Evidence for enhanced electric dipole excitations in deformed rare earth nuclei near 2.5 MeV

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Measurements of the linear polarization of resonantly scattered photons have been used for model independent parity assignments in nuclear resonance fluorescence experiments. The novel result of the present study was the first observation of enhanced *electric* dipole excitations in the deformed nuclei ^{150}Nd and ^{162}Dy at excitation energies of 2.414 and 2.520 MeV, respectively. The transition energies and the enhanced $B(E1)\uparrow$ strengths of 3 and 5×10^{-3} e^2fm^2 support the interpretation in terms of the predicted new type of collective electric dipole excitations in deformed nuclei due to reflection asymmetric shapes like octupole deformations and/or cluster configurations.

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In the past years there have been hints both from experimental work [1-4] and theoretical calculations [5-7] for the occurrence of enhanced *electric* dipole transitions in deformed, heavy nuclei due to reflection asymmetric shapes. Very recently Butler and Nazarewicz [8] discussed and explained intrinsic electric dipole moments in nuclei of the Ra-Th and Ba-Sm region deduced from studies of alternating parity bands with enhanced $E1$ and $E3$ transitions and parity doublets. As discussed by Iachello [9], specificly for the deformed rare earth nucleus ^{150}Nd, rather collective $E1$ *ground state* transitions are expected from states near 3 MeV excitation energy due to α-cluster configurations and/or octupole deformations. Recently Soloviev and Sushkov [10] also explained enhanced $\Delta K=0$ electric dipole excitations in even-even deformed nuclei within a quasiparticle-phonon model. On the other hand, it is well known that in the same excitation energy range, around 3 MeV, strong orbital *magnetic* dipole excitations occur in deformed nuclei, often referred to as the "*scissors mode*." This magnetic mode was discovered in high-resolution electron scattering experiments by Richter and co-workers [11]. Meanwhile it has been investigated in numerous electron and photon scattering experiments (see Refs. [12,13]). These studies showed that the $M1$ strengths can be rather fragmented. Therefore, parity determinations are imperative when searching for the above mentioned new *electric* dipole modes in the same energy region.

The systematics of $K=0$, $J=1^-$ states in rare earth nuclei observed in our previous systematic photon scattering experiments [14] shows that the $K^\pi=0^-$ strength is mainly concentrated in one or two transitions near 1.5

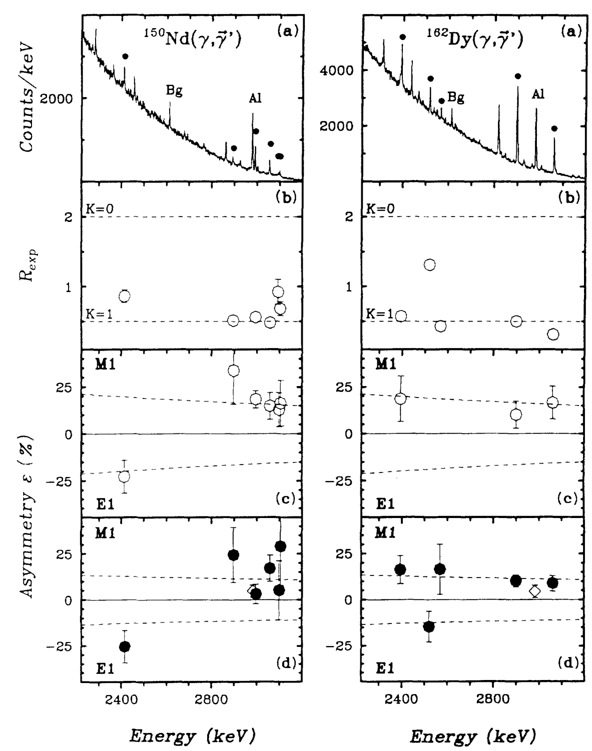

FIG. 1. Experimental results for ^{150}Nd(γ,γ') and ^{162}Dy(γ,γ'). (a) Energy spectra of scattered photons. (b) Decay branching ratios $R_{exp}=B(1\rightarrow 2_1^+)/B(1\rightarrow 0_1^+)$. (c) Asymmetries ϵ measured by the five-Ge-detector polarimeter. (d) Asymmetries ϵ measured by the sectored Ge polarimeter (see text).

