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Correlation between low-lying $M1$ and $E2$ strength in heavy rare earth nuclei

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Magnetic dipole excitation strengths attributable to the scissors mode in even-A rare earth nuclei between $A=140-190$ are collected and presented assuming the excitation energy as an additional signature for the fragments of this mode. In this whole mass region the total $M1$ strength is found to be proportional to the quantity $B(E2;0_1^+\rightarrow 2_1^+)/Z^2$ as has been known before for the Nd and the Sm nuclei. In the upper half of the $N=82-126$ major shell the $M1$ and the $E2$ strengths do not saturate. Both quantities exhibit a rather monotonous increase towards midshell.

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One of the most exciting findings in nuclear spectroscopy in the last decade is the observation of strong low-lying magnetic dipole excitations in deformed nuclei which are frequently referred to as a *scissors mode* [1,2]. A crucial proof of the "scissors" character of this $M1$ mode was the discovery of the so-called "δ^2 law" by Ziegler *et al.* [3] and its confirmation in Refs. [4–6]. In various nuclear models such as microscopical, algebraical, geometrical, and phenomenological models a large effort has been made to predict the energy and the excitation strength of the scissors mode. Nearly all of these models are consistent with a quadratic dependence of its excitation strength on the deformation parameter δ [7–18]. Thus the δ^2 law implies a saturation of the excitation strength of the scissors mode in light rare earth nuclei toward midshell as the deformation δ saturates. This effect is actually observed.

Contrary to the prediction of simple collective models such as the axially symmetric two rotor model which predicts a single scissors mode state, in real nuclei the scissors mode turns out to be fragmented into several states. This fragmentation considerably complicates the detection and identification of the scissors mode.

Since the prediction of the scissors mode [1] in the late seventies and its discovery [2] in 1984 in a high resolution electron scattering experiment the nuclei of the rare earth region have been systematically investigated by means of the nuclear resonance fluorescence (NRF) technique [19–21] which is particularly well suited to study dipole excitations from the ground state. Recent NRF experiments have provided (γ,γ') data on heavier nuclei [22–25]. It is the purpose of this paper to collect and discuss the available data for the even-A rare earth nuclei focusing on their dependence on the nuclear deformation and the numbers of nucleons.

We will first discuss how one can obtain information on the scissors mode from a (γ,γ') NRF experiment. Observables in NRF experiments on even-A nuclei are the excitation energy E, the spin J of the excited level, the branching ratio $R_{\mathrm{exp}}=B(\pi 1;1_i\rightarrow 2_1^+)/B(\pi 1;1_i\rightarrow 0_1^+)$, and the absolute dipole transition strengths $B(\pi 1;0_1^+\rightarrow 1_i)$. If a Compton polarimeter is used as is discussed in Refs. [26–28] information about the parities π of the excited states can be obtained. NRF measurements using a Compton polarimeter have been performed [6,29–31] for the nuclei ^{142,146,150}Nd, ^{160}Gd, and ^{162,164}Dy. For some nuclei additional information about the parities has come from high resolution electron scattering experiments (see e.g., [2,32,33]).

In NRF experiments without a polarimeter device it is difficult to identify the observed dipole excitations as fragments of the scissors mode because there is no direct information about the parity. In these cases it is possible to use indirect information from the rule of thumb, stating that nuclear states with $K=1$ that are strongly excited in (γ,γ') experiments have $\pi=+$ and states with $K=0$ have $\pi=-$. This "rule" works remarkably well in the energy region of the scissors mode around 3 MeV in the cases where it can be tested. A K quantum number can be assigned to a dipole excitation in well-deformed nuclei if the branching ratio R_{exp} of its decay to the ground state and to the 2_1^+ state is observed. This branching ratio can be compared to the predictions of the Alaga rule which yields

$$R_{\mathrm{Alaga}}(K=1)=\frac{B(\pi 1;I_K=1_1\rightarrow I_K=2_0)}{B(\pi 1;I_K=1_1\rightarrow I_K=0_0)}=0.5 \tag{1}$$

and

$$R_{\mathrm{Alaga}}(K=0)=\frac{B(\pi 1;I_K=1_0\rightarrow I_K=2_0)}{B(\pi 1;I_K=1_0\rightarrow I_K=0_0)}=2.0. \tag{2}$$

