RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 59, NUMBER 5 MAY 1999

Time scales of multiple giant dipole resonance excitation and decay

B. V. Carlson[1] and M. S. Hussein[2]

[1]Departamento de Física, Instituto Tecnológico de Aeronáutica—CTA, 12228-900 São José dos Campos, São Paulo, Brazil

[2]Instituto de Física, Universidade de São Paulo, C.P. 66318, São Paulo, 05315-970, Brazil

(Received 4 February 1999)

The effect of particle emission of the intermediate giant dipole resonance on the excitation of the double giant dipole resonance in heavy ion reactions is calculated. General assessment of the time scales involved in such excitation and subsequent decay is given. Both the direct as well as the nondirect, Brink-Axel, paths are considered. [S0556-2813(99)50405-6]

PACS number(s): 25.70.De, 24.30.Cz, 21.10.Re

We have recently suggested [1–6] that a sizable contribution to the double giant dipole resonance (DGDR) cross section can arise from the fluctuating, complex background states occupied due to the damping of the single giant dipole resonance (GDR). This will occur when the collision time is sufficiently long to permit the excitation of a Brink-Axel [7] single giant dipole resonance on top of the complex background. Accordingly, the cross section in the DGDR region is composed of the usual coherent component, possessing a Breit-Wigner energy profile peaked at $E_{\rm DGDR}$ with a width $\Gamma_{\rm DGDR}=2\Gamma_{\rm GDR}$, and a fluctuating Brink-Axel component, which also peaks at $E_{\rm DGDR}$ but has a width of $\Gamma_{B-A}\approx\Gamma_{\rm GDR}$. The integrated cross section is predicted to be enhanced with respect to the harmonic value [8], $\sigma^H_{\rm DGDR}$, by

$$e\equiv\frac{\sigma_{\rm DGDR}}{\sigma^H_{\rm DGDR}}=\left[1+\frac{1}{2}\frac{\Gamma^{\downarrow}_{\rm GDR}}{\Gamma_{\rm GDR}}f(E)\right], \tag{1}$$

where the function $f(E)$ is large at low energies E and gradually drops to zero as the energy increases. Since $\Gamma^{\downarrow}_{\rm GDR}/\Gamma_{\rm GDR}\approx 1$ for heavy nuclei, such as ^{208}Pb, we predict that the enhancement e for such nuclei can attain large values at low bombarding energies, in agreement with experimental findings.

The purpose of this Rapid Communication is to give estimates of the time scales and relative importance of the various processes involved in the excitation and decay of the DGDR. We begin with the most basic of these.

The excitation of a second GDR after the decay of a first will be possible only if the decay occurs before the collision has ended. We can thus obtain an estimate of the relevance of the Brink-Axel excitation mechanism by comparing the Coulomb collision time to the giant dipole resonance decay time. The decay time can be estimated as $\tau_d=\hbar/\Gamma^{\downarrow}_d$, where $\Gamma^{\downarrow}_d$ is the giant resonance spreading width. For ^{208}Pb, we approximate this by the total GDR width of $\Gamma_d\approx 4$ MeV, which yields $\tau_d\approx 16\times 10^{-23}$ s. We estimate the collision time using the schematic time dependence of the Coulomb interaction of Ref. [8],

$$V(t)=\frac{V_0}{1+(\gamma v t/b)^2}, \tag{2}$$

which furnishes a collision time of the order of $\tau_c\approx b/\gamma v$.

In Fig. 1, we compare the decay and collision times for the case of ^{208}Pb+^{208}Pb, as a function of the incident energy per nucleon, using a value of 15 fm for the impact parameter b. We see that at about 150 MeV per nucleon, the collision time is equal to the decay time. At this energy, excitation of the DGDR is enhanced by about 50% due to the hot GDR excitation. At lower energies, the enhancement is even larger. As the collision time decreases slowly with the incident energy, it remains important over a fairly wide energy range, falling to 10% at about 800 MeV per nucleon.

As the hot GDR excitation mechanism proposed in Refs. [1–6] does not depend on the peculiarities of the excited nucleus, we expect it to be common to all elements in the periodic table. We can then ask how the energy range in which it is important varies with the mass of the projectile being excited. To estimate this, we compare the collision and GDR decay times and calculate the value of the projectile energy for which the two are equal. As we have noted above, the DGDR enhancement for the case of ^{208}Pb is about 50% when the decay time and collision time are equal.

