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Dynamical dipole mode in fusion reactions with exotic nuclear beams

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We report the properties of the prompt dipole radiation, produced via a collective bremsstrahlung mechanism, in fusion reactions with exotic beams. We show that the γ yield is sensitive to the density dependence of the symmetry energy below/around saturation. Moreover, we find that the angular distribution of the emitted photons from such fast collective mode can represent a sensitive probe of its excitation mechanism and of fusion dynamics in the entrance channel.

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Production of exotic nuclei has opened the way to explore, in laboratory conditions, new aspects of nuclear structure and dynamics up to extreme ratios of neutron (N) to proton numbers (Z). An important issue addressed is the density dependence of symmetry energy term in the nuclear equation of state, of interest also for the properties of astrophysical objects [1–4]. By employing heavy-ions collision at appropriate beam energy and centrality the isospin dynamics at different densities of nuclear matter can be investigated [3–8].

Here we discuss isospin effects in dissipative collisions at low energies, between 5 and 20 MeV/nucleon, where unstable ion beams with large asymmetry will be soon available. The starting point is that in this energy range, for dissipative reactions between nuclei with different N/Z ratios, the charge equilibration process in the entrance channel has a collective character resembling a large-amplitude giant dipole resonance (GDR). Several microscopic transport simulations like semiclassical Boltzmann-Nordheim-Vlasov (BNV) [9,10], time-dependent Hartree-Fock (TDHF) [11–14], or constrained molecular dynamics [15] have confirmed this scenario. Several experiments based on a comparison between two reactions with different entrance channel charge asymmetry, leading to the same final products, have confirmed the presence of this effect; see Refs. [16,17] and references therein.

The γ yield resulting from the decay of such pre-equilibrium isovector mode can encode information about the early stage of the reaction [9,10,13,18,19]. This collective response is appearing in the lower density intermediate neck region, while the system is still in a highly deformed dinuclear configuration. It is therefore of interest to look at the influence of density dependence of symmetry energy below saturation upon the excitation and dynamics of the prompt dipole mode. The corresponding emission rates can be evaluated, through a "bremsstrahlung" mechanism, in a consistent transport approach to the reaction dynamics, which can account for the whole contribution along the dissipative nonequilibrium path, in fusion or deep-inelastic processes [19]. In this way the data can be directly used to probe the isovector part of the in medium effective interaction below saturation density.

Here we discuss also the expected emission anisotropy of such prompt dipole radiation, due to the neutron/proton oscillation along a definite symmetry axis. This is of interest for planning new experiments and for the relation to the lifetime of such transient collective mode.

Exotic beams. In the following we shall study the features of the pre-equilibrium dipole considering the reaction $^{132}\mathrm{Sn} + {}^{58}\mathrm{Ni}$ ("132" system) at 10 MeV/nucleon, as referred to the same reaction induced by a $^{124}\mathrm{Sn}$ beam ("124" system). From simple arguments a larger initial dipole moment will trigger higher-amplitude isovector oscillations, increasing the chance of a clear experimental observation. During the reaction dynamics the dipole moment is given by $D(t) = \frac{NZ}{A} X(t)$, where $A = N + Z$, and $N = N_1 + N_2$, $Z = Z_1 + Z_2$, are the total number of participating nucleons, while $X(t)$ is the distance between the centers of mass of protons and neutrons. We note that the initial dipole ($t = 0$: touching configuration) attains a value around 45 fm for the exotic $^{132}\mathrm{Sn}$ beam, to be compared to the smaller value 33 fm for the stable "124" system, which can be considered as a reference partner in an experimental comparison.