TABLE I. Results for ^{150}Nd: Excitation energies, ground state widths Γ_0, transition probabilities $B(E1)\uparrow$ and $B(M1)\uparrow$, azimuthal asymmetries ϵ, K-quantum numbers, spins, and parities J^π.

Energy (MeV)	Γ_0 (meV)	$B(E1)\uparrow$ ($10^{-3}e^2$fm^2)	$B(M1)\uparrow$ (μ_N^2)	Asymmetry ϵ (%) 5-detector polarimeter	Sectored Ge polarimeter	K	J^π
2.414	14.9 ± 2.0	3.0 ± 0.4	...	-23 ± 9	-26 ± 9	(0,1)	1^-
2.895	12.1 ± 1.7	...	0.13 ± 0.02	34 ± 18	24 ± 15	1	1^+
2.994	67.0 ± 7.3	...	0.65 ± 0.07	18 ± 5	3 ± 5	1	1^+
3.058	38.2 ± 4.3	...	0.35 ± 0.04	15 ± 7	17 ± 7	1	1^+
3.096	14.9 ± 3.0	...	0.13 ± 0.03	13 ± 9	5 ± 16	1	1^+
3.103	14.4 ± 2.2	...	0.13 ± 0.02	16 ± 12	29 ± 21	1	1^+

MeV with summed strengths of $\sum B(E1)\uparrow\approx20\times10^{-3}$ e^2fm^2 (corresponding to a rather high value of $\approx4\times10^{-3}$ Weisskopf units), whereas the strength at higher energies is rather fragmented. In Ref. [14] the low-lying 1^- states are discussed in terms of $K=0$ rotational bands based on an octupole vibration as suggested by Donner and Greiner [15]. On the other hand, in ^{162}Dy and ^{150}Nd two strong transitions near 2.5 MeV exhibit decay branching ratios of the corresponding levels indicating K mixing [16]. The aim of the present study is to determine the parities of these two states to search for the proposed enhanced *electric* dipole excitations due to an octupole deformation and/or an α clustering and to look for a possible relation to K mixing.

Nuclear resonance fluorescence (NRF) experiments [17] are very suitable to detect this type of dipole excitations, due to the high selectivity of the real photon probe to excite low spin states [mainly dipole ($E1$,$M1$) and to a lesser extent electric quadrupole transitions ($E2$) are induced]. The multipolarities of the transitions can be determined easily from the measured angular distributions. So far in most of the previous systematic photon scattering experiments parity assignments came from a comparison with electron scattering form factors or by applying the Alaga rules [18]. A recent microscopic and phenomenological analysis of the Alaga rule for dipole states by Hammarén *et al.* [19] shows that spin 1 states with strong ground state transition widths exhibit decay branchings as given by the Alaga rules. Within their validity the measured decay branching ratios to the first excited 2^+ states and to the 0^+ ground states (in even-even deformed nuclei) enable us to determine the K quantum numbers of the excited states. Negative parties can be assigned to $K=0$ levels, whereas for $K=1$ states either negative or positive parities are possible. In our present photon scattering experiments parities are assigned model independently by measuring the linear polarization of the scattered photons by using Compton polarimeters. The photon scattering technique [17], the experimental setup and procedure are described in detail in our preceding paper [20].

The experiments have been performed at the bremsstrahlung facility [21] installed at the Stuttgart Dynamitron accelerator [$E_0=4$ MeV, $I\approx0.8$ mA (cw)]. Two different Compton polarimeters have been used simultaneously, a five-detector setup of Ge and Ge(Li) detectors and a sectored single-crystal Ge polarimeter [20].

