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NEW MAGNETIC DIPOLE EXCITATION MODE STUDIED IN THE HEAVY DEFORMED NUCLEUS ^{156}Gd BY INELASTIC ELECTRON SCATTERING[☆]

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The discovery of a new collective magnetic dipole excitation mode in high-resolution inelastic electron scattering on $^{156}_{64}$Gd is discussed in terms of a geometrical two-rotor model and the interacting boson model. Besides in the deformed nucleus ^{156}Gd evidence has also been accumulated for the existence of this mode in ^{158}Gd and for the absence in the transitional nucleus $^{146}_{60}$Nd in agreement with the theoretical prediction.

We report here on first evidence for a low-lying collective $J^\pi = 1^+$ state in heavy deformed nuclei predicted recently. It has been pointed out some time ago [1], that an isovector *magnetic* dipole mode could occur due to a rotation of the nucleus while the deformed bodies of protons and neutrons are rotated with respect to each other around an axis perpendicular to their symmetry axes, i.e. in a two-rotor model (TRM). The orbital (convection) current part of the M1 operator would then be solely responsible for the excitation of this mode. A microscopic approach [2] based on the vibrating potential model (VPM) also predicted such a mode.

Our curiosity, however, to look for this mode has been largely increased when this isovector rotational state has been discussed also in the framework of the interacting boson model [3,4]. In the so called IBA-2, in which proton and neutron degrees of freedom are treated explicitly, only the valence nucleons outside an inert core participate in the collective motion. The predicted 1^+ state corresponds to the bandhead of a $K^\pi = 1^+$ excitation mode, that can be regarded as a (small) amplitude oscillation in terms of the angle between the two symmetry axes of the axially symmetric deformed (valence) neutron and proton bodies (twisting mode). The experimental observation of those antisymmetric modes would either be possible through $K = 1$ admixtures in low-lying states which give rise to small M1 components in e.g., $2^+_2 \to 2^+_1$ transitions. A more direct way is, however, provided by

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the measurement of the excitation energy and the strength of the $K^\pi = 1^+$ member of the band. In fact, a recent more realistic estimate of the excitation energy of this mode in the two-rotor model [5] and an estimate [4] of the expected M1 strength in the SU(3) limit of IBA-2 [6] via the relation

$$B(\mathrm{M1}, 0^+ \rightarrow 1^+) = (3/4\pi)[4N_\pi N_\nu/(N_\pi + N_\nu)] \times (g_\pi - g_\nu)^2 [\mu_\mathrm{N}^2], \qquad (1)$$

encouraged us to search for those 1^+ states in backward angle, high-resolution inelastic electron scattering. The quantities N_π and N_ν are the numbers of proton and neutron bosons, and g_π and g_ν the pair g factors, respectively. An estimate for the latter is obtained from an analysis of g factors of first excited 2^+ states [6].

Iachello [7] has suggested to look for this hitherto not detected M1 mode in the strongly deformed [8] rotational nucleus ^{156}Gd. A recent ^{155}Gd(n, γ) experiment [9] yielded three $J^\pi = 1^+$ states around $E_x = 2$ MeV which are presumably bandheads of two-quasiparticle bands corresponding to "broken pairs" in the IBA embedded in a wealth of low spin states. We looked with high-resolution inelastic electron scattering at low incident electron energies if one of those $J^\pi = 1^+$ states might have the predicted collectivity.

The experiment has been performed at the Darmstadt Electron Linear Accelerator (DALINAC) described elsewhere [10]. The 10 mg/cm^2 thick metallic target foil consisted of ^{156}Gd (93.6% enriched). The inelastically scattered electrons were detected by means of a 169° double focussing magnetic spectrometer operated in the energy loss mode at a scattering angle of $\theta = 165°$ at the bombarding energies $E_0 = 25, 30, 36, 42, 45, 50$ and 56 MeV, at $\theta = 117°$ at 42 MeV and at $\theta = 105°$ at 45 MeV. Targets of ^{158}Gd (30 mg/cm^2, 95.9% enriched) and ^{146}Nd (20 mg/cm^2) were bombarded with electrons of E_0

