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First results on photon strength functions of ^{78}Se from the two-step γ Cascades measurement

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Abstract. Two-step gamma cascades (TSCs) following the radiative capture of thermal neutrons in ^{77}Se were measured at the research reactor at Řež near Prague. Results on photon strength functions (PSFs) of ^{78}Se, obtained from comparison of experimental TSC spectra with outcomes of simulations under different assumptions about level density and PSFs using the DICEBOX algorithm, are presented. The main attention is paid to possible manifestation of the pygmy resonance observed recently in this nucleus in the nuclear resonance fluorescence measurement and low-energy PSF enhancement observed in Oslo-type experiments for all $A \lesssim 100$ nuclei.

1. Introduction

There is a widespread consensus that decay of excited medium-mass and heavy nuclei can be described by the statistical model of the nucleus in terms of the level density (LD) and a set of photon strength functions (PSFs) for individual transition types. Knowledge on PSFs is of great importance for correct description of rates of various nuclear reactions and it is needed in nuclear astrophysics and in the development of nuclear technologies.

The PSFs obtained from different experimental techniques do not always agree well – the most famous examples are probably ^{96,98}Mo [1–3]. Any comparison of PSFs from different techniques for the same nucleus is hence very important.

Results on PSFs of ^{78}Se from nuclear resonance fluorescence (NRF) experiment were published several years ago [4]. The results indicated a presence of a strong resonance structure at γ-ray energy $E_\gamma \approx 9$ MeV, which was identified with the pygmy dipole resonance, and a smooth behavior below $E_\gamma \approx 7$ MeV, which is consistent with the Lorentzian energy dependence of the PSF, down to about 4 MeV. The PSF deduced from the NRF experiment was found to acceptably describe also singles γ-ray spectrum from thermal neutron capture [4]. However, coincidence γ-ray spectra from thermal neutron capture should show significantly higher sensitivity to different PSFs models than the singles spectrum. The comparison of NRF and neutron capture data seems advantageous in ^{78}Se as thermal neutron capture on ^{77}Se proceeds via $J^\pi = 1^-$ state – the same J^π levels are expected to be almost exclusively excited in the NRF experiments.

Another important feature of a PSF is its low-energy enhancement – a strong one has been reported in all $A \lesssim 100$ nuclei from Oslo-type experiments, see e.g. [5]. Contrary to this, coincidence γ-ray spectra from capture of slow neutrons in Mo isotopes indicated that the enhancement is very weak if any [3].

2. Experiment and data analysis

2.1. Experiment and data processing

The measurement was performed at the thermal neutron beam of the neutron guide which is installed at light-water research reactor LWR-15 at Řež. The same target as used for neutron capture measurement in [4], i.e. enriched to 99.66% in ^{77}Se, was irradiated with the uniform neutron flux of $3 \times 10^6\,\mathrm{cm^{-2}s^{-1}}$. The capture γ rays were viewed by a pair of HPGe detectors in close side-to-side arrangement, the sample being situated in between their cylindrical surfaces. The deposited γ-ray energies in the detector pair, together with the detection-time differences, were recorded in a list mode for off-line analysis. The measurement lasted for 300 hours.

Recorded signals were subject to off-line analysis in which the background-free γ-ray spectra of TSCs terminating at selected low-lying levels of ^{78}Se, referred below to as *TSC final levels*, were produced. These spectra were constructed from energies deposited in one of the detectors under the condition that the sum of deposited energies in the detector pair is equal to the difference between the neutron separation energy $S_n = 10.498$ MeV and energy E_f of the TSC final level f. While retrieving these spectra, the detector efficiencies were taken into account, as well as the vetoing effects due to detections of parasitic γ rays, originating from the post decay of TSC final levels. Thanks to high resolution power of Ge detectors the method [2,6] reliably excludes the TSCs populating other levels and rules out the accidental coincidence and Compton-related background. Moreover, it ensures that cascades $E_c \to E_i \to E_f$ from neutron capturing state c at energy $E_c \sim S_n$ via intermediate level i contribute almost exclusively to a given TSC spectrum by a pair of narrow, symmetrically situated lines at γ-ray

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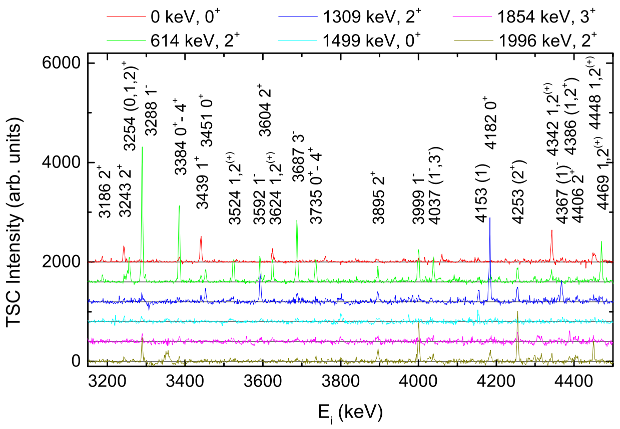

