Large Enhancement of Radiative Strength for Soft Transitions in the Quasicontinuum

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Radiative strength functions (RSFs) for the ^{56,57}Fe nuclei below the separation energy are obtained from the ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe and ^{57}Fe(^{3}He, ^{3}He$'\gamma$)^{57}Fe reactions, respectively. An enhancement of more than a factor of 10 over common theoretical models of the soft ($E_\gamma \lesssim 2$ MeV) RSF for transitions in the quasicontinuum (several MeV above the yrast line) is observed. Two-step cascade intensities with soft primary transitions from the ^{56}Fe(n, 2γ)^{57}Fe reaction confirm the enhancement.

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Unresolved transitions in the nuclear γ-ray cascade produced in the decay of excited nuclei are best described by statistical concepts: a radiative strength function (RSF) $f_{XL}(E_\gamma)$ for a transition with multipolarity XL and energy E_γ, and a level density $\rho(E_i, J_i^\pi)$ for initial states i at energy E_i with equal spin and parity J_i^π yield the mean value of the partial decay width to a given final state f [1]:

$$\Gamma_{if}^{XL}(E_\gamma) = f_{XL}(E_\gamma)E_\gamma^{2L+1}/\rho(E_i, J_i^\pi). \qquad (1)$$

Most information about the RSF has been obtained from photon-absorption experiments in the energy interval 8–20 MeV, i.e., for excitations above the neutron separation energy S_n. Data on the soft ($E_\gamma < 3$–4 MeV) RSF for transitions in the quasicontinuum (several MeV above the yrast line) remain elusive. The first data in the statistical regime were obtained from the ^{147}Sm(n, $\gamma\alpha$)^{144}Nd reaction [2]. They indicate a moderate enhancement of the soft $E1$ RSF compared to a Lorentzian extrapolation of the giant electric dipole resonance (GEDR). For spherical nuclei, in the framework of Fermi-liquid theory, this enhancement is explained by a temperature dependence of the GEDR width [3], the Kadmenskiĭ-Markushev-Furman (KMF) model. However, the experimental technique requires the presence of sufficiently large α widths and depends on estimates of both α and total radiative widths in the quasicontinuum below S_n.

The sequential extraction method developed at the Oslo Cyclotron Laboratory (OCL) [4] has enabled further investigations of the soft RSF by providing unique data for transitions in the quasicontinuum with sufficient averaging. For deformed rare-earth nuclei, it has been shown that the RSF can be described in terms of a KMF GEDR model, a spin-flip giant magnetic dipole resonance (GMDR), and a soft $M1$ resonance [5,6]. In this work, we report on the first observation of a strong enhancement of the soft RSF in ^{56,57}Fe over the model predictions. This enhancement has been found in Oslo-type experiments [7] and is confirmed independently by two-step cascade (TSC) measurements. To our knowledge, at present there exists no theoretical model which can explain an enhancement of this magnitude.

The first experiment, the ^{57}Fe(^{3}He, ^{3}He$'\gamma$)^{57}Fe and ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe reactions, was carried out with 45-MeV ^{3}He ions at the OCL. Particle-γ coincidences were measured by eight Si particle telescopes at 45° with a kinematically dominated energy resolution of ~250 keV and by an array of 28 NaI(Tl) $5'' \times 5''$ γ detectors with a solid-angle coverage of ~15% of 4π and an energy resolution of ~6% at 1.3 MeV. The reaction spin window was $I \sim 2$–$6\hbar$. Primary-γ matrices P were obtained by a subtraction method [8] for excitation-energy windows of 4–10.2 MeV and 3–7.6 MeV for ^{56}Fe and ^{57}Fe, respectively. These matrices were factorized into a level density and total RSF $f_\Sigma(E_\gamma)$ (summed over all multipolarities) according to the Brink-Axel hypothesis [9] by

$$P(E, E_\gamma) \propto \rho(E - E_\gamma)f_\Sigma(E_\gamma)E_\gamma^3. \qquad (2)$$

More details on the experiment and data analysis, including the normalized level densities of ^{56,57}Fe, are given in [10], and references therein.

