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Background: Radiative neutron capture on thulium, which is a monoisotopic element, plays a role in different applications such as nuclear astrophysics or nuclear burning environments. Considerable discrepancies—reaching 20%—exist between evaluations in the unresolved-resonance region. Furthermore, experimental data on statistical γ decay in odd-odd rare-earth nuclei is scarce. There are still open questions about the systematics of the so-called scissors mode in the $M1$ photon strength function, especially in odd-odd nuclei.

Purpose: This work is focused on two main topics—deriving experimental $^{169}\text{Tm}(n, \gamma)$ cross section and studying statistical γ decay of ^{170}Tm , in particular properties of the scissors mode.

Methods: The capture experiments to obtain experimental cross section were performed at the Los Alamos Neutron Science Center using the time-of-flight technique and employing the Detector for Advanced Neutron Capture Experiments. Measured coincident γ -ray spectra were also compared with statistical simulations using the DICEBOX code to test different models of level density and photon strength functions.

Results: The capture cross section was determined from 1.8 eV to 0.97 MeV, the broadest neutron-energy range ever measured for this isotope. Several new resonances have been observed. The statistical γ decay of ^{170}Tm cannot be reproduced without a scissors mode resonance centered at ≈ 3.3 MeV.

Conclusions: The measured cross section in the unresolved-resonance region is generally lower than the latest evaluations. The derived ^{169}Tm s -process abundance is expected to increase by a factor of 1.26, while the changes of the abundances of elements heavier than ^{169}Tm are in the order of 0.2%. The scissors mode properties in ^{170}Tm are similar to those deduced in previous analyses of neighboring nuclei ^{168}Er and ^{166}Ho .

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Thulium is a monoisotopic element with thulium-169 as its only stable isotope. This region of heavy nuclei is primarily created through the astrophysical *rapid* and *slow* (r and s) neutron-capture processes [1]. While the r process is considered to take place in an explosive environment far from stability over a short time scale [2], the main s process is expected to take place in low-mass AGB stars, near stability, largely following the line of β stability [3]. Because each process is estimated to contribute roughly 50% of the total abundances, disentangling the contributions from observations and assigning abundance is a significant challenge [4]. The region around mass 170 (shown in Fig. 1) is of particular interest, as stable ^{170}Er prevents r -process production of higher- Z , $A = 170$ isotopes, making stable ^{170}Yb a so-called

s -only isotope. These isotopes can only be produced by the s process. As such, understanding their production is a powerful tool to determine the conditions where the process is taking place. Further, if the lifetime of an unstable nucleus in the s -process reaction chain is comparable to the timescale for neutron capture, then the nucleus acts as a “branch point” between neutron capture and β decay. ^{170}Tm presents such a branch point, with a half-life of 128 d. As previously discussed, ^{170}Yb is only produced by s process. This s -only isotope provides information about the normalization of the s -process abundances in this mass region. The β decay of ^{170}Tm controls the production of ^{170}Yb , while $^{169}\text{Tm}(n, \gamma)$ reaction is responsible for creation of ^{170}Tm . Precise knowledge of $^{169}\text{Tm}(n, \gamma)$ cross section in the keV region is thus important for understanding the operation of the s process in this region.

In addition to its astrophysical interest, thulium has favorable properties for being used as a diagnostic tool to monitor neutron fluxes in a wide range of man-made nuclear-burning environments. The thulium isotopic chain is formed by isotopes on both neutron-rich and neutron-deficient side of stability with convenient half-lives for post-irradiation analysis. Their cross sections for neutron capture are large and (n, xn) cross sections are thresholded, which makes these reaction products indicators of both low-energy and high-energy

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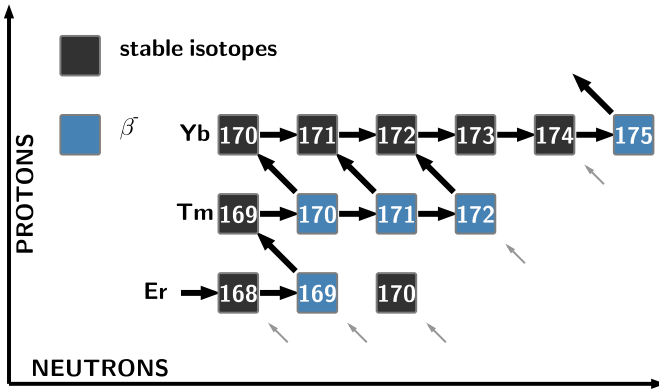


FIG. 1. Reaction path of the s process in the vicinity of ^{169}Tm . Black horizontal arrows indicate neutron capture, while black diagonal arrows indicate β decay. Gray arrows illustrate r process reaction path.

neutrons. Utilizing these characteristics, thulium was used to study reaction-in-flight neutrons in a plasma at the National Ignition Facility [5].

Significant discrepancies exist between different measurements of $^{169}\text{Tm}(n, \gamma)$ cross section in the astrophysically relevant range of energies. These differences are reflected in differences between evaluations. In the region above 100 keV, there is as much as 20% difference between ENDF/B-VIII.0 [6], JEFF 3.3 [7], and JENDL-5 [8] evaluations. Further, the most recent measurement in 2022 by Ren *et al.* [9], which reports cross section from 30 to 300 keV relative to the $^{197}\text{Au}(n, \gamma)$ cross section, is not included in the evaluations.

In the present work, the Detector for Advanced Neutron Capture Experiments (DANCE) was used to measure the $^{169}\text{Tm}(n, \gamma)$ cross section from 1.8 eV up to 0.97 MeV, the first experiment to unify that broad range of neutron energies. This allows independent determination of the Maxwellian-averaged capture cross section (MACS) for temperatures applicable in the astrophysical scenarios.

Further, DANCE is a powerful tool to investigate the γ decay following neutron capture with very high efficiency, allowing the detection of complete γ cascades. The resulting improved knowledge of level density (LD) and photon strength functions (PSFs) is not only crucial for determining γ -ray detection efficiency, but also essential for statistical calculations of neutron-capture cross sections employing the Hauser-Feshbach formalism. There are still many open questions in our understanding of PSFs, such as systematic properties of the so-called scissors mode (SM) manifesting in the $M1$ PSF. This phenomenon has been observed in many even-even and odd-even rare-earth nuclei [10,11] and has also been measured using the DANCE detector [12–14]. However, in odd-odd nuclei, it is still not well understood and there are only two studies, namely, ^{160}Tb [15] and ^{166}Ho [16]. In addition to the $^{169}\text{Tm}(n, \gamma)$ cross section, this paper presents experimental γ -ray coincidence spectra from $^{169}\text{Tm}(n, \gamma)$ using DANCE and a comparison to statistical simulations using the DICEBOX code [17] to draw conclusions about models of LD and PSFs.

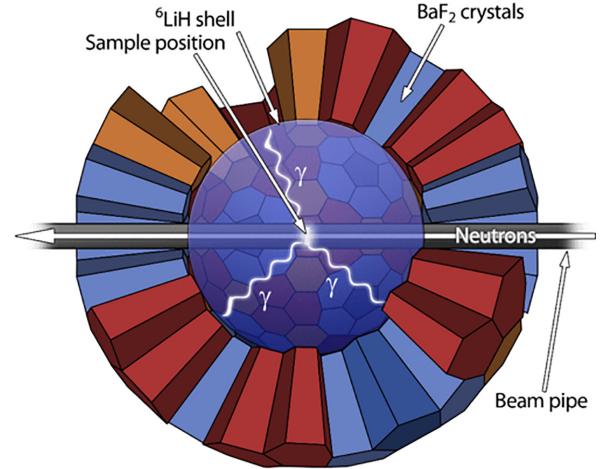


FIG. 2. Geometry of approximately half of the DANCE detector [22]. Different shapes of the individual detectors are distinguished by their corresponding colors.

II. EXPERIMENT

A. Experimental setup

The DANCE detector [18] is stationed at the 20.25-m flight path 14 of the Lujan Center at the Los Alamos Neutron Science Center (LANSCE) [19]. Neutrons are produced by spallation when 800 MeV protons strike a tungsten target at 20 Hz repetition rate [20]. Flight Path 14 views a water-filled backscatter moderator. Neutrons from 1 eV up to 1 MeV were utilized in the present experiment.

DANCE is a multi-detector array composed of 160 BaF_2 scintillators, forming a closed-packed $\approx 3.5\pi$ design, as illustrated in Fig. 2. Its high efficiency and segmentation are designed for detection of total γ -ray energy and multiplicity of the γ rays emitted after the neutron capture on the sample of interest. There are two components in the scintillation light originating from a BaF_2 crystal—a fast component with ≈ 600 ps decay time and a slow component with ≈ 600 ns decay time, allowing precise time reconstruction. The neutron flux is measured by three beam monitors—a silicon detector measuring charged particles from the $^6\text{Li}(n, t)\alpha$ reaction, a ^{235}U fission chamber, and a ^3He proportional counter.

Signals from the individual detectors are digitized using 16-channel CAEN VX1730 digitizers with 500 megasamples per second [21]. Data acquisition starts $\approx 100 \mu\text{s}$ before arrival of each proton pulse and its duration is given by a programmable time window, usually a few ms wide. The width of this time window controls the range of the neutron energies that are observed. Timestamp, charge integrals, and partial waveforms are stored for each detected signal. In addition, a more precise time of the individual event is calculated offline by applying a digital constant fraction algorithm to each partial waveform. To estimate possible dead-time effects, we record the average number of crystals that are integrating a signal as a function of time. For this measurement, we verified the average percentage of busy crystals was below 3.6% for the relevant neutron energies.

