# Study of the $^{169}\mathrm{Tm}(n,\gamma)$ reaction using DANCE facility at LANSCE

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## Motivation

- Thulium – mono-isotopic element, stable isotope $A = 169$, $\sigma_\gamma^0 = 107(2)$ b
- $^{170}$Tm: $T_{1/2} = 128.6$ d ⇒ neutron-flux activation monitor ⇒ good knowledge of $\sigma_\gamma$ needed
- significant discrepancies in unresolved resonance region (URR) data, see Fig. 1
- scarce and discrepant resolved resonance region (RRR) data
- state-of-the-art analyses - *one* in RRR by Wang *et al.* [1] and *one* in URR by CSNS Back-n Collaboration [2]
- photon strength functions (PSFs) and level densities (LD) studied in many neighbouring isotopes, but rarely in odd-odd ones – two-step $\gamma$ cascade (TSC) measurement of $^{160}$Tb [3] & Oslo analysis of $^{166}$Ho [4]
- scissors mode (SM) consistently observed in rare-earth nuclei, but PSFs from different reactions show discrepancies, see Fig. 2
- Back-Shifted Fermi Gas model (BSFG) of LD performs well in deformed rare-earth nuclei

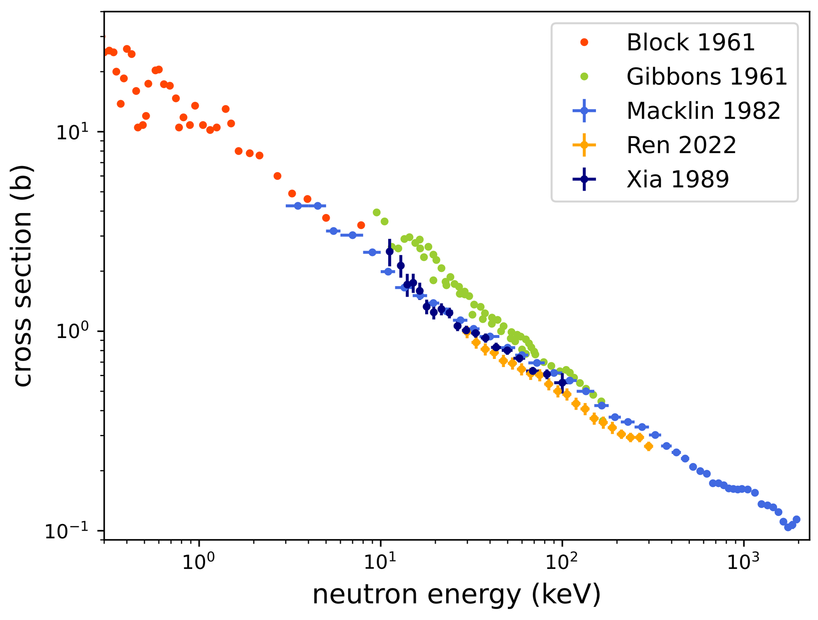


**Figure 1:** Data on $\sigma_\gamma$ in keV region as collected from the EXFOR database [5]. The labels correspond to the entries as listed therein.

