Quantum Calculation of the Dipole Excitation in Fusion Reactions

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The excitation of the giant dipole resonance induced by fusion reaction is studied with N/Z asymmetry in the entrance channel. The time dependent Hartree-Fock solution exhibits a strong dipole vibration which can be associated with a giant vibration along the main axis of the deformed compound nucleus. This dipole motion appears to be nonlinearly coupled to the shape oscillation, leading to a strong modulation of its frequency. These phenomena can be detected in the gamma-ray emission from hot compound nuclei.

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Ordered collective motions are a general property of mesoscopic systems. In metallic clusters, electron vibrations are plasmon excitations. In atomic nuclei, oscillations of protons against neutrons generate giant dipole resonances [1,2]. The general way to excite such modes is to use rapidly varying electromagnetic fields associated with photons or generated by fast electrically charged particles. The collective vibrations can also be thermally excited, as clearly demonstrated in the studies of the γ emission from hot nuclei [3–6]. It has been recently proposed that fusion reactions with N/Z asymmetric nuclei may lead to the excitation of a dipole mode because of the presence of a net dipole moment in the entrance channel [7–9]. The first experimental indications of the possible existence of such new phenomena have been reported in [10] for fusion reactions and in [11] for deep inelastic collisions. However, the real nature of such a vibration is still unclear both from the experimental and the theoretical point of view. In particular, only semiclassical approaches or schematic models have been used to infer the properties of the generated dipole mode.

In this Letter, we present the first quantum calculation of preequilibrium giant collective vibrations using the time dependent Hartree-Fock (TDHF) approach [12–15,16]. TDHF corresponds to an independent propagation of each single particle wave function in the mean field generated by the ensemble of particles. It does not incorporate the dissipation due to two-body interaction [17–19], but takes into account one-body mechanisms such as Landau spreading and evaporation damping [20]. The quantal nature of the single particle dynamics is explicitly preserved, which is crucial at low energy both because of shell effects and of the wave dynamics. Moreover, TDHF is a strongly nonlinear theory. Hence it can exhibit new couplings between collective modes.

In the time dependent Hartree-Fock approach, the evolution of the single particle density matrix $\rho(t) = \sum_{n=1}^{N} |\varphi_n\rangle\langle\varphi_n|$ is determined by a Liouville equation,

$$i\hbar \frac{\partial}{\partial t} \rho - [h(\rho), \rho] = 0\,, \tag{1}$$

where $h(\rho)$ is the mean-field Hamiltonian. We have used the code built by Bonche and co-workers with an effective Skyrme mean field and SLy_4 parameters [21].

The effect of the isospin asymmetry in the entrance channel has been first studied in the ^{20}O + ^{20}Mg fusion reactions at energies close to the Coulomb barrier. Strong quantum effects are expected in these mirror-nuclei reactions leading to the $N = Z$ ^{40}Ca compound system. The density plots obtained in the central collisions at a kinetic energy of 1 MeV per nucleon in the center of mass frame is presented in Fig. 1. The system fuses and shows quadrupole oscillation around a slowly damped prolate deformation. Since ^{20}O and ^{20}Mg have significantly different N over Z ratios (respectively, 1.5 and 0.67), the protons and neutrons centers of mass do not coincide at the initial stage of the collision, in contrast to what is obtained in the fusion of two nuclei with the same N over Z ratio.

Let us first start with head-on-head collisions along the x axis. Adequate observables to study the collective motion induced in this mechanism are the dipole moment Q_d and its conjugated quantity P_d. Q_d is the net distance between protons and neutrons: $Q_d = \frac{NZ}{A}(X_p - X_n)$, where X_p and X_n are the proton and neutron's centers of mass coordinates. Similarly, $P_d = \frac{A}{2NZ}(P_p - P_n)$ where $P_p = \sum_p p_p$ and $P_n = \sum_n p_n$ are the moments of protons and neutrons. In Fig. 2 is plotted Q_d as a function of P_d. As time goes on, we observe a spiral in the collective phase space which signals the presence of a damped collective vibration. Indeed, it originates from oscillations in phase quadrature of the two conjugated dipole variables.