The observed branching ratios R_{exp} can differ from the theoretical predictions due to experimental errors and due to K impurities in the $J=1$ state. A survey of the distribution of the R_{exp} values is given in [34]. We have made the choice to assign a K value of $K=1$ if a decay branch to the 2_1^+ state is observed with a branching ratio less than one. By application of the rule of thumb those states around 3 MeV are considered to have positive parity that fulfill the condition $0<R_{\mathrm{exp}}<1$. This rule has exceptions as has been found in recent polarimeter measurements. In the nucleus ^{150}Nd, for instance, a rather strong 1^- state has been observed at an excitation energy of 2.414 MeV that shows a ground-state branching of $R_{\mathrm{exp}}<1$ [29]. Moreover, a state with $R_{\mathrm{exp}}=0.5$ at 3.751 MeV in the transitional nucleus ^{146}Nd has been identified to be a 1^- state [6]. Because of these exceptions it is useful to consider the excitation energy range

TABLE I. Summed $M1$ strengths in even-A nuclei in the $Z=50$–82, $N=82$–126 shell. All states in the given energy range with branching ratios $0<R_{\mathrm{exp}}<1$ have been included in the sum as is discussed in the text. The errors given have been obtained by quadratically adding the individual errors of the contributing fragments. Possible systematic errors are not considered.

Nucleus	$\Sigma B(M1)\uparrow[\mu_N^2]$	E [MeV]	Ref.
^{142}Nd	0.00(00)	2.7–3.7	[6]
^{146}Nd	0.72(06)	2.7–3.7	[6]
^{148}Nd	0.78(07)	2.7–3.72	[6]
^{150}Nd	1.61(09)	2.68–3.7	[6]
^{144}Sm	0.00(00)	2.7–3.7	[36]
^{148}Sm	0.43(12)[a]	2.7–3.7	[39]
^{150}Sm	0.92(06)	2.7–3.7	[39]
^{152}Sm	2.26(09)	2.7–3.7	[39]
^{154}Sm	2.18(12)	2.7–3.7	[39]
^{154}Gd	2.60(50)	2.7–3.7	[32]
^{156}Gd	2.73(27)	2.7–3.7	[38]
^{158}Gd	3.39(17)	2.7–3.7	[38]
^{160}Gd	2.97(12)	2.7–3.7	[30]
^{160}Dy	2.42(18)	2.7–3.7	[37]
^{162}Dy	2.49(13)	2.7–3.7	[29]
^{164}Dy	3.18(15)	2.7–3.7	[31,40]
^{164}Er	1.45(14)	2.4–3.7	[24]
^{166}Er	2.67(19)	2.4–3.7	[24]
^{168}Er	2.82(42)	2.4–3.7	[24]
^{170}Er	2.63(16)	2.4–3.7	[24]
^{172}Yb	1.94(22)	2.4–3.7	[22]
^{174}Yb	2.70(31)	2.4–3.7	[22]
^{176}Yb	2.66(34)	2.4–3.7	[22]
^{178}Hf	2.04(07)	2.4–3.7	[25]
^{182}W	1.65(10)	2.4–3.7	[23]
^{184}W	1.12(17)	2.4–3.7	[23]
^{186}W	0.82(12)	2.4–3.5	[23]

[a]For the calculation of the total $M1$ strength a printing error in the publication has been corrected.

as an additional signature for the fragments of the scissors mode. Therefore, only those states are assumed to contribute to the scissors mode where a decay to the 2_1^+ state has been observed with a branching ratio of $0<R_{\mathrm{exp}}<1$ and which lie within an energy range of 2.7 MeV$<E<$3.7 MeV for $Z<68$, and 2.4 MeV$<E<$3.7 MeV for $Z\geqslant 68$. The larger energy range for the heavier nuclei accounts for the stronger fragmentation of the scissors mode in them. An additional argument to neglect ($\Delta K=1$) strength below 2.7 MeV in the lighter rare earth nuclei is the existence of low-lying two-quasiparticle $M1$ excitations around 2.5 MeV as reported from a particle transfer experiment [35] on the nucleus ^{164}Dy.

