Exotic break-up modes in heavy ion reactions up to Fermi energies postprint

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Abstract

We discussed recent studies, within the framework of transport theories, on heavy ion reactions between charge asymmetric systems, from low up to Fermi energies. We concentrated on the analysis of ternary breakup events of dynamical origin occurring in semi-central reactions, where the formation of excited systems in various conditions of shape, excitation energy and spin is observed. At beam energies around 20A MeV, we showed how this fragmentation mode emerges from the combined action of surface (neck) instabilities and angular momentum effects, leading to the observation of three aligned massive fragments in the exit channel. At Fermi energies, a transition towards a prompt emission of small fragments from the neck region with larger relative velocity with respect to projectile and target remnants is observed. We also focus on isospin sensitive observables, aiming at extracting information on the density dependence of the isovector part of the nuclear effective interaction and of the nuclear symmetry energy.

Full Text

Preamble

Exotic break-up modes in heavy ion reactions up to Fermi energies

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Keywords: Low and intermediate energy heavy-ion reactions, Fluctuation phenomena, Equation of State
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Introduction

The behavior of nuclear matter under various conditions of density, temperature, and N/Z asymmetry is of fundamental importance for understanding many phenomena involving nuclear systems and astrophysical compact objects. This information can be accessed through heavy ion collision experiments, where transient states of nuclear matter spanning a large variety of regimes can be created. Such studies allow one to learn about the corresponding behavior of the nuclear effective interaction, which provides the nuclear Equation of State (EOS) in the equilibrium limit.

In particular, many investigations are nowadays concentrated on the EOS of asymmetric matter (Asy-EOS), which has comparatively few experimental constraints relative to the symmetric EOS [1]. We stress that this information is essential for understanding important properties of neutron stars, whose crust behaves as low-density asymmetric nuclear matter [2, 3] and whose core may reach extreme values of density and asymmetry. Moreover, the low-density behavior of the symmetry energy also affects the structure of exotic nuclei and the appearance of new features involving the neutron skin, which are currently under intense investigation [4].

Over the past years, several observables sensitive to the nuclear EOS and testable experimentally have been suggested. In this article, we present some recent transport theory results on dissipative collisions across a range of beam energies from just above the Coulomb barrier up to the Fermi energy regime, mainly concentrating on reaction mechanisms occurring at semi-central impact parameters. We focus on new, exotic break-up modes, showing how the fragmentation mechanism reflects the delicate balance between mean-field dynamics, associated shape and volume fluctuations, and rotational effects. Moreover, fragment isotopic properties appear quite sensitive to the low-density behavior of the nuclear symmetry energy.

II. Transport Theories and Effective Interactions

Nuclear reactions are modeled by solving transport equations based on mean field theories, with short-range (2p-2h) correlations included via hard nucleon-nucleon elastic collisions and via stochastic forces, self-consistently evaluated from the mean phase-space trajectory [5].

In the energy range up to a few hundred A MeV, the appropriate tool is the so-called Boltzmann-Langevin (BL) equation

$$\frac{\partial f}{\partial t} + \{f, H\} = I_{\mathrm{coll}}[f] + \delta I[f],$$

where $f(r, p, t)$ is the one-body distribution function, the semi-classical analog of the Wigner transform of the one-body density matrix, $H(r, p, t)$ is the mean field Hamiltonian, I_{coll} is the two-body collision term incorporating the Fermi statistics of the particles, and $\delta I[f]$ is its fluctuating part.

Several approximate treatments of the BL equation have been introduced so far. For instance, in BUU-like models, the fluctuating term $\delta I[f]$ is neglected [7], whereas in the Stochastic Mean Field (SMF) model [8] fluctuations are projected onto coordinate space and are implemented by agitating the spatial density profile.

Effective interactions (associated with a given EOS) can be considered as input to all transport codes, and from comparison with experimental data one can finally obtain hints about nuclear matter properties.

Unless specified, we adopt a soft isoscalar EOS (compressibility $K = 200$ MeV) and the free nucleon-nucleon cross section in the collision integral. We note that the considered compressibility value is favored, for example, from flow, monopole oscillation, and multifragmentation studies [9, 10]. This choice corresponds to a Skyrme-like effective interaction, namely SKM*, for which we take the effective mass as equal to the nucleon bare mass.