In order to associate the observed vibration with the giant dipole resonance (GDR) in the composite nucleus we must study the collective vibration of a ^{40}Ca nucleus.

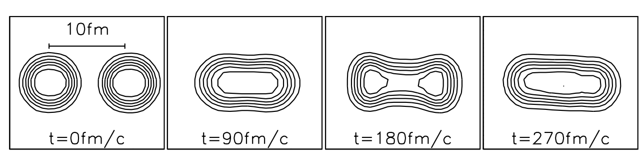

FIG. 1. Density plots, projected on the reaction plane, for the central collision reaction ^{20}O + ^{20}Mg at 1 MeV/u. Lines corresponds to equidistant values of the density.

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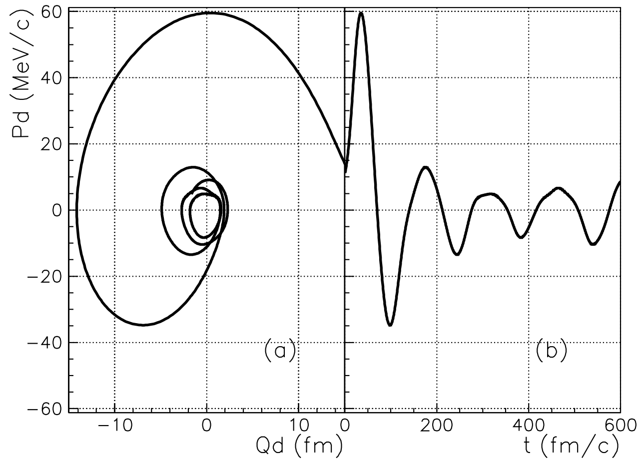

FIG. 2. Time evolution of the dipole vibration. Dipole moment Qd and its conjugate Pd are plotted in the phase space (a) and Pd is plotted in function of time (b).

The GDR associated to the dipole oscillation of a ^{40}Ca ground state has been excited by an isovector dipole field and followed using the TDHF approach. The resulting Q_d moment is plotted as a function of time in Fig. 3c. The period of the observed oscillations is around 80 fm$/c$ which corresponds to an energy $E = 15.5$ MeV in good agreement with Skyrme RPA calculations [19] and close to the experimental value $E \sim 20$ MeV [22]. For the ^{40}Ca formed by fusion (Fig. 3a) it is around 150 fm$/c$. This large difference is due to the deformation of the fused system. Indeed, as we can see in Fig. 1, the compound nucleus relaxes its initial prolate elongation along the axis of the collision with a typical time much larger than the dipole oscillation's period. During the considered time window, the averaged value of the observed quadrupole deformation parameter defined by $\epsilon = \frac{\langle Q_{20}\rangle}{2\sqrt{5}\langle Q_{00}\rangle}$ is around $\epsilon = 0.23$.

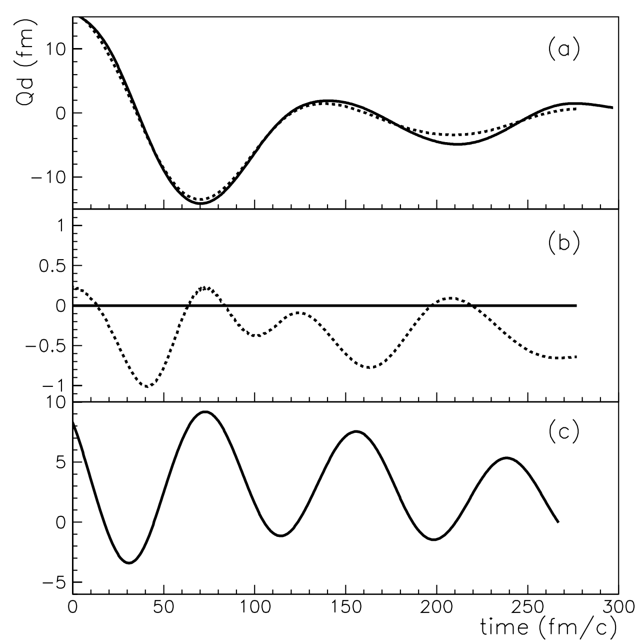

FIG. 3. Time evolution of the component of the dipole moment parallel to the deformation axis (a) and the component perpendicular in the collision plane (b) for the reaction ^{20}O + ^{20}Mg with the impact parameter $b = 0$ fm (solid line) and $b = 4$ fm (dashed line). (c) GDR in the ^{40}Ca with a spherical shape.