The parity information is obtained from the measured asymmetry ϵ:

$$\epsilon=\frac{N_\perp-N_\parallel}{N_\perp+N_\parallel}, \tag{1}$$

where $N_\perp$ and $N_\parallel$ represent the rates of Compton scattered events perpendicular and parallel to the NRF scattering plane defined by the directions of the photon beam and the scattered photons, respectively. The asymmetry ϵ is given by the product of the polarization sensitivity Q of the polarimeter and the degree of polarization P_γ of the scattered photons. At a scattering angle of $\theta=90°$ to the beam axis the polarization P_γ amounts to -1 or $+1$ for pure $E1$ and $M1$ excitations, respectively (0-1-0 spin sequences). Therefore, obviously the sign of the asymmetry ϵ determines the parity.

Figure 1 summarizes the experimental results for the

TABLE II. Results for ^{162}Dy: Excitation energies, ground state widths Γ_0, transition probabilities $B(E1)\uparrow$ and $B(M1)\uparrow$, azimuthal asymmetries ϵ, K-quantum numbers, spins, and parities J^π.

Energy (MeV)	Γ_0 (meV)	$B(E1)\uparrow$ ($10^{-3}e^2$fm^2)	$B(M1)\uparrow$ (μ_N^2)	Asymmetry ϵ (%) 5-detector polarimeter	Sectored Ge polarimeter	K	J^π
2.520	27.7 ± 2.0	5.0 ± 0.4	...	...	-14.6 ± 8.3	(0,1)	1^-
2.395	27.3 ± 1.6	...	0.52 ± 0.03	18.6 ± 12.2	16.3 ± 7.6	1	1^+
2.596	8.7 ± 0.9	...	0.13 ± 0.01	...	16.5 ± 13.6	1	1^+
2.900	153 ± 9	...	1.63 ± 0.10	10.1 ± 7.2	10.2 ± 3.3	1	1^+
3.061	95 ± 8	...	0.86 ± 0.08	16.6 ± 8.9	8.9 ± 4.1	1	1^+

reactions ^{150}Nd($\gamma,\vec{\gamma}'$) (left part) and ^{162}Dy($\gamma,\vec{\gamma}'$) (right part). The upper parts (a) show the (γ,γ') spectra in the energy range 2.2–3.2 MeV measured by the sectored Ge detector. Peaks marked by dots correspond to ground state transitions where a parity assignment could be achieved. In parts (b) the branching ratios $R_{exp}=B(1\rightarrow 2_1^+)/B(1\rightarrow 0_1^+)$ are plotted. The dashed lines correspond to the expectation values for pure $K=0$ and $K=1$ excitations, respectively. In parts (c) the asymmetries measured by the five-detector setup are depicted. The dashed lines correspond to the polarization sensitivity (experimental asymmetries expected for pure $M1$ and $E1$ excitations, respectively) estimated for this setup [22]. Parts (d) show the corresponding results for the asymmetries obtained with the sectored Ge-Compton polarimeter. Here the dashed lines represent the polarization sensitivity of this device determined experimentally in the energy range 0.512–4.4 MeV by using a (γ,γ) cascade in ^{106}Pd and several ($p,p'\gamma$) reactions [23].

In ^{150}Nd the parities of excitations clustered near 3 MeV were confirmed to be positive as already known from our first polarization measurements [20,24]. These transitions, therefore, should be considered to belong to the orbital $M1$ scissors mode. Similar conclusions hold for the states in ^{162}Dy near 3 MeV. However, the surprising new results of the present experiment were the detection of a strong $E1$ excitation at 2.414 MeV in ^{150}Nd and a similar excitation in ^{162}Dy at 2.520 MeV. The negative parity of this 2.520 MeV state could be determined by the improved sectored polarimeter. In addition it should be emphasized that both these $J^\pi=1^-$ states exhibit a decay branching ratio R_{exp} deviating from the expected values for pure $K=0$ and $K=1$ states and therefore hint to a possible K mixing [see parts (b) of Fig. 1].