The symmetry energy $E_{\mathrm{sym}}(\rho)$ appears in the energy density functional

$$\epsilon(\rho, \rho_i) \equiv \epsilon(\rho) + \rho E_{\mathrm{sym}}(\rho_i/\rho)^2 + O(\rho_i/\rho)^4 + \dots,$$

expressed in terms of total ($\rho = \rho_p + \rho_n$) and isospin ($\rho_i = \rho_p - \rho_n$) densities, from which the mean-field potential can be consistently derived (ρ_0 denotes the saturation density).

For some of the reaction mechanisms analyzed, the sensitivity of the simulation results is tested against different choices of the density dependence of the isovector part of the effective interaction. For instance, the symmetry energy behavior associated with three different parameterizations of $C(\rho)$ (the asysoft, the asystiff, and asysuperstiff) is displayed in Fig. 1, with detailed description provided in [5].

The equation is solved numerically by adopting the test particle method [11]. Within our framework, the system is described in terms of the one-body distribution function f, but this function may experience stochastic evolution in response to the action of the fluctuating term $\delta I[f]$. Consequently, the model is suitable for treating the occurrence of instabilities and bifurcations of trajectories in nuclear dynamics.

III. Fragmentation at Low Energy: Ternary Breakup

We discuss semi-peripheral heavy ion collisions in the beam energy range of 10-30A MeV, focusing on the possible occurrence of ternary breakup processes and the features of the associated reaction products. Recent experimental investigations have concentrated on these exotic separation modes, particularly for Au + Au reactions at 15 and 23A MeV [12–14].

Calculations are performed with the SMF approach. Let us first consider the reaction at 15A MeV, $b = [4–6]$ fm. In this case, we observe an almost symmetric neck rupture between projectile-like (PLF) and target-like (TLF) fragments, leading to the formation of two deformed fragments in the majority of events. Important quadrupole and octupole deformations are noticed for the primary PLF/TLF fragments, which may lead to subsequent ruptures (multiple breakup) and, in particular, to ternary breakup events caused by surface instabilities.

An early fragment recognition method is applied to identify the most probable breakup configuration of the PLF (or TLF) fragment. Figure 2 (top panel) shows the mass distribution of the lightest fragment A_1 and heaviest fragment A_2 for impact parameter $b = 5$ fm. Once the masses are normalized to the average mass of the PLF (or TLF) fragment, the results are in good agreement with experimental data [12]. In particular, the calculations reproduce the distance between the A_1 and A_2 centroids and the variance of the mass distribution. Similar results have been recently reported in the context of improved QMD (ImQMD) calculations of Ref. [15], where a detailed comparison with the experimental findings of Ref. [12] is presented.

Results obtained at the higher bombarding energy of 23A MeV are shown in the bottom panel of the figure. The behavior observed for the mass distribution of fragments A_1 and A_2 is quite close to that obtained at 15A MeV; however, variances are larger, reflecting the more dissipative dynamics.

It should be noted that in the calculations of Ref. [15], as well as in SMF simulations at 15A MeV, the lightest fragment (A_1) emerges mainly from the neck region, thus being located at mid-velocity. On the other hand, in the data analysis reported in Ref. [13], the fragment with the largest parallel velocity (F_1) has the smallest mass. In SMF simulations, this feature is present but at higher energy. Indeed, at 23A MeV, owing to increased angular momentum effects, the PLF (or TLF) fragment rotates before reaching its maximum deformation, and a subsequent breakup may take place. This mechanism allows one to test the interplay between the development of surface instabilities and rotational effects, which is governed by the properties of the mean-field interaction. Consequently, in the case of a PLF breakup, for instance, the lightest fragment may emerge with large positive parallel velocity.

Thus SMF results point to the occurrence of a reaction mechanism—neck rupture coupled to angular momentum effects—that could explain the experimental observation. On the other hand, in QMD-like calculations, rotational effects could be missing because of the too-fast reaction dynamics and reduced mean-field effects [16, 17].

In the calculations discussed above, the sensitivity to the symmetry energy parametrization has not been explored so far. It would be extremely interesting to extend these investigations to reactions involving neutron-rich (or even exotic) nuclei [18]. Indeed, the reaction dynamics could be affected by the neutron enrichment of the neck region, related to neutron skin effects and/or isospin migration mechanisms [5, 19]. In this case, one would also expect important sensitivity of the reaction mechanism and the features of the emitted fragments to the isovector terms of the nuclear potential, opening interesting perspectives toward extracting new, independent information on the density behavior of the nuclear symmetry energy [20].