A lower mean energy is expected for this longitudinal collective motion E_{GDR_x} as compared to the one simulated in a spherical ^{40}Ca. Following a macroscopic model for the dipole oscillation we expect the energy of the GDR to evolve with the deformation as

$$E_{\mathrm{GDR}_x} = E_{\mathrm{GDR}}(1 - \epsilon)^2. \tag{2}$$

The frequency of the GDR along the elongation axis fulfills this relation with $\epsilon \approx 0.26$ in good agreement with the observed average deformation.

The dominant role of the deformation in the lowering of the GDR energy can be easily reproduced by performing a Hartree-Fock calculation of a ^{40}Ca nucleus in an external quadrupole field. This external field is kept during all the dynamical evolution so that the deformation does not relax. At time 0 a dipole oscillation is induced by a dipole boost. The resulting dipole oscillations have a lower oscillation period. Using the deformation parameter $\epsilon = 0.23$ we find that this period is close to the one observed in the fusion case and agrees with the phenomenological relation (2).

To get a deeper insight into the dipole oscillation observed in fusion reactions we have analyzed the time evolution of its period. From each point on the collective trajectory this quantity can be inferred from the time needed to reach the opposite side of the observed spiral. The resulting evolution is plotted in Fig. 4a. This period shows oscillations too. On the other hand, we calculated the monopole moment Q_{00} and the quadrupole moment Q_{20} which are presented in Fig. 4b. We can see that those observables oscillations are almost in phase with those in Fig. 4a. This points toward a possible coupling between the dipole mode and another mode of vibration. The evolutions of the monopole and quadrupole moments are very similar. In particular, they have the same oscillation's period around 166 fm$/c$. Therefore, we conclude that they originate from the same phenomenon, the vibration of the density around a prolate shape. This oscillation modifies the properties of the dipole mode in a time dependent way.

In order to investigate if this density vibration is the origin of the observed behavior of the dipole period we can model the induced mode coupling. We consider a harmonic oscillator with a spring constant which varies in time at a frequency ω. This is a simple way to take into account the fact that oscillations of the density, which enter in the mean-field potential of the TDHF equation, modify the dipole restoring force. This is a way to take into account the nonlinear behavior of mean-field dynamic.

It is easy to understand that a lower density as well as an elongated shape induce a weaker restoring force. Thus, variations of the density profiles in the TDHF equation can

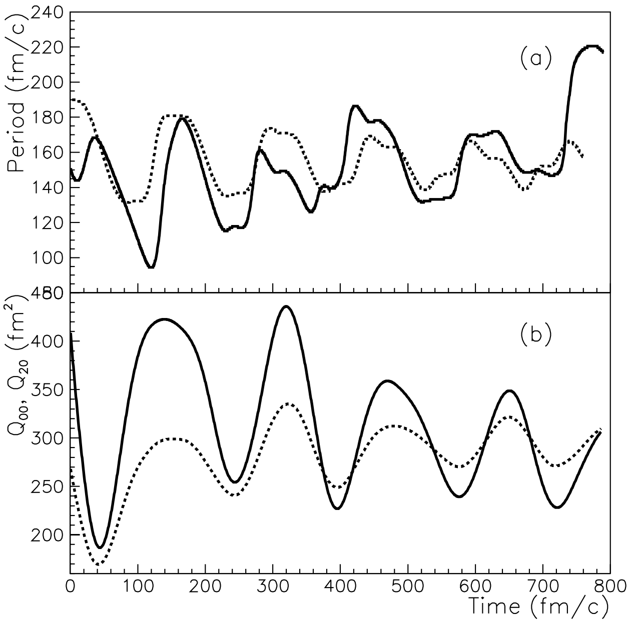

FIG. 4. (a) Time behavior of the dipole period (solid line) and its modelization with the Mathieu's equation (dashed line). (b) Time evolution of the monopole (dashed line) and quadrupole moments (solid line).

