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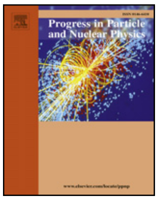

Review

Isospin dynamics in heavy ion collisions: From Coulomb barrier to quark gluon plasma

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ABSTRACT

Heavy Ion Collisions (HIC) represent a unique tool to probe the in-medium nuclear interaction in regions away from saturation. In this report, we present a selection of new reaction observables in dissipative collisions particularly sensitive to the symmetry term of the nuclear Equation of State (Iso-EoS). We will first discuss the Isospin Equilibration Dynamics. At low energies, this manifests via the recently observed Dynamical Dipole Radiation, due to a collective neutron-proton oscillation, with the symmetry term acting as a restoring force. At higher beam energies, Iso-EoS effects will be seen in Imbalance Ratio Measurements, in particular from the correlations with the total kinetic energy loss. For fragmentation reactions in central events, we suggest to look at the coupling between isospin distillation and radial flow. In Neck Fragmentation reactions, important Iso-EoS information can be obtained from the correlation between isospin content and alignment. The high density symmetry term can be probed from isospin effects on heavy ion reactions at relativistic energies (few *A*GeV range). Rather, isospin sensitive observables are proposed from nucleon/cluster emissions, collective flows and meson production. The possibility to shed light on the controversial neutron/proton effective mass splitting in asymmetric matter is also suggested. A large symmetry repulsion at high baryon density will also lead to an "earlier" hadron-deconfinement transition in *n*-rich matter. A suitable treatment of the isovector interaction in the partonic EoS appears very relevant.

1. Introduction: The elusive symmetry term of the EoS

The symmetry energy $E_{\rm sym}$ appears in the energy density $\epsilon(\rho,\rho_3) \equiv \epsilon(\rho) + \rho E_{\rm sym}(\rho_3/\rho)^2 + O(\rho_3/\rho)^4 + \cdots$, expressed in terms of total ($\rho = \rho_p + \rho_n$) and isospin ($\rho_3 = \rho_p - \rho_n$) densities. The symmetry term gets a kinetic contribution

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directly from basic Pauli correlations, and a potential part from the highly controversial isospin dependence of the effective interactions. Both at sub-saturation and supra-saturation densities, predictions based on the existing many-body techniques diverge rather widely, see [1,2].

We recall that the knowledge of the EoS of asymmetric matter is very important at low densities (e.g. neutron skins, pigmy resonances, nuclear structure at the drip lines, neutron distillation in fragmentation, neutron star formation and crust) as well as at high densities (e.g. neutron star mass-radius relation, cooling, hybrid structure, transition to a deconfined phase, formation of black holes). Several observables which are sensitive to the Iso-EoS, and testable experimentally, have been suggested [3–8]. We take advantage of new opportunities in theory (development of rather reliable microscopic transport codes for HIC) and in experiments (availability of very asymmetric radioactive beams, improved possibility of measuring event-by-event correlations) to present new results that are constraining the existing effective interaction models. We will discuss dissipative collisions in a wide range of beam energies, from just above the Coulomb barrier up to the *A*GeV range. Isospin effects on the chiral/deconfinement transition at high baryon density will be also discussed. Low to Fermi energies will bring information on the symmetry term around (below) normal density, while intermediate energies will probe high density regions. The transport codes are based on mean field theories, with correlations included via hard nucleon–nucleon elastic and inelastic collisions, and via stochastic forces, self-consistently evaluated from the mean phase-space trajectory, see [5,9–11]. Stochasticity is essential in order to get distributions, as well as to allow the growth of dynamical instabilities.

Relativistic collisions are described via a fully covariant transport approach, related to an effective field exchange model, where the relevant degrees of freedom of the nuclear dynamics are accounted for [5,12–16]. We will have a propagation of particles, suitably dressed by self-energies that will influence collective flows and in medium nucleon–nucleon inelastic cross sections. The construction of an Hadron–EoS at high baryon and isospin densities will finally allow the possibility of developing a model of a hadron-deconfinement transition at high density for an asymmetric matter [17]. The problem of a correct treatment of the isospin in a effective partonic E0S will be stressed.

We will always test the sensitivity of our simulation results to different choices of the density and momentum dependence of the Isovector part of the Equation of State (Iso-EoS). In the non-relativistic frame, the potential part of the symmetry energy, $C(\rho)$, [5]:

$$\frac{E_{\rm sym}}{A} = \frac{E_{\rm sym}}{A}(kin) + \frac{E_{\rm sym}}{A}(pot) \equiv \frac{\epsilon_F}{3} + \frac{C(\rho)}{2\rho_0}\rho \qquad (1)$$

is tested by employing two different density parametrizations, Isovector Equation of State (Iso-Eos) [3,18], of the mean field: (i) $\frac{C(\rho)}{\rho_0} = 482 - 1638\rho$, (MeV fm^3), for “Asysoft” EoS: $E_{\rm sym}/A(pot)$ has a weak density dependence close to the saturation, with an almost flat behavior below ρ_0 and even decreasing at supra-saturation; (ii) a constant coefficient, $C = 32$ MeV, for the “Asystiff” EoS choice: the interaction part of the symmetry term displays a linear dependence with the density, i.e. with a faster decrease at lower densities and much stiffer above saturation. The isoscalar section of the EoS is the same in both cases, fixed, requiring that the saturation properties of symmetric nuclear matter with a compressibility around 220 MeV are reproduced.

2. Isospin equilibration

2.1. The prompt dipole γ-ray emission

The possibility of an entrance channel bremsstrahlung dipole radiation due to an initial different N/Z distribution was suggested at the beginning of the nineties [19,20]. After several experimental pieces of evidence, in fusion as well as in deep-inelastic reactions, [21,22] and refs. therein, we have now a good understanding of the process and stimulating new perspectives from the use of radioactive beams.

During the charge equilibration process taking place in the first stages of dissipative reactions between colliding ions with different N/Z ratios, a large amplitude dipole collective motion develops in the composite dinuclear system, the so-called Dynamical Dipole mode. This collective dipole gives rise to a prompt γ-ray emission which depends: (i) on the absolute value of the initial dipole moment

$$D(t=0) = \frac{NZ}{A}\,|R_Z(t=0) - R_N(t=0)| = \frac{R_P + R_T}{A} Z_P Z_T \left| \left(\frac{N}{Z}\right)_T - \left(\frac{N}{Z}\right)_P \right|, \qquad (2)$$

being $R_Z = \frac{\Sigma_i x_i(p)}{Z}$ and $R_N = \frac{\Sigma_i x_i(n)}{N}$ the center of mass of protons and of neutrons respectively, while R_P and R_T are the projectile and target radii; (ii) on the fusion/deep-inelastic dynamics; (iii) on the symmetry term, below saturation, that is acting as a restoring force.

A detailed description is obtained in mean field transport approaches, [23,24]. We can follow the time evolution of the dipole moment in the r-space, $D(t) = \frac{NZ}{A}(R_Z - R_N)$ and in p-space, $DK(t) = (\frac{P_p}{Z} - \frac{P_n}{N})$, with P_p (P_n) center of mass in momentum space for protons (neutrons), just the canonically conjugate momentum of the $D(t)$ coordinate, i.e. as operators $[D(t), DK(t)] = i\hbar$. A nice “spiral-correlation” clearly denotes the collective nature of the mode, see Fig. 1.

We can directly apply a bremsstrahlung approach, to the dipole evolution given from the Landau-Vlasov transport [24], to estimate the “prompt” photon emission probability ($E_\gamma = \hbar\omega$):