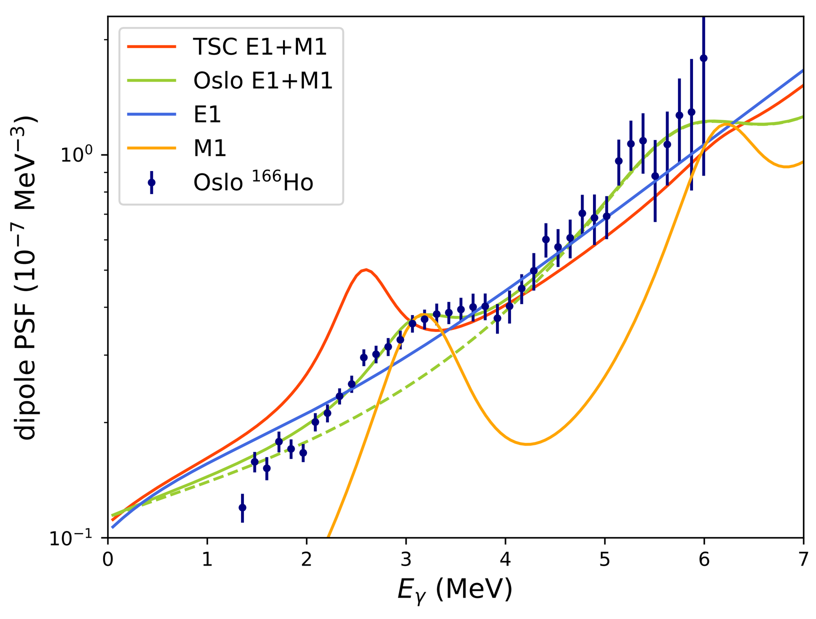


**Figure 2:** PSFs plot. Datapoints labeled Oslo are taken from Ref. [4], curves labeled TSC correspond to PSFs proposed in Ref. [3].

## Experiment and Analysis

- data from Los Alamos Neutron Science Center (LANSCE) of Los Alamos National Laboratory, using the Detector for Advanced Neutron Capture Experiments (DANCE)
- neutrons, with energies from sub-thermal to units of MeV, produced in a spallation reaction of 800-MeV protons striking a tungsten target
- DANCE detector, placed 20.25 m from the spallation target, consists of 160 $BaF_2$ scintillation crystals covering solid angle $\approx 3.5\pi$