be modeled by a corresponding variation of the constant of rigidity in a spring Hamiltonian. In such a model, the equation of motion becomes the Mathieu's equation

$$\frac{\ddot{x}}{\omega_0^2} + \left[1 + \beta\left(\frac{\omega^2}{\omega_0^2} + 2\frac{\omega}{\omega_0}\right)\cos(\omega t)\right]x = 0, \qquad (3)$$

where ω_0 is the pulsation without coupling and ω the pulsation of the density's oscillation while β corresponds to the magnitude of the induced frequency fluctuations. We have computed the numeric solution of Eq. (3) with the typical external frequency of the monopole and quadrupole oscillations. The bare frequency ω_0 and the coupling strength β have been tuned in order to get the same dipole oscillation frequency and typical strength as in the full TDHF calculations. Indeed, because of the presence of the oscillating term, the observed frequency is different from the bare one. The numerical solution of the Mathieu equation shows oscillations with an oscillating period which well reproduces our self-consistent calculations with $\beta = 0.15$ and ω_0 changed by a factor 1.2 from the observed value E_{GDR_x} (see Fig. 4a). From this analysis it appears that the observed dipole motion corresponds to a giant vibration along the main axis of an oscillating prolate shape. The observed modulation of the dipole frequency is a source of additional spreading of the resonance line shape.

Using a coherent state picture the maximal elongation $d_{\max} = \frac{A}{NZ} Q_{d_{\max}} \approx 1.4$ fm is related to the number of excited phonons by the expression

$$n_0 = d_{\max}^2 \frac{M E_{\mathrm{GDR}_x}}{2\hbar^2}, \qquad (4)$$

where $E_{\mathrm{GDR}_x} \approx 8$ MeV is the energy of the GDR along the (x) axis and $M = \frac{NZ}{A} m$ is the reduced mass of the neutron-proton system, m being the nucleon mass. It gives $n_0 \approx 1.9$. Obviously this value is an upper limit because the mean-field dynamics underestimate the consequences of the damping since two-body dissipation is not taken into account. In the same way as Ref. [7,10,23,24], we can compute the γ -decay probability P_γ over $\overline{P_\gamma}$, its mean value in the equilibrium with the expression

$$\frac{P_\gamma}{\overline{P_\gamma}} = \frac{\Gamma^\downarrow + \frac{n_0}{\overline{n_{\mathrm{GDR}}}}\Gamma_{\mathrm{evap}}}{\Gamma^\downarrow} + \Gamma_{\mathrm{evap}}, \qquad (5)$$

where Γ_{evap} is the rate at which the compound system decay (see Ref. [23]) $\Gamma^\downarrow$ is the decaying rate of the phonons and $\overline{n_{\mathrm{GDR}}}$ is the mean number of excited phonons in the equilibrium. The latter can be estimated by $\overline{n_{\mathrm{GDR}}} = 3e^{\frac{-E_{\mathrm{GDR}}}{T}}$ where T is the compound nucleus temperature. For ^{40}Ca at an excitation energy around 96 MeV, we take $\Gamma_{\mathrm{evap}} \approx 0.76$ MeV, $\Gamma^\downarrow \approx 7$ MeV, and $\overline{n_{\mathrm{GDR}}} \approx 0.6$. It gives $\frac{P_\gamma}{\overline{P_\gamma}} \approx 1.2$ which shows that the preequilibrium effects are only a correction for this system since the value for an entrance channel quenching ($n_0 = 0$) of the GDR using the isospin symmetric reaction ^{20}Ne + ^{20}Ne would lead to $\frac{P_\gamma}{\overline{P_\gamma}} \approx 0.9$. It means the first chance gamma emission will be slightly enhanced by about a factor 20%. This is in good agreement with the values reported in the literature [10].