We have employed a mean-field transport approach, based on the BNV equation, which properly describes the self-consistent couplings between various degrees of freedom. The potential part of the symmetry energy, $E_{\mathrm{sym}}/A(\mathrm{pot})$:

$$\frac{E_{\mathrm{sym}}}{A} = \frac{E_{\mathrm{sym}}}{A}(\mathrm{kin}) + \frac{\mathrm{E}_{\mathrm{sym}}}{\mathrm{A}}(\mathrm{pot}) \equiv \frac{\epsilon_{\mathrm{F}}}{3} + \frac{\mathrm{C}(\rho)}{2\rho_0}\rho \tag{1}$$

is tested by employing two different density parametrizations, isovector equation of state (Iso-EOS) of the mean field: (i) $\frac{C(\rho)}{\rho_0} = 482 - 1638\rho$ (MeV fm^3), for "Asysoft" EOS, where $E_{\mathrm{sym}}/A(\mathrm{pot})$ has a weak density dependence close to the saturation, with an almost flat behavior below ρ_0; (ii) a constant coefficient, $C = 32$ MeV, for the "Asystiff" EOS choice, where the interaction part of the symmetry term displays a linear density dependence. As shown in details in Refs. [3,4] these choices represent two classes of widely used effective interactions that still require some confirmation

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from new independent observables. The isoscalar section of the EOS is the same in both cases, corresponding to a compressibility around 220 MeV. In the numerical simulations a test particle approach with 200 Gaussian test particles per nucleon has been employed. In this way we get a good description of the phase-space occupation, essential for the low-energy reaction dynamics. In the collision integral in medium nucleon-nucleon (N-N) cross sections are considered [20]. We perform calculations for three impact parameters ($b = 0$, 2, 4 fm) to cover the region where fusion is mostly observed. To reduce the numerical noise we run 20 events for each set of macroscopic initial conditions and the displayed quantities are the averages over this ensemble.

In Fig. 1 we report some global information concerning the dipole mode in entrance channel.

The time evolution of the dipole moment $D(t)$ for the "132" system at $b = 4$ fm is represented in Fig. 1(a). A similar behavior is seen at $b = 0$, 2 fm. We notice the large amplitude of the first oscillation and the delayed dynamics for the Asystiff EOS related to the weaker isovector restoring force. We can also evaluate the quantity $DK(t) = (\frac{P_p}{Z} - \frac{P_n}{N})$, the canonically conjugate momentum of the $X(t)$ coordinate. The phase-space correlation (spiraling) between $D(t)$ and $DK(t)$ is reported in Fig. 1(c). It nicely points out a collective behavior that initiates very early, with a dipole moment close to the touching configuration value reported above. This can be explained by the fast formation of a well-developed neck mean field that sustains the collective dipole oscillation in spite of the dinuclear configuration with a central zone still at densities below the saturation value.

The role of a large charge asymmetry between the two colliding nuclei can be seen from Figs. 1(b) and 1(d), where we show the analogous dipole phase-space trajectories for the stable ^{124}Sn + ^{58}Ni system at the same value of impact parameter and energy. A clear reduction of the collective behavior is evidenced.

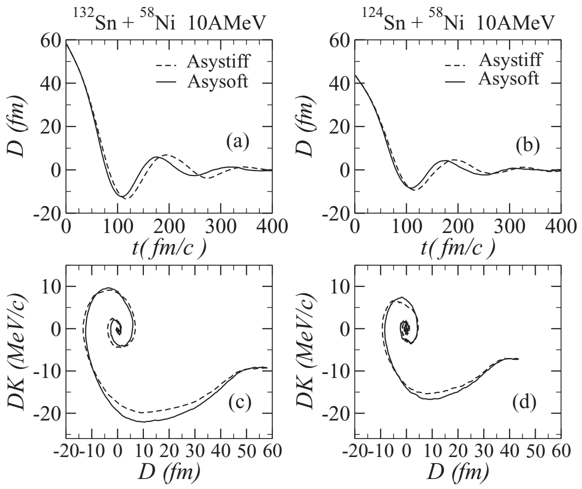

FIG. 1. Dipole dynamics at 10A MeV, $b = 4$ fm centrality. Exotic "132" system: (a) time evolution of dipole moment $D(t)$ in real space; (c) dipole phase-space correlation (see text). Panels (b) and (d): same as before for the stable "124" system. Solid lines correspond to Asysoft EOS and the dashed lines to Asystiff EOS.

