Indian J. Res. Found., (2019) 7, 1-5. ISSN 2454-6577

INDIAN JOURNAL OF RESEARCH FOUNDATION
www.indianjournal.net

RESEARCH ARTICLE

Giant dipole resonance in excited nuclei

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Received 16 November 2018; Accepted 12 February 2019
Available online 15 February 2019

Abstract

The structural transitions of nuclei under extreme conditions of high spin and temperature is examined. The giant dipole resonance (GDR) built on excited states is studied in Samarium nuclei. The static collective model for GDR is used in this work to obtain the resonant energies and the corresponding peak cross sections for ^{152}Sm nuclei. Equilibrium shapes are obtained by finite temperature version of the cranked Nilsson - Strutinsky shell correction method. The shape correlation between the GDR cross section and the predictions by CNS method is made. Results show that the GDR cross section reflects the shapes obtained by CNS method and the theoretical GDR cross sections are in agreement with the experimental data.

Keywords

High spin states of nuclei
Structural transitions
Giant dipole resonance
Cranked Nilsson - Strutinsky method

Introduction

The giant dipole resonance (GDR) has been of central interest in the study of photonuclear reactions. Attempts have been made to delineate the systematics of photon absorption by nuclei in general and of the giant electric dipole resonance in particular, which dominates the absorption process at energies between 10 and 30 MeV. This corresponds to the fundamental frequency for absorption of electric dipole radiation by the nucleus. The semiclassical hydrodynamic model of Goldhaber and Teller [1], Steinwedel and Jenson [2] considers this as the oscillations of the neutrons against the protons. The photoabsorption cross section has a peak at energy between 10 and 30 MeV with a width of about 5 MeV. This peak with such large width is known as the giant dipole resonance. The absorption or emission of photons by a nucleus causes displacement of the protons due to the electromagnetic field of the photons.To keep the centre of mass at rest, the neutrons move in the opposite direction. Due to the strong attraction between protons and neutrons, separating them in this way requires a substantial amount of energy, which is the origin of a restoring force. This restoring force induces an out-of-phase oscillatory displacement of the protons and neutrons. The displacement of charge in a fixed direction produces a dipole moment in the system which couples strongly to electromagnetic fields. The displacement vector can be very simple making dipole modes collective. This collectivity or concentration of a large fraction of the oscillator strength in a small frequency interval, gave this mode the name “Giant Dipole Resonance” (GDR). Giant resonances in general are small amplitude, high frequency, simple, collective modes of excitations of nuclei. The study of giant resonances has been and still is a major topic of research in nuclear physics.

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A 'high spin state' is a state of the nucleus possessing very large value of angular momentum. In heavy ion collisions compound nuclei can be formed at high excitation energies and at very high angular momentum states. At high spin the nuclei is expected to undergo a variety of shape transitions. The two fluid hydrodynamical model of the nucleus explains the giant dipole resonance for spherical as well as for deformed nuclei. The giant dipole resonance for spherical nuclei consists of a single line known as the Lorentz line and for prolate andoblate nuclei it consists of two Lorentzian lines with two peaks having a separation between them which is of the order of the nuclear deformation β. In the case of triaxial nuclei, the giant dipole resonance consists of three Lorentzian lines with three peaks. When the nucleus rotates with high spins, shape changes have been found to occur and it would be of interest to investigate how these shape changes affect their GDR spectra. With this aim, the static collective model [3,4] for GDR is used in this work to obtain the resonant energies and the corresponding peak cross sections for ^{152}Sm, nuclei. Equilibrium shapes are obtained by finite temperature version of the cranked Nilsson - Strutinsky shell correction method.

Absorption Cross Section using Static Collective Model

The hydrodynamic static collective model [5] assumes the nucleus to consist of two fluids, the proton fluid with the density $\rho_p(r,t)$ and the neutron fluid with the density $\rho_n(r,t)$. The total density of the nucleus, $\rho_0(r)$ is assumed to be time – independent

$$\rho_0(r) = \rho_p(r,t) + \rho_n(r,t) \tag{1}$$

This assumption comprises nuclear incompressibility, or to be more precise, the neglect of a coupling of giant resonance modes to nuclear compression modes.

