First Observation of Scissors Mode States in an Odd-Mass Nucleus

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Nuclear resonance fluorescence experiments are reported to search for enhanced $M1$ scissors mode states in the deformed odd-mass nucleus ^{163}Dy. A concentration of dipole strengths near 3 MeV excitation energy is found, which fits nicely into the systematics observed for $M1$ excitations in the neighboring even-even Dy isotopes. The observed strength distribution and the decay branching ratios are discussed in the context of the interacting boson-fermion model.

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The observation in 1984 of strongly $M1$-excited 1^+ states in deformed, doubly even nuclei by Richter and collaborators [1] was eventually interpreted in terms of the oscillation of the neutron and proton distributions against each other in a scissorslike motion [2]. This new collective excitation was predicted both by the two-rotor model [3] and by the neutron-proton interacting boson model (IBM-2), where these modes are associated to nonsymmetric representations in the boson space [4]. To explain the underlying microscopic structure of these states different random-phase-approximation (RPA) calculations have been performed by several groups [5].

Since 1984 numerous electron and photon scattering experiments provided detailed information on the distribution of magnetic dipole strength in deformed even-even nuclei [6]. The $M1$ strength concentrated near 3 MeV was shown to be predominantly of orbital character, consistent with the scissors mode interpretation.

The question of whether scissors mode excitations are to be expected in odd-mass nuclei, and if so what properties they would display, was addressed in Refs. [7,8], which predicted the excitation with observable $M1$ strength of nonsymmetric states for both multi-j and single-j occupation of the odd nucleon. The Darmstadt group recently reported on a search for $M1$ strength in the ^{165}Ho [9]. However, no strong transition with $B(M1)\uparrow \geq 0.1\mu_N^2$ could be detected in the energy range around 3 MeV.

For the present nuclear resonance fluorescence (NRF) experiment the nucleus ^{163}Dy was chosen as a first candidate since the neighboring even-even nuclei ^{162}Dy and ^{164}Dy are well investigated [10]. In both isotopes the orbital $M1$ strength is concentrated in two or three strong transitions and in ^{164}Dy the $M1$ strength is the largest of all rare-earth nuclei. Furthermore, detailed spectroscopic information from (n,γ), $(n,n'\gamma)$, (d,p), and (d,t) reaction studies is available for this isotope [11]. In addition, the single-particle Schmidt g values are smaller for the odd-neutron isotopes in this mass region than they are for the odd-proton isotopes and, as a consequence, one can expect, in the odd-neutron case, orbital $M1$ excitations to more clearly stand out of single-particle $M1$ excitations, an expectation borne out by more detailed calculations [8]. These arguments have led us to conclude that ^{163}Dy is a more favorable case than ^{165}Ho.

The experiments were performed at the NRF facility installed at the high-intensity bremsstrahlung beam of the 4 MV Stuttgart dynamitron [12]. Three high resolution Ge γ spectrometers under angles of 92, 126, and 151 degrees with respect to the incident photon beam measured the intensities and energies of photons resonantly scattered off a ^{163}Dy target (enriched to 92.8%, total mass $\sim$2.8 g). The setup and the experimental technique are described elsewhere [12].

Unfortunately, in odd-mass isotopes the spins J of the states excited in NRF experiments cannot be determined unambigiously from the nearly isotropic angular distributions. In ^{163}Dy with a ground-state spin-parity $J_0^\pi = 5/2^-$, states with $J = 3/2$, $5/2$, and $7/2$ can be excited by dipole transitions.

The results of the experiment are summarized in Table I: the observed excitation energies E, the integrated scattering cross sections I_S, the ground-state transition widths $g\Gamma_0$, the branching ratios Γ_1/Γ_0 for the decay of the excited levels to the first excited state $7/2_1^-$ and ground state, respectively, and the reduced transition probabilities $B(M1)\uparrow$, assuming a positive parity and a spin factor $g = 1$. Figure 1 shows a comparison of the

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TABLE I. Results of the present ^{163}Dy(γ,γ') experiment.

