nucleus tends to produce dinuclear transition states for the fission-like evaporation of a complex nuclear cluster. For example, one calculates that for $E_{\text{total}}/A > 4.5 \text{ MeV}$ the system of the two daughter nuclei $^{192}\text{W}$ and $^{16}\text{O}$, touching at their nuclear surface, has a higher entropy than the $A=208$ parent nucleus $^{208}\text{Pb}$. Hence, $^{16}\text{O}$ cluster emission is likely to occur, even though the nuclear temperature is one order of magnitude lower than the emission barrier.

Numerical HIFGM predictions of emission

**Figure 10:** Dependence of temperature on total excitation per nucleon, predicted by the harmonic approximation Fermi gas model [36].

$E_{\text{therm}}$ and excitation energy per nucleon.
probabilities $p_{\text{cluster}}$ are shown in Fig. 11 for clusters with atomic number $Z_{\text{cluster}}$, relative to the emission probability of a proton, $p_n$. The different logarithmic lines are calculated for different excitation energies $e^* = E_{\text{tot}}/A$ of an $A=197$ (Au) nucleus. As can be seen from this figure, the cluster emission is predicted to be an extremely likely process for excitations exceeding 4-5 MeV per nucleon. One calculates, for example, that $^{16}$O emission from a hot Au nucleus is more likely even than the emission of a proton.

The main reason for this effect is the complexity and high intrinsic level density of massive clusters. Strongly bound clusters or clusters with low densities of states are not so favored, according to the HIFGM. Such unusual schemes of competition between the evaporation of clusters and simpler particles could be responsible for the correlations between $m_{\text{sur}}$ and the joint neutron/LCP multiplicity discussed in the context of Fig. 9.

A more meaningful comparison of HIFGM predictions with experiment requires modeling of the entire evaporation cascade of a hot nucleus, e.g., with a code like GEMINI [22]. Work is underway to modify and expand this code accordingly.

4 CONCLUSIONS

In summary, it has been demonstrated that many of the salient features of dissipative heavy-ion reactions persist at bombarding energies at the upper boundary of the Fermi domain. Even though reconstruction of reaction events is often experimentally problematic, due to high excitations of reaction primaries, $4\pi$ measurements of all decay products have provided examples where reconstruction of these primaries has been possible to a large extent. As a result, one observes dissipative orbiting, for heavy reaction systems at least up to $E/A = 62$ MeV. With these features, one recognizes multi-nucleon exchange as the underlying mechanism, recovering a dissipative reaction environment largely familiar from lower bombarding energies, including incomplete relaxation of mass-to-charge (isospin) asymmetry and excitation energy division.

As a new, transitional feature of the reaction mechanism at the higher energies of interest, emission of complex, intermediate-mass clusters is observed on different time scales. A fast cluster emission mechanism is probably associated with projectile and target breakup in the approach phase. This mechanism is strongly dependent on nuclear overlap and bombarding energy. This mechanism has not yet been studied in any detail and requires dedicated experimentation of non-equilibrium phenomena in heavy-ion reactions at Fermi energies.

In addition, hot primary PLF (TLF) reaction fragments are observed to emit clusters in a delayed, statistical emission process and at times close to reaching asymptotic velocities. The relative stability of hot reaction primaries is understood to be due to nuclear expansion, lowering temperature and evaporation widths of simple particles. A plausible microcanonical model for hot, expanding nuclei, based on the interacting Fermi gas, is able to account qualitatively for the observed cluster decay of such nuclei. In this model, the nuclear surface entropy plays an important role. Thermal stability limits and negative heat capacities are simple, natural consequences of such a model view. A host of new physical phenomena, including interesting isospin dependent effects, have been predicted by the model. The model decay widths are worked into the scheme of a conventional statistical model computer code to accommodate cluster evaporation. With these new tools, the long-standing puzzle of nuclear multifragmentation is finally being solved. In addition, statistical cluster emission promises to define a new research direction exploring a new mode of nuclear decay.

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5 REFERENCES