To appreciate if these differences can be observed experimentally we estimate the γ yield in a bremsstrahlung approach [19,21]:

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}|D''(\omega)|^2, \qquad (2)$$

where $E_\gamma = \hbar\omega$ is the photon energy and $|D''(\omega)|^2$ is the Fourier transform of the dipole "acceleration" $D''(\omega) = \int_{t_0}^{t_{\max}} D''(t)e^{i\omega t}dt$. For each event t_0 represents the onset time of the collective dipole response (phase-space spiraling) and $t_{\max}$ the "damping time," i.e., the time step corresponding to an almost flat $D(t)$ behavior.

In Refs. [12,14] the precompound dipole radiation yield is evaluated via a stationary oscillatory model for a time-dependent charged source, described in a TDHF approach. We note that the "bremss" procedure used here is more realistic in the general case of nonequilibrium reaction dynamics: in fact, while for stationary conditions, when $|D''(\omega)|^2 = \omega^2|D(\omega)|^2$, we recover the same results, see Ref. [19], in the presence of damping effects the transient nature of such fast collective mode is consistently accounted for [22]. As we will clearly see in the following, the damping dynamics, underestimated in a TDHF scheme, is in fact important for the excitation function of the fast dipole radiation and for the expected angular anisotropy.

In Fig. 2(a) we report the power spectrum, $|D''(\omega)|^2$ in semicentral "132" reactions for the different Iso-EOS choices. The γ multiplicity is simply related to it; see Eq. (2). We clearly observe a lower value of the centroid, as well as a reduced total yield, in the Asystiff case, due to the weaker restoring force for the dynamical dipole in the dilute "neck" region, where the symmetry energy is smaller [3]. Slightly wider distributions are obtained in the Asysoft case, due to the larger neutron evaporation, that damps the collective oscillation. The corresponding results for the stable "124" system are drawn in Fig. 2(b). As expected from the larger initial charge asymmetry, the prompt dipole emission is increased for the exotic n-rich beam.

From Eq. (2) we can get the total, energy- and impact-parameter-integrated, yield for the two systems and the two Iso-EOS. We find 3.0×10^{-3} (2.5×10^{-3}) for ^{124}Sn and 5.7×10^{-3} (4.4×10^{-3}) for ^{132}Sn in the Asysoft (Asystiff) case.

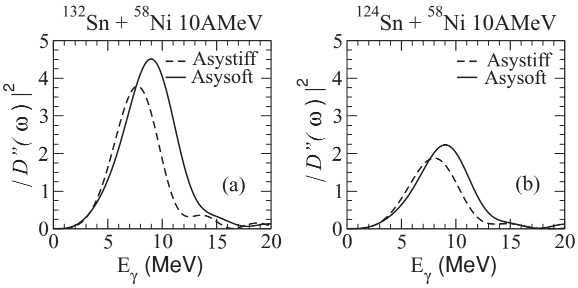

FIG. 2. (a) Exotic "132" system. Power spectra of the dipole acceleration at $b = 4$ fm (in c^2 units). (b) Corresponding results for the stable "124" system. Solid lines correspond to Asysoft EOS and the dashed lines to Asystiff EOS.

A detailed analysis of the sensitivity of the results to the symmetry energy choice can be performed just fitting the dipole oscillations by a simple damped oscillator model, $D(t) = D(t_0)e^{i(\omega_0+i/\tau)t}$, where $D(t_0)$ is the value at the onset of the collective dinuclear response, ω_0 the frequency that depends on the symmetry energy choice, and τ the damping rate, related to two-body N-N collisions and neutron emission. The power spectrum of the dipole acceleration is given by

$$|D''(\omega)|^2 = \frac{\left(\omega_0^2 + 1/\tau^2\right)^2 D(t_0)^2}{(\omega-\omega_0)^2 + 1/\tau^2}, \tag{3}$$