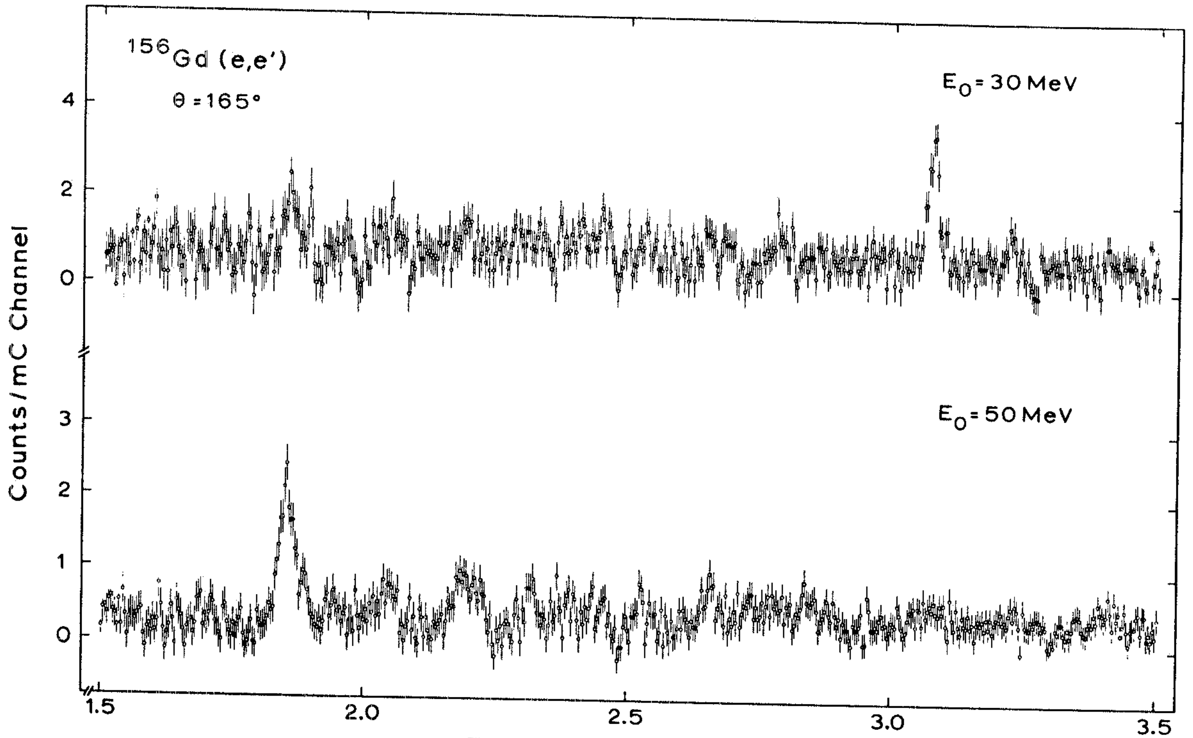

Fig. 1. Two samples of background subtracted backward angle ^{156}Gd(e, e') spectra indicating the almost uniform excitation of many low-spin states in the measured excitation energy region except for a strongly excited $J^\pi = 1^+$ state seen in the $E_0 = 30$ MeV spectrum at $E_x = 3.075$ MeV and a known $J^\pi = 3^-$ state at $E_x = 1.852$ MeV in the $E_0 = 50$ MeV spectrum.

= 25 MeV and inelastically scattered electrons were detected at $\theta = 165°$.

The overall energy resolution achieved in the spectra varied between 22 and 35 keV (fwhm). Two background subtracted spectra (obtained with a procedure described in ref. [11]) measured in 4 keV steps are shown in fig. 1. The spectra have been unfolded using the shape of the elastic line. Furthermore, we took the position of known states [9] as input parameters. The spectrum taken at the low bombarding energy $E_0 = 30$ MeV reveals a rich fine structure of excited low-spin states up to 2.5 MeV in agreement with the known experimental levels. The three previously found $J^\pi = 1^+$ states at $E_x = 1.966, 2.027$ and 2.186 MeV are buried in this grass of levels. The only strong transition is to a state at $E_x = 3.075$ MeV. This state is almost absent in the $E_0 = 50$ MeV spectrum, in which, however, a collective $J^\pi = 3^-$ state [12] at $E_x = 1.852$ MeV is strongest. The state at $E_x = 3.075$ MeV dominates all measured spectra at low incident electron energies and has a form factor behaviour (see below) consistent with a $J^\pi = 1^+$ assignment.

We are fairly confident that this newly discovered $J^\pi = 1^+$ state has all the properties of the proposed collective M1 mode. We discuss the different arguments now in turn.

Excitation energy. The experimental excitation energy is $E_x = 3.075$ MeV. The latest predictions in the various models are:

TRM:

$$E_x \approx 42\delta A^{-1/6}\ \text{MeV} = 4.7\ \text{MeV}, \tag{2}$$

VPM:

$$E_x \approx 53\delta A^{-1/3}\ \text{MeV} = 2.5\ \text{MeV}, \tag{3}$$

SRA:

$$E_x \approx 56\delta A^{-1/3}\ \text{MeV} = 2.7\ \text{MeV}. \tag{4}$$

In eqs. (2)–(4), $\delta = 0.258$ is the mass deformation parameter [8] of ^{156}Gd and $A = 156$. The third model prediction is based on a sum rule approach (SRA) assuming that due to the nuclear deformation the rotational isovector state couples to the $K = 1$ component of the isovector giant quadrupole resonance [13]. The experimental number is indeed reasonably close to those predictions.