All signals that are detected within a preset coincidence window—in this analysis 5 ns—are grouped into one event. Due to Compton scattering, one γ ray may deposit its energy in several neighboring detectors. To describe the number of emitted γ rays more accurately, a dynamic clusterization (add-back) of detectors is performed in the analysis. Each constructed event is then characterized by neutron energy E_n , total detected γ -ray energy E_{sum} , number of clusters that were hit—cluster multiplicity M —and a set of cluster γ -ray energies E_{cl} .

B. Energy and time calibrations

Measurements with the γ -ray sources ^{22}Na and ^{88}Y were carried out before and after the experiment and their known lines were used for energy calibration of the DANCE detectors. ^{226}Ra , which is a chemical homologue of Ba present in the scintillators, is part of an α decay chain and therefore intrinsic radioactivity originating from it is always present. Due to different intensity ratios of slow-versus-fast components for α and γ particles, pulse-shape discrimination can be used to differentiate between the two events types. The α -decay lines were then used for run-by-run corrections for gain shifts in the detectors [23]. We employed a 200 keV detection threshold for all crystals in our analysis.

The relative timing of each crystal may change slightly between runs due to synchronization of the digitizers. Run-by-run time alignment of all detectors to one another was performed assuming zero time difference between Compton scattered signals in two neighboring detectors.

The time-of-flight (TOF) for each event can be expressed as $\text{TOF} = \text{TOF}_{L_0} + \text{TOF}_{\text{moder}} + \Delta\text{TOF}$, where TOF_{L_0} is the average time a neutron travels the flight path with a length L_0 , $\text{TOF}_{\text{moder}}$ is the time neutron spends in the moderator and ΔTOF is a constant global time offset related to the properties of the start signal received from the facility as well as local electronics and cabling. Due to the complicated moderation process which depends on E_n , simulations modeling the spallation target and the surrounding moderator [24] were used to obtain $\text{TOF}_{\text{moder}}$ correction to the measured TOF.

To derive the ΔTOF and precise length of the flight path L_0 , DANCE data from $^{197}\text{Au}(n, \gamma)$ were used. The R -matrix code SAMMY [25] was used to fit ΔTOF and L_0 by comparing the experimental data with the ENDF/B-VIII.0 evaluation in the whole region where ^{197}Au resonance parameters are reported. The derived values of ΔTOF and L_0 were then used in ^{169}Tm data analysis.

C. Samples

We used two primary samples during the measurements—both 1×1 inch ^{169}Tm self-supporting metal foils with 5.08×10^{-3} cm and 2.07×10^{-4} cm nominal thicknesses. These values correspond to areal densities of 1.69×10^{-4} atoms/b and 6.87×10^{-6} atoms/b, respectively. The thin sample was used for low E_n region to reduce self-attenuation effects and the thicker sample was used at larger E_n for improved statistics. There is a non-negligible impurity component in both samples identified as ^{181}Ta ; which is discussed in Sec. III D.

In addition, we measured an 867 Å-thick, 2-cm diameter ^{197}Au sample and a 97.4-mg, 4-mm diameter ^{208}Pb sample, used for the normalization of the neutron flux and scattered-neutron background description, respectively. Precise knowledge of the ^{197}Au sample properties is essential for normalization, therefore the sample was analyzed with Rutherford backscattering spectrometry to confirm its areal density. The Tm and Au samples used in our campaign are larger than the beam spot, i.e., have the beam interception factor of one.

III. DATA ANALYSIS

The (n, γ) cross section as a function of neutron energy E_n can be calculated in the thin-sample approximation as

$$\sigma(E_n) = \frac{1}{nS} \frac{C(E_n) - B(E_n)}{\varepsilon(E_n) \phi(E_n)}, \quad (1)$$

where $C(E_n)$ is the count rate in counts/s measured with the sample, $B(E_n)$ is the background count rate, $\varepsilon(E_n)$ is the detection efficiency for a γ cascade, $\phi(E_n)$ is the neutron flux in neutrons/(s cm²), n is the areal density in atoms/b, and S is the illuminated sample area. Individual quantities entering Eq. (1) are discussed in the following subsections, while the efficiency $\varepsilon(E_n)$ is discussed in detail in Sec. IV B.

A. Capture count rate and background subtraction

To distinguish capture events from background contribution, DANCE relies on calorimetric information as a function of E_n . Information on E_{sum} and M of each event provides a powerful tool to improve signal-to-background ratio.

There are multiple sources of background in DANCE measurements [23]. First, cosmic radiation, accelerator background and β decay coming from ^{226}Ra decay chain are considered time-independent background. The majority of these events have $M = 1$ and $E_{\text{sum}} \lesssim 3.5$ MeV. Second, there is a time-dependent, beam-related background which is a function of E_n . This component is mostly given by neutrons scattering off the sample and captured in the detectors. It can be characterized by using the ^{208}Pb sample, which has a significantly larger elastic-scattering cross section than capture cross section. It can therefore be considered as a pure scatterer.

The dominant capture rate of scattered neutrons in the BaF₂ crystals comes from the capture on Ba isotopes. The relevant stable isotopes and their respective Q values for radiative neutron capture are: ^{134}Ba with $Q = 6.973$ MeV, ^{135}Ba with $Q = 9.108$ MeV, ^{136}Ba with $Q = 6.906$ MeV, ^{137}Ba with $Q = 8.612$ MeV, and ^{138}Ba with $Q = 4.723$ MeV [26]. As the Q values for ^{135}Ba and ^{137}Ba are notably larger than ^{169}Tm Q value of 6.592 MeV [27], we can safely assume that events with $E_{\text{sum}} \gtrsim 8$ MeV come exclusively from neutron scattering.

We thus normalized ^{208}Pb E_{sum} spectra to ^{169}Tm ones in the range $E_{\text{sum}} = 8.3$ –10.0 MeV, and subtracted this contribution. We applied this background correction for each E_n bin, example spectra are shown in Fig. 3. It is important to note that the E_{sum} shape is different for ^{208}Pb and ^{169}Tm in the low- E_{sum} region, most prominently around 1 MeV, where the

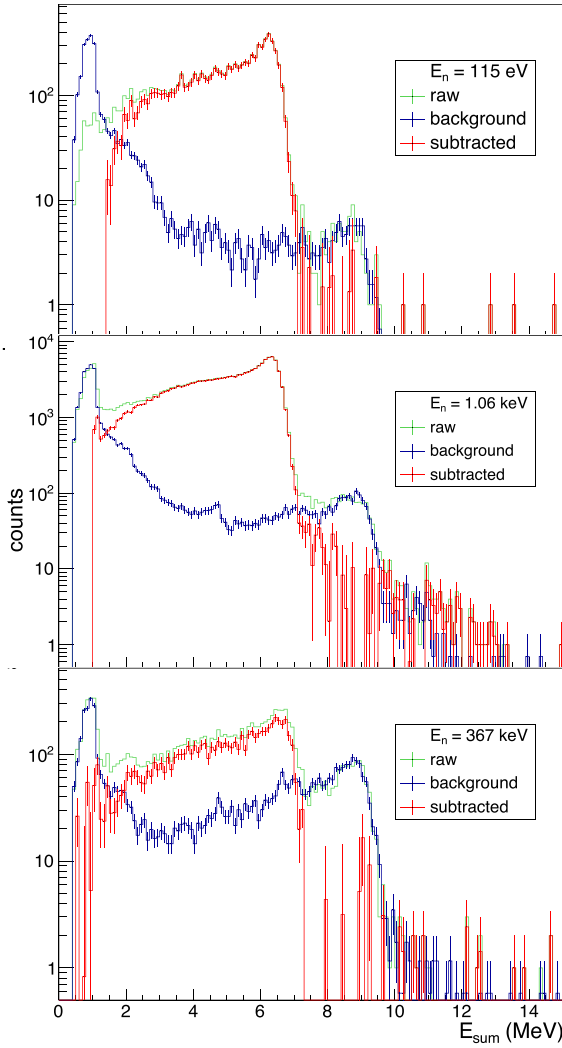


FIG. 3. Raw sum-energy spectra (green) from the thick Tm sample and background contribution (blue) originating from scattered neutrons subtracted from the spectra. Each panel corresponds to a different E_n indicated in the legend. Spectra are plotted for $M = 2-5$.

counts originate from photons coming down the beam pipe and interacting with the sample, creating electron-positron pairs and subsequently two annihilation photons with 511 keV energy each. These two photons are detected as one event with the corresponding $E_{\text{sum}} \approx 1$ MeV. Because the cross section for this interaction scales roughly with Z^2 , we expect a larger contribution for the ^{208}Pb sample than for ^{169}Tm and therefore over-subtraction in the E_{sum} spectra around this peak. However, any over-subtraction up to $E_{\text{sum}} \approx 3.5$ MeV, which is dominated by photon scattering, does not impact our results as we construct background-subtracted counts by integrating the spectra over $E_{\text{sum}} = 4.0 - (6.8 + E_n)$ MeV and $M = 2 - 5$. The choice of these gates reflects properties of ^{169}Tm , such as its radiative-capture Q value, and the best signal-to-background ratio achievable.

To study γ emission probabilities, we construct multi-step cascade (MSC) spectra, which are the spectra of E_{cl} for given M and given E_{sum} interval, we use an even narrower cut

on sum-energy $E_{\text{sum}} = 5.8-6.8$ MeV to put emphasis on cascades which deposit all of their energy in the DANCE array. We construct these spectra for all cluster multiplicities for well-resolved singlet resonances with known spin assignment [6,26] and sufficient statistics. The $M = 1$ MSC spectra show huge fluctuations between individual resonances and are only 1 MeV wide by construction. The $M \geq 5$ MSC spectra do not display significant structures and their intensity significantly decreases with multiplicity. While we have checked $M = 1$ and $M \geq 5$ spectra during the analysis, we chose not to present them for the sake of clarity. For the comparison with simulations, all experimental spectra for a given resonance were normalized by one common factor given by the integral of the $M \geq 2$ sum-energy spectrum in the corresponding aforementioned E_{sum} range.