The "total $M1$ strength" of the scissors mode is obtained from the experiments [6,22–25,32,36–39] by summing the $M1$ excitation strengths of all fragments of the mode. For ^{148}Nd as well as ^{150}Nd the excitation strength of one state less than 20 keV outside of the energy window has been included in the sum. In ^{164}Dy the large spin flip strength of $B(M1)_{\mathrm{spin}}=0.5\mu_N^2$ around 3.1 MeV determined in [40] has been subtracted. The measurement on ^{186}W has been carried

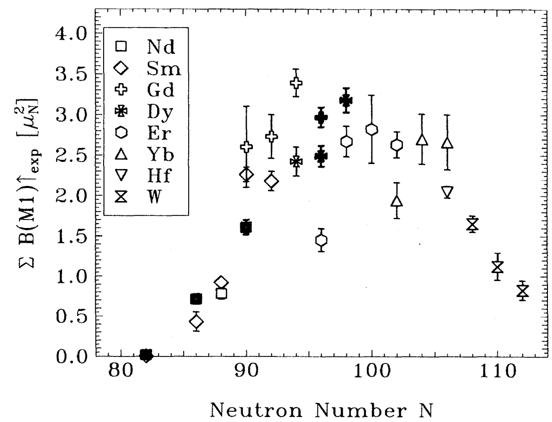

FIG. 1. Summed $M1$ strengths for the even-A rare earth nuclei in the energy range of the scissors mode. The plotted $B(M1)$ strengths are taken from Table I. For some nuclei (solid symbols) parities have been determined by Compton polarimeter measurements (see [6,29–31]). For the other nuclei (open symbols) all $\Delta J=1$, $\Delta K=1$ excitations in a certain energy range have been considered. Detailed explanations are given in the text.

out with an end-point energy of 3.5 MeV, and hence some fragments of the scissors mode between 3.5 and 3.7 MeV may be lost. The data point for ^{154}Gd is from an (e,e') measurement [32].

In Table I the "total $M1$ strengths" of the scissors mode are presented for the even-A rare earth nuclei. These same data are also shown in Fig. 1 where they are plotted versus the neutron number N. The error bars have been calculated by quadratically summing up the errors for those states defined to be fragments of the scissors mode by the procedure described above. Possible systematical errors are not taken into consideration.

In the energy range in question the observed $M1$ strength vanishes for spherical nuclei and increases toward midshell where a saturation value of about $B(M1)\uparrow=2.6\mu_N^2$ is reached. Two nuclei, ^{164}Er and ^{172}Yb, apparently show lower values. We note however, that the NRF target for ^{164}Er had only a poor isotopical enrichment and hence some strength may be lost in the large background. Just above the neutron midshell $N=104$ the strength begins to drop again to about $1\mu_N^2$ in ^{186}W.

From the δ^2 law [3,6] observed in the light rare earth nuclei one expects to find a proportionality between the total $M1$ strength and the square of the nuclear deformation in the heavier nuclei as well. For rigid, axially symmetric, quadrupole deformed nuclei $\beta_2=1.585\times\sqrt{B(E2)[\mathrm{s.p.u.}]}/Z$ is a simple measure of the quadrupole deformation.

To be model independent we will now investigate the ratio of the total $M1$ strength to $B(E2;0_1^+\rightarrow 2_1^+)/Z^2$ as the $B(E2;0_1^+\rightarrow 2_1^+)$ value exhausts more than 90% of the whole low-lying $E2$ excitation strength in all collective nuclei [41]. To separate a trivial mass dependence single particle units[1] (s.p.u.) have been used for the transition strengths in the calculation of the quantity $B(M1)*Z^2/B(E2)$ which is

[1]$B_{sp}(M1;0\rightarrow 1)=5.37\mu_N^2$, $B_{sp}(E2;0\rightarrow 2)=0.297A^{4/3}e^2$ fm^4.

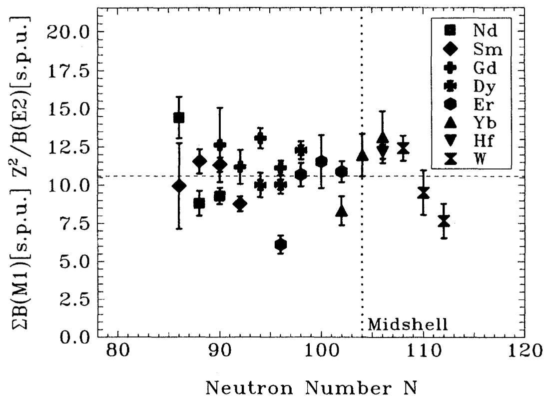

FIG. 2. Ratios of the total $B(M1)$ values from Table I and $B(E2;0_1^+ \rightarrow 2_1^+)$ values from [43] times the square of the nuclear charge Z.