Figure 1. A part of TSC spectra corresponding to cascades via intermediate levels at $E_i = E_\gamma + E_f$ =3100–4500 keV. The vertical offset of spectra for different final TSC levels is applied to make the figure more readable.

energies $E_c - E_i$ and $E_i - E_f$; only $\lesssim 1\%$ of cascades contribute to the spectrum outside these lines [7]. In these respects, the TSC method is instrumentally the cleanest method among others designed for studying PSFs – no unfolding neither detector-response simulations are needed. The only parasitic structures in the spectra (for $E_\gamma > 511$ keV) are well-understood "bipolar structures" [6] which appear as "broad peaks" in the TSC spectra. A detailed description of the facility and construction of TSC spectra can be found in [6].

To express yields of TSC spectra in well-defined intensity units, we need to know an intensity of at least one distinct TSC cascade via a well-resolved low-lying level. There are several suitable cascades in ^{78}Se – seven of them, ending at the ground or the first excited state, were used with relative intensities per neutron capture taken from [8]. Relative intensities of these cascades are reasonably consistent with our data. We were able to retrieve TSC spectra corresponding to six TSC final levels at $E_f = 0$ keV (0^+), 613 keV (2^+), 1309 keV (2^+), 1499 (0^+), 1854 keV (3^+), and 1996 keV (2^+); only four of them with the highest statistics – those at $E_f = 0$, 613, 1309, and 1996 keV – were used for analysis of PSFs in this contribution. The TSC spectra can be used not only for the purpose of studying PSFs, but also for obtaining information on J^π of some low-lying levels and on decay pattern in region of low level density. A part of TSC spectra is shown in Fig. 1, where the horizontal axis displays the energy of intermediate state of a cascade, E_i. The figure illustrates that – due to low density of states in ^{78}Se – the TSC spectra consist almost exclusively of well-resolved transitions in the region corresponding to decay of states below excitation energy of about 4.5 MeV. The region corresponding to decay of states at higher energies shows only a few well-resolved transitions and contains an intensity from unresolved peaks as well.

2.2. Simulations

TSC spectra are products of a complicated interplay between PSFs and LD. To get information about these quantities we adopted a trial-and-error approach in which we compared the experimental TSC spectra with their predictions based on simulation of γ cascades under various model assumptions about PSFs and LD. For simulations we used the Monte-Carlo code DICEBOX [9], which allowed us, among others, to keep control on uncertainties of simulated TSC spectra due to Porter-Thomas (PT) fluctuations of individual transitions intensities [10] and due to possible deviations of exact number of levels from predictions of a smooth level density formula.

Relatively low LD of ^{78}Se allowed us to simulate high number – usually 2000 – of fictitious nuclei, called below *nuclear realizations*, for several combinations of PSFs and LD. Each nuclear realization is characterized by energies, spins and parities as well as decay properties of each level in the level scheme and individual nuclear realizations differ due to involved fluctuations. 10^6 independent, generally multistep cascades, that connect the neutron capturing state with the ground state, were simulated in each nuclear realization and simulated TSC intensity was obtained. To suppress influence of fluctuations involved in simulations as well as experimental uncertainties we binned TSC spectra into relatively coarse bins of the width of 200 keV.

All information about levels below excitation energy $E_x = 3.53$ MeV, including their decay and feeding via primary transitions, was taken from [8]. Individual levels above E_x were generated according to the Constant-Temperature (CT) or back-Shifted Fermi Gas (BSFG) models of LD, given by closed-form formulae with the values of adjustable parameters taken from [11]. No parity dependence of the LD was assumed above E_x. It shows up that predicted TSC intensities are not very sensitive to the LD model – the only difference is usually that the distribution of predicted TSC intensities with the CT model is usually broader than with the BSFG model. Transitions of $E1$, $M1$ and $E2$ were considered above $E_x = 3.53$ MeV in simulations and selection rules for transitions between individual levels were applied. Models for $E1$ and $M1$ transitions are described in Sect. 3. Lorentzian parametrization of the Giant Electric Quadrupole Resonance from [12] was used for $E2$ transitions.

3. Results and discussion

TSC spectra obtained for several PSFs combinations were compared to experimental data. We started with the PSFs combination proposed from NRF experiment in Ref. [4]. In reality, the NRF data yields information on the PSF only for $E_\gamma \gtrsim 4$ MeV and an extrapolation has to be used for lower E_γ – a simple Lorentzian form was proposed in [4] at these energies. The $M1$ PSF was parametrized according to Ref. [13] as a sum of three Lorentzian components corresponding to the scissors mode and the isoscalar and isovector spin-flip modes. These PSFs are visualized in Fig. 2(a) and were found to acceptably describe also singles spectrum from the thermal neutron capture [4].