E (keV)	I_s (eV b)	$g\Gamma_0$ (meV)	Γ_1/Γ_0	$B(M1)\uparrow$[a] (μ_N^2)
1942	11.3 ± 1.7	11.1 ± 1.7		0.131 ± 0.021
2104	2.2 ± 0.6	2.5 ± 0.6		0.023 ± 0.006
2180	16.4 ± 2.1	25.9 ± 4.1	0.26 ± 0.06	0.216 ± 0.041
2213	13.9 ± 2.2	23.6 ± 4.6	0.33 ± 0.08	0.188 ± 0.043
2472	6.3 ± 1.0	10.0 ± 1.6		0.057 ± 0.009
2542	8.0 ± 1.2	13.5 ± 2.0		0.071 ± 0.010
2566	5.9 ± 1.0	10.2 ± 1.7		0.052 ± 0.008
2587	13.7 ± 1.8	23.8 ± 3.2		0.119 ± 0.016
2918	4.6 ± 0.8	10.1 ± 1.8		0.035 ± 0.006
2958	23.4 ± 2.9	66.4 ± 8.6	0.23 ± 0.04	0.222 ± 0.033
2967	5.1 ± 0.9	11.6 ± 2.0		0.038 ± 0.006
2976	4.5 ± 0.7	10.5 ± 1.8		0.034 ± 0.006
3037	10.3 ± 1.5	42.3 ± 10.6	0.71 ± 0.14	0.130 ± 0.036
3045	11.7 ± 1.6	28.3 ± 3.9		0.087 ± 0.012
3057	6.2 ± 0.9	15.0 ± 2.3		0.045 ± 0.007
3087	4.5 ± 0.8	39.0 ± 10.4	2.49 ± 0.55	0.115 ± 0.036
3099	8.8 ± 1.2	41.2 ± 10.9	0.85 ± 0.17	0.120 ± 0.033
3107	4.7 ± 0.8	31.0 ± 11.4	1.31 ± 0.32	0.089 ± 0.030

[a]Assuming $g = 1$ ($J = 5/2$) and $M1$ transitions.

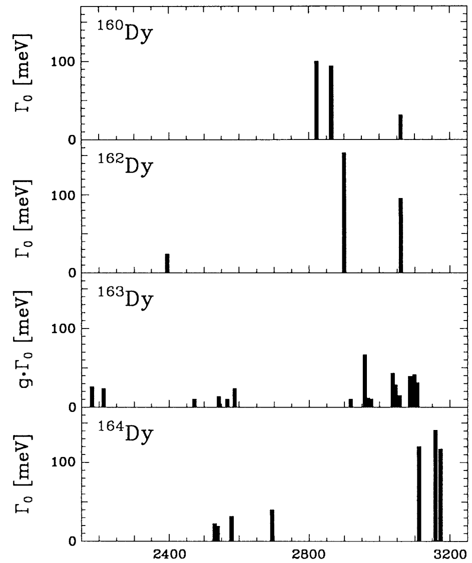

FIG. 1. Dipole strength distribution in ^{163}Dy (this experiment) in comparison with that in even-even Dy isotopes obtained in previous NRF measurements [10].

transition strengths observed in ^{163}Dy with our previous data for ^{160,162,164}Dy [10]. Because of the unknown J in the case of ^{163}Dy the quantity $g\Gamma_0$ is plotted. The factor $g = (2J+1)/(2J_0+1)$ amounts to 2/3, 1, and 4/3 for spins $J = 3/2$, 5/2, and 7/2, respectively. There is a clear concentration of dipole strength in ^{163}Dy near 3 MeV which fits nicely into the systematics of the even Dy isotopes, where the corresponding peaks are claimed to have a scissorslike character [10,13,14].

The ground state of ^{163}Dy arises predominantly from the $f_{7/2}$ and $h_{9/2}$ orbits, and an extension of the formalism presented in Ref. [8] is required. For a single orbit, the lowest-energy configurations of the odd-mass nucleus are described in terms of the single particle strongly coupled to the core's $K^\pi = 0^+$ ground-state band, which in a first approximation can be associated to the $(2N,0)$ representation of the SU(3) limit of the interacting boson model [15]. In turn, the scissors mode states arise from the coupling of the particle to the $K^\pi = 1^+$ band which is associated to the $(2N-2,1)$ SU(3) representation [8]. Closed formulas for various properties of the scissors mode states can then be evaluated, which can be used as a guide for more realistic calculations using the interacting boson-fermion model (IBFM) [16].

The single-j analysis cannot be applied as it stands to ^{163}Dy, but some simple assumptions allow its generalization. The two dominant orbits in ^{163}Dy can be considered to be pseudospin partner orbits [17], that is, with $j = \tilde{l} \pm 1/2$ where $\tilde{l}$ is the pseudo-orbital angular momentum of the odd particle ($\tilde{l} = 4$ in ^{163}Dy). If we further assume that the strong coupling of the particle to the (axially symmetric) core involves the pseudo-orbital part only, we find states of the form

$$|K_R, K_{\tilde{l}}\tilde{l}, K_L LJM_J\rangle = \sum_{M_L\sigma} \langle LM_L 1/2\sigma|JM_J\rangle |K_R, K_{\tilde{l}}\tilde{l}, K_L LM_L\rangle |1/2\sigma\rangle \ , \tag{1}$$