rather constant for all nuclei considered as can be seen from Fig. 2. We thus conclude that the excitation strength of the scissors mode is approximately proportional to the quantity $B(E2;0_1^+ \rightarrow 2_1^+)/Z^2$ for all stable even-A nuclei in the mass region $A \approx 140-180$. On average we obtain the relation

$$B(M1)_{\mathrm{Sc}}[\mathrm{s.p.u.}(M1)] = \frac{10.6}{Z^2} B(E2)[\mathrm{s.p.u.}(E2)]. \quad (3)$$

It should be emphasized that this correlation between $M1$ and $E2$ strength is found to be also valid in the upper half of this major shell.

From Fig. 1 one sees that the total $M1$ strength already starts to decrease just above the neutron midshell at $N=104$ in the Hf and W nuclei. There, the upper half of the $Z=50-82$ proton major shell is already partially filled. To investigate the saturation behavior of the total $M1$ strength in more detail it is useful to consider its dependence on the P factor [42] which scales the proton neutron interaction. $P=N_pN_n/(N_p+N_n)$ is the product of the numbers of the valence protons and neutrons divided by their sum. Shell closures for the calculation of P have been considered at $Z=50{,}82$ and $N=82{,}126$. Above midshell N_p and N_n denote the numbers of valence holes. In this major shell P is maximal for the nucleon combination ($Z=66$, $N=104$). Therefore, we consider a nucleus with mass $A=66+104=170$ to lie at midshell. In the following the stable even-A rare earth nuclei with a mass $A \leqslant 170$ will be referred to as *group I* and the stable even-A nuclei in the $N=82-126$ shell with a mass $A>170$ will be referred to as *group II*.

The total $M1$ strengths from Table I are plotted versus the P factor in Fig. 3 where the data points for nuclei belonging to group II are emphasized. The data for the two groups lie close to two distinct tracks. It should be noted that the functional dependence of $B(M1)$ on P for group II is less pronounced than for group I because of the smaller number of data points. However, up to $P \approx 8$ the total $M1$ strength increases monotonously for the W, Hf, and Yb nuclei. In contrast to group I (see also Ref. [4]) the $M1$ strength for group II does not saturate.

Because of the proportionality of the total $M1$ strength and the quantity $B(E2)/Z^2$ for the nuclei of group II as well, it is interesting to investigate the P dependence of the $B(E2)$ strength. For all stable even-A nuclei in the $N=82-126$ major shell Fig. 4 shows the $B(E2;0_1^+ \rightarrow 2_1^+)$ values taken from Ref. [43]. Again the $B(E2)$ values are given in single particle units.

As was already seen for the total $M1$ strength the dependence of the $E2$ strength for group II on the P factor differs from that of group I. While undergoing a shape transition from the γ-soft Pt isotopes to the rigid deformed nuclei near midshell the increase of the $E2$ strength with P

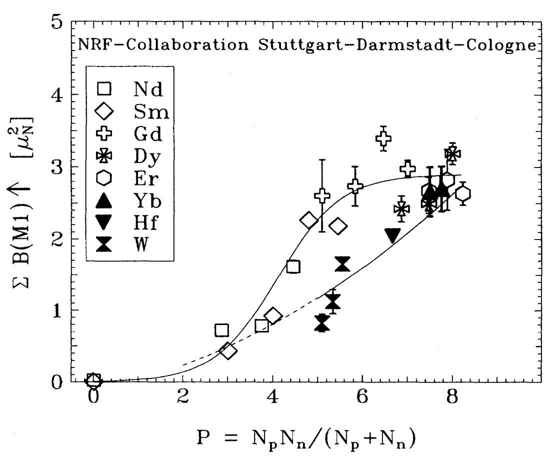

FIG. 3. Experimentally observed total $M1$ strength plotted versus the P factor. Solid symbols denote Yb, Hf, and W nuclei with $A \geqslant 170$. The data points fall on two distinct tracks for nuclei with either more or less nucleons than 170. The points for ^{164}Er and ^{172}Yb have been omitted in the figure as they cannot be compared to the other points as noted above. The lines are drawn only to guide the eye.