To obtain a general estimate, we use a global systematic for the GDR energy and total width, $\varepsilon_d=43.4A^{-0.215}$ MeV and $\Gamma_d=0.3\varepsilon_d$ [9], to approximate the decay time as $\tau_d=\hbar/\Gamma_d$. We assume a projectile of mass A_p incident on ^{208}Pb, to estimate the collision time as

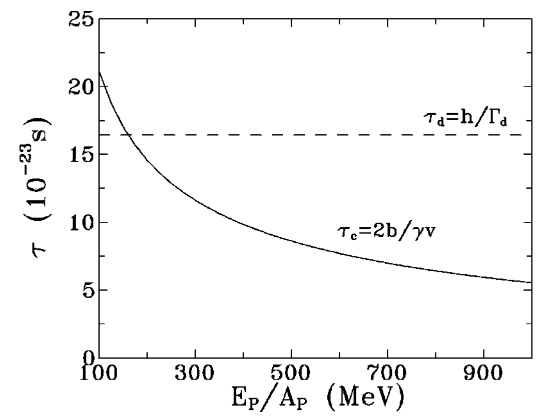

FIG. 1. Collision time τ_c (solid line) and GDR decay time τ_d (dashed line) for the system ^{208}Pb+^{208}Pb at an impact parameter of $b=15$ fm as a function of the projectile energy per nucleon.

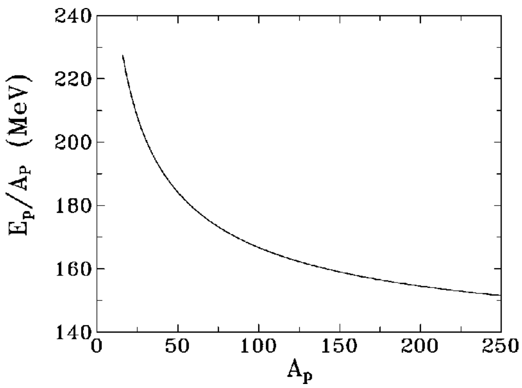

FIG. 2. Energy per nucleon at which the collision time and giant dipole resonance decay time of a projectile in a collision with ^{208}Pb are approximately equal, as a function of the mass number of the projectile.

$$\tau_c = \frac{b}{\gamma v} \approx \frac{r_0(A_p^{1/3}+208^{1/3})}{\gamma v}, \quad r_0 = 1.23 \text{ fm}.$$

Equating the two expressions yields the curve of Fig. 2. From the figure, we conclude that the energy range in which the fluctuation contribution to the DGDR excitation is important grows slightly larger as the projectile mass decreases but remains of the same order of magnitude throughout the mass table.

However, collective excitation of GDR phonons and their decay to a statistical background of excited states are not the only processes that occur in these collisions. As is well known, an excited nucleus eventually decays by emitting particles and/or photons. Such an emission can occur directly from the the GDR or, more commonly, from the equilibrated background of statistical states. Particle emission affects the distribution of occupations and may modify the relative contributions of the coherent and fluctuating excitation processes. We thus wish to estimate the relative importance of these emission processes. We first estimate the contribution of direct emission from the GDR. We then estimate the contribution of emission from the background of statistical states.

To estimate the escape width $\Gamma_d^{\uparrow}$ of the giant dipole resonance, we model the resonance as a one-particle, one-hole state and assume that its decay occurs by pre-equilibrium nucleon emission. Expressions for differential pre-equilibrium emission rates, based on detailed balance considerations, were deduced long ago [10,11]. For the case of nucleon emission, the expression for the differential emission width takes the form

$$\frac{d\Gamma_{d\nu}^{\uparrow}}{d\epsilon_\nu}(E,\epsilon_\nu) = \frac{2}{\pi^2\hbar^2}\mu_\nu\epsilon_\nu\sigma_\nu(\epsilon_\nu)\left(\frac{Z}{A}\right)^{z_\nu} \times\left(1-\frac{Z}{A}\right)^{1-z_\nu}\frac{\omega(p=0,h=1,E-S_\nu-\epsilon_\nu)}{\omega(p=1,h=1,E)}, \tag{3}$$

where z_ν and ϵ_ν are the charge and energy of the emitted nucleon, while A, Z, and E are the mass number, charge, and energy of the emitting nucleus. The factor $\sigma_\nu(\epsilon_\nu)$ is the cross section for absorption of nucleons of type ν by the nucleus $(Z-z_\nu, A-1)$, which we estimate in terms of the geometrical cross section and the Coulomb barrier as

$$\sigma_\nu(\epsilon_\nu) \approx \pi R^2\left(1-\frac{V_{c\nu}}{\epsilon_\nu}\right)\theta(\epsilon_\nu - V_{c\nu}), \tag{4}$$

where θ is the Heaviside step function.