B. Neutron flux

Beam monitors (BM) measure the neutron flux simultaneously with the experiment downstream from DANCE. Nevertheless, the neutron flux $\phi(E_n)$ entering Eq. (1) corresponds to the flux measured at the sample position. This is expressed in the following equation:

$$\phi(E_n) = \kappa \frac{C_{\text{BM}}(E_n)}{\sigma_{\text{BM}}(E_n)}, \quad (2)$$

where $C_{\text{BM}}(E_n)$ is the measured BM count rate and $\sigma_{\text{BM}}(E_n)$ is the corresponding BM reaction cross section. Finally, κ is the normalization factor, independent of E_n , which reflects the BM efficiency, the number of BM atoms in the beam and the expansion of the beam spot from the sample position to the BM location.

We derived the neutron flux normalization κ from the $^{197}\text{Au}(n, \gamma)$ standard resonance at 4.9 eV. We used resonance parameters from ENDF/B-VIII.0 evaluation with SAMMY. The overall normalization factor was fit to the experimental data with SAMMY, as shown in Fig. 4.

We employed the ^6Li BM for $E_n < 10$ keV due to the smooth shape of its corresponding cross section in this region. Above 20 keV, we constructed the neutron flux from ^{235}U BM data. The region between 10 and 20 keV was used to normalize ^{235}U to ^6Li . A ^3He BM was also used, but only as a consistency check.

The energy dependence of the neutron flux can be found in Fig. 5. It is important to note that due to the aluminum component in the beam pipe, there is a strong attenuation of neutrons with E_n close to ^{27}Al resonances at 34.8, 86.3, 142.9, and 203 keV. This leads to very large uncertainties of the calculated cross section at these energies and therefore we do not report these few data points.

C. Self-attenuation corrections

There exist several self-attenuation effects, which increase with the thickness of the sample. We used SAMMY to derive corrections for these effects in the resolved-resonance region (RRR), using ENDF/B-VIII.0 evaluated cross section. Evaluated resonance parameters, together with the experimental thickness and areal density of the given sample were used in the SAMMY input to calculate cross section with self-shielding,

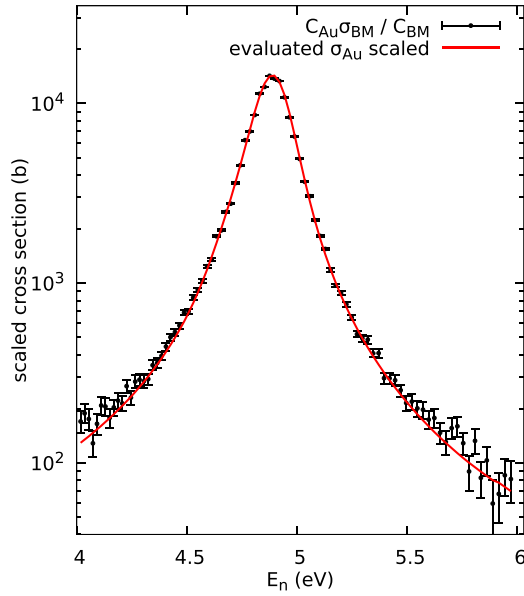


FIG. 4. $^{197}\text{Au}(n, \gamma)$ standard resonance at 4.9 eV measured by DANCE and used for normalization of the neutron flux. The scaled cross section from ENDF/B-VIII.0 is also shown.

single, and multiple scattering included. A user-defined resolution function for the spallation target [20] was employed to account for resolution broadening. Then a ratio between cross section from SAMMY with and without self-attenuation effects was calculated. This ratio, naturally different for the two samples with different thicknesses, was then used to correct for self-attenuation effects in the two experimental data sets. We verified that two options provided by SAMMY—to calculate multiple scattering analytically and using the Monte Carlo method—yielded consistent results. The derived correction factor is between 0.97–1.07 for the thin sample and 0.73–4.12 for the thick sample. To suppress self-attenuation effects, we combined the above-mentioned two data sets, more details are discussed in Sec. V.

This method relies on the ENDF/B-VIII.0 evaluated $^{169}\text{Tm}(n, \gamma)$ cross section, which gives a good agreement

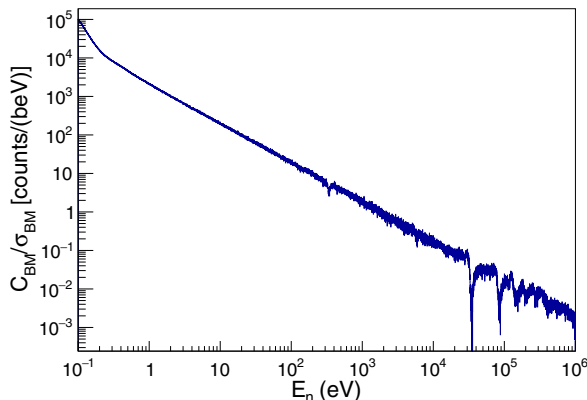


FIG. 5. Energy dependence of the neutron flux measured at DANCE.

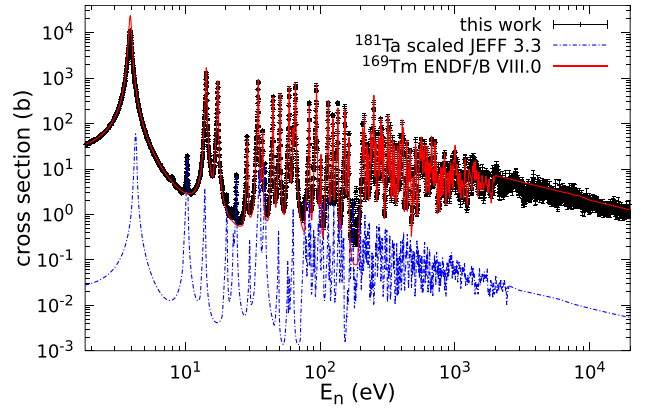


FIG. 6. Experimental $^{169}\text{Tm}(n, \gamma)$ cross section from the thick target before contaminant subtraction, compared with ENDF/B-VIII.0 evaluated $^{169}\text{Tm}(n, \gamma)$ cross section (red) and scaled JEFF 3.3 $^{181}\text{Ta}(n, \gamma)$ cross section (blue). Evaluated cross sections are broadened with Doppler broadening and user-defined resolution function derived from simulations.

with our experimental data in the RRR. There is no evaluated uncertainty reported. Therefore, we estimated the maximum uncertainty of the self-attenuation corrections in the following fashion: we increased and decreased the evaluated cross section by 10% and calculated the correction factor as described above. For the strongest ^{169}Tm resonance, which corresponds to the largest corrections, the difference in the derived correction factor was 0.5%. This provides us with a very conservative estimate of the maximum uncertainty we expect from this method.

We employed SAMMY in the RRR, which is up to $E_n = 1.945$ keV for ENDF/B-VIII.0. For higher E_n , in the so-called unresolved-resonance region (URR), we used SESH [28] to determine self-attenuation corrections. They were found to be negligible for both samples.

D. Contaminant characterization

Despite the 99.9% purity of the samples reported by the manufacturer, we identified resonances in the experimental data that did not originate from ^{169}Tm . DANCE is a powerful tool to distinguish neutron captures on different isotopes based on the shape of their E_{sum} spectra, especially if they have different S_n . Analyzing E_{sum} of these resonances and comparing the experimental cross section with evaluations, we confirmed an impurity coming from ^{181}Ta with $S_n = 6.06294$ MeV [29]. Because there was no information about its abundance in the sample assays, we estimated this value using SAMMY by fitting a combination of the evaluated $^{169}\text{Tm}(n, \gamma)$ and $^{181}\text{Ta}(n, \gamma)$ cross section to the experimental data. We show the obtained contributions from $^{169}\text{Tm}(n, \gamma)$ and $^{181}\text{Ta}(n, \gamma)$ in Fig. 6. The obtained fitted factor is then given by the abundance of ^{181}Ta and the detection efficiency for ^{181}Ta γ cascades. We estimated the ^{181}Ta abundances to be 1.21(24)% and 0.79(16)% for the thin and thick samples, respectively.

We used the ^{181}Ta evaluated cross section from JEFF 3.3 scaled by the corresponding factor to subtract this

contribution from the experimental cross section for each sample. We conservatively estimated a 20% uncertainty in the ^{181}Ta abundance, which was then propagated to the uncertainty of the subtracted cross section. The subtracted contribution is most prominent at low E_n in the centers of the strongest ^{181}Ta resonances, while at $E_n \gtrsim 1$ keV it is generally very small and below 1%.

IV. SIMULATIONS

In the current work, we have simulated the statistical γ decay following the neutron capture with two goals. The first is to understand the detection efficiency of the DANCE array for Tm capture events, which is required to extract the neutron-capture cross section. The second is to learn about the level density and the photon strength functions in Tm. This latter effort will be discussed in more detail in Sec. VI. The observed MSC and sum-energy spectra are a convolution of the nuclear level density, the photon strength functions, and the detector response. Thus, it is not realistic to directly extract the PSFs and LD from the experimental spectra. Instead, we employ a trial-and-error forward approach in which the simulated cascades are used as an input to the GEANT4 model of the detector array and compared to the experimental counterparts. In this way, inconsistent model combinations can be rejected. In particular, for the efficiency determination, as long as the models reliably reproduce the spectral shape, the efficiency is largely independent of the true decay pattern. In fact, the variation of acceptable models provides a measure of the systematic uncertainty in the model chosen in the efficiency determination.

