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Low-energy M1 excitation mode in ^{172}Yb

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Abstract

The multipolarity of a soft ($E_\gamma = 3.3(1)$ MeV) resonance in the total radiative strength function (RSF) of ^{172}Yb is determined. For this reason, the level density and total RSF of ^{172}Yb have been extracted from primary-γ spectra from the $^{173}\text{Yb}(^3\text{He}, \alpha\gamma)^{172}\text{Yb}$ reaction. In a second experiment, two-step-cascade (TSC) intensities have been measured in the $^{171}\text{Yb}(n_{\text{th}}, \gamma\gamma)^{172}\text{Yb}$ reaction. These intensities are compared to statistical-model calculations which are entirely based on experimental values of the level density and RSF from the former experiment. This comparison implies M1 assignment of the soft resonance. The strength of the M1 resonance is $B(\text{M1}\uparrow) = 6.5(15)\ \mu_{\text{N}}^2$.

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Unresolved transitions produced in the γ decay of excited nuclei are best described by statistical concepts: a radiative strength function (RSF) and level density yield mean values of transition matrix elements [1]. For hard γ rays, ($E_\gamma \sim$ 7–20 MeV), the RSF is determined by the giant electric dipole resonance (GEDR) [2]. The soft tail of the GEDR has been investigated by a variety of methods involving neutron capture, most notably by primary γ rays [3]. For deformed rare-earth nuclei, a bump in the total RSF (summed over all multipolarities) around 3 MeV is inferred from total γ spectra [4–6]. In the same region, a concentration of M1 strength (scissors mode) is reported in nuclear resonance fluorescence (NRF) experiments [7]. In two-step-cascade (TSC) experiments [8], a connection between these two observations has been made under the assumption of an enhanced scissors mode. However, after 25 years of investigation, the multipolarity of the bump in the RSF is still under debate. E1 multipolarity is consistent with, e.g., neutron-skin oscillations from which the clearest signal of neutron and proton radii differences could be deduced, but also other types of excitation such as a toroidal mode could generate E1 strength below the GEDR [9]. M1 multipolarity implies evidence of an enhanced scissors mode. The well-tested Oslo method [10] gives accurate data on the level density and

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total RSF. Systematic studies of several rare-earth nuclei have firmly established the bump in the soft RSF [11]. In this work, we determine virtually model-independently the multipolarity of this bump by a newly developed method [12] that combines the results from the Oslo method with an auxiliary TSC experiment.

The TSC method is based on the measurement of multiplicity-two γ cascades between fixed initial i and final f levels (see, e.g., [8] and references therein). A convenient initial state is that formed in thermal or average resonance capture (ARC); the final state can be any low-lying discrete state. TSC spectra are determined by the branching ratios of the initial and intermediate states (expressed as ratios of partial to total widths Γ) and by the level density ρ of intermediate states with spin and parity J_m^π

$$I_{if}(E_1,E_2) = \sum_{XL,XL',J_m^\pi} \frac{\Gamma_{im}^{XL}(E_1)}{\Gamma_i}\rho\big(E_m,J_m^\pi\big)\frac{\Gamma_{mf}^{XL'}(E_2)}{\Gamma_m} + \sum_{XL,XL',J_{m'}^\pi} \frac{\Gamma_{im'}^{XL}(E_2)}{\Gamma_i}\rho\big(E_{m'},J_{m'}^\pi\big)\frac{\Gamma_{m'f}^{XL'}(E_1)}{\Gamma_{m'}}. \quad (1)$$

The sums in Eq. (1) are restricted to give valid combinations of the level spins and parities and the transition multipolarities XL. Summing over all possibilities is necessary since neither the ordering of the two γ rays, nor the multipolarities of the transitions nor the spins and parities of the intermediate levels are known. The two transition energies are correlated by $E_1 + E_2 = E_i - E_f$, thus, TSC spectra can be expressed as one-dimensional spectra of one transition energy E_γ only. TSC spectra are symmetric around $E_\gamma^{\mathrm{sym}} = (E_i - E_f)/2$; integration over E_γ yields twice the total TSC intensity I_{if} if both γ rays are counted in the spectra. The knowledge of the parities π_i[1] and π_f ensures that I_{if} depends roughly speaking on the product of two RSFs around E_γ^{sym} [12], i.e., $f_{\mathrm{E1}}^2 + f_{\mathrm{M1}}^2$ for $\pi_i = \pi_f$ and $2 f_{\mathrm{E1}} f_{\mathrm{M1}}$ for $\pi_i \neq \pi_f$. I_{if} depends also on the level density. This usually prevents drawing firm conclusions from TSC experiments alone [8]. A combined analysis of Oslo-type and TSC experiments, however, enables one, with the help of the experimental level density, to establish firmly the sum and product, respectively, of all contributions to f_{M1} and f_{E1} at energies of the soft resonance, thus determining its multipolarity [12]. For this goal, the partial widths of Eq. (1) are expressed via

