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Dedicated to Prof. A.F.R. de Toledo Piza on the occasion of his 60th birthday

Time scales of multiple giant dipole resonance excitation and decay*,†

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Abstract

We examine the time scales of the competing processes involved in double giant resonance excitation and decay.

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The Coulomb excitation of two-phonon giant resonances at intermediate energies has generated considerable interest in the last few years [1]. The isovector double giant dipole resonance (DGDR) has been observed in ^{136}Xe [2], ^{197}Au [3], and ^{208}Pb [4–6]. The isoscalar double giant quadrupole resonance has also been observed in the proton emission spectrum from the collision of ^{40}Ca with ^{40}Ca at a laboratory energy of 44 A Mev [7]. When the data on DGDR excitation for ^{136}Xe and ^{197}Au are compared with coupled-channel Coulomb excitation calculations [8], it is found that, in the harmonic approximation, the calculated cross sections are a factor of 2 to 3 smaller than the measured ones. A similar discrepancy, albeit somewhat smaller, is found for ^{208}Pb.

Several effects that are not taken into account in the coupled-channel theory have been considered as possible explanations of this discrepancy. As examples, we mention the effect of anharmonicities [9,10] and the quenching of the 1^+ DGDR state [11]. In several recent works [12–17], we have suggested a potentially important mechanism for this discrepancy, that of the Coulomb excitation of a GDR on the background states populated by the decay of a previously excited GDR, as shown in Fig. 1. The importance of such 'hot' collective excitations in nuclear gamma emission was suggested long ago by Brink and Axel [18]. Due to the complicated nature of the noncollective background states, the amplitude for this excitation process varies rapidly with energy and possesses an average close to zero. Its contribution to the cross section can be sizable, however.

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 this excitation mechanism by comparing the Coulomb collision time to the giant dipole resonance decay time. The decay time can be estimated as $\tau_d = \hbar/\Gamma_d^\downarrow$, where $\Gamma_d^\downarrow$ 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,

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

which furnishes a collision time of the order of $\tau_c \approx 2b/\gamma v$.

In Fig. 2, 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 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 here 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, $\varepsilon_d = 43.4\,A^{-0.215}$ MeV and $\Gamma_d = 0.3\,\varepsilon_d$ [19], 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

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

Equating the two expressions yields the curve of Fig. 3. 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.

Giant resonances have many characteristics that suggest a treatment in terms of simple collective degrees of freedom. The first and foremost of these is their classical interpretation in terms of macroscopic shape oscillations of the nucleus. The properties of multiple excitations of these resonances would then suggest that they are simple bosonic degrees of freedom. The Brink-Axel hypothesis, which assumes that a giant dipole resonance may be constructed on each of the intrinsic excited states of the nucleus, suggests that the resonances can be considered as degrees of freedom independent of the intrinsic states. Of course, the microscopic representation of the giant resonances, in terms of of the intrinsic particle-hole states, implies that their treatment as independent degrees of freedom can only be approximate. Yet, in many instances, it seems to be a very good approximation.

We treat the giant resonance as an independent degree of freedom and label the states of the nucleus with both a collective index n, denoting the number of collective dipole phonons, and a statistical one s, denoting the number of collective phonons that have decayed into the incoherent background. The class of states denoted by the pair of indices n and s thus possesses n phonons of collective excitation and an incoherent background excitation obtained through the decay of another s phonons. In the limit of harmonic phonons, these states would have an excitation energy of $(n+s)\varepsilon_d$ and a width of $n\Gamma_d$, where ε_d is the energy of the giant dipole resonance and Γ_d is its spreading width. A schematic representation of the states and the transitions between them is given in Fig. 4.