A. Modeling of statistical γ decay

We used the DICEBOX code [17,30] to simulate the decay scheme and the individual γ cascades. This Monte Carlo code assumes validity of the statistical model of γ decay above some excitation energy, referred to as the critical energy E_{crit} . To estimate the impact of fluctuations in the number of nuclear levels and of the Porter-Thomas (PT) fluctuations of partial radiative widths, we simulated 20 different artificial nuclei, the so-called *nuclear suprealizations* (NS), for each model combination. The uncertainty due to the finite number of simulated cascades is present as well and we simulated 10^5 cascades within each artificial nucleus unless specified otherwise.

As the statistical model cannot describe the decay of low-lying nuclear levels, the decay scheme below the critical energy is taken from existing spectroscopic data or their evaluation. In our case we have chosen $E_{\text{crit}} = 960$ keV and the decay scheme was taken from the ENSDF evaluation [27]. The internal conversion is accounted for in the whole excitation energy domain by taking evaluated α coefficients when available [27] or results of calculations from BrIcc [31]. The initial excitation energy for cascade modeling was set to the neutron separation energy $S_n = 6.592$ MeV [27] unless specified otherwise.

The response of the DANCE detector, calculated using the GEANT4 package [32,33], was subsequently applied to

simulated γ cascades. The same cuts, histogram binning, and normalization as for the experimental spectra were applied to the simulated spectra. The resulting sum-energy and MSC spectra are drawn as mean $\pm$ standard deviation intervals calculated from the 20 NS and 10^5 cascades.

In general, the average total radiative width, $\bar{\Gamma}_\gamma$, is the only quantity from DICEBOX simulations that depends on the absolute values of PSFs. Moreover, $\bar{\Gamma}_\gamma$ is independent of the detector-response simulations. As such, it can serve as an important anchor for the PSF models. A reliable independent information on $\bar{\Gamma}_\gamma$, for example from the fits of neutron resonances, is thus essential. We discuss $\bar{\Gamma}_\gamma$ in more detail in Sec. VIC.

There are many models of LD and PSFs available in the literature. Those used in simulations presented in this article are introduced in Sec. VI. For more details see Ref. [34]. There are several different closed-form formulas for $E1$ PSF which describe the giant electric dipole resonance (GEDR), such as standard Lorentzian (SLO), generalized Lorentzian (GLO), or modified generalized Lorentzian (MGLO), see Refs. [12,35]. On the other hand, the magnetic dipole resonances in the $M1$ PSF are usually taken in the SLO form.

B. Detection efficiency

We performed the simulations of the detector efficiency ε for the whole range of E_n relevant for the cross section measurement considering neutron orbital momenta $\ell_n \leq 2$. For a given model combination and J^π of the capturing state, we calculated the efficiency as the ratio of the number of events within the yield construction cuts, see Sec. III A, to the number of simulated neutron captures. In practice, we used a 100-keV E_n grid for the simulations.

The resulting values, corresponding to an average of individual ε for all possible J^π of the capturing states and for several model combinations that provided a satisfactory description of the MSC and sum-energy spectra, more details in Sec. VIB, are shown together with an *ad hoc* interpolation in Fig. 7. For $E_n \lesssim 10$ keV, $\varepsilon = 62.34(40)\%$. The dependence of the efficiency on E_n , as shown in Fig. 7, comes purely from the increase of initial excitation energy and the widening of the E_{sum} cut with E_n —given by $E_{\text{sum}} = 4.0 - (6.8 + E_n)$ MeV.

The presented uncertainty of ε , also listed in Table I, consists of a contribution from a given model combination and J^π , typically reaching $\simeq 0.3\%$, and of differences in predictions of different models and J^π 's. Note that thanks to the similarity of the individual values of ε and the way we construct the final efficiency, it does not depend on any assumptions about the actual contribution of different ℓ_n to the cross section.

V. CROSS SECTION RESULTS

The experimental cross section for $^{169}\text{Tm}(n, \gamma)$ reaction is shown in Fig. 8 for the range of $E_n = 1.8$ eV–0.97 MeV. We combined data sets from two samples in the following fashion—for $E_n > 300$ eV, all experimental points come from the thick-sample data exclusively. For $E_n \leq 300$ eV, data from the thin sample are used when the experimental cross

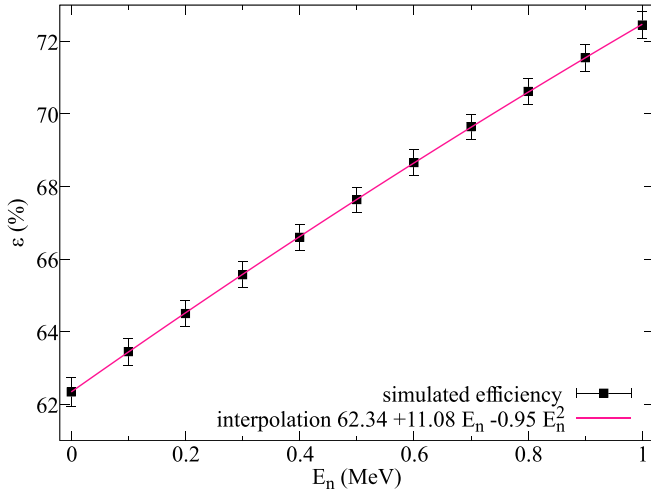


FIG. 7. Efficiency as a function of E_n . The interpolation with a quadratic function is shown, constant term was fixed to $\varepsilon = 62.34\%$. Total uncertainties described in the text are shown for simulated points.

section is above 10 b to limit self-attenuation effects, while below 10 b thick-sample data points are taken. As discussed in Sec. III B, we do not report a few data points near ^{27}Al transmission dips in the neutron flux. The derived experimental cross section is corrected for self-attenuation effects and ^{181}Ta contribution is subtracted.

In the following subsections, we discuss uncertainties of the derived cross section, a comparison with available literature data in the RRR and URR, CoH_3 calculations, and astrophysical implications. We refer to the regions where resonance parameters are available in the evaluations as RRR and to regions where only a point-wise cross section and the corresponding interpolation is reported as URR.

A. Uncertainties

Statistical uncertainties of the derived cross section are related to the number of counts measured with DANCE and the

TABLE I. Relative systematic uncertainties of the derived $^{169}\text{Tm}(n, \gamma)$ cross section. Uncertainty components of the neutron flux normalization are listed separately.

Uncertainty component	$E_n < 10 \text{ keV}$ $E_n \geq 10 \text{ keV}$	
	1σ uncertainty (%)	
Areal density of ^{197}Au		1.0
Extraction of κn_{Au}		2.0
^{197}Au evaluated cross section		2.7
Neutron flux normalization		3.5
Areal density of ^{169}Tm		1.0
BM evaluated cross section	0.5	1.8
DICEBOX simulations		0.6
GEANT4 simulations		1.5
Self-attenuation corrections		<0.5
total	4.0	4.4

employed beam monitors. Uncertainty originating from the background subtraction using ^{208}Pb sample was propagated into the cross section uncertainty for each E_n bin.

There are several sources of the systematic uncertainties, summarized in Table I. The neutron flux normalization, which is relative to gold (more details given in Sec. III B) has three uncertainty components. First, the uncertainty in the areal density of the measured ^{197}Au sample was determined by Rutherford Backscattering technique. Second, the extraction of the κ normalization parameter from SAMMY was repeated for several different subsets of the experimental ^{197}Au data and the uncertainty was derived as a standard deviation of the average value of κ . The last component is the uncertainty of the evaluated $^{197}\text{Au}(n, \gamma)$ cross section used for fitting, which is reported in the ENDF/B-VIII.0 evaluation. The overall neutron flux normalization uncertainty is 3.5% and introduces the largest contribution to the total systematic uncertainty. Another uncertainty related to the neutron flux comes from the evaluated cross sections for ^6Li and ^{235}U in the beam monitors, see Eq. (2). The final systematic uncertainty was obtained by adding individual systematic uncertainties in quadrature.

The uncertainty of the detection efficiency derived from DICEBOX and GEANT4 simulations is discussed in detail in Sec. IV B. For a discussion of the uncertainty related to the self-shielding, single, and multiple scattering corrections, see Sec. III C. Furthermore, a 20% uncertainty of the subtracted ^{181}Ta contribution was propagated for each E_n bin into the final uncertainty of the calculated $^{169}\text{Tm}(n, \gamma)$ cross section, see Sec. III D. Final uncertainties of the cross section that are shown in the figures include both statistical and systematic contributions.

B. Comparison with evaluations in RRR

We compared our experimental results with the three recent evaluations -ENDF/B-VIII.0, JEFF 3.3, and JENDL-5, see Fig. 8. We used reported resonance parameters to calculate the evaluated cross section with SAMMY and employed a user-defined broadening function derived from simulations of the spallation target at LANSCE, together with Doppler broadening at 300 K. ENDF/B-VIII.0 reports resonance parameters up to 1.95 keV, while JEFF 3.3 stops at 5.56 keV and JENDL-5 at 1.13 keV. The three evaluations are almost identical up to ≈ 700 eV—we observe all the reported resonances and a few new ones discussed below. Above 1 keV, ENDF/B-VIII.0 seems to agree better with our data than JEFF 3.3,¹ which appears to overestimate the cross section by $\sim 50\%$.

One of the regions where our results differ significantly from all evaluations is $E_n = 170\text{--}200$ eV, as shown in Fig. 9. Our data clearly reveal resonance structures not reported in any of the above-mentioned evaluations. It is worth noting that such a gap without any resonance is extremely unrealistic given the evaluated average s -wave resonance spacing D_0 [6–8]. There are, however, two data sets available in EXFOR that observed a resonance in this region—de Barros *et al.* [36]

¹Note that there are some very questionable resonance parameters in JEFF 3.3 in the keV region, e.g., $\Gamma_\gamma(3.709 \text{ keV}) = 21.68 \text{ eV}$.

