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LOW-LYING DIPOLE EXCITATIONS IN THE DEFORMED EVEN–EVEN ISOTOPES $^{154-160}$Gd*

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Properties of the low-energy electromagnetic dipole states in even–even $^{154-160}$Gd isotopes have been studied within rotational, transitional and Galilean invariant Quasiparticle Random Phase approximation (QRPA) method. It has been shown that the main part of spin-1 states, observed at energy $2 \div 4$ MeV in $^{154-160}$Gd may have M1 character and may be interpreted as the main fragments of the scissors mode. The calculations indicate the presence of a few prominent negative parity $K^{\pi} = 1^{-}$ states in $2 \div 4$ MeV energy interval in $^{154-160}$Gd.

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1. Introduction

Low-lying dipole excitations in heavy nuclei, including low-lying orbital magnetic dipole mode often referred as the scissors mode, are of great interest in the modern nuclear structure physics [1]. The existence of such isovector excitation has been predicted within a semi-classical two-rotor model [2] and the interacting boson model [3] with proton–neutron degrees of freedom. The mode was first observed in ^{156}Gd in high-resolution electron scattering experiments in 1984 [4]. Today, this mode is known as the general phenomena for the isotopes with permanent deformation in wide region beginning from the light nuclei up to the actinides also including the transitional and γ-soft nuclei (see Ref. [5–8] and references therein). However, till now, the

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parity assignment is not always possible in those experiments, so experimentally observed parity-unknown dipole states with $\Delta K = 1$ quantum numbers are usually assigned using Alaga rules as belonging to the magnetic dipole states [6]. In the (γ, γ') scattering experiments on ^{160}Gd nucleus, the E1 states with the $\Delta K = 1$ quantum number have been observed at energies below 4 MeV [8]. This observation was supported in our previous theoretical work on ^{160}Gd [9], ^{176}Hf [10] and experimentally by Savran on ^{172,174}Yb [11]. These results showed that not all of the $\Delta K = 1$ transitions are of M1 character in deformed nuclei. So, it would be very interesting to investigate other even–even Gd isotopes and look for a possibility to observe electric dipole states with $K^\pi = 1^-$ in these nuclei as well. In this respect, the Gd isotopic chain with its stable even–even isotopes, with a considerable ground state deformation [12], offers the rare possibility to study the $K^\pi = 1^-$ mode properties in nuclei of the $A = 160$ mass region.

In this study, the features of the low lying magnetic and electric dipole modes have been investigated in the even–even $^{154-160}$Gd nuclei. There, by selecting suitable separable effective isoscalar and isovector forces within QRPA, without introducing any additional parameters, rotational as well as translational and Galilean invariance of the model Hamiltonian have been restored for the description of M1 modes [13] and for the calculation of E1 excitations [14] in even–even $^{154-160}$Gd nuclei, respectively.

2. Results and discussion

The numerical calculations have been made for the even–even $^{154-160}$Gd isotopes. The single particle energies were obtained from the Warsaw deformed Woods–Saxon potential [15]. The pairing interaction constants, chosen according to Soloviev [16], are based on the single-particle levels corresponding to the nucleus in question. The model contains a single parameter only for the calculation of either M1 ($\chi_{\sigma\tau} = 40/A$ MeV [17]) or E1 ($\chi_1 = 300/A^{5/3}$ MeV fm^{-2} [14]) transitions.

TABLE I

Comparison of summed B(M1) and B(E1) values in the energy range 2–4 MeV for $^{154-160}$Gd.

Nuclei	$K=1$ ΣB(M1) (μ^2)		$K=0$ ΣB(M1) (μ^2)		$K=1$ ΣB(E1) (10^{-3}e^{2}fm^2)		$K=0$ ΣB(E1) (10^{-3}e^{2}fm^2)	
	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp. [7,8]
$^{154}_{64}$Gd	2.12	2.60 ± 0.50	0.127	—	24.40	—	2.69	—
$^{156}_{64}$Gd	2.40	2.66 ± 0.51	0.157	—	17.87	—	3.36	9.5 ± 2.4
$^{158}_{64}$Gd	2.12	2.61 ± 0.35	0.037	—	20.80	—	4.72	11.2 ± 3.4
$^{160}_{64}$Gd	3.18	3.56 ± 0.38	0.359	—	19.71	9.5 ± 1.3	1.58	6.5 ± 0.9

Now, we shall discuss $B(\mathrm{E1})$ and $B(\mathrm{M1})$ values and compare the calculated results with the experimental data of [7,8], which are shown in Table I.

