Evidence for $M1$ Scissors Resonances Built on the Levels in the Quasicontinuum of ^{163}Dy

M. Krtička,[1] F. Bečvář,[1,*] J. Honzátko,[2] I. Tomandl,[2] M. Heil,[3] F. Käppeler,[3] R. Reifarth,[4] F. Voss,[3] and K. Wisshak[3]
[1]Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, CZ-180 00 Prague 8, Czech Republic
[2]Nuclear Physics Institute of the Czech Academy of Sciences, CZ-250 68 Řež near Prague, Czech Republic
[3]Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, D-76021 Karlsruhe, Germany
[4]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
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Spectra of two-step γ cascades following the thermal ^{162}Dy$(n, \gamma)^{163}$Dy reaction have been measured. Distinct peaklike structures observed at the midpoints of these spectra are interpreted as a manifestation of the low-energy isovector $M1$ vibrational mode of *excited* ^{163}Dy nuclei.

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In 1976, Hilton [1] and later Lo Iudice and Palumbo [2] predicted a new isovector $M1$ collective vibrational mode in deformed nuclei. The prediction in Ref. [2] was based on the geometrical two rigid rotors model (TRRM) embodying the concept of scissorslike contraoscillations of deformed neutron and proton fluids. The first experimental indications for the existence of this mode have been reported by Bohle *et al.* [3] from the high-resolution electron inelastic scattering and by Berg *et al.* [4] from the inelastic γ-ray scattering. This pioneering work [1–4] has initiated one of the most relevant developments in nuclear physics during the last two decades. In this period many theoretical models, substantially differing from the TRRM, were elaborated for the low-energy $M1$ mode, as reviewed in Ref. [5], and a large number of (γ, γ') experiments devoted to this subject were undertaken, see, e.g., Ref. [6], and references therein. Hereafter, this mode, regardless of its real nature, is referred to as a scissors mode or scissors resonance (SR).

The most reliable conclusions about the SR have been drawn from the data on $M1$ strength from (γ, γ') experiments for 30 even-even nuclei with $A = 134$–194. From surveys [6,7] of these data it can be found that the SR energy, E_{SR}, follows with an accuracy of ± 0.15 MeV a weak systematic mass dependence $E_{\mathrm{SR}} \propto A^{-0.23}$. From the same data, one can expect $E_{\mathrm{SR}} \approx 3.10$ MeV for the Dy isotopes. It has been found [8] that the summed $M1$ reduced strength, $\Sigma B(M1)\uparrow$, correlates with the square of the deformation parameter δ.

One may ask what would be the outcome of the (γ, γ') experiments with *excited* deformed nuclei used as a target in conditions where their initial excitation energy is varied. If the well-known Brink hypothesis [9], proposed originally for the giant $E1$ resonance, is applicable to the SR, such *gedanken* experiments will display a predominant absorption of γ rays with energies near 3 MeV, independent of the initial excitation. In a paraphrased formulation of the Brink hypothesis, separate SRs of the same shape and size will be built on the ground state and on each of the excited levels of the target nuclei.

The question arises of not only whether these SRs exist, but also whether their manifestations are seen in a *real* experiment. In this Letter we seek an answer to this question and demonstrate that without the postulation of SRs residing on excited levels in ^{163}Dy, including levels with a relatively high excitation around 3 MeV, it would hardly be possible to account for the behavior of our new data on two-step γ cascades (TSCs), following the thermal-neutron capture in ^{162}Dy. This finding reveals indirectly noteworthy properties of photoexcitation of an excited heavy nucleus and it opens possibilities of extended and deeper studies of the scissors mode.

If the paradigm of the photon strength function [10] is applicable and all SRs are of identical Lorentzian shape, the photon strength function $S_{\gamma}^{(M1)}(E_{\gamma})$ that governs the $M1$ γ decay will include the following SR term:

$$S_{\gamma}^{(M1,\mathrm{SR})}(E_{\gamma}) = \frac{16\pi}{27(\hbar c)^3}\frac{E_0}{\arctan(2E_0/\Gamma_{\mathrm{SR}})}\Sigma B(M1)\uparrow \times \frac{\Gamma_{\mathrm{SR}}E_{\gamma}}{(E_{\gamma}^2 - E_{\mathrm{SR}}^2)^2 + E_{\gamma}^2\Gamma_{\mathrm{SR}}^2}, \tag{1}$$