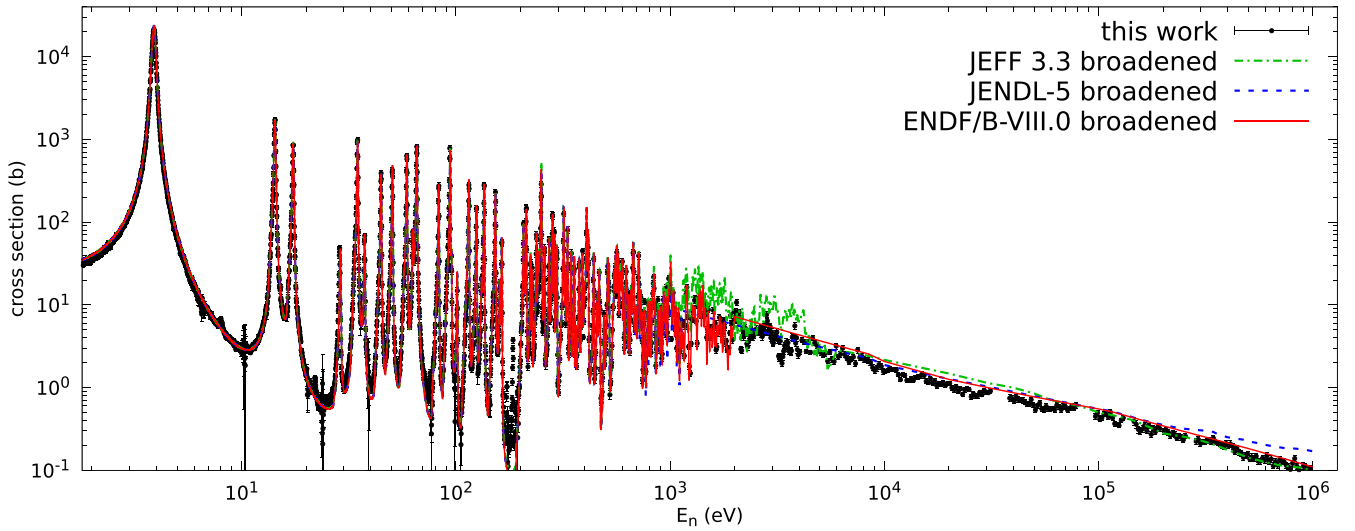


FIG. 8. Experimental cross section for the whole measured energy range compared with ENDF/B-VIII.0, JEFF 3.3, and JENDL-5 evaluations. Evaluated cross sections are broadened with Doppler broadening and user-defined resolution function derived from simulations.

report only the resonance energy of 185.0 eV, while Arbo *et al.* [37] report the energy of 185.4 eV and a resonance width times total peak cross section of 4 b.eV. Neither of the references reports measured resonance widths or spin.

Altogether, we observe eight new resonances in our data. To estimate their energies and $g\Gamma_n$, we assumed the average $\Gamma_\gamma = 86$ meV from ENDF/B-VIII.0 [6], fixed this parameter in SAMMY and fitted the resonance energy and Γ_n . A list of the obtained values is shown in Table II. All new resonances are unambiguously assigned to ^{169}Tm based on their E_{sum} spectra.

C. Comparison with evaluations in URR

In Fig. 10, we compare our measured capture cross section with different data sets available in EXFOR in the URR.

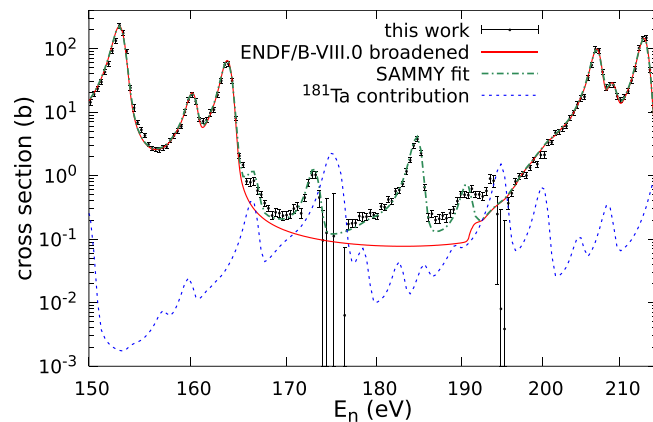


FIG. 9. New resonances observed in ^{169}Tm experimental data, compared with broadened ENDF/B-VIII.0 evaluation (red). For simplicity, we do not plot JEFF 3.3 and JENDL-5 evaluations, as they report almost identical cross section as ENDF/B-VIII.0 in this region. SAMMY fit of four new resonances is plotted in green. Subtracted contribution of the ^{181}Ta impurity in the sample (blue) is also shown.

The largest discrepancy between previously measured data is between 10 and 100 keV, where our results are lower than Gibbons [38], Macklin [39], and Xia [40] by up to $\sim 60\%$. Results from the recent measurement in 2022 by Ren *et al.* [9] are consistent within 1σ with our data. We observe fluctuations in the cross section that are expected due to the presence of individual resonances up to ~ 6 keV.

Similarly as in the RRR, we compared our results with ENDF/B-VIII.0, JEFF 3.3, and JENDL-5 evaluations, see Fig. 11. In the region between 10 keV and 100 keV, our data are generally smaller than the evaluated cross section. Above 100 keV, JEFF 3.3 is consistent with our results, while ENDF/B-VIII.0 slightly and JENDL-5 considerably overestimates our data. This behavior is not surprising, as the evaluations originate mainly from the above-discussed datasets.

D. CoH₃ calculations

We carried out the statistical Hauser-Feshbach model calculation for the neutron-induced reaction on ^{169}Tm with the CoH₃ code [41], as shown in Fig. 11. The code features a

TABLE II. New resonances in ^{169}Tm . Their energies, $g\Gamma_n$ and the corresponding uncertainties come from the SAMMY fit. Radiative widths Γ_γ were fixed to 86 meV.

E_R (eV)	$g\Gamma_n$ (meV)
8.037(6)	0.00072(4)
22.03(1)	0.00141(6)
71.85(2)	0.0136(7)
75.57(2)	0.0199(8)
166.46(4)	0.055(8)
173.07(5)	0.086(12)
184.69(2)	0.316(8)
190.61(4)	0.056(3)

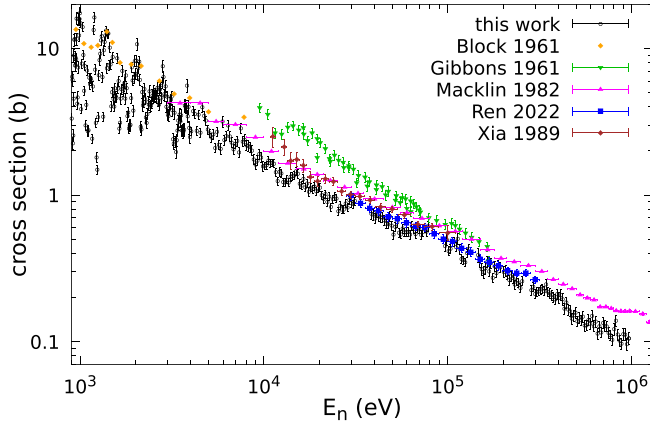


FIG. 10. Experimental cross section in the URR compared with data available in EXFOR in this region.

rigorous treatment of strongly coupled channels in the statistical model by performing the so-called Engelbrecht-Weidenmüller transformation [42–44]. This model is particularly suitable for ^{169}Tm , since this nucleus is largely deformed and it shows a strong collective excitation.

For the coupled-channels model calculation, we coupled six discrete levels from the $\frac{1}{2}^+$ ground state to the $\frac{11}{2}^+$ 368 keV level, which belong to the ground state rotational band. First, we employed the global coupled-channels optical potential of Kunieda *et al.* [45] with the deformation parameters taken from the finite range droplet model (FRDM) [46,47], then some modest modifications were made to reproduce experimental total cross sections [48,49] in the fast energy range as well as the data of Foster and Glasgow [50] above 2.3 MeV. We found that the deformation parameters of $\beta_2 = 0.293$, $\beta_4 = -0.024$, and $\beta_6 = -0.023$, which were taken from FRDM, with 2% increase in the real potential depth, fit these experimental data well. Note that since there is no total cross section experimental data between 5 keV (the highest energy point of Tellier) and 2.3 MeV (the lowest

energy of Foster and Glasgow), the energy dependence of the optical potential in the fast energy range solely relies on the global fitting by Kunieda *et al.*

The statistical Hauser-Feshbach model calculation was performed with the aforementioned modified Kunieda potential. Although the charged particle emission could be negligible in our energy range of interest as the target mass number is relatively high, we included the proton and α -particle emission channels, since they are exothermic (the Q values for the proton and the α -particle channels are 429 keV and 7.44 MeV, respectively). We employed the global potential of Avrigeanu *et al.* [51] for the α particle and the Koning-Delaroche potential [52] for the proton. The level density parameter of the Gilbert-Cameron level density model [53,54] for ^{170}Tm was adjusted to obtain the evaluated average s -wave resonance spacing D_0 of 7.28 eV [55]. The average total radiative width $\bar{\Gamma}_\gamma = 86$ meV was also taken from the same reference. Since the Reference Input Parameter Library, RIPL-3 [35] includes slightly different values of $\bar{\Gamma}_\gamma = 97$ meV and $D_0 = 8.5$ eV, we also performed the CoH₃ calculation with these parameters. However, the calculated capture cross sections are very similar, because the ratios $\bar{\Gamma}_\gamma/D_0$ are close to each other, hence we do not show the RIPL-3 case here.

E. Astrophysical implications

Neutrons in stellar environment have energies described by a Maxwell-Boltzmann distribution, which is a function of the temperature $k_B T$. The capture cross section $\sigma(E_n)$ measured with DANCE was converted to a Maxwellian-averaged capture cross section (MACS) according to the following formula:

$$\sigma_{\text{MACS}}(k_B T) = \frac{2}{\sqrt{\pi}} \left(\frac{\mu}{k_B T} \right)^2 \int_0^\infty \sigma(E_n) E_n e^{-\frac{E_n}{k_B T}} d(E_n), \quad (3)$$

where μ is the reduced mass.

