Is There Evidence for a Nuclear Foucault Pendulum?

R. R. Hilton
Physics Department, Technical University Munich, 8046 Garching, Germany
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Recent observations of the giant dipole resonance in states at higher angular momentum and temperature have shown an effective narrowing of the resonance. It is pointed out that this may be interpreted as a signature of rotation of the nucleus about a symmetry axis. In this limit, the giant dipole orientation freezes in the plane of rotation, the analog of the Foucault pendulum positioned at the North Pole. All effects of rotation, other than those of pure deformation, cease to be present. In this region it is thus possible to probe the nuclear shape directly, uncontaminated by rotational effects.

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Since the original experiments of Newton *et al.*,[1] there has been continuing intensive interest in the giant dipole resonance at high spin and temperature.[2] The possibility of building such a resonance on excited states was already implicit in the work of Brink[3] and explicitly conjectured by Morinaga.[4] In a recent investigation by Morsch *et al.*,[5] we appear to have, for the first time, clear evidence for a narrowing of the giant dipole resonance at high angular momentum and temperature. These results were obtained in experiments performed at the Oak Ridge Holifield Heavy Ion Research Facility accelerator in which ^{159}Tb was bombarded by ^{16}O ions at energies of 300 and 400 MeV. The giant dipole width extracted from their analysis shows an abrupt narrowing at an angular momentum of around 40 and above. It is the purpose of this Letter to bring attention to the fact that such a phenomenon may be interpreted as the signature of rotation of the nucleus about a symmetry axis. In this region, an exotic phenomenon may occur. In the limit of rotation about a symmetry axis, the giant dipole orientation freezes in the plane of rotation, the analog of the Foucault pendulum positioned at the North Pole. All effects of rotation, other than those of pure deformation, cease to be present. The giant dipole splitting reduces to the two modes along and perpendicular to the rotation axis, with frequencies determined by the unrotating restoring-force constants appropriate to the deformation. Under these circumstances, the additional electromagnetic splitting, which is inevitably expected from the rotating dipole, vanishes and a simple natural explanation of the resonance narrowing results. In this region, it is thus possible to probe the nuclear shape directly, uncontaminated by rotational effects.

Within the framework of a cranked deformed oscillator in which dipole-dipole two-body forces have been taken into account, an exactly soluble model description of the rotating giant dipole may be established.[6] Its essential results have been corroborated in subsequent large-scale investigations for the case of prolate-deformed nuclei rotating perpendicular to the symmetry axis.[7]

The Hamiltonian H', seen in a frame rotating with angular velocity Ω about the x axis having angular momentum J_1, takes the form

$$H' = H - \Omega J_1 . \tag{1}$$

The eigenvalues $\tilde{\omega}'_\nu$ corresponding to eigenstates Ψ_ν of this Hamiltonian do not, however, represent energies of the system. The energy must be computed in the laboratory frame, using the expression

$$E_L(\nu) = \langle \Psi_\nu | H' | \Psi_\nu \rangle + \Omega \langle \Psi_\nu | J_1 | \Psi_\nu \rangle . \tag{2}$$

The true excitation energy is established from

$$E_L(\nu, I+\Delta I) - E_L(0,I) = \tilde{\omega}'_\nu + (\partial E_L/\partial I)\Delta I = \tilde{\omega}'_\nu + \hbar \Omega \Delta I . \tag{3}$$

This expression takes into account the effects of changes of angular momentum on the excitation energy which may be encountered during the excitation. As excitation of the giant dipole resonance involves changes of angular momentum $\Delta I = \pm 1, 0$ along the axis of rotation, a further splitting of the resonance, in addition to that anticipated due to the triaxial shape, is therefore to be expected, viz.,

$$\tilde{\omega}'_1, \quad \tilde{\omega}'_2 \pm \hbar \Omega, \quad \tilde{\omega}'_3 \pm \hbar \Omega . \tag{4}$$

This will, in general, exhibit itself as a further broadening of the resonance. Such an effect is present classically as well as quantum mechanically and has the same origin as that of the frequency splitting which is incurred by a radiating dipole aerial in rotation.

At very high spins, nuclei may go over into a regime in which they are almost oblate,[8,9] with the approximate symmetry axis the axis of rotation. The equations of motion governing the neutron-proton separation coordinate r' in the y'-z' plane of the rotating frame, recast in polar coordinate form, read

$$\frac{d[r'^2(\dot{\vartheta} - \Omega)]}{dt} = \tfrac{1}{2} r'^2 (\bar{\omega}_3^2 - \bar{\omega}_1^2) \sin(2\vartheta) , \tag{5}$$

where $\bar{\omega}_1, \bar{\omega}_3$ represent the unrotating giant-dipole restoring-force constants perpendicular to the rotation axis, and ϑ represents the orientation of r' with respect to the rotating axes. This equation is valid in both classical and quantum mechanics and in the limit of axial symmetry. In the limit $\bar{\omega}_1 = \bar{\omega}_3$, this implies a freezing of the orientation of the dipole mode in the y-z plane, with respect to the fixed laboratory frame, the analog of the Foucault pendulum positioned at the North Pole. Under these circumstances, all effects of rotation on the giant dipole, other than those due to deformation, cease to be present and the resonance energies are again determined by the unrotating restoring forces appropriate to the deformation. This should also be accompanied by a simultaneous marked reduction in the effective widths of both the high- and low-energy components of the giant dipole resonance by the additional splitting $2\hbar\Omega$ caused by its rotation with respect to the laboratory frame. It is this signature which, we believe, has recently been observed.[5]