The last factor in the expression for the differential escape width is the ratio of the final to initial state densities. We estimate these using the Williams densities [12],

$$\omega(p=0,h=1,E-S_\nu-\epsilon_\nu) = g\,\theta(E-S_\nu-\epsilon_\nu),$$

$$\omega(p=1,h=1,E) = g^2 E\,\theta(E), \tag{5}$$

where g is the single-particle density of states at the Fermi energy, which can be related to the usual level density parameter a as $g = 6a/\pi^2$.

Substituting, and neglecting the A dependence of the reduced mass, we can rewrite the differential emission width as

$$\frac{d\Gamma_{d\nu}^{\uparrow}}{d\epsilon_\nu}(E,\epsilon_\nu) = \frac{1}{3\hbar^2}m_N\pi R^2\left(\frac{Z}{A}\right)^{z_\nu}\left(1-\frac{Z}{A}\right)^{1-z_\nu}\frac{(\epsilon_\nu - V_{c\nu})}{aE} \times\theta(\epsilon_\nu - V_{c\nu})\,\theta(E-S_\nu-\epsilon_\nu), \tag{6}$$

which we may integrate immediately, to obtain

$$\Gamma_{d\nu}^{\uparrow}(E) = \frac{1}{6\hbar^2}m_N\pi R^2\left(\frac{Z}{A}\right)^{z_\nu}\left(1-\frac{Z}{A}\right)^{1-z_\nu}\frac{(E-S_\nu-V_{c\nu})^2}{aE}. \tag{7}$$

We approximate the giant resonance escape width as the sum of the contributions of neutron and proton emission,

$$\Gamma_d^{\uparrow} \approx \frac{1}{6\hbar^2}m_N\pi R^2\frac{1}{aE_d}\left[\left(\frac{Z}{A}\right)(E_d-S_p-V_c)^2\theta(E_d-S_p-V_c) +\left(1-\frac{Z}{A}\right)(E_d-S_n)^2\right], \tag{8}$$

where we have evaluated the energy of the emitting nucleus at the resonance energy.

We have evaluated the expression for the escape width $\Gamma_d^{\uparrow}$ along the stability valley of the mass table, using values for the separation energies taken from liquid drop systematics, the GDR resonance parameter systematics of Ref. [9] and the Coulomb barrier parametrization of Ref. [13],

$$V_c = \frac{1.44 Z_p Z_t}{1.07(A_p^{1/3}+A_t^{1/3})+2.72} \quad \text{MeV}.$$

Our results are shown in Fig. 3, in which we plot the ratio of the escape width to the total width $\Gamma_d^{\uparrow}/\Gamma_d$ as a function of the mass number. This ratio is just the branching ratio for direct particle emission from the GDR. We see from the figure that, for low values of the mass, the branching ratio drops rapidly as the mass increases. For values of the mass above $A=50$, the branching ratio is below 3%, where it remains for all higher values of the mass.

The GDR can also decay through direct or semidirect photon emission. The branching ratios for these processes,

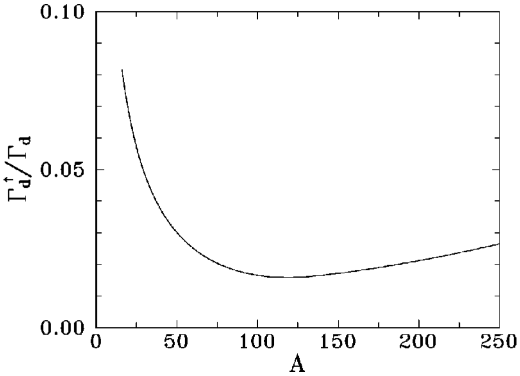

FIG. 3. Ratio of the direct escape width to the total giant dipole resonance width as a function of the mass number of the nucleus.

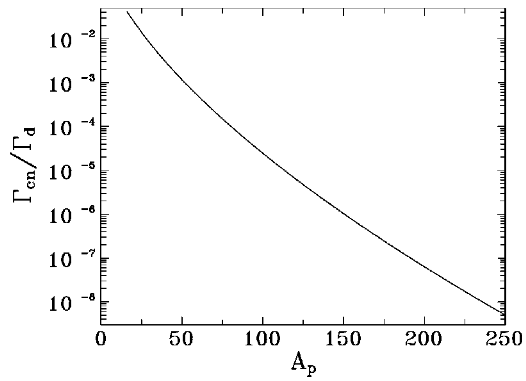

FIG. 4. Ratio of the compound nucleus escape width to the total giant dipole resonance width as a function of the mass number of the nucleus.

however, are much smaller than that of direct particle emission. We can thus conclude that the total branching ratio for escape is never more than a few percent of the total, except in the case of extremely light nuclei, and that it has little effect on the relative contributions of the DGDR and the hot GDR to two phonon excitations of the nucleus.