In order to compute the properties of the preequilibrium GDR in fusion we shall also study nonzero impact parameters. In particular, the interplay of dipole vibration and deformation can be affected by the rotation. In addition to the center of mass coordinate system with x along the beam axis and y perpendicular to the reaction plane we defined a new coordinate system x', y', z', where x' is the deformation axis and $y = y'$ is the rotation axis. For the head on head reaction studied before, those two frames are the same. In this case, for symmetry reasons the dipole moments along the $z' = z$ and y axis are zero at every time.

If we consider now a finite b, the symmetry forbids the vibration to occur only along y. In this case, the amplitude of the oscillations along x' slightly decreases with the impact parameter (Fig. 3a, dashed line) whereas an oscillation along z' appears (Fig. 3b, dashed line). First we can see that the period of the dipole oscillation perpendicular to the deformation axis is lower than one along the deformation axis. It is another consequence for the prolate deformation of the nucleus indeed the energy of this excitation along z' should obey the relation $E_{\mathrm{GDR}_{z'}} = E_{\mathrm{GDR}}(1 + \epsilon)$. This relation gives a value of the oscillation's period of 67 fm/c which is the observed one on (Fig. 3b). The oscillation along z' shows a lower amplitude than this along x' (approximatively 1% in relative intensity). This oscillation along the z' axis results from a weak symmetry breaking due to the rotation of the system. Indeed, the changing to the rotating frame $x', y = y', z'$ leads to the Hamiltonian with a nondiagonal term

$$H' = R(t)HR^{-1}(t) + \dot{\alpha}J_y, \quad (6)$$

where H' is the Hamiltonian in the rotating frame, $\dot{\alpha}$ is the time derivative of the angle between the two frames, and J_y is the generator of the rotations around y. The last term induces a motion along the z' axis from a dipole vibration along x'. This is indeed what is happening since initially the dipole mode is along the x' axis.

If we now compute the number of excited phonons we see almost no variation of the total phonon number n_0 with b. Therefore the conclusions reached for $b = 0$ can be extended to the full range of impact parameters b.

Let us now study the role of the incident energy. The lack of two-body damping in TDHF does not enable us to go up in energy with this system. So we investigate a lower energy 0.5 MeV per nucleon which is the Coulomb barrier. In this case, the number of exciting phonons is 1.0. This value is lower than one obtained at 1 MeV/u because the maximum dipole moment decreases with decreasing energy. Therefore the number of preequilibrium phonons is lower at lower energy.

We have also investigated the role of the mass of the reactions partners to study if the preequilibrium effects survive in heavier compound systems. We have computed the ^{40}Ar + ^{40}Ti at 1 MeV per nucleon in the center of mass system (slightly above the fusion barrier). We have observed exactly the same phenomenology with a strong excitation of preequilibrium GDR. The calculated $n_0 = 0.6$ is smaller than the n_0 obtained for lighter nuclei reaction. This comes from the fact that the reaction with small nuclei is less damped than the one involving more nucleons. However, the preequilibrium GDR is also strong in the heavier fusion reaction.

In summary, preequilibrium effects related to the N/Z asymmetry in the entrance channel have been for the first time investigated using the TDHF approach. The relation between the mean oscillation's period and the shape of the nucleus has been established. Because of the deformation the average dipole frequency along the deformation axis is lower than the usual GDR one, while we observe a weak vibration at higher frequency in the perpendicular direction in the collision plane. In this direction, the oscillation occurs only for a nonzero impact parameter. The evolution of the period has been modeled by a Mathieu's spring model so that the link between the observed phenomena and the giant dipole resonance has been established. The frequency modulation due to this nonlinear coupling between modes plays the role of an additional spreading of the GDR frequency. The results show that preequilibrium gamma emission is expected in the case of fusion reaction with asymmetric N/Z nuclei.

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