In Tables I and II the numerical results of the present study are summarized together with the decay widths Γ_0 and transition probabilities $B(M1)\uparrow$ and $B(E1)\uparrow$ as measured in our previous and present (γ,γ') experiments [25,26].

The strong low-lying $E1$ excitations cannot be explained by an extrapolation of the isovector giant dipole resonance to the low-energy region. Following the procedure outlined in Refs. [9,27] and assuming a Porter-Thomas strength distribution the probability to find such strong excitations as observed here is less than 1%. Therefore, we have to look for other explanations.

Iachello has proposed α clustering as a mechanism to explain enhanced $E1$ transitions in the energy range 2–3 MeV in deformed nuclei [9]. Within this clustering picture the static dipole moment D amounts to

$$D_{cluster}=2e[(N-Z)/A]R_0(A_1^{1/3}+4^{1/3}),\ A=A_1+4. \tag{2}$$

This dipole moment leads to an $E1$ transition strength of

$$B(E1,\text{cluster})=\eta^2\frac{9}{4\pi}\frac{\langle D^2_{cluster}\rangle}{6} \tag{3}$$

for soft clustering (deformed nuclei), where η represents the cluster amplitude mixed into the ground state. Even small admixtures, e.g., $\eta^2=1\times10^{-3}$, can explain the order of magnitude of the transition strengths observed in the experiments. For α clustering an $E1$ sum rule can be deduced [28]

$$S_1(\alpha+A_1)=\frac{9}{4\pi}\frac{(N-Z)^2}{A(A-4)}\frac{(\hbar c)^2}{2Mc^2}e^2. \tag{4}$$

This sum rule value is exhausted to about 1% and 3% by the observed $E1$ transitions in ^{150}Nd and ^{162}Dy, respectively.

A second mechanism producing strong $E1$ excitations based on previous suggestions [29–31] has also been discussed by Iachello [9]. In the case of a nucleus with a permanent octupole deformation, electrostatic effects create a dipole moment

$$D_{oct}=0.000687AZ\beta_2\beta_3\ (e\,\text{fm}), \tag{5}$$

where β_2 and β_3 are the quadrupole and octupole deformation parameters, respectively. This dipole moment then leads to an enhanced $E1$ transition strength of

$$B(E1,\text{octupole})=\frac{9}{4\pi}\frac{\langle D^2_{oct}\rangle}{6} \tag{6}$$

for a soft deformation. Assuming reasonable values [4,7,8] of $\beta_2=0.25$ and $\beta_3=0.1$ the $B(E1)$ values given in Table III agree very well with the experimental results.

TABLE III. Comparison of experimentally observed $E1$ strengths with model predictions. For the cluster configuration a ground-state admixture of $\eta^2=0.001$ has been assumed; for the octupole deformation model deformation parameters of $\beta_2=0.25$ and $\beta_3=0.1$ are used to estimate the strengths (see text).

Nucleus	E_x (MeV)	$B(E1)\uparrow$ ($10^{-3}e^2\,\text{fm}^2$) α clustering	Octupole def.	Experiment
^{150}Nd	2.414	1.29	2.9	3.0±0.4
^{162}Dy	2.520	1.15	4.0	5.0±0.4

Both the cluster and the octupole-shaped models are able to explain at least the right order of magnitude of the observed $E1$ strengths. However, on the basis of the presented (γ,γ') results it is not possible to distinguish between the different excitation mechanisms proposed. There is a need for further experiments, in particular for (e,e') form factor measurements to get a deeper insight into the nuclear structure of these new enhanced $E1$ excitations near 2.5 MeV in deformed nuclei in the rare earth mass region.

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