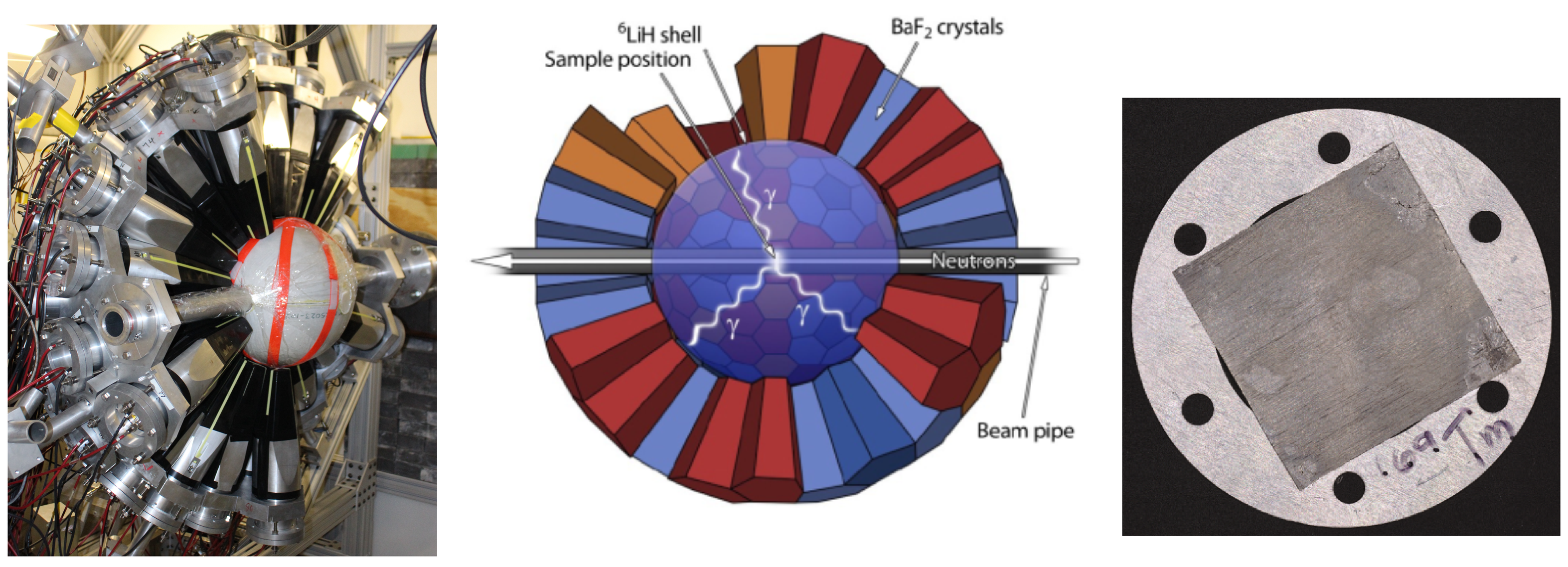


**Figure 3:** Left: One hemisphere of the DANCE detector. Center: A sketch of the DANCE detector. Right: High resolution image of the thick Tm sample mounted on a frame.

- neutron flux monitored by a silicon detector measuring $^6\mathrm{Li}(n,t)$ reaction, $^{235}$U fission chamber, and $^3$He proportional counter
- cross section normalization using the standard 4.9 eV resonance in $^{197}\mathrm{Au}(n,\gamma)$
- events with $E_{\mathrm{sum}} \geq 4.0$ MeV and multiplicity $M \geq 2$ used to extract the cross section
- the multi-step cascade (MSC) spectra constructed from 1-MeV wide interval around the $Q$-value using 20 resonances with $J^\pi = 1^+$
- background due to scattered neutrons subtracted using ancillary measurement with Pb sample
- $\gamma$ cascades generated under various assumptions on PSFs and LD models using DICEBOX code were subsequently processed by GEANT4 simulation of the DANCE array

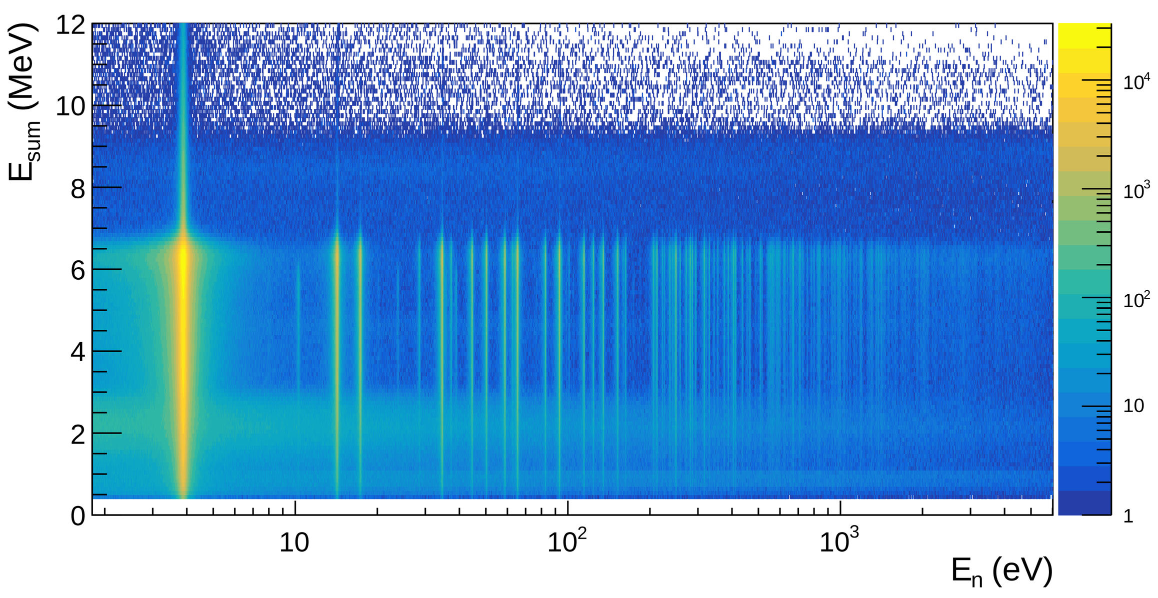


**Figure 4:** Two dimensional experimental spectrum for thin Tm sample, horizontal axis shows time-of-flight after transformation to neutron energy. Events with $M = 2-5$ were used to construct the spectrum.