We consider the Coulomb excitation of a collective degree of freedom of a projectile nucleus by an inert target and the subsequent decay of the collective states into complex intrinsic ones. In terms of the state labels we have defined, the usual coherent DGDR excitation proceeds by a collective excitation from the ground state to the n=1, s=0 GDR state followed by a subsequent collective excitation to the n=2, s=0 DGDR state, before the n=1, s=0 GDR phonon has decayed into the n=0, s=1 background of statistical states. The fluctuating, hot GDR excitation is initiated in the same manner, with a collective excitation from the ground state to the n=1, s=0 GDR state. However, the hot GDR is excited, through the Brink-Axel mechanism, on the statistical background of n=0, s=1 states, which are populated by the decay of the single GDR. The n=1, s=1 hot GDR has an excitation energy similar to that of the DGDR and appears very similar to it experimentally. The hot GDR contribution to the cross section can also be of comparable size to that of the

DGDR, as we have discussed above and shown in recent calculations [15–17].

However, collective excitation of GDR phonons and their decay to a statistical background of excited states are not the only processes that occur in such collisions. As is well known, an excited nucleus eventually decays by emitting particles and/or photons. Such 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 [20,21]. For the case of nucleon emission, the expression for the differential emission width takes the form

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

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

$$\sigma_\nu(\epsilon_\nu) \approx \pi R^2\left(1-\frac{V_{c\nu}}{\epsilon_\nu}\right)\theta(\epsilon_\nu - V_{c\nu}), \quad (3)$$

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 [22],

$$\omega(p=0,h=1,E-S_\nu-\epsilon_\nu) = g\,\theta(E-S_\nu-\epsilon_\nu)$$
$$\omega(p=1,h=1,E) = g^2 E\,\theta(E), \quad (4)$$

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

$$\frac{d\Gamma^{\uparrow}_{d\nu}}{d\epsilon_\nu}(E,\epsilon_\nu) = \frac{1}{3\hbar^2}\, m_N\, \pi R^2 \left(\frac{Z}{A}\right)^{z_\nu}\left(1-\frac{Z}{A}\right)^{1-z_\nu} \frac{(\epsilon_\nu - V_{c\nu})}{aE}\, \theta(\epsilon_\nu - V_{c\nu})\theta(E - S_\nu - \epsilon_\nu), \quad (5)$$

which we may integrate immediately, to obtain

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

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

$$\Gamma^{\uparrow}_d \approx \frac{1}{6\hbar^2} m_N\, \pi R^2 \frac{1}{aE_d}\left[\left(\frac{Z}{A}\right)(E_d - S_p - V_c)^2\, \theta(E_d - S_p - V_c) + \left(1-\frac{Z}{A}\right)(E_d - S_n)^2\right], \quad (7)$$

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

We have evaluated the expression for the escape width $\Gamma^{\uparrow}_d$ 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. [19] and the Coulomb barrier parametrization of Ref. [23],

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

Our results are shown in Fig. 5, in which we plot the ratio of the escape width to the total width, $\Gamma^{\uparrow}_d/\Gamma_d$, 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, 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,

$$\Gamma_{cn}(E) \approx 14 \exp(-4.69\sqrt{A/E}) \quad \text{MeV}. \tag{8}$$

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. 6, 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.

REFERENCES

[1] See eg. H. Emling, Prog. Part. Nucl. Phys. **33**, 729 (1994); Ph. Chomaz and N. Frascaria, Phys. Rep. **252**, 275 (1995).

[2] R. Schmidt *et al.*, Phys. Rev. Lett. **70**, 1767 (1993).

[3] T. Aumann *et al.*, Phys. Rev. C **47**, 1728 (1993).

[4] J.L. Ritman *et al.*, Phys. Rev. Lett. **70**, 533 (1993); **70**, 2659(E), (1993).

[5] J.R. Beene, Nucl. Phys. **A569**, 163c (1993).

[6] K. Boretzky *et al.*, Phys. Lett. B **384**, 30 (1996).

[7] Ph. Chomaz *et al.*, Nucl. Phys. **A318**, 41 (1994).

[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] C. Volpe, F. Catara, Ph. Chomaz, M.V. Andres, and E.G. Lanza, Nucl. Phys. **A589**, 521 (1995).

[10] P.F. Bortignon and C.H. Dasso, Phys. Rev. C **56**, 574 (1997).

[11] C.A. Bertulani, V.Yu. Ponomarev, and V.V. Voronov, Phys. Lett. B **388**, 457 (1996).

[12] B.V. Carlson, M.S. Hussein, and A.F.R. de Toledo Piza, Phys. Lett. **B431** 249 (1998).