The photo – absorption cross section of nuclei plays an important part in understanding the giant resonances. The absorption cross section is defined as the average energy absorbed per unit time per incoming energy flux. The average incident flux of the electromagnetic wave is

$$S_{ave} = \frac{C}{8\pi} E^2 \tag{2}$$

where E is the electric field. Therefore the absorption cross section σ is given by

$$\sigma = \frac{(E.D)_{ave}}{S_{ave}} \tag{3}$$

where D is the dipole moment. We know that the rotating nuclei are statically deformed. It was Danos [3] and Okamato [4] who have applied the static collective model for an axially symmetric ellipsoid. Three degenerate giant dipole modes exist in the case of spherical nuclei. In the case of an ellipsoid, these three degenerate modes split into two, in such a way that one mode oscillates along the long axis of the ellipsoid and two degenerate modes oscillating in the plane perpendicular to the long axis. As giant resonances are standing sound waves in the nucleus, we can expect normal modes of wavelengths $\lambda_i \, \alpha \, R_i$ where R_i are the radii in the three ellipsoidal axes. Therefore for the frequencies $\omega_i \alpha \ Ri^{-1}$ and hence the energies are proportional to the reciprocal radii. It was Danos who calculated the ratio of energies along the axes a and b

$$\frac{E_b}{E_a} = 0.911 \frac{a}{b} + 0.089 \text{or}$$

$$\frac{E_b - E_a}{E_a} = 0.911 \left(\frac{a-b}{a}\right) \tag{4}$$

Therefore, in the case of axially deformed nuclei, the absorption cross section exhibits two peaks in the giant resonance region. The separation between the peaks is proportional to the deformation β.For a prolate nucleus, the upper component of the giant resonance contains twice as much integrated cross section as the lower one (i.e β> 0 or a > b) and vice versa for oblate nuclei. Thus the form of the giant resonance absorption cross section gives direct information not only on the magnitude but also on the sign of the nuclear deformation. The GDR cross section takes the form [4]

$$\sigma = \frac{4\pi e^2}{CM} \frac{NZ}{A} \sum_n \frac{2}{z_n{}^2 - 2} \cdot \frac{\Gamma\omega^2}{(\upsilon_n^2 - \omega^2)^2 + \Gamma^2\omega^2} \tag{5}$$

The above eqn. (2.5) exhibits a typical resonance structure where the individual resonances have a Lorentzian shape. By using the semi classical theory of the interaction of photons with nuclei, the shape of a fundamental resonance in the absorption cross section is that of the Lorentz curve.

$$\sigma(E) = \frac{\sigma_m}{1 + \left[\left(E^2 - E_m^2\right)^2 / E^2\Gamma^2\right]} \tag{6}$$

where the Lorentz parameters E_m, σ_m and Γ are the resonance energy, peak cross section and full width at half maximum respectively.

In the case of spherical nuclei, the giant dipole resonance consists of one Lorentz line. The peak cross section σ_m for spherical nuclei is given by [6]

$$\sigma_m = 60\frac{2}{\pi}\times\frac{NZ}{A}\frac{1}{\Gamma_m}\left(0.86(1+\alpha)\right) \qquad (7)$$

where Γ_m is the width at half maximum and α is an adjustable parameters.

For statically deformed nuclei, the giant resonance consists of two such Lorentz lines corresponding to the absorption of photons which induce oscillations of the neutron and proton fluids in the nucleus against each other. In such cases,

$$\sigma(E) = \sum_{i=1}^{2} \frac{\sigma_{mi}}{1+\left[\left(E^2 - E_{mi}^2\right)^2 / E^2\Gamma_i^2\right]} \qquad (8)$$

where i = 1, 2 correspond to the lower and higher energy lines. The lower energy line corresponds to oscillations along the longer axis and the higher energy line corresponds to oscillations along the shorter axis. In the case of triaxial nuclei, the giant dipole resonance consists of three such Lorentz lines corresponding to the oscillations along each of the non – degenerate axes.

For deformed spheroidal nuclei, the peak cross sections σ_{m1} and σ_{m2} are determined using

$$\sigma_{m1}\Gamma_{m1} + \sigma_{m2}\Gamma_{m2} = 60\frac{2}{\pi}\frac{NZ}{A}[0.86(1+\alpha)] \qquad (9)$$

When the areas under the Lorentz curves are considered, for spherical nuclei, the area under the Lorentz curve is given by

$$\int_0^{\alpha} \sigma(E)dE = \frac{\pi}{2}\sigma_m\Gamma \qquad (10)$$

For deformed nuclei, the assumed area under the two – line Lorentz curve is given by

$$\int_0^{\alpha} \sigma(E)dE = \frac{\pi}{2}\left(\sigma_{m1}\Gamma_1 + \sigma_{m2}\Gamma_2\right)$$

Also, it was predicted that the ratio of the area under the lower – energy component of the giant resonance to that under the higher energy component to be $\frac{1}{2}$ for prolate and 2 for oblate nuclei. The values for the area ratio

$$R_A = \sigma_{m1}\Gamma_1 / \sigma_{m2}\Gamma_2$$

can be obtained from the Lorentz parameters. It was found that the area ratio R_A leads to some uncertainty in its value for prolate and oblate nuclei [7].