RSFs are brought to an absolute scale by normalizing them to the average total radiative width $\langle\Gamma_\gamma\rangle$ of neutron resonances [5]. The error of the absolute normalization is estimated to be ~20%. For normalization, the assumption of equal amounts of positive- and negative-parity states at any energy below S_n is made. The violation of this as-

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sumption for low excitation energies introduces a systematic error to the absolute normalization in the order of $\sim$4%. In the case of ^{56}Fe, also the value of $\langle \Gamma_\gamma \rangle$ has to be estimated from systematics. However, branching ratios needed for the subsequent analysis of TSC measurements are independent of the absolute normalization of the total RSF and are consequently not affected by the above assumptions. The normalized RSFs in ^{56,57}Fe are displayed in Fig. 1. To ensure that the total RSFs do not depend on excitation energy, we have extracted them also from two distinct partitions (in excitation energy) of the primary-γ matrices. The striking feature of the RSFs is a large strength for soft transitions, which has not been observed in the case of rare-earth nuclei, where we used the same analysis tools [5].

The soft transition strength constitutes an enhancement of more than a factor of 10 over common RSF models recommended in compilations [11]. To our knowledge, no other model can, at present, reproduce the shape of the total RSF either. A schematic temperature dependence of the RSF is taken into account in the KMF model. It is, however, insufficient to describe the data. Phenomenologically, the data are well described as a sum of a renormalized KMF model, Lorentzian descriptions of the GMDR and the isoscalar $E2$ resonance, and a power law modeling the large enhancement at low energies:

$$f_\Sigma = K\left(f_{E1} + f_{M1} + \frac{A}{3\pi^2 c^2 \hbar^2} E_\gamma^{-B}\right) + E_\gamma^2 f_{E2}. \qquad (3)$$

The parameters for the RSF models are taken from systematics [11]. The fit parameters for ^{57}Fe are $K = 2.1(2)$, $A = 0.47(7)$ mb/MeV, and $B = 2.3(2)$ (E_γ in MeV). However, the good description of the enhancement by a power law should not prevent possible interpretations as a low-lying resonance or a temperature-related effect.

To ensure that the observed enhancement is not connected to peculiarities of the nuclear reaction or analysis method, a TSC measurement based on thermal neutron capture has been performed to confirm the findings. It has been shown that TSC intensities from ordered spectra can be used to investigate the soft RSF [12,13]. The TSC technique for thermal neutron capture has been described in [14]. It is based on multiplicity-two events populating low-lying levels. Here, we will give only a brief description of some of the details.

The TSC experiment, i.e., the ^{56}Fe$(n, 2\gamma)^{57}$Fe reaction, was performed at the dual-use cold-neutron beam facility of the Budapest Research Reactor (see [15,16], and references therein). About 2 g of natural iron was irradiated with a thermal-equivalent flux of 3×10^7 cm^{-2} s^{-1} cold neutrons for $\sim$7 days. Single and coincident γ rays were registered by two high-purity Ge detectors of 60% and 13% efficiency at a distance of 8 cm from the target and with an energy resolution of several keV. They were placed at 62.5° with respect to the beam axis in order to minimize the effect of angular correlations.

TSCs populating discrete low-lying levels in ^{57}Fe produce peaks in the summed-energy spectrum shown on the left panel of Fig. 2. Gating on the unresolved doublet of the $1/2^-$ ground state and the $3/2^-$ first excited state at 14 keV yields the TSC spectrum on the right panel of Fig. 2. Spectra to other final levels were not investigated due to their lower statistics and higher background. The TSC spectrum is compressed to 250-keV-wide energy

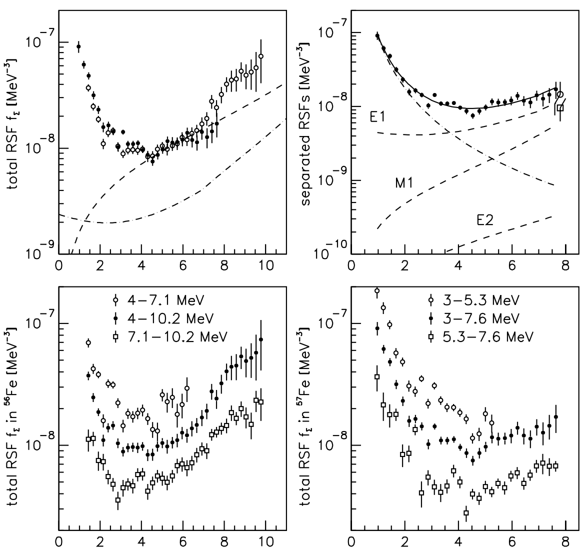

FIG. 1. Upper left panel: Total RSF f_Σ of ^{57,56}Fe (solid and open circles, respectively); Lorentzian (dashed line) and KMF model (dash-dotted line) descriptions of the GEDR. Upper right panel: Fit (solid line) to ^{57}Fe data and decomposition into the renormalized $E1$ KMF model, Lorentzian $M1$ and $E2$ models (all dashed lines), and a power law to model the large enhancement for low energies (dash-dotted line). Open symbols are estimates of the $E1$ (circle) and $M1$ (square) RSF from hard primary-γ rays [21]. Lower panels: Total RSF in ^{56}Fe (left) and ^{57}Fe (right) for different excitation-energy windows indicated in the figure. Open circles and squares are offset by a factor of 2 and 0.5 with respect to their true values.