The MACS values were calculated by numerical integration of the experimentally derived cross section for $k_B T = 5$ –100 keV and compared with recent evaluations, shown in Fig. 12. The integration was truncated at 0.97 MeV, the highest energy determined in the measurement. For the range of temperatures considered in Table III, higher-energy contributions are negligible. The calculated values and their comparison with KADoNiS astrophysical database [56] can be found in Table III. As the MACS has a direct impact on astrophysical nucleosynthesis reaction rates, we further used our experimental values as an input for a main component s -process simulation network using the NETZ tool with a standard neutron:seed ratio [57]. NETZ predicts a slightly increased abundance of ^{169}Tm from the main component of the s -process reaction chain, with the ratio of 1.26 relative to baseline calculations. The derived changes of abundances for ^{170}Yb and other downstream nuclei are in the order of 0.2%. This is consistent with the observed, reduced cross section and this region of s -process nucleosynthesis being in flow equilibrium. A more detailed stellar calculation would be needed to evaluate the impact on the ^{170}Tm branch point.

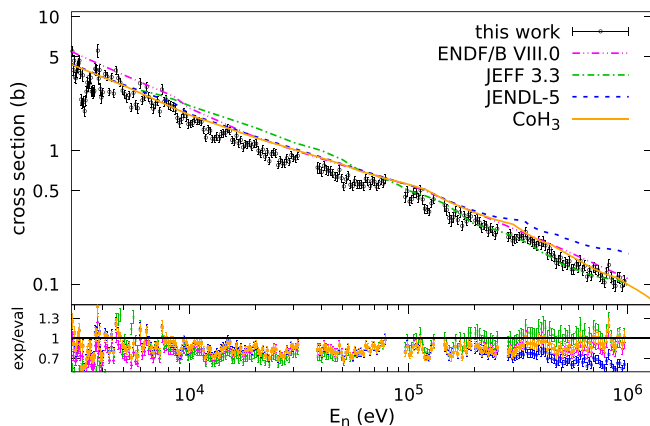


FIG. 11. Top panel: Experimental cross section in the URR compared with ENDF/B-VIII.0, JEFF 3.3, and JENDL-5 evaluations and CoH₃ calculations. Bottom panel: Ratio of the experimental over evaluated/calculated cross section.

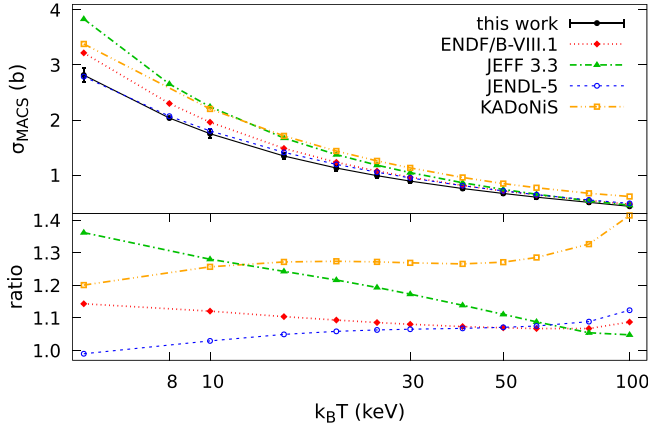


FIG. 12. Top panel: Comparison of MACS determined in this work with evaluated values and KADoNiS astrophysical database [56]. Bottom panel: The ratio of MACS with respect to this work.

VI. PSF AND LD RESULTS

To facilitate the comparison between experimental and simulated spectra, we have constructed the mean sum-energy and MSC spectra from the normalized spectra of individual resonances using the maximum likelihood fit as introduced in Ref. [13]. We have used 19 resonances with $J^\pi = 1^+$ and six resonances with $J^\pi = 0^+$ to calculate the mean experimental intensity I_{exp} and the fluctuation of the experimental intensity ϕ_{exp} for each bin considering the experimental uncertainties. In Figs. 14–17 we plot the experimental data as $I_{\text{exp}} \pm \phi_{\text{exp}}$. The uncertainty of I_{exp} typically reaches ~ 2 –3 %. The experimental spectra for both s -wave resonance spins are similar and display the same features, e.g., those related to the presence of the scissors mode (SM) in $M1$ PSF manifested by bumps near 3 MeV in $M = 2$ and 3 MSC spectra.

Hence, we do not show figures for both resonance spins for all, but only two model combinations here, all are available in Ref. [34]. The descriptions of all spectra were checked during the analysis and the results presented here are based on the

TABLE III. Calculated MACS from this measurement compared to KADoNiS values [56], full uncertainties (statistical + systematic) are listed.

$k_B T$ (keV)	KADoNiS σ_{MACS} (b)	This work σ_{MACS} (b)
5	3.381	2.816(125)
10	2.200	1.751(77)
15	1.711	1.345(59)
20	1.436	1.127(50)
25	1.257	0.988(44)
30	1.129	0.890(39)
40	0.956	0.755(33)
50	0.845	0.665(29)
60	0.769	0.598(26)
80	0.668	0.504(22)
100	0.610	0.432(19)

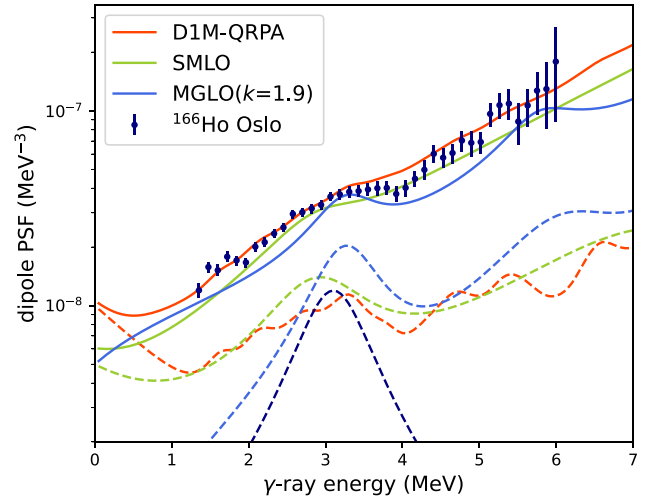


FIG. 13. Comparison of PSFs from our best model and previously proposed models together with the Oslo experimental data. Full lines indicate sum of $E1$ and $M1$ PSFs and dashed lines indicate the corresponding $M1$ PSF.

ability of a given model combination to describe spectra for both resonance spins.

A. Comparison to literature models

From all the LD and PSFs models available in the literature, see for example overview in RIPL-3 [35] and references therein, we opt to test the recent recommendation for $E1$

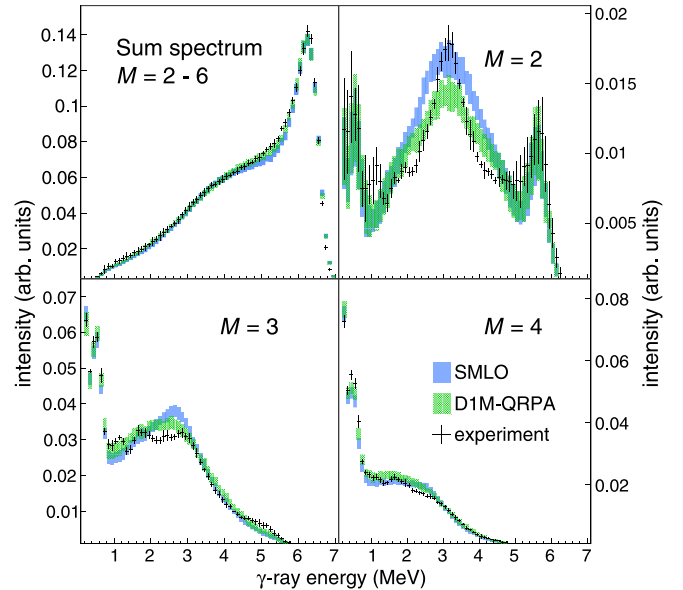


FIG. 14. Comparison of experimental and simulated spectra from $J^\pi = 1^+$ resonances for multiplicities indicated by the labels. The PSFs models were taken from the Refs. [58,59]. The HFB LD from RIPL-3 [35] was used for both model combinations. The color bands correspond to results of simulations calculated as mean $\pm$ standard deviation from 20 NS and 10⁵ cascades. The experimental spectra are drawn as $I_{\text{exp}} \pm \phi_{\text{exp}}$, see Sec. VI.

and $M1$ PSFs as published in the reference database for photon strength functions [58] and IAEA PSF database [59] featuring two models, namely the phenomenological simple modified Lorentzian (SMLO) model and the model based on D1M-QRPA calculation. Authors include also a phenomenological $M1$ low-energy enhancement (LEE) in the exponential form $C \times \exp(-\eta E_\gamma)$ with $\eta = 0.8 \text{ MeV}^{-1}$ and $C \lesssim 1 \times 10^{-8} \text{ MeV}^{-3}$. Both these PSFs models are visualized in Fig. 13. To check the impact of LD we have coupled these PSFs with several different LD models including the Hartree-Fock-Bogoliubov (HFB) calculations available in the RIPL-3 database [35] and in the TALYS code [60,61], and the constant temperature (CT) and back-shifted Fermi gas (BSFG) analytical formulas with parameters from Refs. [62,63]. None of the combinations gave a perfect description of data, the closest one was achieved by using D1M-QRPA PSFs with HFB LD from RIPL-3, see Figs. 14 and 17.