## Comparison with models from literature

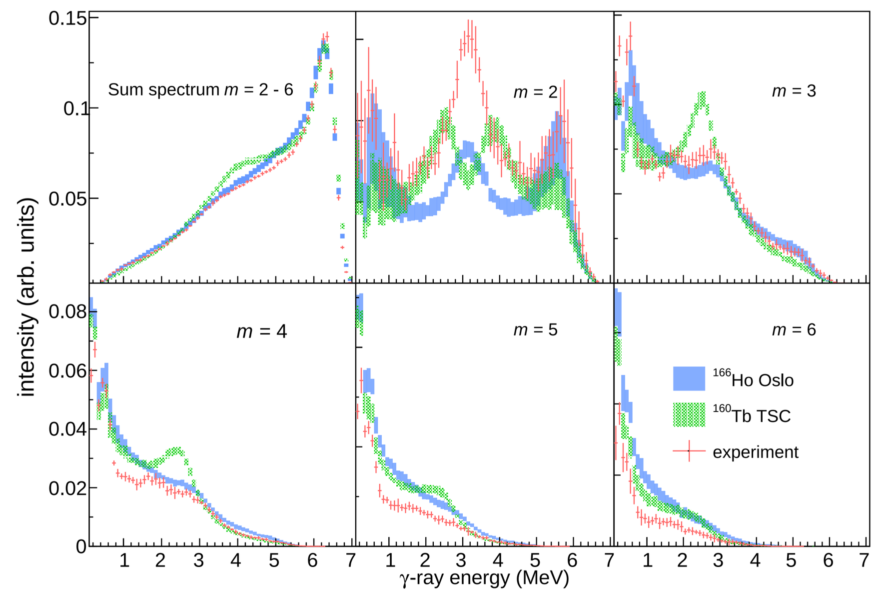


**Figure 5:** Comparison of experimental and simulated spectra. LD and PSFs were taken from $^{166}$Ho Oslo analysis [4] and $^{160}$Tb TSC measurement [3].

- PSF parameters taken from Oslo analysis of $^{166}$Ho [4] with SM at 3.14(7) MeV, width of 0.98(9) MeV, and the integrated strength $\sum B(M1) = 4.2(5)\,\mu_N^2$, $E1$ PSF given by GLO model plus pygmy resonance, paired with BSFG LD from Ref. [6]
- $^{160}$Tb TSC analysis [3] proposed SM at 2.6 MeV and 0.6 MeV wide, with $\sum B(M1) = 6(1)\,\mu_N^2$ in conjunction with MGLO $E1$ PSF and BSFG LD model [6]
- unsatisfactory description of our experimental data with both proposed model combinations and their parameters

## Photon strength functions

- significant influence of SM on the decay
- our data are sensitive to the type of transitions, SM-like resonance in $E1$ PSF significantly worsens description of experimental data, see Fig. 6 ⇒ $M1$ SM observed
- so far best description achieved with SM at 3.2 MeV, width of 1.0 MeV and strength about $9\,\mu_N^2$
- we can not rule out energy of SM as high as 3.5 MeV, see Fig. 7
- SM located at energies lower than 3 MeV gives much worse results, see Fig. 7
- the favorable $E1$ PSF model is MGLO [7], best results found for $k = 5$, LD given by BSFG model [8]
- other model combinations provide acceptable description of experiment, e.g. KMF $E1$ model paired with CTF LD ⇒ model uncertainty of efficiency in cross section calculation