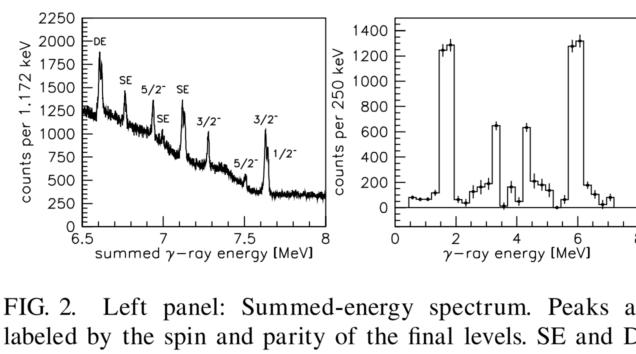

FIG. 2. Left panel: Summed-energy spectrum. Peaks are labeled by the spin and parity of the final levels. SE and DE denote single- and double-escape peaks. Right: Efficiency-corrected and background-subtracted TSC spectrum gated on the unresolved doublet of the ground and first excited state. The spectrum is compressed into 250-keV-wide energy bins. Error bars include statistical errors only.

bins. When the sequence of the two γ transitions is not determined experimentally, cascades with soft (discrete) secondary transitions are registered in the TSC spectrum as peaks on top of a continuum of cascades with soft primary transitions. Absolute normalization of TSC spectra is achieved by normalizing to five strong, discrete TSCs for which absolute intensities of their hard primary transitions and branching ratios for their secondary transitions are known [17]. The estimated error of the normalization is ~20%. In the following, the smooth part of the TSC spectrum will be investigated in more detail.

In order to separate cascades with soft primary and soft secondary transitions in the TSC spectra, we use the fact that the spacing of soft, discrete secondary transitions in regions of sufficiently low level density is considerably larger compared to the detector resolution. Thus, soft secondary transitions will reveal themselves as discrete peaks. On the other hand, soft primary transitions will populate levels which are spaced much closer than the detector resolution and will hence create a continuous contribution. Separation of soft primary and secondary transitions is therefore reduced to a separation of individual peaks from a smooth continuum (by, e.g., a fitting procedure) in the appropriate energy interval [13].

The spin of the compound state in ^{57}Fe populated by s-wave neutron capture is $1/2^+$. Thus, in the excitation-energy region 0.55–1.9 MeV, there are only three levels which can be populated by primary $E1$ transitions: the $1/2^-$ level at 1266 keV, the $3/2^-$ level at 1627 keV, and the $3/2^-$ level at 1725 keV. All other levels have spins $5/2^-$ and higher and can be populated only by transitions with $M2/E3$ and higher multipolarity. Assuming that γ transitions of such high multipolarities have a negligible contribution to the TSC spectrum, we do not take them into account in the further analysis. TSCs to the ground and first excited states involving the three above-mentioned levels as intermediate levels can easily be identified from their corresponding peaks in the TSC spectrum. Their contribution to the TSC spectra is subtracted. The remaining, continuous TSC spectrum in the specified energy range can be assigned to TSCs with soft primary γ transitions. This smooth part of the TSC spectrum is used to test the soft RSF obtained from the Oslo-type experiment. Estimations based on the known level density in ^{57}Fe [10] show that soft primary transitions in the energy interval 0.55–1.9 MeV populate ~150 levels. Assuming that primary and secondary transitions fluctuate according to a Porter-Thomas distribution, we estimate systematic intensity uncertainties to be ~25% for this energy interval. Finally, also the midpoint of the TSC spectrum, where energies of primary and secondary transitions are equal (and hence known), has been used in the subsequent analysis. For other energy intervals, the determination of the sequence of the two transitions in TSCs is subject to large uncertainties; thus, they are unsuitable for the present analysis.