$$\Gamma_{x\to y}^{XL}(E_\gamma) = f_{XL}(E_\gamma)E_\gamma^{2L+1}D_x \quad (2)$$

in terms of RSFs and level spacings D_x. Eq. (2) actually gives only the average value of the Porter–Thomas distributed partial widths [13]. The total width Γ is the sum over all partial widths. The distribution of total widths becomes more and more peaked with increasing number of components [13]. The level density for a given spin and parity is calculated from the total level density by

$$\rho\big(E_x,J_x^\pi\big) = \rho(E_x)\frac{1}{2}\frac{2J_x+1}{2\sigma^2}\exp\left[-\frac{(J_x+1/2)^2}{2\sigma^2}\right], \quad (3)$$

where σ is the spin cut-off parameter, and we assume equal numbers of positive- and negative-parity levels. This assumption and Eq. (3) have been verified from the discrete level schemes of rare-earth nuclei [14]. Thus, all quantities for calculating TSC spectra are based on experimental data. Furthermore, using Oslo data for the level density and RSF in statistical-model calculations have yielded total γ-cascade spectra after neutron capture in excellent agreement with experiment (see Fig. 5 in Refs. [11,15]).

The combined analysis is applied to the nucleus ^{172}Yb which has been investigated by the ^{173}Yb(^{3}He, $\alpha\gamma$)^{172}Yb reaction in Oslo and by the ^{171}Yb($n,\gamma\gamma$)^{172}Yb reaction at the Lujan Center of the Los Alamos Neutron Science Center (LANSCE). The Oslo data have been reported in [10,11]. Thus, only a short summary is given. The experiment was performed using a 45-MeV ^{3}He beam on a metallic, enriched, self-supporting target. Ejectiles were identified and their energies measured using particle telescopes at 45°. In coincidence with α particles, γ rays were detected in an array of 28 NaI detectors. From the reaction kinematics, α energy is converted into E_x, and γ-cascade spectra are constructed for a range of E_x bins. The γ spectra are unfolded and the primary-γ spectra are extracted using a subtraction method (see, e.g., [14] and references therein). The spectra are factorized into a level density and a total RSF by applying the Brink–Axel hypothesis [16,17]. The level density is normalized by comparison to discrete levels at low E_x and to the average neutron-resonance spacing at the neutron-separation energy S_n [10]. The RSF is normalized using the average total width of neutron resonances, and is decomposed into a constant-temperature[2] Kadmenskiĭ–Markushev–Furman (KMF) E1 model [18], a single-humped spin-flip M1 model, and a soft dipole resonance [11]. These models are chosen since they give a good phenomenological description of the experimental RSF. The single-humped spin-flip M1 model in particular is also recommended in [19]. In systematic studies of total average radiative widths, radiative capture cross sections, and γ-ray spectra, a very similar combination of E1 and M1 models as used in our work has been found to describe the experimental data best [20]. Concerning the shape of the soft dipole resonance, there is very little precedence in the literature. However, earlier studies assume in general a Lorentzian form [4,6]. In the present work, we have improved on the normalization of the level density and the RSF and included an isoscalar Lorentzian E2 model [19] giving

$$f_{\mathrm{tot}} = K(f_{\mathrm{E1}} + f_{\mathrm{M1}}) + E_\gamma^2 f_{\mathrm{E2}} + f_{\mathrm{soft}}, \quad (4)$$

[1] One assumes that only neutron s-wave capture occurs.

[2] The constant temperature compared to an excitation-energy dependent temperature in the KMF model is motivated by (i) the resemblance of the level density to a constant-temperature model, (ii) a better phenomenological description of the total RSF, (iii) self-consistency with the Brink–Axel hypothesis, and (iv) improved descriptions of isomeric- and photon-production cross sections in other rare-earth nuclei, see, e.g., [21,22].