which from Eq. (2) leads to a total yield proportional to $\omega_0\tau(\omega_0^2 + 1/\tau^2)D(t_0)^2 \simeq \omega_0^3\tau D(t_0)^2$ because $\omega_0\tau > 1$. We clearly see the effect of the Iso-EOS on the total yield, through the quantity $\omega_0^3\tau$, that is slightly dependent on the system. Hence, from the above relation, the difference of the yields associated with two different systems, that is the quantity usually exploited in the experimental analysis [17], depends on the Iso-EOS and the sensitivity is amplified when using exotic, more asymmetric beams, due to the factor $D(t_0)^2$, allowing for a clear experimental observation. It is worth mentioning that, according to our fit, we find that that the parameter $D(t_0)$ may be less than the touching point dipole amplitude, especially in the Asystiff case and for the exotic neutron-rich system. A delay in the onset of the collective response is expected and so a more reduced $D(t_0)$ with respect to the initial "geometrical" value; see also the following. In fact, we find that the ratio of the total, impact parameter integrated yields obtained with the two Iso-EOS (Asysoft relative to Asystiff) is larger in the ^{132}Sn case. We obtain 1.2 for the ^{124}Sn reaction and 1.3 in the ^{132}Sn case. This result points to other interesting Iso-EOS studies that can be performed from an accurate measurement of spectrum and yield of the prompt dipole radiation.

Anisotropy. In addition to the total γ spectrum, the corresponding angular distribution can be a sensitive probe to explore the properties of pre-equilibrium dipole mode and the early stages of fusion dynamics. In fact a clear anisotropy vs. the beam axis has been recently observed [23]. For a dipole oscillation just along the beam axis we expect an angular distribution of the emitted photons like $W(\theta) \sim \sin^2\theta \sim 1 + a_2 P_2(\cos\theta)$ with $a_2 = -1$, where θ is the polar angle between the photon direction and the beam axis. Such extreme anisotropy will be never observed because in the collision the prompt dipole axis will rotate during the radiative emission. In fact the deviation from the $\sin^2\theta$ behavior will give a measure of the time interval of the fast dipole emission. Just for comparison with statistical compound nucleus GDR radiation we remind that in the case of a prolate nucleus with a collective rotation, for the low-energy component we can have an anisotropy parameter $a_2 = -1/4$, averaging over all possible rotation angles and all possible orientations of the collective angular momentum (orthogonal to the beam axis) [24]. Orientation fluctuations can even reduce such anisotropy [25].

These results cannot be translated directly to the case of the dynamical dipole. As we see from our calculations (Fig. 1) the pre-equilibrium oscillations extend over the first 250–300 fm/c. During this time interval, depending also on the centrality and energy, the deformed nucleus may not complete a full rotation on the reaction plane. Let us denote by ϕ_i and ϕ_f the initial and final angles of the symmetry axis (which is also oscillation axis) with respect to the beam axis, associated respectively to excitation and complete damping of the dipole mode. Then $\Delta\phi = \phi_f - \phi_i$ is the rotation angle during the collective oscillations. We can get the angular distribution in this case by averaging only over the angle $\Delta\phi$ obtaining

$$W(\theta) \sim 1 - \left(\tfrac{1}{4} + \tfrac{3}{4}x\right)P_2(\cos\theta) \tag{4}$$

where $x = \cos(\phi_f + \phi_i)\frac{\sin(\phi_f-\phi_i)}{\phi_f-\phi_i}$.

It is easy to see that for $\Delta\phi = 0$ and $\Delta\phi = 2\pi$ we recover the two cases discussed above. Moreover, if $\phi_f = \phi_i = \phi_0$ (i.e., the orientation is frozen at an angle ϕ_0 with respect to the beam axis), Eq. (4) gives an $a_2 = -(1 - \frac{3}{2}\sin^2\phi_0)$, with a change of sign for $\phi_0 \geqslant 55^\circ$, i.e., a decrease of $W(\theta)$ around $\theta \approx \pi/2$. The point is that meanwhile the emission is damped.

Within the bremsstrahlung approach we can perform an accurate evaluation of the prompt dipole angular distribution using a weighted form where the time variation of the radiation emission probability is accounted for

$$W(\theta) = \sum_{i=1}^{t_{\max}} \beta_i W(\theta, \Phi_i). \tag{5}$$

We divide the dipole emission time in Δt_i intervals with the corresponding Φ_i mean rotation angles and the related radiation emission probabilities $\beta_i = P(t_i) - P(t_{i-1})$, where $P(t) = \int_{t_0}^{t} |D''(t)|^2 dt / P_{\text{tot}}$ with P_{tot} given by $P(t_{\max})$, total emission probability at the final dynamical dipole damped time.