An initial assessment of this effect may be made on assuming that the influence of pairing effects is small at these spins and temperatures ($T \approx 2$–3 MeV). Assuming a rigid-body moment of inertia $\mathcal{J}_1$, one obtains for the width reduction the estimate

$$2\hbar\Omega = 2(I/\mathcal{J}_1)\hbar^2 = I144A^{-5/3}[1-\sqrt{5/4\pi}\beta\cos(\gamma - 2\pi/3)]^{-1}\ \text{MeV}. \tag{6}$$

For angular momentum $I \approx 40$, taking as typical deformation values before the oblate transition $\beta \approx 0.15$ and $\gamma = 10°$–$30°$, we obtain, for a rare-earth nucleus with $A \approx 160$, a value of around 1.2 MeV.

In the highly excited region leading to the oblate phase the angular momentum must not necessarily remain clamped along any particular body-fixed axis. On giving up the requirement that the angular momentum always be aligned along the x axis of the dipole motion, an additional broadening may be expected. If the angular momentum component is no longer at this fixed orientation, further splitting of the dipole energies results from the fact that any individual component is in simultaneous rotation about more than one axis. (This has also been noted independently.[10]) An orientation (α, ϕ) of the angular momentum $\mathbf{I}$ with respect to the dipole axes leads to rotation-induced splittings of the ith dipole component energy of value

$$\mp I_j/\mathcal{J}_j \mp I_k/\mathcal{J}_k, \quad i,j,k \text{ cyclic permutations } 1,2,3, \tag{7}$$

in which the angular momentum components are given by

$$I_1 = I\sin\alpha\cos\phi, \quad I_2 = I\sin\alpha\sin\phi, \quad I_3 = I\cos\alpha. \tag{8}$$

Probing over all orientations, we obtain a continuous distribution of splittings leading to a maximum broadening for the ith direction of magnitude

$$(2I/\mathcal{J}_j)[1+(\mathcal{J}_j/\mathcal{J}_k)^2]^{1/2}, \quad i,j,k \text{ cyclic permutations } 1,2,3. \tag{9}$$

Using our previous shape parameters, and assuming rigid-body rotation, we obtain for the broadening to be expected from such effects values in the range 1.7–1.8 MeV. Thermal shape fluctuations, if they represent rapid fluctuations about the oblate shape, should not modify our conclusions about the rotational decoupling of the dipole.

In the experiments, abrupt simultaneous reductions in the widths of both the high- and low-energy components of the giant dipole resonance of around 1.5–2 MeV have been observed. From the fact that these observations have been obtained from a window of states having a range of angular momentum it would already appear possible to surmise that the oblate shape remains stable over a number of excited high-spin states.

Nuclei at still higher angular momentum may once again assume triaxial shapes[7,8] before ultimately fissioning. Abrupt broadening in the widths is therefore to be expected in this region, which would pinpoint such a bifurcation. We thus have in this effect a new tool with which to examine the evolution of such shape bifurcation through the variation of the width with angular momentum as this becomes available.

One should bear in mind that the behavior of the nucleus plays a decisive role in our evaluation. In all these assessments, rigid-body rotation has been assumed. Non-rigid-body rotation, due to residual pairing, for example, or higher angular momentum, could lead to much larger effects. The cumulative action of other possible sources of narrowing[11] has not been taken into account. On the other hand, superrigid moments of inertia from either shape[12] or single-particle spin realignment effects,[13] before or after bifurcation, would, in contrast, lower these values. In all cases, however, substantial information about the nature of the nucleus under extreme conditions would become available.

It should also not be forgotten that the experimental analysis of the spectra has been carried out on a two-peak basis (prolate shape). Triaxial shapes, before bifurcation to an oblate shape, would imply that the higher giant dipole component comprises two unresolved peaks, the effect of which will be to contribute to an apparent narrowing of the width in the transition. Such consequences must be distinctly disentangled.

For light nuclei, the effect would be enhanced due to the higher angular velocity Ω involved. In ^{24}Mg, for example, prolate-oblate transitions taking place at angular momentum $I \approx 12$, on taking typical shape-parameter values of $\gamma \approx 10°$–$30°$ and $\beta \approx 0.3$–0.4, would lead to width narrowings of around 11–14 MeV. Light nuclei would therefore seem a worthwhile area for investigation.

Furthermore, Eq. (3) is not restricted to the dipole excitation alone. It is valid for any excitation involving angular momentum change, as it invokes only very general energy-angular-momentum relations. This is a particular example of a new effect representing the sudden decoupling of a state from the angular momentum. We may speculate on analogous rotational decoupling effects occurring in other resonances, such as those of the high-lying giant quadrupole, for which the effect would be even more marked due to the larger changes in angular momentum involved in the excitation.

It is tempting to speculate further. The frozen form of the dipole γ-radiation distribution in the oblate region should be distinctive. Perhaps additional anisotropies of the decaying γ's, for some range of angular momentum, might be detectable.

In these observations we would appear to have the first evidence for a nuclear Foucault pendulum, with the possibility of its use as a new tool in studying nuclei under extreme conditions. Naturally, the full ramifications of the potential measurement of absolute orientations are not to be overlooked.

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