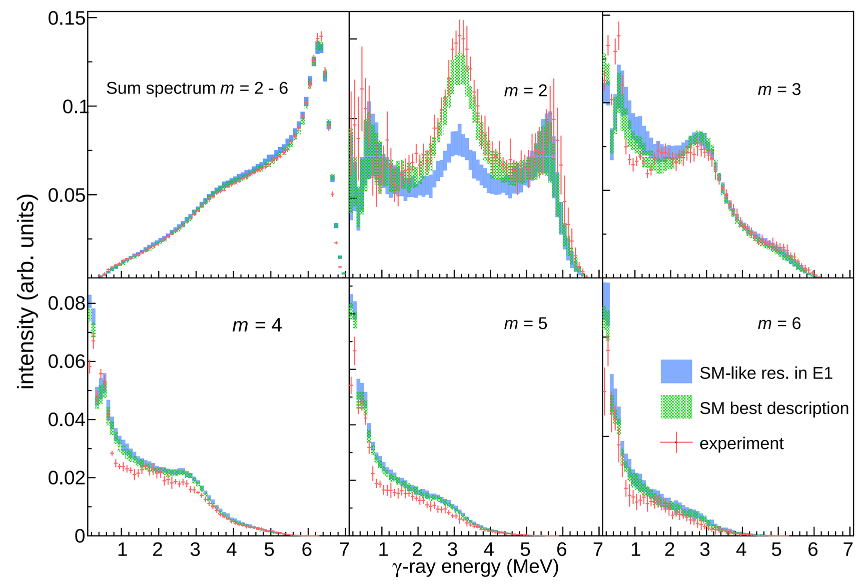


**Figure 6:** Comparison of exp. and sim. spectra. The BSFG LD [8] and MGLO $E1$ PSF [7] models were used. See text for details on the low-lying PSF resonance.

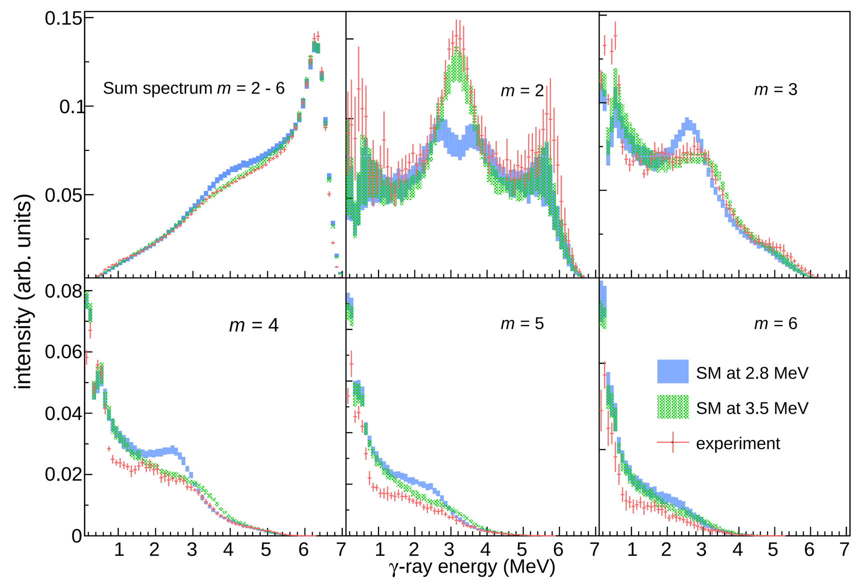


**Figure 7:** Comparison of exp. and sim. spectra. The model combination is the same as in Fig. 6, but the SM was centered at 2.8 MeV and 3.5 MeV, respectively.