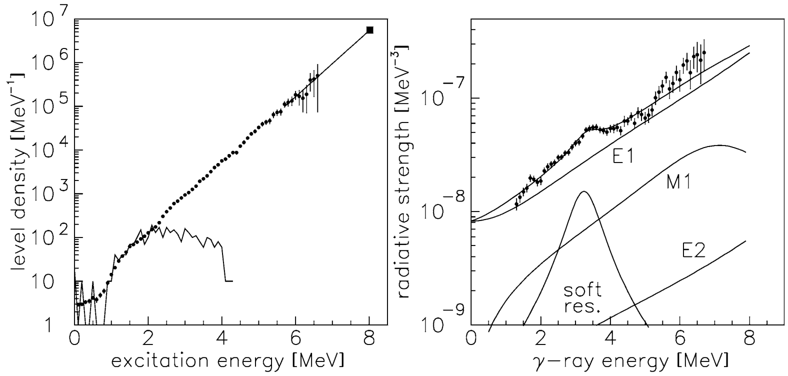

Fig. 1. Left panel: total level density (filled circles), constant-temperature extrapolation (solid line), level density at S_n from average neutron-resonance spacing (filled square) [19], and level density from counting of discrete levels (jagged line) [23]. Right panel: total RSF (filled circles), fit to the data, and decomposition into RSFs of different multipolarities (solid lines). Inclusion of the soft resonance in the fit decreases χ^2_{red} from ~ 5.1 to ~ 1.3. Since this value is close to unity, inclusion of additional non-statistical structures cannot significantly improve the fit.

where K is a scaling factor of the order of one. Since quadrupole transitions populate levels within a broader spin interval than dipole transitions, Eq. (4) is of an approximative nature only. Given the weakness of quadrupole transitions and the level of experimental uncertainties, however, this approximation is believed to be sufficient. The improved data, the fit to the total RSF, and its decomposition into different multipolarities are given in Fig. 1. The parameters for the E1 RSF are taken from [11], those for the M1 and E2 RSFs from [19], where we use the $f_{\text{E1}}/f_{\text{M1}}$ systematics at ~ 7 MeV giving values in agreement with ARC work [24]. The fit parameters are: the constant temperature of the KMF model $T = 0.34(3)$ MeV, the normalization coefficient $K = 1.7(1)$, and the three parameters of the soft resonance $E = 3.3(1)$ MeV, $\Gamma = 1.2(3)$ MeV, and $\sigma = 0.49(5)$ mb.[3]

For the ^{171}Yb$(n,\gamma\gamma)^{172}$Yb experiment, we used ~ 1 g of enriched, dry Yb_2O_3 powder encapsulated in a glass ampule, mounted in an evacuated beam tube and irradiated by collimated neutrons with a time-averaged flux of $\sim 4 \times 10^4$ neutrons/cm^2 s at ~ 20 m from the thermal moderator. γ rays were detected by one shielded and segmented $\sim 200\%$ clover and two 80% Ge(HP) detectors, placed at ~ 12 cm from the target in a geometry to minimize angular-correlation effects and contributions from higher-multiplicity cascades. Single and coincident γ rays were recorded simultaneously. The experiment ran for ~ 150 h yielding $\sim 10^7$ coincidences. The relative detector efficiencies from 1–9 MeV were determined by two separate runs of ~ 12 h each, before and after the ^{171}Yb$(n,\gamma\gamma)^{172}$Yb experiment, using the ^{35}Cl$(n,\gamma)^{36}$Cl reaction and its known γ intensities [25]. Also, a standard calibrated ^{60}Co source has been measured to adjust the relative curves to an absolute scale. The energy-summed coincidence spectrum (Fig. 2, upper panel) shows distinct peaks corresponding to TSCs between S_n and several low-lying states. The two strongest peaks have ~ 4000 counts each. TSC spectra were obtained by gating on four peaks. Relative intensities of primary versus secondary γ rays were determined from singles spectra and are in agreement with Ref. [24] but contradict the in the literature preferred data of Ref. [27] where the intensity of primary γ rays is consistently smaller by a factor of three.[4] Absolute primary intensities were determined by using new data on absolute secondary γ-ray intensities [28] and subsequent scaling of primary intensities to these values using the relative intensities of [24]. These absolute primary intensities are $\sim 20\%$ higher than in [24]. TSC intensities are normalized to