As mentioned in Sec. I, the PSFs and LD in odd-odd rare-earth isotopes were studied only in two cases before—in the two-step γ cascade (TSC) measurement of ^{160}Tb [15] and using the so-called Oslo method applied to $(\alpha, p)^{166}\text{Ho}$ [16] reaction. We have adopted the original model interpretation of these data from the respective articles to test against our experimental data. Specifically, the TSC analysis [15] proposed SM at 2.6 MeV and 0.6 MeV wide, with $\sum B_{\text{SM}} = 6(1) \mu_N^2$, the $M1$ PSF also contained a spin-flip (SF) resonance. This $M1$ PSF was used in conjunction with MGLO $E1$ PSF [12] and BSFG LD model [62]. The Oslo analysis of ^{166}Ho [16] proposed a SM at 3.14(7) MeV, with a width of 0.98(9) MeV, and an integrated strength $\sum B_{\text{SM}} = 4.2(5) \mu_N^2$. The $E1$ PSF was given by the GLO model [35] with addition of a pygmy resonance of the SLO form, see Fig. 13. These PSFs were paired with BSFG LD model with parameters from Ref. [62]. The predictions of these two model combinations are compared to our experimental data in Fig. 15.

Our experimental spectra hint at the presence of SM at energy just above 3 MeV. Any model combination, that does not feature such SM, cannot reproduce the middle part of $M = 2$ and the bump at $\approx 3 \text{ MeV}$ in $M = 3$ MSC spectrum simultaneously. This is the case in the model combination proposed from the TSC analysis, and to an extent with the IAEA-proposed models (SMLO, D1M-QRPA), where the $M1$ strength is spread in wide interval and not concentrated enough at around 3 MeV, see Fig. 13. It turns out that the MSC spectra are rather sensitive to the energy-dependent ratio of $M1$ to $E1$ PSF and not to their absolute values.

The inability of the Oslo ^{166}Ho model combination to match our data stems from the choice of the GLO model for $E1$ PSF, which features relatively high low-lying strength, accompanied by a pygmy resonance in the $E1$ PSF. This $E1$ shape and the resulting $M1$ to $E1$ PSF ratio necessarily leads to the wings of $M = 2$ MSC spectra being too intense with respect to the middle-energy region of the spectrum, and the multiplicity distribution being shifted towards higher values, i.e. $M \geq 4$ MSC spectra being overestimated. This does not necessarily imply that the Oslo data are in disagreement with ours, it means that the original *interpretation* of the Oslo data is.

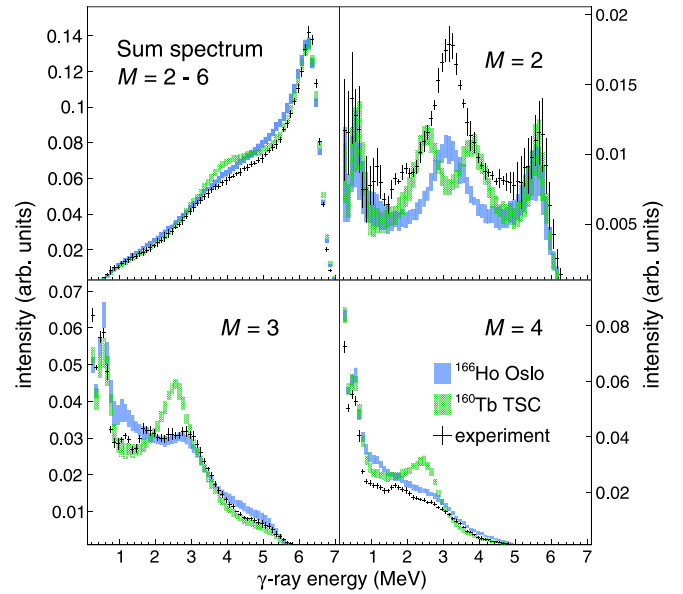


FIG. 15. The same as in Fig. 14 but for different model combinations. The LD and PSFs models with their parameters were taken from ^{166}Ho Oslo analysis [16] and ^{160}Tb TSC measurement [15], respectively, see Sec. VI A for details.

As described above, we have used the CoH₃ code [41] to calculate the cross section in URR. The $\bar{\Gamma}_\gamma$ is calculated internally from models of LD, $E1$, and $M1$ PSF with parameters drawn from systematics [64]. We have also used LD and PSFs from CoH₃ to simulate MSC spectra. The suggested position of SM [64] is above 4 MeV, which results in disagreement with our experimental MSC spectra [34]. However, the SM parameters can be adjusted while keeping the same value of $\bar{\Gamma}_\gamma$. When the SM is shifted down to 3.3 MeV, its width adjusted to 1.0 MeV and strength to $\sigma_{\text{SM}} = 2.38 \text{ mb}$, both at variance with proposed systematics [64], we obtain much better description of our experimental spectra, see Fig. 16. While these simulations have their flaws, one should keep in mind that all parameters but the SM ones are calculated from *global* systematics.

B. Search for optimal PSFs

We performed a search to obtain a better description of our experimental spectra by sampling the SM parameters and the SF strength in conjunction with various $E1$ PSF and LD models. It turns out that the SM has a major influence on the decay—our data are, by the presence of bumps near 3 MeV, sensitive enough to pin down its energy and width to about a tenth of MeV. Moreover, the spins and parities of initial and final levels together with selection rules for electromagnetic transitions allow us to confirm that we observe a resonance structure near 3.3 MeV which must be dominantly in the $M1$ PSF. Postulating a SM-like resonance solely in the $E1$ PSF, i.e., having only the SF resonance in the $M1$ PSF, or having the same electric and magnetic contribution significantly worsens the description of the experimental data [34].

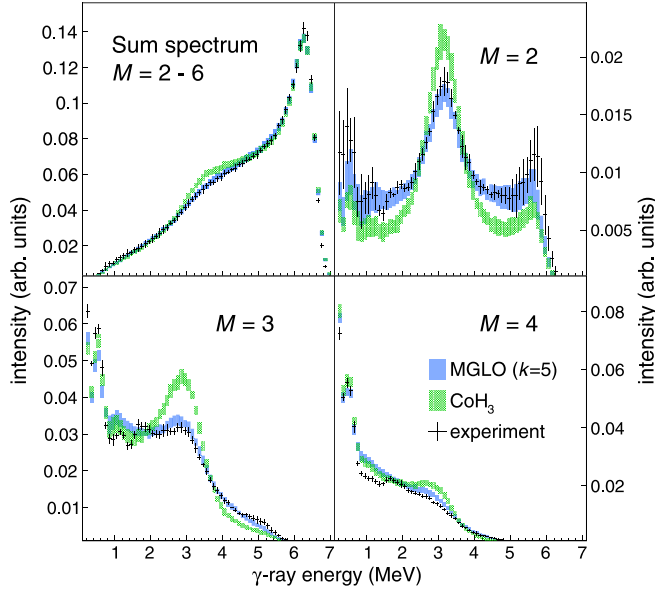


FIG. 16. The same as in Fig. 14 but for different model combinations. The model combination MGLO($k = 5$) corresponds to the MGLO($k = 5$) $E1$ PSF, SM at 3.3 MeV and BSFG LD model, see Sec. VIB for details. The model combination labeled “CoH₃” corresponds to the PSFs and LD models used in the CoH₃ code [41] with adjusted SM parameters, see Sec. VIA for details.

As mentioned above, our analysis does not provide absolute values of dipole PSF, i.e., the SM strength. To make the absolute normalization we can select the model combinations with $\bar{\Gamma}_\gamma$ close to the evaluated one, or alternatively reparametrize or scale the PSFs to match the evaluated $\bar{\Gamma}_\gamma$, see Sec. VIC.

A very good description was achieved using MGLO $E1$ PSF model [12], the BSFG model of LD with parameters from Ref. [63], and SM resonance at 3.3 MeV, with the width of 1.0 MeV. The MGLO model has several adjustable parameters, namely k that most importantly influences the slope of the γ -ray energy dependence below S_n , F_K which determines the low-energy limit and was suggested to be 0.7 in Ref. [65], and an energy shift Δ that is typically set to the energy shift from BSFG LD, $\Delta = E_1 = -0.96$ MeV [63]. We use these values of F_K and Δ unless specified otherwise. We then require $k = 5$ and the SM strength $\approx 11(1)\mu_N^2$ to match our spectra. In practice, to reproduce the intensity at the sides of $M = 2$ and around 5 MeV in $M = 3$ MSC spectra we further needed to use relatively large extra dipole strength at γ -ray energies above about 4.5 MeV, see Fig. 13. This can be achieved by an increase of the SF mode strength with respect to the systematics from RIPL-3 [35] by a factor of about 3–5 or by an introduction of a pygmy resonance in $E1$ PSF of the equivalent strength. Results with both $E1$ and $M1$ origin of this additional strength are virtually indistinguishable. Contrary to this, our detailed analysis [34] indicates that the resonance at 3.3 MeV must be dominantly in $M1$ PSF, hence it is natural to attribute it to the SM. Predictions with this model, labeled as MGLO($k = 5$), are shown in Fig. 16.