with

$$|K_R, K_{\tilde{l}}\tilde{l}, K_L LM_L\rangle = \sum_R \sqrt{2R+1} \begin{pmatrix} R & \tilde{l} & L \\ -K_R & \mp K_L + K_R & \pm K_L \end{pmatrix} [1+(-1)^R \delta_{K_R 0}]^{1/2} |K_R R, K_{\tilde{l}}\tilde{l}; LM_L\rangle \ , \tag{2}$$

where $|K_R R, K_{\tilde{l}}\tilde{l}; LM_L\rangle$ represents a weak-coupling state, that is, a state in which the core angular momentum R is coupled with $\tilde{l}$ to L. Furthermore, K_R, $K_{\tilde{l}}$, and K_L are the projections of R, $\tilde{l}$, and L, respectively, on the axis of symmetry and are conserved quantities in the strong-coupling basis. With these assumptions the $M1$ strength may be evaluated in closed form as in the single-j case [18].

We present the results of our analysis for the excitation of scissors mode states in ^{163}Dy in Table II in the columns $\tilde{l} = 4$. In the upper half of the table we list the three states which have largest $B(M1)\uparrow$ values; all other states are excited with significantly smaller strengths.

TABLE II. Calculated excitation and decay of nonsymmetric (ns) states in ^{163}Dy.

		$B(M1; J_i \to J_f)$ (μ_N^2)			$B(E2; J_i \to J_f)$ $(10^{-3} e^2\,\mathrm{b}^2)$		
J_i	J_f	$\tilde{l}=4$	$j=7/2$	$j=9/2$	$\tilde{l}=4$	$j=7/2$	$j=9/2$
$5/2_1$	$3/2_{ns}$	0.41	0.45	0.45	0.17	0.31	0.31
$5/2_1$	$5/2_{ns}$	0.20	0.18	0.18	0.34	0.42	0.42
$5/2_1$	$7/2_{ns}$	0.62	0.66	0.65	0.44	0.58	0.58
$3/2_{ns}$	$5/2_1$	0.61	0.68	0.68	0.25	0.46	0.46
$3/2_{ns}$	$7/2_1$	0.00	0.00	0.00	0.67	0.69	0.68
$5/2_{ns}$	$5/2_1$	0.20	0.18	0.18	0.34	0.42	0.42
$5/2_{ns}$	$7/2_1$	0.44	0.29	0.50	0.00	0.02	0.02
$5/2_{ns}$	$9/2_1$	0.00	0.00	0.00	0.66	0.71	0.71
$7/2_{ns}$	$5/2_1$	0.47	0.49	0.49	0.33	0.43	0.43
$7/2_{ns}$	$7/2_1$	0.17	0.09	0.16	0.43	0.47	0.46
$7/2_{ns}$	$9/2_1$	0.02	0.02	0.02	0.23	0.21	0.21

The $B(M1)$ values depend on the square of the difference between the neutron and proton boson g factors, which is taken from [19], $(g_\nu - g_\pi)^2 \sim 0.36\mu_N^2$. We also give in Table II the corresponding $B(E2)$ values which depend on the square of the difference between the boson quadrupole charges. Though expected to be fairly small, this is more difficult to calculate; a reasonable estimate is given in [20], $(e_\nu - e_\pi)^2 \sim 0.000\,36\, e^2\,\mathrm{b}^2$. This results in $M1$ being the dominant excitation of the scissors mode states.

The three states that are appreciably excited have spins $J = 7/2$, $3/2$, and $5/2$ (in order of decreasing strength). We also list, in the lower half of Table II, their decay into the symmetric states, which are all predicted to belong to the ground-state band. This follows from the collective nature of the transitions, which do not alter the pseudo-orbital single-particle projection. As the validity of the pseudospin symmetry in ^{163}Dy is questionable, we also performed calculations in which only one single-particle orbit (either $f_{7/2}$ or $h_{9/2}$) is strongly coupled to the core. The results are listed in Table II in the columns $j = 7/2$ and $j = 9/2$. The $M1$ excitation results do not differ significantly from each other or from those for $\tilde{l} = 4$; the decay, however, is more sensitively dependent on the single-particle j and/or the coupling scheme.

On the basis of these results one may attempt an interpretation of some of the observed scissors mode states. For example, the 2958 keV level is strongly $M1$ excited (relative to other levels) and has an $M1$ branching ratio $R = 0.23$; both features are in qualitative agreement with the calculated $J = 7/2$ scissors mode state.

A numerical IBFM calculation has also been carried out. Details of this calculation will be presented elsewhere [18]. We remark here that the numerical analysis confirms the general picture obtained from the strong-coupling calculation. The strength is predicted to spread out over a larger number of states, however, in accordance with the observations, while the *summed* strength remains of the same order of magnitude.