There are more theories other than the elementary hydrodynamic theory of the giant resonance that include the coupling of quadrupole (surface) oscillations to the main dipole (volume) vibrations of the nucleus. Even though these do not affect the peak photo absorption cross section, they affect the smoothness of the giant resonance curves. Since the present work aims at studying in general, the shape changes of heavy nuclei at high spins, these couplings are not considered.

Shapes of Excited Nuclei by Cranked Nilsson Strutinsky Method

The Nilsson-Strutinsky method is one among the most feasible way to do systematic calculations of the nuclear energy as a function of deformation and/or excitation.The Strutinsky's method of shell corrections [8-10] has been successfully used in calculations of the nuclear deformation energy, with the concept dividing the total nuclear binding energy in to a smooth liquid-drop energy E_{LDM} and an oscillating shell correction energy δE.The shell energy calculations for non-rotating case (I=0) assumes a single particle field in tri-axial Nilsson model in the rotating frame [11]

$$H_0 = \sum h_0 \qquad (11)$$

where h_0 is the triaxial Nilsson Hamiltonian given by

$$h_0 = \frac{p^2}{2m} + \frac{1}{2}m\sum_{i=1}^{3}\omega_i^2\chi_i^2 + Cl.s + D(l^2 - 2\langle l^2\rangle) \qquad (12)$$

The three oscillator frequencies ω_i are given by the Hill Wheeler parameterization as

$$\omega_x = \omega_0 \exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos\left(\gamma - \frac{2}{3}\pi\right)\right] \qquad (13)$$

$$\omega_x = \omega_0 \exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos\left(\gamma - \frac{4}{3}\pi\right)\right] \qquad (14)$$

$$\omega_x = \omega_0 \exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos\gamma\right] \qquad (15)$$

With the constraint of constant volume for equipotentials

$$\omega_x\omega_y\omega_z = \omega_0^{3} = \text{constant}, \qquad (16)$$

where the oscillator frequency is chosen as

$$\hbar\omega_0 = \frac{45.3}{(A^{1/3}+0.77)} MeV \qquad (17)$$

In the expression for h_0(in eqn. 12), the term $\langle l^2 \rangle$ has been doubled to obtain better agreement between the Strutinsky-smoothed moment of inertia and the rigid rotor value. Accordingly, the parameter D corresponding to a mass region has to be predetermined with the help of single-particle levels in the given mass region. The Hamiltonian (12) is diagonalized in cylindrical representation up to N=11 shells. Here N_{osc} is the harmonic oscillator principal quantum number.For the rotating case $(I \neq 0)$, the Hamiltonian becomes

$$H_\omega = H_0 - \omega J_z = \sum h_\omega, \qquad (18)$$

where

$$H_\omega = h_0 - \omega J_z, \qquad (19)$$

if it is assumed that the rotation takes place around the z-axis. The single particle energy e_i^ω and the wave function ϕ_i^ω are given by $h_\omega \phi_i^\omega = e_i^\omega \phi_i^\omega$ (20)

The spin projections are obtained as

$$\langle m_i \rangle = \langle \phi_i^\omega | j_z | \phi_i^\omega \rangle \qquad (21)$$

The total shell energy is given by

$$E_{sp} = \sum \langle \phi_i^\omega | h_0 | \phi_i^\omega \rangle = \sum \langle e_i \rangle \qquad (22)$$

where $e_i^\omega = \langle e_i \rangle - \hbar\omega \langle m_i \rangle$ (23)

Thus $E_{sp} = \sum e_i^\omega + \hbar\omega I$ (24)

The total spin I from the shell model is given by

$$I = \sum \langle m_i \rangle \qquad (25)$$

The sums should be carried out over the occupied states where the occupation is determined from the order of the quantities e_i^ω.

The total energy in cranked Nilsson Strutinsky prescription is thus given by

$$E_T(T,I;\beta,\gamma) = E(T,I;\beta,\gamma) - TS - \tilde{E}(T,I;\beta,\gamma) + E_{RLDM} \qquad (26)$$

Where E_{RLDM} is the rotating liquid drop energy

Results and Discussion

The investigation of structural changes of nuclei at high excitation energy is a topic of current interest in nuclear structure studies [12]. For studying the shapes of hot rotating nuclei, the main experimental technique used is to measure the GDR built on their ground or excited states. Isovector giant dipole resonance is one of the most important collective modes of nuclei. There has recently been a great deal of speculation concerning how the strength might evolve in medium mass and heavy nuclei. Theoretical studies are beginning to appear, but there is as yet very little experimental data. The GDR cross sections in excited nuclei show a very interesting evolution as signature for shape transitions. We have made an attempt to study such shape transitions and to see how the GDR cross section reflects these shapes.