IV. Solution of the Full BL Equation for Fermionic Systems

We now move to discuss recent developments concerning the solution of the BL equation (1) in full phase space. This is the aim of the Boltzmann-Langevin One-Body model (BLOB) [21]. In this approach, the conventional Uehling-Uhlenbeck average collision integral is replaced by a similar form where binary collisions, instead of acting only on two test particles a, b, rather involve extended phase-space agglomerates of test particles of equal isospin $A = a_1, a_2, ...$, $B = b_1, b_2, ...$, to simulate collisions between nucleon wave packets:

$$\bar{I}[f]+\delta I[f] = g \int\int dp_b d\Omega\, W(AB \leftrightarrow CD) F(AB \to CD) = \int\int dp_b \langle |v_a - v_b| \rangle F(AB \to CD),$$

where

$$F(AB \to CD) = (1 - f_A)(1 - f_B) f_{Cf} D - f_{Af} B (1 - f_C)(1 - f_D).$$

At each time interval, the full phase space is scanned for collisions and test-particle agglomerates are redefined in phase-space cells of volume h^3. The above procedure introduces correlations that are then exploited through a stochastic collision procedure. As a consequence, fluctuations develop spontaneously in phase space with the correct amplitude, corresponding (at equilibrium) to a variance equal to $f(1-f)$ for volumes containing N_{test} test particles, where N_{test} is the number of test particles per nucleon [22]. Since the N_{test} test particles involved in collisions that are not successful can be sorted again into new agglomerates to attempt new collisions within the same time interval, the cross section contained in the transition rate W in Eq. (2) corresponds to the nucleon-nucleon cross section divided by N_{test}: $\sigma = \sigma_{NN}/N_{\text{test}}$. We note that the transition rate $W(AB \leftrightarrow CD)$ is the average of the elementary transition rates $W(ab \leftrightarrow cd)$ over the ensemble Σ of all couples of test particles belonging to the agglomerates A and B with velocities v_a and v_b.

The BLOB model applies a precise shape-modulation technique [23] that ensures the occupancy distribution does not exceed unity at any phase-space point in the final states, leading to correct Fermi statistics for the distribution function f in terms of both mean value and variance. The main constraint of this procedure is to impose a phase-space metric characterized by phase-space cells of volume h^3. However, the metric of each (momentum and coordinate) stochastic space is unconstrained in general.

In the present calculations, we impose maximum compactness for the agglomerates in momentum space that neither violates Pauli blocking nor energy conservation. However, beyond the present application to Fermi energies, further attention should be paid to the compactness of the wave packets also in coordinate space when dealing with effects like collective flow and stopping, which become relevant at intermediate energies.

The BLOB approach has been tested in the schematic case of nuclear matter contained in a box with periodic boundary conditions. For systems initialized inside the unstable (spinodal) region of the nuclear matter phase diagram, it appears that the stochastic collision integral induces thermal fluctuations that are amplified by the unstable mean field, in agreement with the standard nuclear dispersion relation [24].

V. Fusion-Multifragmentation Competition in Central Collisions

Before discussing the phenomenology of semi-central reactions, we test the BLOB approach for describing central heavy-ion collisions at Fermi energies, which have been widely investigated in past years from both experimental and theoretical perspectives [9, 10].

For convenience (because experimental data exist, measured by the INDRA collaboration [25]), we simulate the reaction ^{136}Xe+^{124}Sn at 25 and 32A MeV. In this situation, the system is close to the threshold between fusion and multifragmentation (below for 25A MeV, above for 32A MeV). The BLOB transport model is employed with a soft EOS ($K = 200$ MeV), a linear Asy-EOS, an in-medium cross section as prescribed in Ref. [26], with $N_{\text{test}} = 40$, and with statistics of 600 events. The dynamics is followed for a time of 300 fm/c.

Figure 3 shows the evolution of the size of inhomogeneities that develop in the potential landscape as a function of time for the two incident energies 25 and 32A MeV. These inhomogeneities correspond to blobs of matter that, if the dynamics is sufficiently explosive, may eventually leave the system as emitted fragments. At short times, spinodal instabilities tend to split the system into several fragments of comparable size, corresponding approximately to the region of Neon. Later on, this mechanism enters into competition with a process of partial coalescence determined by the mean-field resilience, which tends to revert the system to a compact shape and is more effective at the lowest incident energy.