## Cross section

- combination of thin sample data, up to 300 eV, and thick sample data above 300 eV up to almost 1 MeV
- efficiency by DICEBOX & GEANT4 practically the same for all $J^\pi$ of $s$- and $p$-wave resonances
- SAMMY and SESH codes used to calculate self-shielding and multiple-interaction corrections

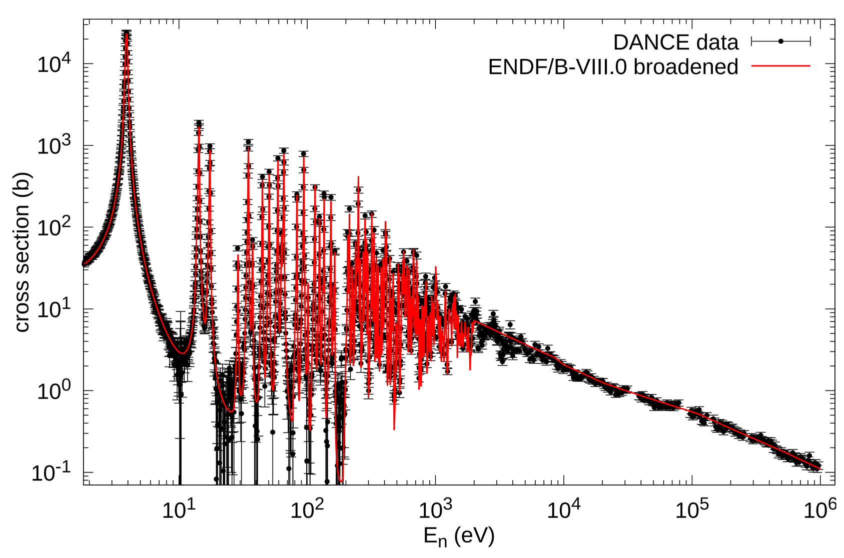


**Figure 8:** Comparison of our experimental cross section with evaluated $^{169}$Tm cross section from ENDF/B-VIII.0, broadened by the resolution function of the spallation target Mark III at LANSCE.

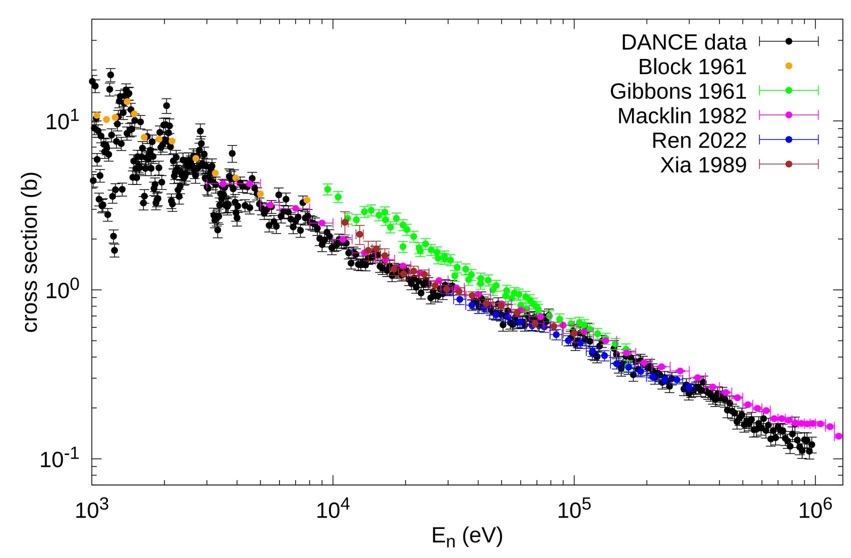


**Figure 9:** Comparison of our experimental cross section in the URR with corresponding data as collected from the EXFOR database [5]. The labels correspond to the entries as listed therein.

## Summary and Outlook

- overall our cross section in excellent agreement with ENDF/B-VIII.0 evaluation
- we observe significant structures up to $E_n \sim 6$ keV
- our cross section data disagree with ones by Gibbons and the high energy part of Macklin's
- new resonance identified at $E_n = 184.7(5)$ eV
- our MSC spectra clearly show enormous influence of scissors mode on the decay
- to finish the MSC analysis: consistency check with $0^+$ resonances spectra and fine scan of SM and $E1$ PSF parameters

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