The decay of the statistical background states may also have an effect on our estimate of the importance of the hot GDR, by allowing the states on which it is to be excited to decay before the excitation occurs. To evaluate the importance of this process, we estimate the compound nucleus decay width using a phenomenological expression,

$$\Gamma_{cn}(E)\approx 14\exp(-4.69\sqrt{A/E})\quad \text{MeV}. \tag{9}$$

In principal, we should compare the compound nucleus decay time $\tau_{cn}=\hbar/\Gamma_{cn}$ with the collision time τ_c in order to evaluate the importance of the decay process relative to the characteristic time available for the collective excitation. However, as the collision time is energy dependent and as we have seen that it is of about the same order of magnitude as the GDR decay time $\tau_d=\hbar/\Gamma_d$, we will instead compare the compound nucleus decay time to the GDR decay time by comparing the corresponding widths. We do this in Fig. 4, in which we plot the ratio $\Gamma_{cn}(E_d)/\Gamma_d$ as a function of the mass number. We observe that the value of the compound decay width is on the order of a few percent of that of the GDR width, for the lightest nuclei shown ($A\approx 16$), and that it decreases exponentially for larger values of the mass, reaching a value of about 10^{-7} of the GDR width in the case of ^{208}Pb. We thus conclude that this decay process also has little effect on our estimate of hot GDR excitation.

In summary, we have evaluated the characteristic time scales of the processes which contribute to giant dipole resonance excitation and decay. We have found that both coherent and fluctuating contributions to the multiple phonon cross sections can be important. The latter arise through the Brink-Axel mechanism, in which a GDR resonance is excited on the statistical background of excited states populated through the decay of a previous GDR phonon. We have found that photon and particle emission make corrections to these processes on the order of only a few percent, except in the case of very light nuclei. With the exception of these cases, particle emission can thus normally be neglected in the development of the GDR excitation and decay process. This does not say that the excited nucleus does not decay by photon and/or particle emission, for this it does. However, this decay usually occurs long after the GDR has been excited and then decayed to the statistical background states.

This work was supported in part by FAPESP and by the CNPq.

[1] B. V. Carlson, M. S. Hussein, and A. F. R. de Toledo Piza, Phys. Lett. B **431**, 249 (1998).

[2] B. V. Carlson, L. F. Canto, S. Cruz-Barrios, M. S. Hussein, and A. F. R. de Toledo Piza, Ann. Phys. (N.Y.) (in press).

[3] L. F. Canto, B. V. Carlson, S. Cruz-Barrios, M. S. Hussein, and A. F. R. de Toledo Piza, Fluctuation Contributions to Double Giant Dipole Resonance Excitation Cross Sections, Proceedings of the XX Brazilian Nuclear Physics Workshop, Guaratinguata, Brazil, 1997 (World Scientific, Singapore, in press).

[4] B. V. Carlson, M. S. Hussein, and A. F. R. de Toledo Piza, ''Semiclassical description of multiple giant dipole resonance excitation and decay'' (submitted).

[5] L. F. Canto, B. V. Carlson, S. Cruz-Barrios, M. S. Hussein, and A. F. R. de Toledo Piza, Semiclassical Coulomb Excitation of a Damped Oscillator and the Brink-Axel Mechanism, Proceedings of the International Workshop on Collective Excitations, Serra Negra, Brazil, 1998 (World Scientific, Singapore, in press).

[6] B. V. Carlson, M. S. Hussein, A. F. R. de Toledo Piza, and L. F. Canto, Semiclassical Description of Multiple Giant Dipole Resonance Excitation and Decay, Proceedings of the International Workshop on Collective Excitations [5].

[7] D. Brink, Ph.D. thesis, Oxford University, 1955; P. Axel, Phys. Rev. **126**, 671 (1962).

[8] L. F. Canto, A. Romanelli, M. S. Hussein, and A. F. R. de

Toledo Piza, Phys. Rev. Lett. **72**, 2147 (1994); C. A. Bertulani, L. F. Canto, M. S. Hussein, and A. F. R. de Toldeo Piza, Phys. Rev. C **53**, 334 (1996).
[9] G. Reffo (private communication).
[10] C. K. Cline and M. Blann, Nucl. Phys. **A172**, 225 (1971).
[11] C. K. Cline, Nucl. Phys. **A186**, 273 (1972).
[12] F. C. Williams, Jr., Phys. Lett. **31B**, 184 (1970).
[13] R. M. DeVries and J. C. Peng, Phys. Rev. C **22**, 1055 (1980).