This picture results in a large variety of exit channels for a given macroscopic initial condition (entrance channel), ranging from fusion to multifragmentation and passing through very asymmetric configurations with small fragment multiplicity (eventually binary) and large size asymmetry. Such intermediate configurations may recall asymmetric fission, with the difference that the distribution of momentum transfer could reach large values more compatible with multifragmentation. These results indicate that the BLOB dynamics can describe the development of a large variety of configurations in fragmentation events of dissipative collisions, even at the lowest energy considered (25A MeV), in agreement with experimental observations. We note that this latter result was not reproduced by SMF simulations, which, owing to the approximate treatment of fluctuations, underestimate fragment production in low-energy reactions [27].

VI. Overview on a Landscape of Exit Channels

To present a more general survey, we extend the set of simulations to a full range of impact parameters and complete the dynamical calculation with a further decay process of the hot fragments through a statistical evaporation model [28]. We maintain the same reaction, ^{136}Xe+^{124}Sn, but additionally vary the impact parameter b.

The left panel of Fig. 4, still restricted to central collisions, shows the evolution of the multiplicity of (primary) fragments larger than Be as a function of incident energy (colored distribution with the average marked by a solid line). As expected, fragmentation is favored as beam energy increases within the energy window considered here. However, it should be noted that the distribution of the (final) fragments, obtained after the evaporation process, reaches a maximum above about 35A MeV and falls above 50A MeV due to the increasingly reduced size of fragments surviving the evaporation stage.

The right panel of Fig. 4 shows the dependence of the average primary fragment multiplicity as a function of impact parameter. We observe that at large incident energies, the maximum corresponds to central collisions because the multifragmentation channel dominates the reaction cross section. On the other hand, at smaller incident energies, the maximum moves to more peripheral collisions and is reduced to events with three or four fragments, indicating that around 30A MeV and for semi-central impact parameters (6 fm) the system oscillates between binary mechanisms and ternary splits, where intermediate mass fragments (IMF) are formed in the neck region. This latter mechanism will be discussed in the next section.

VII. Isospin Dynamics in Neck Fragmentation

It is now well established that the largest part of the reaction cross section for dissipative collisions at Fermi energies proceeds through the Neck Fragmentation channel, with IMF directly produced in the interacting zone in semi-peripheral collisions on very short time scales [29]. Interesting isospin transport effects can be predicted for this fragmentation mechanism since clusters are formed in dilute asymmetric matter but always in contact with the projectile-like and target-like remnant regions at nearly normal densities. In the presence of density gradients, we expect a neutron flow toward the neck clusters, and this effect should be larger for a stiffer symmetry energy around saturation [5]. This is shown in Fig. 5, where the asymmetry of the neck region is plotted for two Asy-EOS choices (soft and stiff), compared to the PLF-TLF asymmetry, for SMF simulations of Sn + Sn reactions at 50A MeV, $b = 6$ fm.

This isospin migration effect can be estimated on the basis of simple energy balance considerations. Starting from a residue of mass A_{res} and a neck of mass A_{IMF}, we assume that the mass A participating in isospin exchange is approximately equal to the mass of the neck, while it is small relative to the mass of the residue. This leads to the asymmetry $(\beta + \Delta\beta)$ of the neck and to a total asymmetry $\beta_{\text{res}} = [\beta(A_{\text{res}} - A) + (\beta - \Delta\beta)A]/A_{\text{res}} = \beta - \Delta\beta A/A_{\text{res}}$ of the residue, with $\Delta\beta$ to be determined by minimization of the symmetry energy. The corresponding variation of the symmetry energy is equal (apart from a constant) to

$$\Delta E_{\text{sym}} = A_{\text{res}} E_{\text{sym}}(\rho_R)\beta_{\text{res}}^2 + A E_{\text{sym}}(\rho_I)(\beta + \Delta\beta)^2,$$

where ρ_R and ρ_I are the densities of the residue and neck regions, respectively. The minimum of the variation ΔE_{sym} yields

$$\frac{E_{\text{sym}}(\rho_R)}{E_{\text{sym}}(\rho_I)}.$$

From this simple argument, the ratio between the IMF and residue asymmetries should depend only on symmetry energy properties and, in particular, on the difference of the symmetry energy between the residue and neck regions, as appropriate for isospin migration. It should also be larger than one, even more so for the asystiff than for the asysoft EOS, as indicated by Fig. 5.