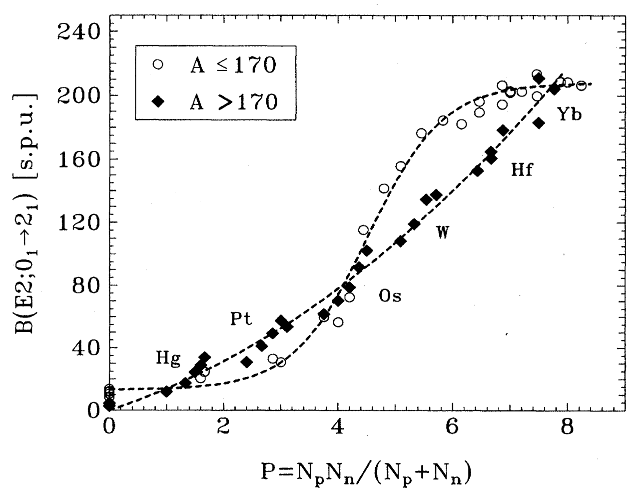

FIG. 4. $B(E2;0_1^+ \rightarrow 2_1^+)$ in single particle units plotted versus the P factor for all stable even-A nuclei of the $N=82-126$ shell. The nuclei with $A \leqslant 170$ constitute a shape transition path from the spherical $N=82$ nuclei to the axially deformed rotors near midshell while the nuclei with $A>170$ undergo a shape transition from axially deformed to γ-soft rotors. The data points lie on two well-separated tracks for the different shape transitions. The dashed lines have been fitted to the data taken from [43].

is not as steep as its increase from the spherical nuclei around $N=82$ to the rigid rotors in the first half of the shell. The dashed line for the second half of the shell is the simple two parameter parabola $B(E2;0_1^+\rightarrow 2_1^+)/[\text{s.p.u.}]=[11.8+1.926P]\times P$ fitted to the data only to guide the eye. Group II exhibits no or at least a much weaker saturation of the $E2$ strength than group I [44]. It should be noted that some of the difference in the two tracks can be attributed to the influence of additional hexadecapole deformation of these nuclei as is discussed in Ref. [45]. A detailed analysis of the pairing factors following the argumentation of Heyde and Richter [46], that is beyond the scope of this paper, may account for the different saturation behaviors of group I and group II.

We conclude, however, that valence holes are not equivalent to valence particles as they lead to a different behavior of nuclear properties as the low-lying $E2$ and $M1$ strengths. The IBA (see e.g., [47]) does distinguish between valence particles and valence holes only by the use of different sets of parameters in the Hamiltonian that reflect the underlying shell structure.

To summarize, a collection of the available total $M1$ excitation strengths has been presented for the even-A nuclei of the rare earth region using the excitation energy of $J_K^\pi=1_1^+$ states as an additional signature for the fragments of the scissors mode. The summed $M1$ strength obtained depends smoothly on the number of nucleons and is proportional to $B(E2;0_1^+\rightarrow 2_1^+)/Z^2$. We have shown that the correlation between the low-lying $M1$ and $E2$ excitation strengths holds above midshell as well as below midshell. For the stable nuclei of the upper half of the shell $Z=50-82$, $N=82-126$ no saturation is observed for either the $E2$ or the $M1$ strength as a function of the P factor. For both quantities there are two distinct tracks for nuclei below, respectively, above $A=170$, reflecting the slightly asymmetric position of the most deformed nuclei in these major shells [48]. This asymmetry may hint at the different effect of valence particles and valence holes on the nuclear structure.

The $M1$ excitation strength of the scissors mode has been proven to be a quantity closely related to the $B(E2;0_1^+\rightarrow 2_1^+)$ strength and thus related to the quadrupole deformation properties of nuclei. It would be very interesting to study the scissors mode in γ-soft and transitional nuclei. Therefore, (γ,γ') experiments on the heavier Os and Pt nuclei are highly recommended as well as systematic parity determinations and particle transfer experiments on known dipole excitations in all stable even-A rare earth nuclei to confirm the conditions to the data used in this analysis. Up to now the influence of γ softness and differences in the deformations of the proton and neutron fluids as recently found to play an important role for the magnetic moments of transitional nuclei [49] on the excitation strength and fragmentation of the scissors mode has not been discussed in detail. The theoretical effort should therefore be extended to these nuclei to gain a deeper insight in this elementary nuclear excitation and the deformation dependent behavior of atomic nuclei.

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