with

$$E_0 = \sqrt{E_{\mathrm{SR}}^2 - \Gamma_{\mathrm{SR}}^2/4},$$

where E_{γ} is the γ-ray energy, E_{SR} is the SR energy, Γ_{SR} is the SR damping width, while the sum $\Sigma B(M1)\uparrow$ represents the overall reduced $M1$ strength that would be observed from the (γ, γ') reaction for *all* energies of the incident γ rays. Knowing $S_{\gamma}^{(M1)}(E_{\gamma})$, the behavior of strongly fluctuating partial radiation widths is described as follows: the partial radiation width $\Gamma_{a\gamma b}$ for an $M1$ transition $a \rightarrow b$ is a random realization of the Porter-Thomas distribution and the expectation value of $\Gamma_{a\gamma b}$ is equal to $S_{\gamma}^{(M1)}(E_{\gamma})E_{\gamma}^3/\rho(E_a)$, where $\rho(E_a)$ is the level density for fixed J^{π} at an initial excitation energy E_a. These simple rules represent the model that we adopted for fragmentation of the $M1$ strength.

The resonance term $S_{\gamma}^{(M1,\mathrm{SR})}(E_{\gamma})$ should lead to enhancement of those $M1$ transitions whose energies E_{γ} are close to E_{SR}. Such transitions occur copiously in γ cascades, accompanying the slow-neutron capture. Thanks to this, the first indication that SRs are also built on excited levels can be drawn from data on the *integrated* intensities of the TSCs, following the capture of thermal neutrons in ^{162}Dy [11]. This finding has been corroborated later by the data on TSCs, accompanying the thermal-neutron capture in ^{149}Sm and ^{155,157}Gd, and also from the data on multistep γ cascades, following the capture of neutrons with energy of several tens of keV in ^{149}Sm and ^{155,157,158}Gd [12]. Although the TSC data are compatible with the assumption that SRs reside on all levels, it turns out that reliable statements can be made only in regard to the SRs built on a few levels with an excitation of at most 1.5 MeV in the nuclei studied.

While studying the ^{162}Dy(^{3}He, ^{3}He$'\gamma$)^{162}Dy reaction Schiller *et al.* [13] extracted primary γ-ray spectra for several groups of highly excited initial levels in ^{162}Dy. A broad bump was observed at low γ-ray energies. From its permanent presence the authors concluded that either $E1$ or $M1$ low-energy resonances with a width of $\Gamma \approx$ 1.1 MeV are built on presumably all the ^{162}Dy levels with excitation energies up to ≈ 8 MeV. As follows from [13], in the range of level energies 2.2–4.3 MeV the deduced resonances display a stable energy of 2.60 MeV within an accuracy of better than 50 keV. Without doubt, if SRs are built on all levels they have to manifest themselves in the (^{3}He, ^{3}He$'\gamma$) data. However the above-mentioned energy of the resonances and their value of Γ are apparently in disagreement with the rich (γ, γ') data for even-even nuclei [6]. In addition, the multipolarity of the deduced resonances could not be determined. Hence, the observed bump in Ref. [13] cannot be unambiguously accounted for as a manifestation of the SRs.

To summarize, persuading evidence for SRs built on levels, situated above ≈ 2.5 MeV, where they tend to form an unresolved level quasicontinuum, is still missing.

As the neutron binding energy of ^{163}Dy is low, $B_n =$ 6271 keV, three positive-parity levels in ^{163}Dy, residing at relatively low energies of 251, 781, and 884 keV, are allowed to be populated from the $J^\pi = 1/2^+$ thermal-neutron capturing state by cascades of $M1$-$M1$ type with energies of both participating $M1$ transitions close to the expected resonance energy of the scissors mode, $E_{\mathrm{SR}} =$ 3.10 ± 0.15 MeV. If SRs are built on every excited level, including the levels in the quasicontinuum, this narrow group of the $M1$-$M1$ cascades should display an enhanced intensity. The enhancement is expected to be particularly strong for the TSCs terminating at the $J^\pi = 5/2^+$, 251 keV level, as the total energy they carry almost exactly equals $2E_{\mathrm{SR}}$. The ^{162}Dy$(n, \gamma)^{163}$Dy reaction thus appears to be a promising source of information on the role of the $M1$ scissors mode.

Our measurements were undertaken with a sample enriched in ^{162}Dy using a dedicated setup, incorporating a pair of HPGe detectors [14]. We accumulated what we call the TSC γ-ray spectra. Each of these represents the energy distribution of a mixture of primary and secondary γ rays that belong to all TSCs initiating at the capturing state c and terminating at a prefixed final level f in ^{163}Dy. Any of these cascades contributes to the TSC spectrum with the intensity given by the product of the branching intensities $I_{c\rightarrow i} \times I_{i\rightarrow f}$ for the decay of the capturing state c and an encountered intermediate level i.