The excitation energy is the eigenvalue of an equation which is identical in the TRM and IBA. The parameters entering the equation have been estimated by a semi-classical procedure in the TRM but have not been evaluated theoretically in the IBA. If, however, the experimental excitation energy is used to adjust the strength λ of the Majorana term (related to the "symmetry energy" in the mass formula) in the IBA-2 hamiltonian that is responsible for the energetic splitting between the low-lying symmetric states and the antisymmetric neutron–proton boson states, one obtains $\lambda = 0.2$ MeV, in reasonable agreement with what is known from off-diagonal magnetic dipole matrix elements between low-lying 2^+_i $(i = 1, 2\ 3)$ states [6].

Transition strength. The experimental transition strength is $B(\text{M1})\uparrow = 1.3 \pm 0.2\ \mu_\text{N}^2$ using an IBA-2 form factor for extrapolation to the photon point. Theoretical estimates are:

TRM:

$$B(\text{M1})\uparrow = 0.035\delta A^{3/2}\mu_\text{N}^2 = 17.6\mu_\text{N}^2, \tag{5}$$

SRA:

$$B(\text{M1})\uparrow = 0.043\delta A^{4/3}\mu_\text{N}^2 = 9.3\mu_\text{N}^2, \tag{6}$$

IBA:

$$B(\text{M1})\uparrow = 2.5\mu_\text{N}^2. \tag{7}$$

The expression for the transition strength, which was not derived in the VPM, has been derived in the SRA and coincides with that of the TRM. The numerical discrepancy is due to a different estimate of the parameters entering the excitation energy.

The IBA prediction is based upon (i) the assumption that the IBA-2 M1 operator has the form

$$T(\text{M1}) = (3/4\pi)^{1/2}(g_\pi L_\pi^{(1)} + g_\nu L_\nu^{(1)}), \tag{8}$$

taking $L_\rho^{(1)} = \sqrt{10}(d_\rho^+ d_\rho)^{(1)}$ and $\rho = (\pi, \nu)$, (ii) the use of wavefunctions for the SU(3) limit of IBA-2, and (iii) taking for the number of bosons $N_\pi = 7$ and $N_\nu = 5$, respectively, and for the gyromagnetic factors [6] of the pairs $g_\pi = 0.90$ and $g_\nu = -0.05$. The IBA prediction is closest to reality, since in the sum rule approach the bare single-particle values for the gyromagnetic factors have been used and since – contrary to the assumptions of the two-rotor model – only the nucleons outside the inert core contribute predominantly to the transition strength.

Form factors. The form factors of the weakly excited 1_3^+ bandhead [9] at E_x = 2.186 MeV and the form factor of the collective rotational state E_x = 3.075 MeV are displayed in fig. 2. The form factor of the 1_3^+ bandhead state has been difficult to extract since a known 2^+ state is very close in excitation energy to the 1_3^+ state. The different q dependence, however, of the respective M1 and E2 form factors allowed the evaluation of the M1 form factor shown in the left-hand side of fig. 2. This form factor is well described by a calculation in which a two-neutron quasiparticle configuration ($\nu f_{7/2}-\nu f_{5/2}$) has been assumed for the $J^\pi = 1^+$ state. The form factor of the E_x = 3.075 MeV collective state, however, is best reproduced in terms of a microscopic IBA-2 form factor. The latter is obtained from a microscopic calculation of the fermion structure of the $L = 2$ correlated D-pair and a simple fermion–boson mapping procedure. Note that a TRM form factor also agrees with the IBA-2 prediction.

Other deformed nuclei. The newly found M1 mode should of course not be unique to ^{156}Gd but be a general property of heavy deformed nuclei. Having until now spent a lot of run time (5 months) investigating the ^{156}Gd nucleus we started to look for the new mode in other heavy deformed nuclei. For that we scaled the $\delta A^{-1/3}$ prediction for the excitation energy to $64\delta A^{-1/3}$ such that the location of the collective 1^+ state in ^{156}Gd is properly described and looked at ^{146}Nd and ^{158}Gd. In ^{146}Nd which is not a good rotor, an (e, e′) backward-angle spectrum taken showed no collective 1^+ state at the expected excitation energy E_x = 1.8 MeV. In terms of the IBA model this can be understood from the fact that the M1 operator (8) acting on a spherical ground state, $|s_\pi^{N_\pi} s_\nu^{N_\nu}\rangle$, gives zero. The spectrum taken with a ^{158}Gd target is displayed in fig. 3 together with a ^{156}Gd spectrum measured under the same conditions. Due to the larger target thickness of ^{158}Gd as compared to ^{156}Gd the energy resolution of the ^{158}Gd spectrum is poorer. As fig. 3 demonstrates we see indeed a strongly excited state within 70 keV of the predicted exctitation energy that is of the expected transition strength in the deformed nucleus ^{158}Gd. We are presently measuring the form factor of this state and extend those time consuming measurements to the other deformed nuclei ^{154}Sm, ^{164}Dy, ^{168}Er