As it can be seen, the calculated electric dipole states mainly have $\Delta K{=}1$ character. Our calculated magnetic dipole summed strength values are in very good agreement with experimental ones. The relative contribution of the calculated positive parity $\Delta K = 0$ states to the summed $B(\mathrm{M1})$ strength below 4 MeV is less than 10%. The experimental data [8] on ^{160}Gd suggest that the $\Delta K = 0$ contributions of the magnetic dipole strength should be small.

The calculation indicates the presence of several magnetic dipole states, which mainly have $\Delta K = 1$ character. Our orbit-to-spin ratio analysis shows that these excitations have predominantly orbital character that belongs to the scissors mode for $^{154-160}$Gd. Besides, the analysis shows that theory predicts one well pronounced magnetic dipole strength around 3 MeV for the $^{154-158}$Gd nuclei. However, in the experiment one well pronounced magnetic $K^\pi = 1^+$ state and several dipole states with unknown parity and K-quantum number have been observed. Indeed, in contrary to the neighbouring well deformed ^{156,158}Gd isotopes, ^{160}Gd shows a completely different structure. An example showing a direct comparison of theoretical results with experimental dipole strength distributions deduced from (γ,γ') experiments [7,8] is given in Fig. 1 for ^{158,160}Gd. Plotted values are the reduced

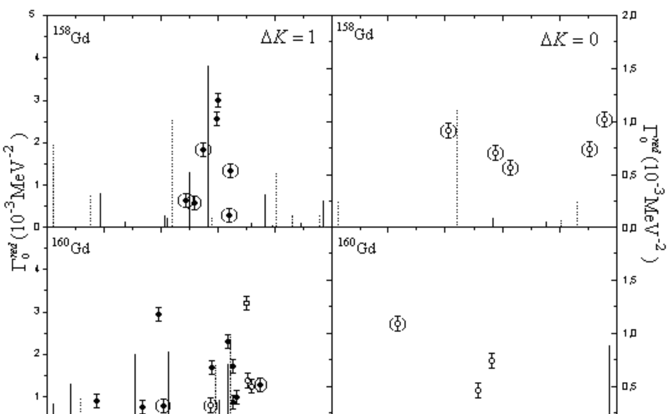

Fig. 1. Experimental reduced dipole ground-state transition widths distributions in ^{158,160}Gd [7,8] compared to the QRPA calculations. Calculated M1 transitions strengths are shown as a solid line and E1 transitions as dashed line, respectively. Full symbols and open symbols denote the experimental data for M1 and E1, respectively. Open symbols marked in parenthesis belong to the experimental data for tentative parity and K quantum number, whereas full symbols in parenthesis belong to transitions for which no parity could be proposed in experiment.

ground-state transition widths $\Gamma_0^{\rm red} = \Gamma_0/E_\gamma^3$ as a function of the excitation energy, separately for $\Delta K = 1$ and $\Delta K = 0$ transitions, respectively. Because the absolute value of $\Gamma_0^{\rm red}$ for $\Delta K = 1$ transitions are a few times stronger than for $\Delta K = 0$, we use different transitions scales for them which are given on the left and the right side of the figure, respectively. Experimentally, for the ^{158}Gd nucleus three states with tentative negative parity are observed in energy range 2.4–3.4 MeV. As it can be seen from the figure, in contrary to ^{158}Gd six negative parity dipole states have been observed in ^{160}Gd [8]. Out of those, three states with summed $\Gamma_0^{\rm red} = 3.3\times10^{-3}$ MeV^{-2} have $K = 1$ quantum number.

In agreement with the experiment, our calculations for ^{160}Gd also show two well pronounced and one weak negative parity $I^\pi K = 1^-1$ excitations with the summed $\Gamma_0^{\rm red} = 4.7 \times 10^{-3}$ MeV^{-2} around 3.3 MeV. Thus, theory predicts several negative parity 1^- dipole excitations with $\Delta K = 1$ in energy range 2.5–3.5 MeV. Such pictures are also valid for the all $^{154-158}$Gd isotopes. Since the experiment could not establish the parity of many low lying dipole states, the claim that all $\Delta K = 1$ states are of magnetic character is at least an open question. Therefore, additional experimental evidence is needed to resolve the issue.

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