For getting the TSC spectra we employed a modification of the sum-coincidence method. Thanks to the use of the HPGe detectors the extracted TSC spectra are background-free and need, in essence, no deconvolution [15]. Because of the incapability to distinguish between primary and secondary γ rays, the TSC spectra are symmetrical with respect to their midpoints. We accumulated them for several well-resolved final levels f in ^{163}Dy. To suppress the noise from the violent Porter-Thomas fluctuations, all the spectra obtained were projected onto a coarse energy scale with 100 keV wide bins.

The most relevant of these TSC spectra, normalized to absolute intensity units, are plotted in Fig. 1 where they are compared with the outcome of three separate series of simulations based on various assumptions about the makeup of the photon strength function $S_\gamma^{(M1)}$. The first series was performed assuming no contribution of SRs to $S_\gamma^{(M1)}$; see the six plots in the upper part of Fig. 1. In the second series, the SRs built on a full set of levels below 2.5 MeV were considered to contribute to $S_\gamma^{(M1)}$; see the middle part of Fig. 1. Finally, for the third series of simulations we postulated that SRs reside on *all levels* in ^{163}Dy, which implies that we assumed a permanent contribution of the term given by Eq. (1) to $S_\gamma^{(M1)}$; see the plots in the lower part of Fig. 1. The quantities E_{SR}, Γ_{SR}, and $\Sigma B(M1)\uparrow$ were treated as free parameters. Regarding the remaining entities, responsible for the emission of γ cascades, the following common assumptions were adopted while performing all the simulations: (i) for $\rho(E)$ the constant-temperature level-density formula [16] is valid, (ii) the $E1$ photon strength function $S_\gamma^{(E1)}$ is given by the semiempirical extension [17] of the model proposed in Ref. [18], and (iii) the low-energy wing of the $M1$ spin-flip resonance doublet, observed in Ref. [19], contributes to $S_\gamma^{(M1)}$. The photon strength functions used are plotted in Fig. 2. Simulations of the TSC spectra and their rms Porter-Thomas uncertainties were performed using the DICEBOX algorithm [20].

The complete absence of SRs leads to predictions of TSC spectra that are in sharp disagreement with the data. Specifically, the simulations are not able to account for any of the peak structures at the midpoints of the TSC spectra. Postulating SRs at levels below 2.5 MeV radically improves the agreement with all three TSC spectra for the negative-parity final levels, but the sharp disagreement with the spectra for the positive-parity levels becomes even worse. In contrast to this, the assumption that SRs reside on all ^{163}Dy levels, including the levels in the quasicontinuum, leads to a dramatic remedy: peaks at the midpoints of all the TSC spectra are predicted and are in relatively good quantitative agreement with