[13] B.V. Carlson, L.F. Canto, S. Cruz-Barrios, M.S. Hussein, and A.F.R. de Toledo Piza, "Multiphonon and "hot"-phonon isovector electric-dipole excitations", submitted for publication.

[14] 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", to appear in Proceedings of the XX Brazilian Nuclear Physics Workshop, World

Scientific, Sept. 1997.

[15] B.V. Carlson, M.S. Hussein, and A.F.R. de Toledo Piza, "Semiclassical description of multiple giant dipole resonance excitation and decay", submitted for publication.

[16] 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", to appear in Proceedings of the International Workshop on Collective Excitations", World Scientific, Serra Negra, Brazil, Sept. 1998.

[17] 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", to appear in Proceedings of the International Workshop on Collective Excitations", World Scientific, Serra Negra, Brazil, Sept. 1998.

[18] D. Brink, D. Phil. Thesis, Oxford University, Unpublished (1955); P. Axel, Phys. Rev. **126**, 671 (1962).

[19] G.Reffo, private communication.

[20] C.K. Cline, M. Blann, Nucl. Phys. **A172**, 225 (1971).

[21] C.K. Cline, Nucl. Phys. **A186**, 273 (1972).

[22] F.C. Williams Jr., Phys. Lett. **31B**, 184 (1970).

[23] R.M. DeVries and J.C. Peng, Phys. Rev. C **22**, 1055 (1980).

FIGURES

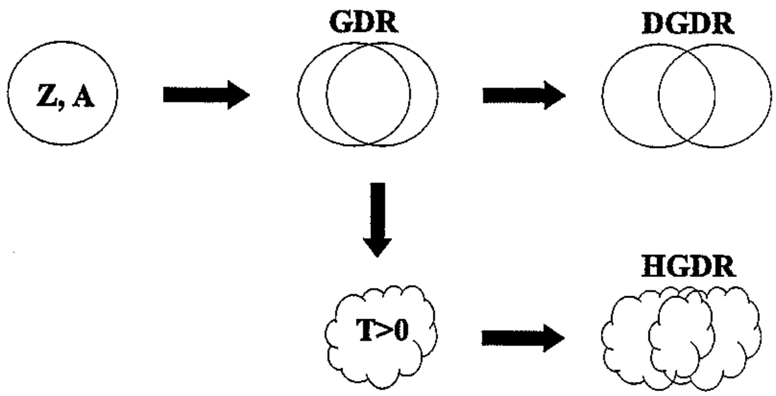

FIG. 1. Cartoon depiction of the conventional double giant dipole resonance excitation (DGDR) and the alternative 'hot' giant dipole excitation (HGDR) discussed here.

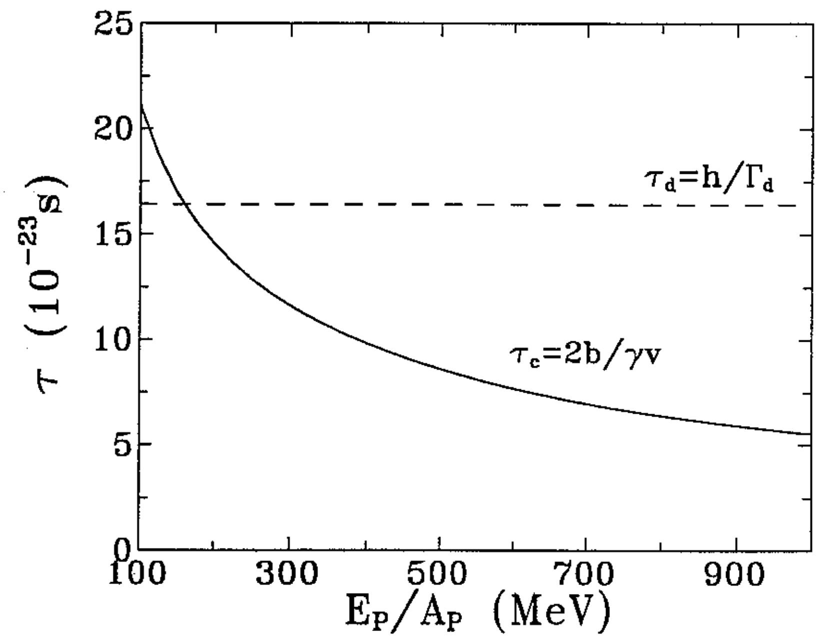

FIG. 2. Collision time τ_c (solid line) and GDR decay time τ_d (dashed line) for the system ^{208}Pb + ^{208}Pb at an impact parameter of b=15 fm as a function of the projectile energy per nucleon.