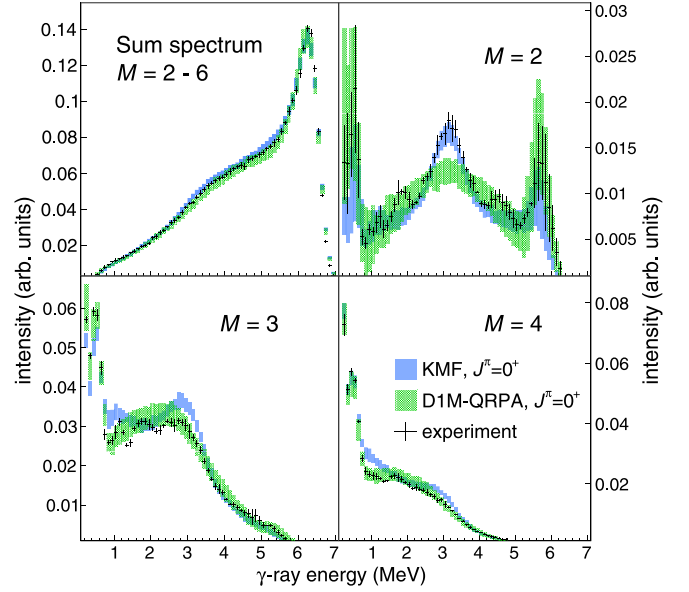


FIG. 17. The same as in Fig. 14 but for resonances with $J^\pi = 0^+$ and for different model combinations. The PSFs were taken from Refs. [58,59] for the D1M-QRPA combination, see Sec. VIA for details. The “KMF” model combination uses $E1$ KMF formula [65] with $M1$ PSF and LD as described in the Sec. VIB.

Nonetheless, this model combination significantly overestimates $\bar{\Gamma}_\gamma$, see Sec. VIC. To match the ENDF value of 86 meV from compilation [55], we would need to scale down the PSFs by a factor of 2.22 or adjust the parameters of MGLO model. Specifically, adjusting to $k = 2.1$ and $\Delta = 0$, or to $k = 1.9$, $\Delta = -2.7$, and $F_K = 0.25$ —labeled hereafter as MGLO($k = 1.9$)—we obtain practically indistinguishable $E1$ PSF below S_n with respect to the down-scaled MGLO($k = 5$). The corresponding scaling in $M1$ PSF lowers the SM strength to $5\mu_N^2$ and the required pygmy $E1$ resonance has maximum cross section of $\simeq 2.0$ mb. These adjusted PSFs yield practically the same $M1/E1$ PSF ratio, hence maintain the good description of experimental spectra as presented in Fig. 16, see Ref. [34].

An acceptable (although slightly worse than with the MGLO model) description of MSC spectra can be obtained also with the $E1$ PSF model of the Kadomenskij, Markushev, and Furman (KMF) [65], which has a similar energy dependence as the MGLO with $k = 1.7$ and $\Delta = -0.5$, both with original $F_K = 0.7$. The results of simulations using the KMF paired with the BSFG LD parametrization from Ref. [63] and with the same SM, SF, and pygmy parameters as presented in the previous paragraphs are shown in Fig. 17. Despite a very different, higher $M1/E1$ PSF ratio, this model combination provides similar results. Nevertheless, there are obvious shortcomings, e.g. in the ≈ 3 MeV bump in $M = 3$ MSC spectrum. Moreover, such high $M1$ PSF is at variance with observed intensity of primary transitions [27], hence we deem this model combination unrealistic.

We were able to achieve acceptable description of our experimental spectra also with the CT LD model [63] paired with either KMF or MGLO($k = 2$) $E1$ PSF model, the SM

strength has to be close to $5 \mu_N^2$. However, as in the previous case, these model combinations overestimate the ≈ 3 MeV bump in $M = 3$ MSC spectrum and $M \geq 4$ intensity in general, which makes the BSFG LD model favorable. The overall description is similar to the “KMF” one presented in Fig. 17, see Ref. [34].

We further tested other commonly-used $E1$ PSF models including SLO, GLO, and EGLO. No combination of these models with adjusted $E1$ and $M1$ PSF parameters with any level-density model could provide as good of reproduction of the experimental spectra as that achieved by the previously discussed MGLO model combinations. Introducing any significant LEE, which is higher than or similar to the low-energy limit of D1M-QRPA and KMF, spoils the agreement by shifting the simulated intensities towards higher multiplicities. We confirmed that we are practically insensitive to the $E2$ PSF, which we tested by changing a constant $E2$ PSF up to the value of $10^{-10} \text{ MeV}^{-5}$.

C. Total radiative width and comparison to other data

As mentioned above, our spectra are not sensitive to the absolute values of PSFs, the $\bar{\Gamma}_\gamma$ is the only quantity which is. The situation in literature is as follows: an earlier compilation by Mughabghab [55] gives $\bar{\Gamma}_\gamma = 86(7) \text{ meV}$. ENDF/B-VIII.0 [6] adopted individual resonance parameters from therein, as well as this average value for the RRR, but in the URR used values of 122 meV, 61 meV, and 96.5 meV for $\ell = 0, 1$, and 2, respectively. JEFF 3.3 [7] uses 92 or 119 meV in RRR and around 123 meV in URR for all ℓ 's. JENDL-5 [8] uses 86 meV in RRR, as resonance parameters are taken from Mughabghab [55], and 92 meV in URR for all ℓ 's. In later compilation [26] Mughabghab changed the proposed $\bar{\Gamma}_\gamma$ to 120(7) meV, but used 97 meV for bound state, which is a value much closer to the average of listed individual Γ_γ 's. The URR values are cited as 120(4) and 64.9(63) meV for $\ell = 0$ and 1, respectively. The situation is overall inconsistent with statistical model predictions, see below, especially the abrupt increase of $\bar{\Gamma}_\gamma$ ($\ell = 0$) between RRR and URR in ENDF/B-VIII.0.

None of the above-listed sources indicates that s -wave resonances with different spins would differ drastically in their radiative widths. In our simulations we have never observed significant differences in $\bar{\Gamma}_\gamma$ for different spins of s - and p -wave resonances unless we have used the HFB LD. These densities however display features, namely the so-called even-odd spin staggering in the spin distribution and parity asymmetry, up to relatively high excitation energies, which might be unrealistic, especially in an odd-odd nucleus.

The $\bar{\Gamma}_\gamma$ values for selected model combinations are listed in Table IV. To normalize PSFs we chose to anchor them to the $\bar{\Gamma}_\gamma = 86 \text{ meV}$, because it is used in RRR by two evaluated data libraries and it can be used to successfully describe our URR data using CoH_3 , see Sec. V D. As mentioned above from this it follows that the best model combination consists of the MGLO($k = 1.9$) $E1$ PSF, the $M1$ SM at 3.3 MeV and 1.0 MeV wide with $\sum B_{\text{SM}} = 5.0(5) \mu_N^2$, and BSFG LD [63]. The position and width of SM matches the parameters deduced in the ^{168}Er MSC analysis [14], the strength of the

TABLE IV. Total radiative widths of s -wave resonances. Top part corresponds to models from literature, the middle to models well or acceptably reproducing our experimental spectra.

Model		$\bar{\Gamma}_\gamma$
PSF	LD	(meV)
^{160}Tb TSC ^a	BSFG [62]	141(3)
^{166}Ho Oslo ^b	BSFG [62]	118(3)
D1M-QRPA	HFB [35]	37.2(35)/175(5) ^c
SMLO	HFB [35]	30.9(26)/146(4) ^c
MGLO($k = 5$)	BSFG [63]	191(4)
MGLO($k = 1.9$)	BSFG [63]	85(2)
KMF	BSFG [63]	124(3)
KMF	CT [63]	40.5(10)
MGLO($k = 2$)	CT [63]	45.5(12)
Compilation [55]		86(7)
Compilation [26]		120(7)

^aFor s -wave resonances in ^{160}Tb $\bar{\Gamma}_\gamma = 101(2) \text{ meV}$ [26].

^bFor s -wave resonances in ^{166}Ho $\bar{\Gamma}_\gamma = 84(5) \text{ meV}$ [26].

^cTwo values correspond to $\bar{\Gamma}_\gamma$ for resonances with spin 0 and 1, respectively.

mode is consistent within uncertainties with their value of $3.74(116) \mu_N^2$. The SM strength in ^{170}Tm is also very close to the one proposed by Oslo analysis of ^{166}Ho [16], but this agreement might be accidental as dipole PSF is rather different, see Fig. 13.

As explained in Sec. VIB, the parameters of MGLO model and the SM and SF resonance strengths can be adjusted to match any reasonable value of $\bar{\Gamma}_\gamma$, the scaling of SM strength is linear with the ratio of $\bar{\Gamma}_\gamma$'s. In other words, if the anchoring value of $\bar{\Gamma}_\gamma$ changes to 120 meV, the SM strength needed to describe our spectra would be $\sum B_{\text{SM}} = 7.0(7) \mu_N^2$.

VII. CONCLUSIONS

The $^{169}\text{Tm}(n, \gamma)$ reaction was measured with DANCE at LANSCE using the time-of-flight technique. The neutron capture cross section was determined for $E_n = 1.8 \text{ eV} - 0.97 \text{ MeV}$. Cross section values in the URR are generally smaller than the latest evaluations [6–8]. In the RRR, we report eight new resonances that are not included in any of the evaluations. We confirmed the results of the latest measurement by Ren *et al.* [9] in the URR and extended them to a larger energy range.

We investigated the impact of our results on stellar nucleosynthesis calculations. The experimental cross section converted to MACS was used with NETZ [57] to calculate s -process abundances in the region of $A \approx 170$. ^{169}Tm abundance is expected to increase by a factor of 1.26, while the difference in the abundance of elements heavier than ^{169}Tm is in the order of 0.2%.

The experimental multistep cascade spectra from $^{169}\text{Tm}(n, \gamma)$ were compared with DICEBOX simulations to study LD and PSFs, with the focus on the SM properties. The model parameters from the only two previously measured data sets in odd-odd rare-earth nuclei are inconsistent with our observations. Furthermore, the proposed SMLO and

D1M-QRPA models from the reference database for photon strength functions [58] do not show satisfactory description of the spectra. It has been observed that SM in $M1$ PSF has a significant impact on the shape of the simulated spectra—the best agreement was achieved with SM at 3.3 MeV, width of 1.0 MeV, and strength comparable with that derived from analysis of MSC spectra in neighboring ^{168}Er , coupled with the MGLO $E1$ PSF model. The BSFG model of LD is favored.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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