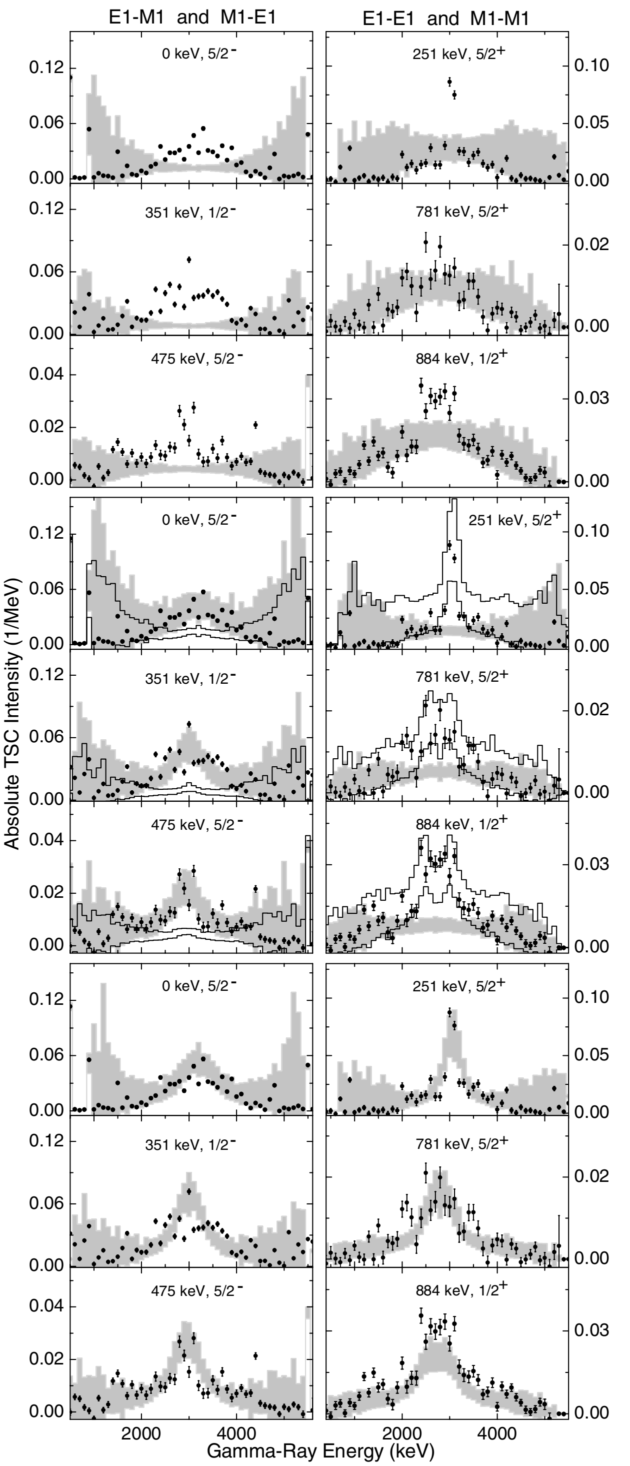

FIG. 1. Experimental TSC spectra from the ^{162}Dy$(n, \gamma)^{163}$Dy reaction (points with error bars) and their model predictions. Shaded areas represent predicted TSC intensities together with the associated rms Porter-Thomas uncertainties for the cases when SRs are absent (upper six plots), when SRs are postulated for all levels below 2.5 MeV (middle six plots), and when SRs reside on all ^{163}Dy levels (lower six plots). Predictions from postulating $E1$ pygmy resonances are depicted by the areas between the two histograms (middle six plots). Final-level excitation energies and J^{π} values are indicated.

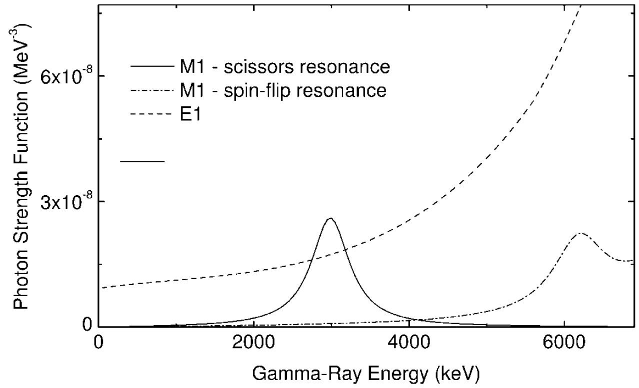

FIG. 2. The photon strength functions adopted for simulating the ^{163}Dy TSC spectra. The $E1$ photon strength following Ref. [17] is temperature dependent; the shown curve for $S_{\gamma}^{(E1)}(E_{\gamma})$ refers to the γ decay of the neutron capturing state.

simulations. This has been achieved by choosing the common SR parameters $E_{SR} = 3.0$ MeV, $\Gamma_{SR} = 0.60$ MeV, and $\Sigma B(M1)\uparrow = 6.2\,\mu_N^2$, where μ_N stands for the nuclear magneton.

We also examined an alternative that the peaks in TSC spectra are artifacts of 3 MeV "pygmy" $E1$ resonances of an unknown origin, assuming tacitly that the Brink hypothesis is valid for them. Varying the common width and the parameter $\sum B(E1)\uparrow$ of the postulated pygmy resonances we reached the best fit which is illustrated in the middle part of Fig. 1. As can be seen, the predictions agree reasonably well with the TSC data for positive-parity final levels, but they strongly disagree with the remaining TSC data. On these grounds we reject the $E1$ origin of the peaklike structures in the TSC spectra.

To be strict, $S_{\gamma}^{(E1)}$ and the spin-flip term of $S_{\gamma}^{(M1)}$ are reasonably known only at γ-ray energies of 6–8 MeV. To assess consequences of limited knowledge of these quantities at energies of interest, 1–5 MeV, we undertook scores of additional simulations of TSC spectra using a variety of artificial monotonous extrapolations of $S_{\gamma}^{(E1)}$ and the spin-flip term of $S_{\gamma}^{(M1)}$ from the "safe" region of 6–8 MeV towards low energies. A subset of these simulations involved a SR contribution to $S_{\gamma}^{(M1)}$ according to Eq. (1). It turned out that only with this subset were we able to reproduce the most prominent qualitative feature of all TSC spectra—the peak at their midpoints. The effects from SRs thus seem robust. Moreover, none of the additional simulations led to a meaningful improvement of the achieved *quantitative* accord between the data and the predictions shown in the lower part of Fig. 1.