The systematics displayed in Fig. 1 for the average energy of the scissors mode states in the even-even isotopes displays an approximate linear variation with valence particle number. This result is consistent with a Majorana interaction in the IBM-2 Hamiltonian which has the expectation value $\alpha(\frac{1}{2}N - F)(\frac{1}{2}N + F + 1)$, where α is the strength of the Majorana term and F is the F-spin quantum number, which takes the value $F = \frac{1}{2}N - 1$ for the scissors mode states [15]. For ^{163}Dy our assumption of strong coupling of the core to the odd neutron's pseudo-orbital angular momentum gives rise to an energy formula in the large-N limit of the form

$$
\begin{aligned}
E\{[N-f,f](\lambda,\mu)K_R, K_{\tilde{l}}\tilde{l}, K_L LJM_J\} = & -\kappa(\lambda^2+\mu^2+\lambda\mu+3\lambda+3\mu) + \alpha\left(\tfrac{1}{2}N - F\right)\left(\tfrac{1}{2}N + F + 1\right) \\
& - \lambda\{\sqrt{\tfrac{5}{2}}\Gamma R_{\tilde{l}}[3K_{\tilde{l}}^2 - \tilde{l}(\tilde{l}+1)] + \Lambda \tfrac{1}{3} R_{\tilde{l}}^2 [3K^2 - \tilde{l}(\tilde{l}+1)]^2\}\ ,
\end{aligned}
$$

where $F = \frac{1}{2}N - f$ and $R_{\tilde{l}} = [(2\tilde{l}-1)\tilde{l}(2\tilde{l}+1)(\tilde{l}+1)(2\tilde{l}+3)]^{-1/2}$. This expression is equivalent to formula (3.4) of Ref. [8] with $j \to \tilde{l}$, $K_j \to K_{\tilde{l}}$, and $K \to K_L$ and corresponds to a particle-core interaction which includes quadrupole and exchange contributions with strengths Γ and Λ, respectively [21]. Since the (λ,μ) and N values (for both symmetric and nonsymmetric states) are the same in ^{162}Dy and ^{163}Dy, this energy formula implies that the scissors mode states in the latter nucleus are, in the strong-coupling picture, expected to occur in a region centering around 3 MeV, where the $J = 1^+$ states in ^{162}Dy are observed.

We emphasize that the $E1$ character of the transitions observed in ^{163}Dy cannot be ruled out on experimental grounds. In the neighboring even-even isotopes, however, the positive parities of the levels around 3 MeV are deduced from electron scattering experiments [13] in the case of ^{164}Dy and for ^{162,164}Dy from photon linear polarization measurements [14,22]. Given the smooth variation of the energy of these levels as a function of neutron number, this strongly suggests an $M1$ character of the transitions to the 3 MeV levels in ^{163}Dy. The situation is less clear for the other levels in ^{163}Dy observed around 2.2 and 2.5 MeV. For example, the latter might be related to the 2.5 MeV levels in ^{162}Dy (not shown in Fig. 1; see [14]), in which case the associated transitions would have $E1$ character.

An RPA calculation for the nucleus ^{163}Dy could conceivably give us a better insight into the structure of the observed levels (e.g., one-quasiparticle or three-quasiparticle). We note that an interpretation of the ^{163}Dy levels around 3 MeV as one-quasiparticle states seems unlikely since calculations for odd-mass nuclei in the same mass region in the context of the Nilsson model [9] predict considerable $M1$ strength to one-quasiparticle states below 1.5 MeV but none to one-quasiparticle states around 3 MeV. Thus an RPA description of the ^{163}Dy levels necessarily would require three-quasiparticle states, but it remains to be investigated whether the observed levels correspond to collective superpositions of such three-quasiparticle states. In this respect it is useful to recall the situation in ^{164}Dy where both types of excitations exist: fairly pure two-quasiparticle states near 2.5 MeV [23] and more strongly $M1$-excited (i.e., presumably more collective) states around 3.1 MeV. Again, energy systematics would favor the more collective interpretation of the 3 MeV levels in ^{163}Dy.

It is not clear as yet whether these strong $M1$ excitations are as common a phenomenon in odd-mass nuclei as they are in even-even isotopes. Nevertheless, we believe the odd-mass scissors mode has important theoretical consequences for the following reason. One of the outstanding problems related to the scissors mode in deformed even-even nuclei is that no scissors mode state is observed other than $J^\pi = 1^+$ states, which are conjectured to be the bandhead of $K^\pi = 1^+$ band. This is understandable since $M1$ is by far the most favored excitation mode of these states [24]. In odd-mass nuclei, in contrast, $M1$ excitation out of the $J \neq 0$ ground state can lead, in general, to the bandhead as well as to other members of a single scissors mode band. A detailed experimental study of the scissors mode states in odd-mass nuclei can thus shed light on their band structure and perhaps once and for all settle the question of the collectivity of these states.

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