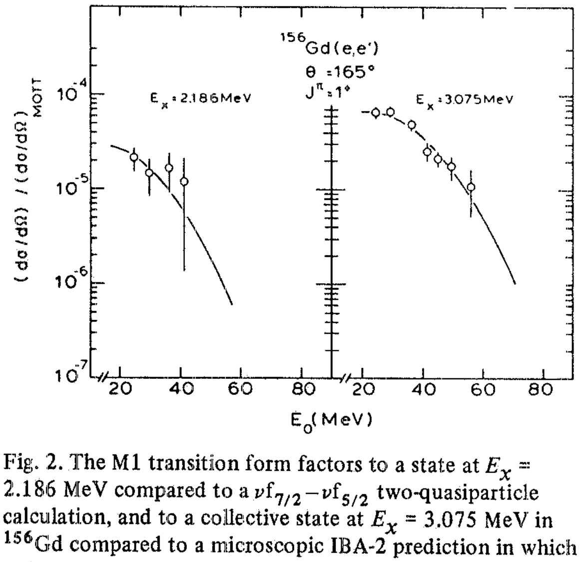

Fig. 2. The M1 transition form factors to a state at E_x = 2.186 MeV compared to a $\nu f_{7/2}-\nu f_{5/2}$ two-quasiparticle calculation, and to a collective state at E_x = 3.075 MeV in ^{156}Gd compared to a microscopic IBA-2 prediction in which only the normalization is a free parameter.

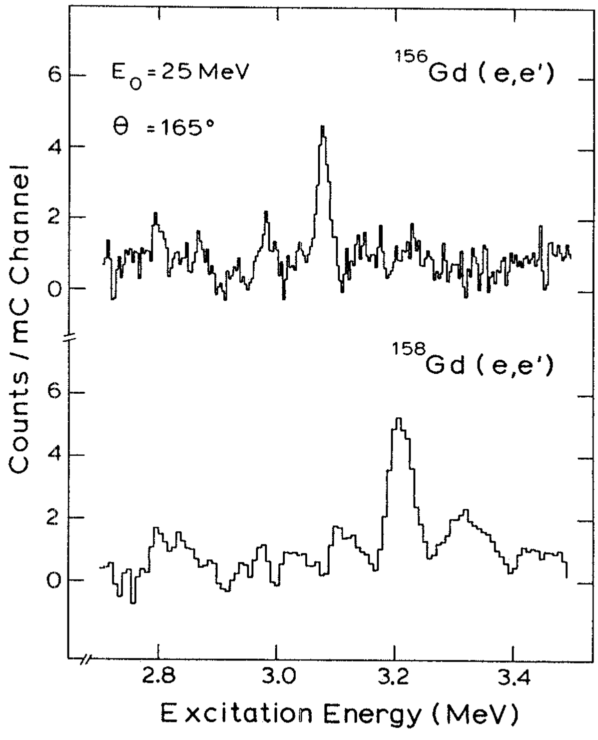

Fig. 3. Comparison of two backward-angle (e, e′) spectra taken on the deformed nuclei ^{156}Gd and ^{158}Gd at an incident energy of E_0 = 25 MeV. Since the ^{158}Gd target was three times as thick as the ^{156}Gd target the energy resolution is poorer.

and ^{174}Yb. It is also important to find the other members of the $K^\pi = 1^+$ band.

As we have seen the new collective M1 mode is connected intimately to other magnetic properties like the g factors of the first excited 2^+ states in even–even nuclei. It is another example of the fact that differences in neutron and proton quadrupole deformations are responsible for most magnetic properties of collective states [14,15].

After completion of this article we have been sent a preprint [16] in which the $K^\pi = 1^+$ state discussed here is treated in the collective model making use of the RPA with results very similar to those given above.

This work has clearly very much been stimulated by Franco Iachello. We thank him and Wolfgang Knüpfer and Bernard Metsch for several discussions, H.-G. Andresen (Mainz) for the loan of the ^{158}Gd target and Dr. E. Spamer for his excellent help with the accelerator beams.

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