Comparison of simulated spectral intensity for this PSFs combination with experimental data is made in Fig. 3. Vast majority of experimental points in the midparts of TSC spectra sits on the tail of expected (generally asymmetric) distribution; for many of them there are only a few nuclear realizations with higher predicted TSC intensities indicating that simulations underestimate spectral intensity at these energies.

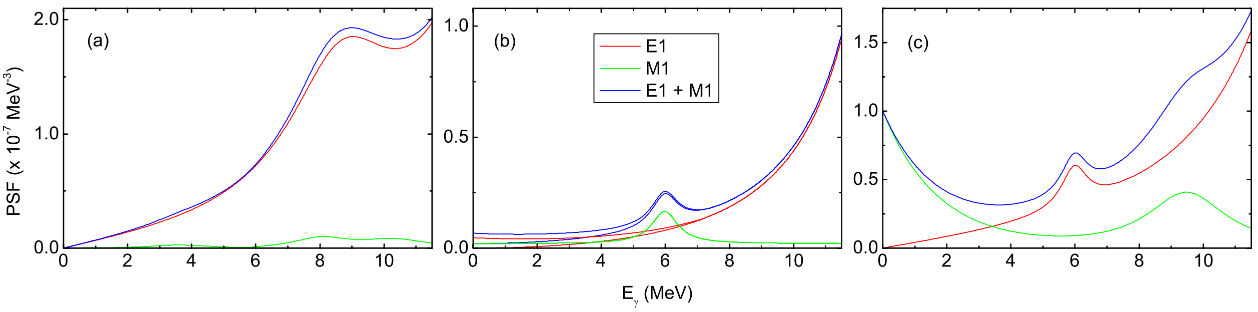

Figure 2. Models of PSFs used in presented simulations: (a) the model based on NRF data [4], for predicted TSC spectra see Fig. 3, (b) the model, which acceptably reproduces experimental spectra, for predicted TSC spectra see Fig. 4, (c) the model with a low-energy $M1$ PSF enhancement, for predicted TSC spectra see Fig. 5.

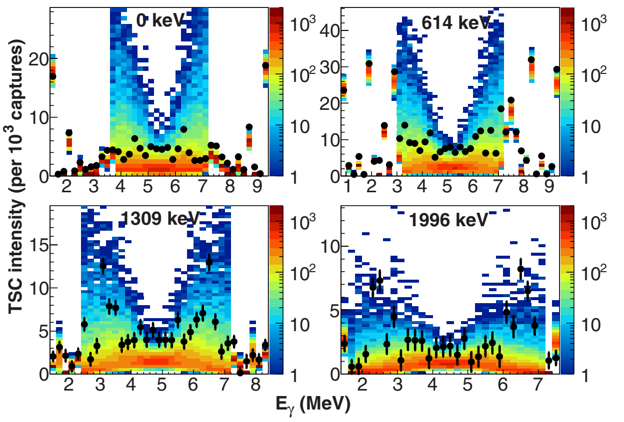

Figure 3. Comparison of simulated TSC spectra with experimental data for the PSFs model combination proposed from NRF experiment [4] and shown in Fig. 2(a). Experimental data are shown as black points, the color histogram shows the distribution of simulated TSC intensity from 2000 nuclear realizations. The energy of the TSC final level, E_f, is indicated in each panel.

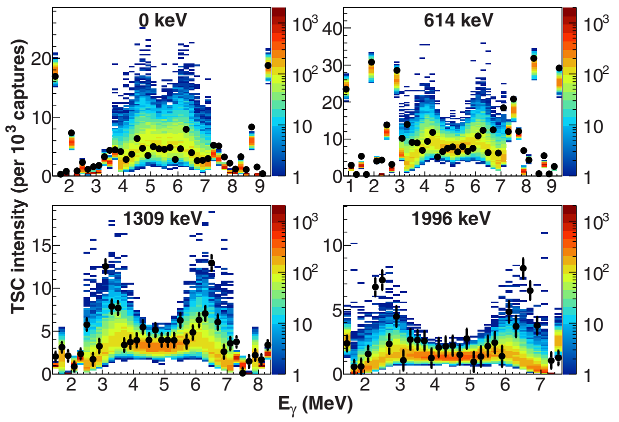

Figure 4. Comparison of simulated TSC spectra with experimental data using the PSFs combination from Fig. 2(b). See Fig. 3 for description of the figure layout.