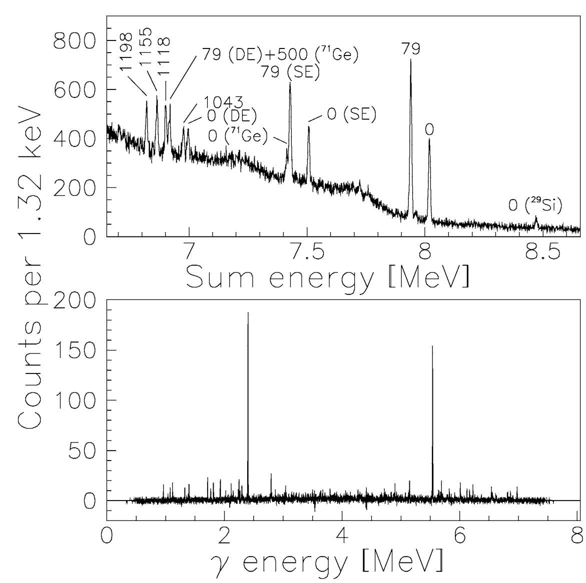

Fig. 2. Upper panel: energy-summed coincidence spectrum from the ^{171}Yb$(n,\gamma\gamma)^{172}$Yb reaction. Peaks are labeled by the energy of the final state. Peaks denoted by ^{71}Ge and ^{29}Si are due to n capture in the detector and in the glass ampule, respectively. SE and DE stands for single- and double-escape peaks, respectively. Lower panel: TSC spectrum for the 2_1^+ final state. The slight asymmetry is due to the energy-dependent resolution of the detectors.

[3] The cited parameters are mean values obtained from the ^{173}Yb$(^3$He$,\alpha\gamma)^{172}$Yb and ^{172}Yb$(^3$He$,^3$He$'\gamma)^{172}$Yb reaction data reported in Ref. [26].

[4] A possible problem in Ref. [27] is that they used two different detectors to measure on the one hand primary, high-energetic and on the other hand secondary, low-energetic γ-ray intensities. Most likely, they failed to achieve a consistent efficiency calibration between the two detectors.

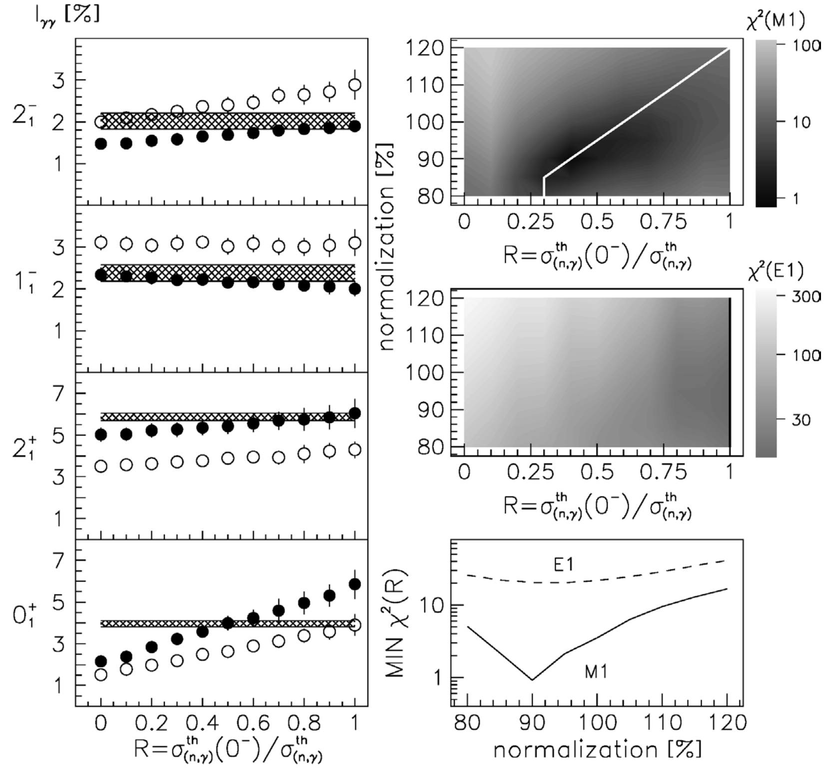

Fig. 3. Left: range of allowed experimental values (hatched areas) for TSC intensities to final states (from top to bottom) 2_1^- at 1198 keV, 1_1^- at 1155 keV, 2_1^+ at 79 keV, and the 0_1^+ ground state. Full and open symbols correspond to calculations for different R with M1 and E1 multipolarity for the soft resonance, respectively. Error bars are estimated uncertainties due to Porter–Thomas fluctuations. Right: combined χ^2 for all four TSC intensities as function of R and N for M1 (upper panel) and E1 multipolarity (middle panel). The lines connect minimal values of χ^2 with respect to variations in R for any given N. For E1 multipolarity, this minimum is always obtained for $R = 1$ irrespective of N. Lower right: projection of the χ^2 surface onto the lines in the panels above.