The isospin migration mechanism is responsible for the emission of rather "exotic" (neutron-rich) fragments from the neck region. Moreover, as discussed above, the fragment N/Z is nicely dependent on the parametrization employed for the symmetry potential. This latter effect has been recently investigated also in the context of the BLOB model, for ^{112,124}Sn + ^{58,64}Ni reactions at 35A MeV, $b = 6$–8 fm, for which recent experimental data exist [19]. Fig. 6 shows the average N/Z of the fragments emitted from the neck region as a function of their charge for the two reactions considered and two parametrizations of the symmetry energy (stiff and soft). Quite neutron-rich fragments are produced, especially in the stiff case, in good agreement with the experimental data [19].

VIII. Conclusion

We have undertaken an analysis of new fragmentation modes that have been the focus of recent experimental investigations and may develop in low and Fermi energy heavy ion collisions. At low energies, the possibility of observing ternary breakup processes of dynamical origin is explored within the SMF model, examining the concurrent role of surface mean-field instabilities, dissipative effects, and angular momentum. Indeed, large quadrupole and octupole deformation effects develop in binary exit channels of semi-central reactions, which may lead to subsequent breakup of the PLF/TLF fragments. At Fermi energies, IMF are directly emitted from the low-density neck region. In reactions between neutron-rich systems, we observe a neutron flow toward the neck, yielding quite exotic primary fragments. This effect, also confirmed by calculations with the new BLOB model, nicely depends on the stiffness of the symmetry potential, allowing one to obtain new information on the low-density behavior of the nuclear symmetry energy.

References

[1] Danielewicz P, Lacey R and Lynch W G. Determination of the equation of state of dense matter. *Science*, 2002, 298: 1592–1596. DOI: 10.1126/science.1078070

[2] Lattimer J M and Prakash M. Neutron star observations: Prognosis for equation of state constraints. *Phys Rep*, 2007, 442: 109–165. DOI: 10.1016/j.physrep.2007.02.003

[3] Burrello S, Colonna M and Matera F. Pairing effects on spinodal decomposition of asymmetric nuclear matter. *Phys Rev C*, 2014, 89: 057604. DOI: 10.1103/PhysRevC.89.057604

[4] Piekarewicz J, Agrawal B K, Colò G, et al. Electric dipole polarizability and the neutron skin. *Phys Rev C*, 2012, 85: 041302. DOI: 10.1103/PhysRevC.85.041302

[5] Baran V, Colonna M, Greco V, et al. Reaction dynamics with exotic nuclei. *Phys Rep*, 2005, 410: 335–476. DOI: 10.1016/j.physrep.2004.12.004

[6] Ayik S, Gregoire C. Fluctuations of single-particle density in nuclear collisions. *Phys Lett B*, 1998, 212: 269–272. DOI: 10.1016/0370-2693(88)91315-9

[7] Li B A, Das C B, Das Gupta S, et al. Momentum dependence of the symmetry potential and nuclear reactions induced by neutron-rich nuclei at RIA. *Phys Rev C*, 2004, 69: 011603(R). DOI: 10.1103/PhysRevC.69.011603

[8] Colonna M, Di Toro M, Guarnera A, et al. Fluctuations and dynamical instabilities in heavy-ion reactions. *Nucl Phys A*, 1998, 642: 449–460. DOI: 10.1016/S0375-9474(98)00542-9

[9] Chomaz P, Colonna M and Randrup J. Nuclear spinodal fragmentation. *Phys Rep*, 2004, 389: 263–440. DOI: 10.1016/j.physrep.2003.09.006

[10] Borderie B and Rivet M F. Nuclear multifragmentation and phase transition for hot nuclei. *Prog Part Nucl Phys*, 2008, 61 (Book Series): 551–601, and refs. therein. DOI: 10.1016/j.ppnp.2008.01.003

[11] Guarnera A, Colonna M and Chomaz Ph. 3D stochastic mean-field simulations of the spinodal fragmentation of dilute nuclei. *Phys Lett B*, 1996, 373: 267–274. DOI: 10.1016/0370-2693(96)00152-9

[12] Skwira-Chalot I, Siwek-Wilczyńska K, Wilczyński J, et al. Dynamical evolution of the ^{197}Au + ^{197}Au system at 15 MeV/nucleon. *Int J Mod Phys E*, 2006, 15: 495–499. DOI: 10.1142/S0218301306004429