To detect the shape transitions theoretically we have obtained the GDR cross sections in ^{152}Sm as a function of spin. In the calculations performed in this work, the cranked Nilsson -Strutinskymethod is first used to obtain the shape and deformation of the considered nuclei as a function of spin [12]. The Nilsson Hamiltonian is diagonalized in cylindrical representation up to N = 11 shells using the appropriate constants which are applicable for the nuclear region considered. The energy eigen values are generated for γ ranging from -180° to -120° in steps of -10° and β ranging from 0.0 to 1.2 in steps of 0.1. The cranking frequency ω_c is varied from 0.0 to 0.3 in steps of 0.03. The single particle routhians are generated with spin values I = 0 $\hbar$ to 60 $\hbar$ for ^{152}Sm nuclei.The Hill – Wheeler expressions for frequencies have been used in the cranked Nilsson model in order to take care of large deformations involved in the calculations.

In the second phase of this work, the equilibrium deformations β and γ obtained by the Strutinsky method is used to calculate the semi axes of the nuclei considered and the results are presented in table 1. The peak energies are evaluated using these values and the peak cross sections corresponding to these peak energies are then obtained. The calculated values of resonant energies and peak cross sections for the considered nuclei are presented in table 2. The sample result of GDR Lorentzian curve for ^{152}Smis presented in figure 1. One can see from this figure that the two peaks obtained at spin 60 ħ represents the oblate spheroidal shape of the nucleus. It is to be noted from the results presented in the tables 1and 2 that the GDR cross sections beautifully reflect the nuclear shape changes that take place at higher spins. Our results show that the theoretical GDR cross sections are in agreement with the experimental data. The experimental data in the higher energy region is quite scattered and as a result of this the experimental GDR width is quite larger.

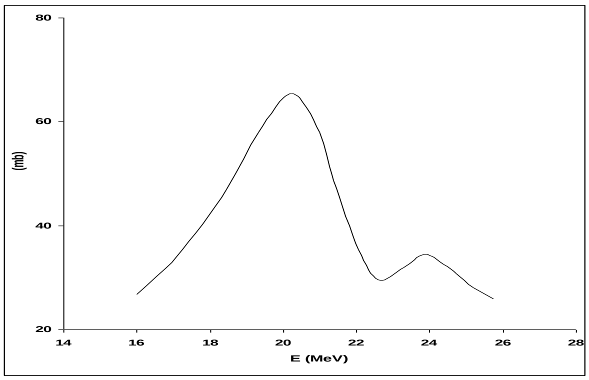

Fig 1 GDR Lorentzian curve for ^{152}Sm

Table 1 Shape transitions in ^{152}Sm with spin

I (h)	γ (deg)	β	E (MeV)	Shape
0.00	-120	0.2	-2.61	Prolate
10.00	-120	0.3	-3.12	Prolate
19.99	-140	0.1	-0.96	Triaxial
29.98	-150	0.2	1.21	Triaxial
39.99	-160	0.3	3.18	Triaxial
49.97	-170	0.0	5.65	Spherical
59.99	-180	0.2	10.78	Oblate

Table 2 The resonant energies and peak cross sections for the nuclei ^{152}Sm at different spins.

Nucleus ^{A}X	Spin I (ħ)	E_m (MeV)	σ_m (mb)	E_{m_1} (MeV)	σ_{m_1} (mb)	E_{m_2} (MeV)	σ_{m_2} (mb)	E_{m_3} (MeV)	σ_{m_3} (mb)	Shape
^{152}Sm	0	-	-	19.43	36.52	25.38	69.86	-	-	Prolate
	10	-	-	19.52	36.01	26.03	69.06	-	-	Prolate
	20	-	-	18.43	34.52	20.85	34.95	21.19	35.21	Triaxial
	30	-	-	19.04	32.18	21.16	32.83	22.46	31.42	Triaxial
	40	-	-	19.25	32.48	21.51	32.89	23.16	32.15	Triaxial
	50	20.62	92.51	-	-	-	-	-	-	Spherical
	60	-	-	20.04	63.44	23.86	36.53	-	-	Oblate

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