Apart from the presence of the above-mentioned peaks in the TSC spectra the equally important signature of the ubiquitous SRs is the distinct sharpness of the peak in the spectrum for the 251 keV level. In view of *simultaneous* fulfilling the resonance condition for both steps of the contributing $M1$-$M1$ cascades the shape of the 3 MeV peak in this spectrum is approximately described by the *square* of the Lorentzian function and, as a consequence, the expected FWHM of the peak is to be equal to $\approx 0.64\,\Gamma_{SR}$. This is surprisingly well reproduced by the data. With increasing energy of positive-parity final levels the peak in the TSC spectra broadens and tends to split, as only one of the $M1$ transitions $c \rightarrow i$ or $i \rightarrow f$ may fully resonate at a time. All this indicates that the scissors mode *per se*, indeed, displays distinct and consistent resonance behavior that could not, for principal reasons, be revealed so clearly from (γ, γ') data.

The value $E_{SR} = 3.0$ MeV we arrived at agrees well with systematics of (γ, γ') data for even-even nuclei [6].

The deduced value $\Sigma B(M1)\uparrow = 6.2\,\mu_N^2$ falls into the range of $5.7\mu_N^2$–$6.8\mu_N^2$ predicted for the scissors-mode strength of the well-deformed nuclei [21]. If SRs are of the Lorentzian shape the part of this value that comes from the conventionally used γ-ray energy region of 2.5–4.0 MeV will be represented by $4.8\mu_N^2$. The three highest values of $\Sigma B(M1)\uparrow$ determined for the same region from the (γ, γ') experiments belong to ^{158}Gd, ^{160}Gd, and ^{164}Dy, being equal, respectively, to $(3.7 \pm 0.5)\mu_N^2$, $(3.6 \pm 0.4)\mu_N^2$ [7], and $(5.5 \pm 0.4)\mu_N^2$ [22]. As one sees, the values for ^{158,160}Gd are noticeably lower than $4.8\mu_N^2$. However, following our simulations, the idea for which is outlined in Ref. [11], this disagreement can be fully accounted for by the loss of the $M1$ strength due to the threshold for observation of the isolated γ lines in (γ, γ') experiments. As for ^{164}Dy, in view of the low threshold [22], the lost strength is to be $\simeq 0.4\,\mu_N^2$. On the whole, the TSC and (γ, γ') data are in satisfactory accord, which suggests that the SRs of odd deformed nuclei and the ground-state SRs of their even-even neighbors are of the same strength. A similar comparison involving the (γ, γ') data for odd nuclei would be difficult since no firm conclusions about the behavior of $\Sigma B(M1)\uparrow$ have been drawn for these nuclei from the (γ, γ') experiments [23].

If SRs built on the ground states of even-even nuclei are also of Lorentzian shape, summing the $M1$ strength from the (γ, γ') experiments over a limited γ-ray energy region will lead to biased estimates of the *total* sum $\Sigma B(M1)\uparrow$. Specifically, for $\Gamma_{SR} = 0.6$ MeV and the region 2.5–4.0 MeV such estimates should belong not to the full sum, but only to its 78% fraction. Referring to a previous analysis [7] this assessment might be crucial for setting reliable constraints on parameters of the yet undiscovered *second scissors mode* [24,25] whose energy is anticipated near 25 MeV [26]. However, all this reasoning is speculative as it raises and falls with justifiability of the adopted model for fragmentation of the $M1$ strength. Detailed studies of TSCs in other nuclei are needed.

In summary, we have observed peaklike structures in the spectra of two-step γ cascades following the neutron capture in ^{162}Dy. In line with the Brink hypothesis we have interpreted them as a manifestation of scissors resonances built on excited levels in ^{163}Dy, including the levels in the quasicountinuum. Our data thus suggest that the magnetic-dipole vibrations of a deformed nucleus that are induced by incident photons with energies near 3 MeV display the pattern that should be independent of an initial excitation of the nucleus. This remarkable property of the deformed neutron and proton fluids might speak in favor of a mode which is almost disentangled from the other degrees of freedom of the system.

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*Corresponding author.
Email address: becvar@mbox.troja.mff.cuni.cz

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