[13] Wilczynski J, Skwira-Chalot I, Siwek-Wilczyńska K, et al. Observation of fast collinear partitioning of the ^{197}Au + ^{197}Au system into three and four fragments of comparable size. *Phys Rev C*, 2010, 81: 024605. DOI: 10.1103/PhysRevC.81.024605

[14] Cap T, Siwek-Wilczyńska K, Skwira-Chalot I, et al. Aligned ternary partitioning of the ^{197}Au + ^{197}Au system at 23A MeV beam energy. *Phys Scripta*, 2014, 89: 054005. DOI: 10.1088/0031-8949/89/5/054005

[15] Li Y, Yan S, Jiang X, et al. Dynamical effects in heavy-ion induced ternary breakup. *Nucl Phys A*, 2013, 902: 1–20. DOI: 10.1016/j.nuclphysa.2013.02.015

[16] Colonna M, Ono A and Rizzo J. Fragmentation paths in dynamical models. *Phys Rev C*, 2010, 82: 054613. DOI: 10.1103/PhysRevC.82.054613

[17] Rizzo J, Colonna M and Ono A. Comparison of multifragmentation dynamical models. *Phys Rev C*, 2007, 76: 024611. DOI: 10.1103/PhysRevC.76.024611

[18] Cammarata P, Colonna M, Bonasera A, et al. Sifting through the remnants of heavy-ion collisions for observables sensitive to the nuclear equation of state. *Nucl Instrum Meth A*, 2014, 761: 1–6. DOI: 10.1016/j.nima.2014.05.108

[19] De Filippo E, Pagano A, Russotto P, et al. Correlations between emission timescale of fragments and isospin dynamics in ^{124}Sn + ^{64}Ni and ^{112}Sn + ^{58}Ni

reactions at 35A MeV. *Phys Rev C*, 2012, 86: 014610. DOI: 10.1103/PhysRevC.86.014610

[20] Li B A, Ramos À, Verde G, et al. Topical issue on nuclear symmetry energy. *Eur Phys J A*, 2014, 50: 9–11. DOI: 10.1140/epja/i2014-14009-x

[21] Napolitani P and Colonna M. Bifurcations in Boltzmann–Langevin systems. *Phys Lett B*, 2013, 382–386. DOI: 10.1016/j.physletb.2013.08.005

[22] Rizzo J, Chomaz Ph and Colonna M. A new approach to solve the Boltzmann–Langevin equation for fermionic systems. *Nucl Phys A*, 2008, 806: 40–64. DOI: 10.1016/j.nuclphysa.2008.02.304

[23] Napolitani P and Colonna M. Boltzmann-Langevin one-body dynamics for fermionic systems. *Eur Phys J Web of Conf*, 2012, 31: 00027–00033. DOI: 10.1051/epjconf/20123100027

[24] Colonna M and Chomaz Ph. Unstable infinite nuclear matter in stochastic mean field approach. *Phys Rev C*, 1994, 49: 1908–1916. DOI: 10.1103/PhysRevC.49.1908

[25] Gagnon-Moisan F, Galichet E, Rivet M F, et al. New isospin effects in central heavy-ion collisions at Fermi energies. *Phys Rev C*, 2012, 86: 044617. DOI: 10.1103/PhysRevC.86.044617

[26] Danielewicz P. Hadronic transport models. *Acta Phys Pol B*, 2002, 33: 45–64; Coupland D D S, Lynch W G, Tsang M B, et al. Influence of transport variables on isospin transport ratios. *Phys Rev C*, 2011, 84: 054603. DOI: 10.1103/PhysRevC.84.054603

[27] Bonnet E, Colonna M, Chbihi A, et al. Investigation of collective radial expansion and stopping in heavy ion collisions at Fermi energies. *Phys Rev C*, 2014, 89: 034608. DOI: 10.1103/PhysRevC.89.034608

[28] Durand D. An event generator for the study of nuclear collisions in the Fermi energy domain (I). Formalism and first applications. *Nucl Phys A*, 1992, 541: 266–298. DOI: 10.1016/0375-9474(92)90097-4

[29] De Filippo E, Pagano A, Wilczynski J, et al. Time sequence and time scale of intermediate mass fragment emission. *Phys Rev C*, 2005, 71: 044602. DOI: 10.1103/PhysRevC.71.044602

Note: Figure translations are in progress. See original paper for figures.