Too low predicted intensity in the midparts of TSC spectra likely comes from strong preference of high-energy primary $E1$ transitions, see Fig. 2(a). Any PSFs combination aiming to better reproduce the experimental spectra should allow more primary transitions to higher excitation energies. In addition, resonance structures seem to be present in experimental TSC spectra – one at $E_\gamma \approx$ 6.5 MeV and the other (complementary) one at $E_\gamma = E_c - E_f - E_\gamma$. They originate from cascades with $E_\gamma =$ 6–7 MeV strong primary transitions, which presence should be reflected by the PSFs models.

We tried to simulate spectral TSC intensity with several different PSFs combinations having these features. For $E1$ PSF we usually used the temperature-dependent KMF model from [14] and $M1$ consisted of a combination of the single-particle and spin-flip models. As shown in Fig. 4, significantly better reproduction of experimental spectra than in Fig. 3 can be achieved with these PSFs combinations – PSFs plotted Fig. 2(b) were used in this particular case. The reproduction of the resonance structures near $E_\gamma = 6.5$ MeV is still not perfect but it can likely be improved by presence of a stronger resonance in a PSF at this E_γ. We can likely not unambiguously determine the type of transitions responsible for the resonance structure. Predictions similar to that in Fig. 4 can be reached also with a resonance structure in $E1$ PSF. No restrictions on transition type can be drawn from other data because strong primary transitions to levels of both parities near excitation energy of 4 MeV were reported in [8]. The resonance structure at $E_\gamma \approx 6$ MeV seems to be visible also in the singles spectrum from thermal neutron capture [4]. However, huge expected fluctuations in predictions of the spectral intensity for the singles spectrum prevented to conclude if the bump in the spectrum is a feature of PSFs or a mere fluctuation.

We can not completely exclude a possibility that decay of levels below about 4 MeV is not fully statistical. This is hinted by the observation of a few secondary transitions from these levels which are expected to be of $E2$ type [8]. These decays would naturally restrain us from drawing definite conclusions about the presence of a resonance structure in a PSF near $E_\gamma = 6$ MeV and would indicate that the description of γ decay within the statistical model down to low excitation energies is not completely justified.

We also tried to check a possibility of a presence of a low-energy PSF enhancement similar to that reported from Oslo-type experiments [5]. Simulated TSC spectra with the PSFs combination from Fig. 2(c) are shown in Fig. 5. Used parametrization of the enhancement does not correspond to any specific nucleus but describes its reported size. So far, we have tested the low-energy enhancement only in $M1$ PSF using its exponential dependence on E_γ. Simulated spectral intensity in Fig. 5 does not reproduce experimental data at all. Too low predicted intensity in

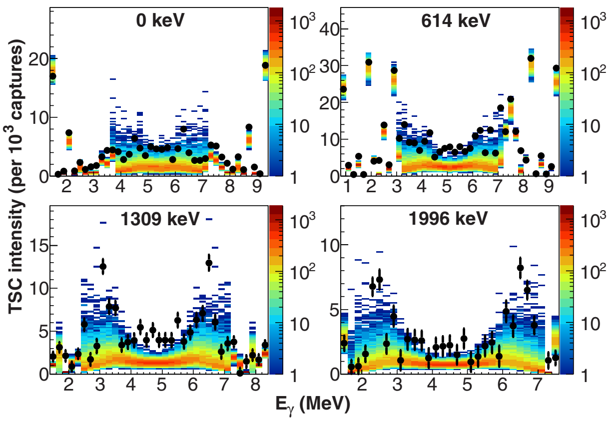

Figure 5. Comparison of simulated TSC spectra with experimental data for the PSFs model with a low-energy PSF enhancement, see Fig. 2(c) for the PSFs shape. See Fig. 3 for description of the figure layout.

the midparts of TSC spectra is a consequence of a shift in multiplicity distribution toward higher values due to preference of transitions with low E_γ. It shows up that predicted spectral intensity is similar to that in Fig. 5 even for much weaker enhancement – experimental TSC spectra can not be reproduced even if the size of the enhancement is reduced by a factor of 3–4. A search for maximum possible size of the enhancement is in progress.

It is to be noted that predicted TSC spectra are sensitive only to E_γ dependence of PSFs and to ratios of PSFs for different types and insensitive to absolute values of PSFs. In addition, as intensities of primary transitions to levels below $E_x = 3.53$ MeV were taken from experiment, the simulations are virtually insensitive to PSFs for $E_\gamma \gtrsim 7$ MeV.

4. Summary and outlook

The spectra of two-step γ cascades following thermal neutron capture on ^{77}Se were measured. Obtained spectra were compared to predictions made with several combinations of PSFs models. We found that neither predictions of the PSFs combination based on the NRF measurement nor predictions with a strong low-energy PSFs enhancement reproduce the experimental spectra well. A PSFs model combination which does not contain any of these two distinct features but instead has a resonance-like structure at $E_\gamma \approx 6.5$ MeV seems to be required to reproduce experimental spectra. More detailed analysis of required properties of possible structures in PSFs is in progress.

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