(i) the absolute primary intensity and secondary branching ratio of one, strong, individual TSC and (ii) by effectively estimating the number of neutron captures during the experiment from secondary singles lines, their absolute intensities, and absolute detector efficiencies. Both methods give equal results within their error bars.

TSC intensities are compared to calculations according to Eq. (1) assuming either E1 or M1 multipolarity for the soft resonance [12]. One parameter in these calculations is the contribution to the thermal radiative neutron-capture cross section $\sigma_{n,\gamma}^{\text{th}}$ from the two possible spins (0^- and 1^-) involved in neutron s-wave capture on ^{171}Yb. The compilation [29] assumes 0^- for the sub-threshold resonances which contribute 88% to $\sigma_{n,\gamma}^{\text{th}}$. Another 4% comes from 0^- resonances above threshold, giving in total a 92% contribution of 0^- states. On the other hand, there is no strong evidence that all contributing sub-threshold resonances have 0^-. Examination of hard primary γ rays [24,27] reveals many strong transitions populating 2^+ levels, indicating that a sizable portion of $\sigma_{n,\gamma}^{\text{th}}$ stems from 1^- resonances. Therefore, we performed calculations for a set of ratios $R = \sigma_{n,\gamma}^{\text{th}}(0^-)/\sigma_{n,\gamma}^{\text{th}}$. These calculations show, however, that only the TSC intensity to the 0_1^+ state has a strong dependence on this ratio.

In order to estimate the effect of Porter–Thomas fluctuations, we performed 100 Monte Carlo simulations for each value of R assuming either M1 or E1 multipolarity of the soft resonance. In the simulations every partial radiative width is randomized according to the Porter–Thomas distribution. Total widths are calculated as a sum of randomized partial widths. To minimize the impact of Porter–Thomas fluctuations, we only compare TSC intensities integrated over a ~ 2.4-MeV-broad energy range in the center of the spectra [8] (see left panels of Fig. 3).

Systematic errors not included in the statistical uncertainties are (i) corrections due to non-isotropic angular correlations of TSCs which have been estimated to be less than $\sim 3\%$ and are thus neglected, (ii) uncertainties in the absolute scale of our detection efficiency, and (iii) uncertainties of primary and secondary intensities. The latter two uncertainties result in correlated uncertainties of the absolute scale of all four integrated TSC intensities in the order of $\sim$ 10–20%. Comparison between experiment and calculation is therefore performed for a number of overall normalization factors N applied to all four experimental TSC intensities simultaneously. χ^2 surfaces assuming M1 and E1 multipolarity of the soft resonance are calculated as function of R and N (upper right panels of Fig. 3). The least χ^2 of 20.2 for E1 multipolarity is obtained for $R = 1.0$ and $N = 95\%$. The least χ^2 of 0.92 for M1 multipolarity is obtained for $R = 0.4$ and $N = 90\%$. Within our assumptions we can therefore rule out E1 multipolarity for the soft resonance on a high confidence level. More generally, the ability to describe all four integrated TSC intensities with one set of values for N, R, and the multipolarity of the soft resonance constitutes independent support for the experimental values of the level density and total RSF from the Oslo experiment and the validity of the decomposition of the latter. More pointedly, since the level density and total RSF (including its decomposition) have been published before the present TSC experiment had even been performed, the calculated TSC intensities are de facto predictions which are confirmed by the present experiment for one reasonable set of values for N, R, and the M1 hypothesis for the soft resonance.

Other sources for systematic uncertainties exist. One is connected to the assumption of statistical γ decay. For some nuclei such as ^{208}Pb, a direct neutron-capture mechanism has been discussed. We neglect the possibility of contributions from such a reaction mechanism and assume a compound-like reaction mechanism for the neutron capture, followed by statistical γ decay, since ^{171}Yb is located close to the maximum of the 4s-neutron strength function. Objections have also been raised against the inputs of the statistical-model calculations, i.e., the experimental level density and RSF, especially the decomposition of the latter into RSFs of different multipolarities. In order to estimate the systematic effect of uncertainties in those input parameters, we have, as an example, substituted the 4-MeV-wide M1 spin-flip resonance based on the work of Kopecky [30,31] and adapted in [19] by an 8-MeV-wide M1 spin-flip model which simulates the two-humped M1 response observed in inelastic proton scattering off ^{154}Sm [32]. However, in order not to contradict the experimental f_{E1}/f_{M1} systematics at 7 MeV, such a model has to have twice the integrated strength than the Kopecky 4-MeV-wide M1 spin-flip model, making it barely realistic. For a corresponding calculation as in Fig. 3 and assuming M1 multipolarity for the soft resonance, the 8-MeV-wide M1 spin-flip model gives rise to an increase of the minimal χ^2 from 0.92 to 6.8. Such a significant deterioration shows the sensitivity achieved in the analysis of the TSC experiment using Oslo data.