In the present analysis, the intensity of ordered TSCs between an initial and final state is calculated on the basis of the statistical model of γ decay from compound states:

$$I_{if}(E_1, E_2) = \sum_{XL,XL',J_m^\pi} \frac{\Gamma_{im}^{XL}(E_1)}{\Gamma_i} \rho(E_m, J_m^\pi) \frac{\Gamma_{mf}^{XL'}(E_2)}{\Gamma_m}, \quad (4)$$

where E_1 and E_2 are the energies of the first and second transition in the TSC which are connected by $E_i - E_f = E_1 + E_2$. Γ_{im} and Γ_{mf} are partial decay widths and Γ_i and Γ_m are total decay widths of the initial and intermediate (m) levels, respectively. The average values of these widths can be calculated from the RSF by Eq. (1). Summing in Eq. (4) is performed over all valid combinations of multipolarities XL and XL' of transitions and of spins and parities of intermediate states. Thus, TSC spectra depend on the same level density and RSFs which are extracted from the Oslo-type experiment; see, e.g., Eqs. (2) and (3).

Statistical-model calculations with experimental values for the level density and the total RSF have been performed assuming the decomposition of f_Σ according to Eq. (3) and a standard spin-parity distribution for intermediate states [18]. Four calculations were performed: one by neglecting the third term in Eq. (3), i.e., without the soft pole of the RSF, and the other three under the assumption of $E1$, $M1$, and $E2$ multipolarity, respectively, for this term. In Fig. 3, results are compared to experimental data for energies where ordering of TSCs can be achieved. The calculation without the soft pole does not reproduce the data at all. The experimental TSC intensity integrated over the 0.5–2.0 MeV energy region exceeds the calculated one by a factor of 4.8(13). For calculations under the assumption of $E1$, $M1$, and $E2$ multipolarities for the soft pole, this factor is reduced to 1.3(4), 1.0(3), and 1.4(4), respectively. Thus, any multipolarity is acceptable. Since the two lowest data points require an extrapolation of the total RSF below

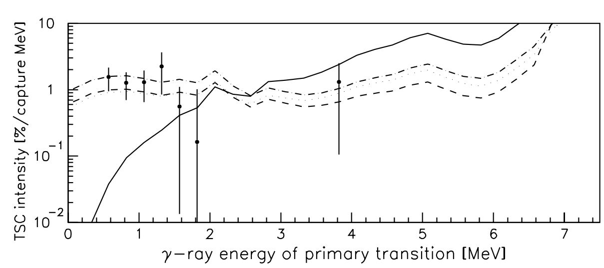

FIG. 3. Experimental TSC intensities (compressed to 250-keV-broad γ energy bins) for cascades with soft primary γ rays and at the midpoint of the spectrum (data points with error bars). Error bars include statistical and systematic uncertainties due to Porter-Thomas fluctuations. Lines are statistical-model calculations based on experimental data for the level density and f_Σ, neglecting (solid line) and assuming $E1$ (dashed line), $M1$ (dash-dotted line), and $E2$ (dotted line) multipolarity for the soft pole of the RSF.

1 MeV γ energy, we have performed calculations with different extrapolations including a resonance and an exponential description of the enhanced soft transition strength, avoiding the pole for $E_\gamma \to 0$. For these extrapolations the experimental TSC intensity for the lowest γ energy is not so well reproduced as before. Finally, we have performed calculations where the ratio of the negative-parity levels to the total number of levels decreases linearly from ~90% at 2.2 MeV to ~50% at ~7.6 MeV excitation energy. As expected, TSC intensities with soft primary γ rays are rather insensitive to this variation as well.

In conclusion, an enhancement of more than a factor of 10 of soft transition strengths (a soft pole) in the total RSF has been observed in Oslo-type experiments using the ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe and ^{57}Fe(^{3}He, ^{3}He$'\gamma$)^{57}Fe reactions. This enhancement cannot be explained by any present theoretical model. The total RSF has been decomposed into a KMF model for $E1$ radiation, Lorentzian models for $M1$ and $E2$ radiation, and a power law to model the soft pole. In a second experiment, TSC intensities from the ^{56}Fe(n, 2γ)^{57}Fe reaction were measured. Statistical-model calculations based on RSFs and level densities from the Oslo-type experiment were performed. These calculations can reproduce the experimental TSC intensities with soft primary γ rays only in the presence of the soft pole in the total RSF. The uncertainties due to Porter-Thomas fluctuations of TSC intensities do not allow us to draw definite conclusions about the multipolarity of the soft pole. For better selectivity, averaging over many initial n resonances will be needed. The satisfying reproduction of the experimental TSC data constitutes support for the physical reality of the soft pole, independent from the Oslo-type experiment. It should be noted that this support was gained by using a different nuclear reaction, a different type of detector, and a different analysis method. Finally, as further supporting evidence, we would like to mention that preliminary results on a chain of stable Mo isotopes also indicate the presence of a soft pole in the total RSF [19], while in the case of ^{27,28}Si, the Oslo method was able to reproduce the total RSF constructed from literature data on energies, lifetimes, and branching ratios available for the complete level schemes [20].

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