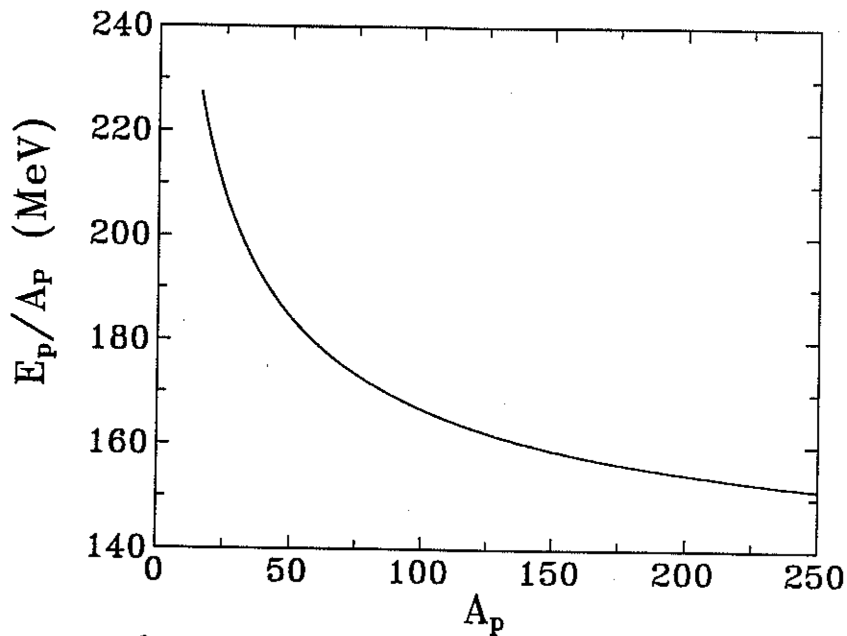

FIG. 3. Energy per nucleon at which the collision time and giant dipole resonance decay time of a projectile in a collision with ^{208}Pb are approximately equal, as a function of the mass number of the projectile.

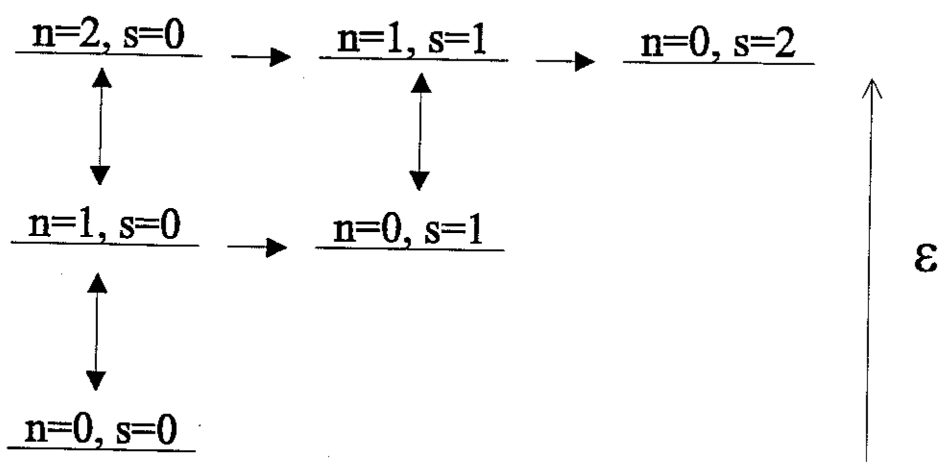

FIG. 4. Schematic representation of the collective/statistical states and their transitions. The vertical arrows represent the two-way coherent excitation/de-excitation of collective phonons. The horizontal arrows represent the one-way statistical decay of the collective phonons. ε denotes the excitation energy.