In Fig. 3(a) panel, we plot the time dependence of the rotation angle, for the "132" system, extracted from dynamical

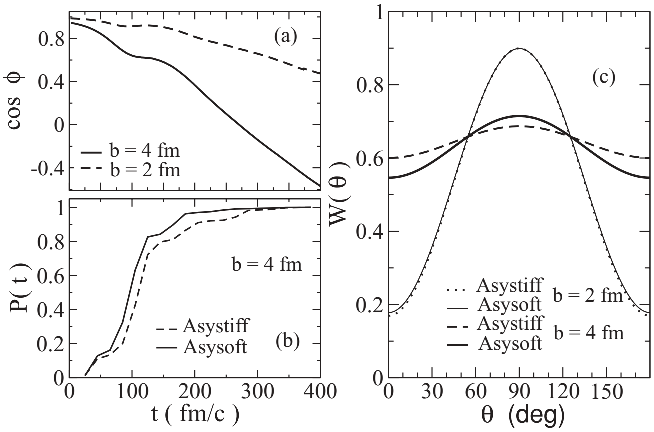

FIG. 3. "132" system. (a) Time dependence of the rotation angle at $b = 2$ fm (dashed line) and $b = 4$ fm (solid line). (b) Time evolution of the emission probability $P(t)$, see text, for $b = 4$ fm impact parameter. (c) Weighted angular distributions for $b = 2$ fm and $b = 4$ fm centralities for different symmetry term choices. Dashed lines for the Asystiff choice and solid lines for Asysoft. The Iso-EOS effects on the rotation angle are negligible.

simulations at $b = 2$ fm and $b = 4$ fm. We note that essentially the same curves are obtained with the two Iso-EOS choices: the overall rotation is mostly ruled by the dominant isoscalar interactions. Symmetry energy effects will be induced by the different time evolution of emission probabilities.

This is shown in Fig. 3(b) for the "132" system at the $b = 4$ fm impact parameter. We clearly see that the dominant emission region is the initial one, between 50 and 150 fm/c, while the dinuclear system rotates of about 20°, roughly from 40° to 60°. Another interesting point is the dependence on the symmetry energy. With a weaker symmetry term (Asystiff case) the $P(t)$ is a little delayed and presents a smoother behavior. As a consequence we can expect possible symmetry energy effects even on the angular distributions.

This is shown in Fig. 3(c), where we have the weighted distributions, Eq. (5), for $b = 2$ fm and $b = 4$ fm impact parameters, with the two choices of the symmetry energies below saturation. For more central collisions, due to the small rotation of the oscillation axis, the delay effect in the asystiff case does not affect the angular distribution. For more peripheral reactions we see a larger contribution at forward/backward angles, although the bump around $\pi/2$ is still present due to the decreasing emission probability at later times when the larger rotations contribute. Altogether we get wider "dipole" angular distributions with respect to the beam axis, in agreement with the first available data [23]. Moreover, as evidenced by the results at $b = 4$ fm, we expect to see a sensitivity to the slope of the symmetry term below saturation in presence of larger rotation velocities, i.e., in fusion events with high spin selection.

Summarizing, we have shown, within a mean-field transport approach, that in fusion with exotic nuclei an enhanced pre-equilibrium dipole emission can be observed with a peculiar angular distribution related to its early emission. The features of this collective mode are sensitive to the density dependence of symmetry energy below saturation. The larger emission with the exotic beam will enhance the observation of Iso-EOS effects.

The angular distributions are also sensitive to the fusion dynamics and dipole excitation mechanism and lifetime. The results presented here can be important to plan new experiments.

In conclusion, the dynamical dipole mode appears to be a suitable probe to test the symmetry energy term in the nuclear EOS as well as to scrutinize the early entrance channel dynamics in dissipative reactions with radioactive beams.

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