Since we now have established M1 multipolarity for the soft resonance with the help of the auxiliary TSC experiment, we can proceed and calculate the integrated strength of this resonance by

$$B(\mathrm{M1}\uparrow) = \frac{9\hbar c}{32\pi^2}\left(\frac{\sigma\Gamma}{E}\right)_{\mathrm{soft}}, \tag{5}$$

which gives a value of 6.5(15) μ_N^2. This value is entirely determined from the earlier Oslo-type experiment. It is in agreement with the sum-rule approach for soft, orbital M1 strength assuming bare g factors[5] [33] but is more than twice the ground-state strength reported from NRF experiments [7]. This discrepancy has generated a great deal of controversy. A thorough discussion of this is far beyond the scope of this work and would in our opinion unduly shift the focus away from our experimental result which is the determination of the multipolarity of a previously observed, soft resonance in the RSF of ^{172}Yb.

In an effort to defuse previous controversies, we would therefore only like to mention two additional points beside the possible effect of the finite temperature which should be taken into account in any comparison of the present result with NRF experiments. Firstly, by their very nature, integrated TSC intensities are not sensitive to the degree of fragmentation or concentration of strength. Secondly, detailed data on ground-state transitions from NRF experiments constrain very little the analysis of the present experiment in the sense that a very small fraction of the observed integrated TSC intensity can be attributed to transitions which have been previously observed in NRF experiments. Inspecting the experimental TSC spectra at γ energies for which strong ground-state transitions have been observed in NRF experiments shows that TSC intensities with these particular γ energies are in no way enhanced over TSC intensities with other γ energies. This is explained by the fact that TSC experiments are not sensitive to absolute ground-state decay widths, but only to branching ratios.

The present discussion would be quite one-sided without mentioning that (i) many strong transitions from NRF experiments have also been seen in inelastic electron scattering [34], (ii) lifetime estimates of a few select 1^+ states from NRF experiments have been confirmed by the Doppler-shift method in inelastic neutron scattering experiments [35], and (iii) the suspected orbital nature of the scissors mode has been confirmed in inelastic proton scattering [36].

For further discussions of the discrepancy between the present result and the results from NRF measurements we refer to the opinions of an independent group [8]. A soft M1 resonance with similar strength as ours has also been observed by this group [37], however, their analysis is based on schematic models for the level density and total RSF[6] and comparison is made with calculated TSC spectra instead of the more robust integrated TSC intensities. The discussion in their articles provides some complementary comments on the discrepancy between their observation of an enhanced scissors-mode strength and the NRF results.

In conclusion, the soft resonance found in the decomposition of the total RSF of ^{172}Yb from Oslo-type experiments has been determined to be of M1 multipolarity by an auxiliary TSC measurement. The strength of the M1 resonance is $B(\mathrm{M1}\uparrow) = 6.5(15)\ \mu_N^2$ which is entirely determined by the former experiment. Assuming M1 multipolarity for similar soft resonances in other rare-earth nuclei investigated by the Oslo method gives consistent strengths of $\sim 6\ \mu_N^2$ for various even and odd Dy, Er, and Yb nuclei, and reduced strengths of $\sim 3\ \mu_N^2$ for the more spherical Sm nuclei; the centroids of these resonances increase weakly with mass number [15]. Our observation constitutes a virtually model-independent identification of the scissors mode in the quasicontinuum. The strength of this elementary M1 excitation in the quasicontinuum is twice the strength of the respective ground-state excitation. It is controversial whether this discrepancy is due to a genuine physics

[5] Bare g factors are likely appropriate for excitations built upon states above the pairing gap, i.e., in the quasicontinuum, which are the subject of the present work.

[6] One inconsistency in their analysis is the use of a variable temperature in the KMF model and a constant temperature in the level-density model.

effect such as the response to a finite temperature, or whether there might be more mundane explanations related to deficiencies in the respective experiments or analysis methods. It will be interesting to see how this conflict is resolved in the future.

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