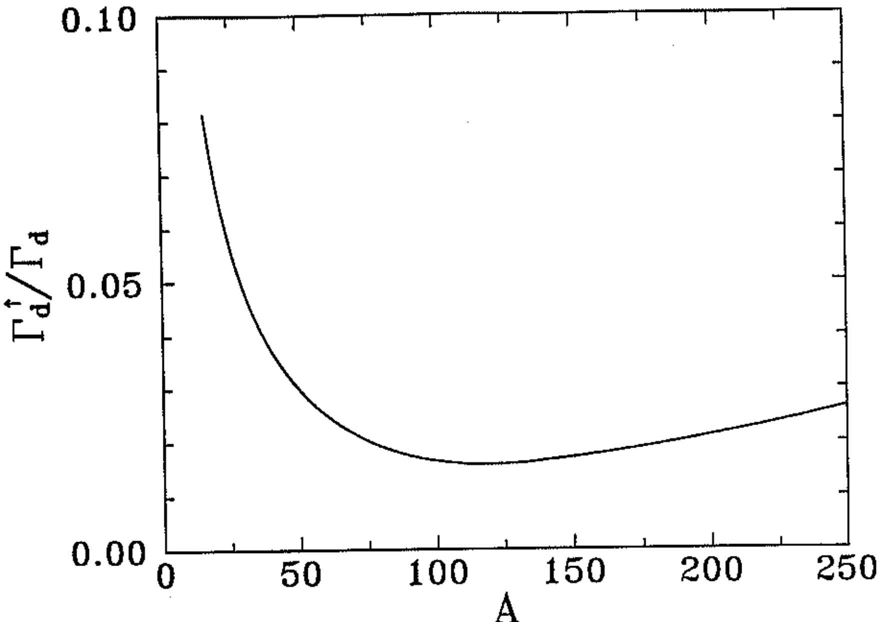

FIG. 5. Ratio of the direct neutron escape width to the total giant dipole resonance width as a function of the mass number of the nucleus.

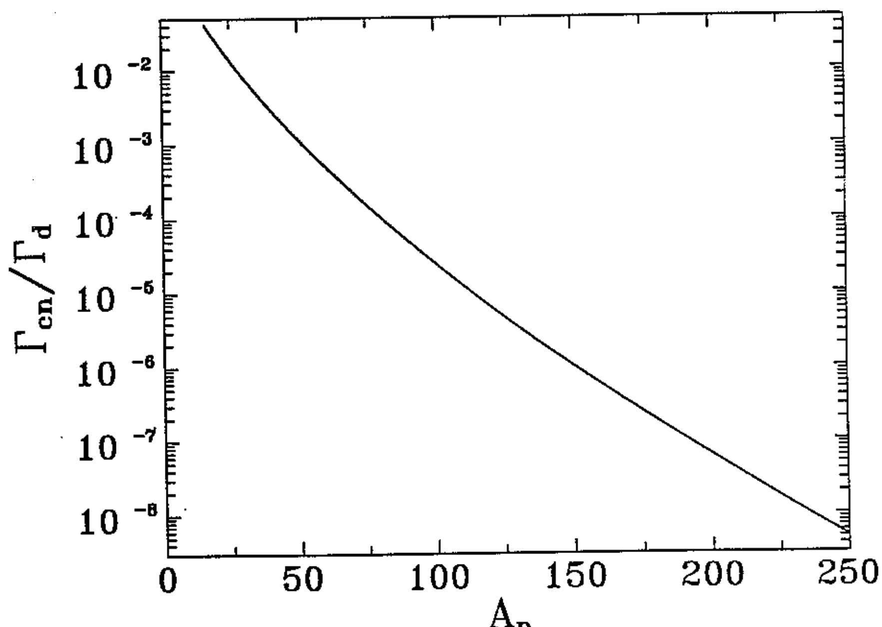

FIG. 6. Ratio of the compound nucleus escape width to the total giant dipole resonance width as a function of the mass number of the nucleus.