

ASTROPHYSICAL REACTION RATES AND THE LOW-ENERGY ENHANCEMENT IN THE γ STRENGTH*

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An unexpected enhancement in the γ -strength function for $E_\gamma < 3$ MeV for Ti, Sc, V, Fe, and Mo nuclei close to the valley of stability has been discovered at the Oslo Cyclotron Laboratory. Provided that this enhancement is present also in very neutron-rich nuclei, it could give an increase in the neutron-capture rates up to two orders of magnitude. However, it is still an open question whether this structure persists when approaching the neutron drip line.

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1. Introduction

The γ -ray strength function characterizes average electromagnetic decay properties of excited nuclei. This quantity is indispensable for calculating nuclear reaction cross sections and reaction rates relevant for astrophysical applications. Recent studies [1, 2] clearly show the importance of a precise description of the γ -ray strength function at low energies, especially for a

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proper understanding of the nucleosynthesis of the elements heavier than iron by the rapid neutron-capture process (r-process). So far, however, the astrophysical site hosting such an r-process remains unknown.

The nuclear physics group in Oslo has performed measurements on the γ -ray strength functions below neutron threshold of various light and medium-mass nuclei (see, *e.g.*, [3–5]). These data have revealed an unexpected increase in the γ -decay probability at low γ -ray energies. This enhancement is seen to be present typically for $E_\gamma \leq 3$ MeV. In contrast to other soft resonances observed previously such as the $M1$ scissors mode [6, 7], the physical origin of the enhancement remains unknown. There is, for the time being, no established theory that is able to explain this *upbend* phenomenon (see Fig. 1, left).

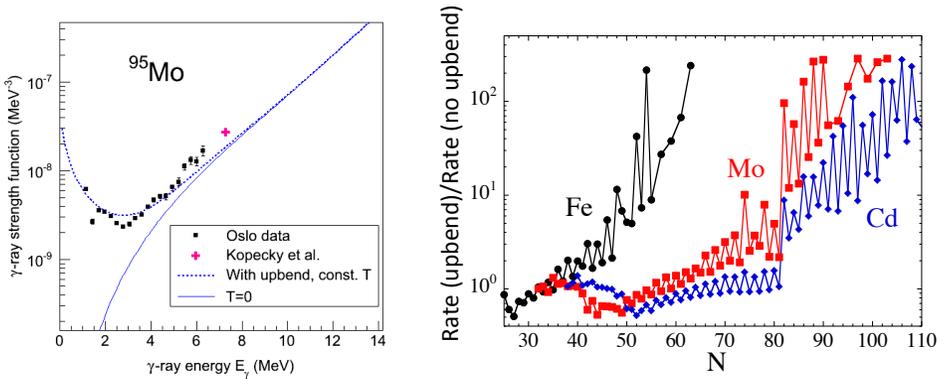


Fig. 1. Left: Oslo data of the γ -strength function of ^{95}Mo (black squares, from Ref. [4]), and models of the strength assuming zero temperature (solid/blue line) and with a constant temperature $T_f = 0.30$ MeV, including also a parameterization of the upbend (dashed line). Right: Ratios of (n, γ) reaction rates at $T = 1 \times 10^9$ K, with and without the upbend in the γ strength, for Fe, Mo, and Cd isotopes approaching the neutron drip line. See Ref. [8] for details.

2. The Oslo method

The experiments were performed at the OCL using a light-ion beam delivered by the MC-35 Scanditronix cyclotron. Self-supporting targets enriched to $\approx 95\%$ in the isotope of interest, and with a thickness of ≈ 2 mg/cm² were placed in the center of the multi-detector array CACTUS [9]. CACTUS consists of 28 collimated NaI(Tl) γ -ray detectors with a total efficiency of 15.2(1)% for $E_\gamma = 1332$ keV. The charged ejectiles were measured with the Silicon Ring (SiRi) particle-detector system [10]. The SiRi system consists of eight 130 μm thick silicon detectors, where each

of them is divided into eight strips. Each of these segmented, thin detectors are put in front of a $1550\ \mu\text{m}$ thick back detector. The full SiRi system covers scattering angles between $40\text{--}54^\circ$ and a solid-angle coverage of $\approx 6\%$.

The excitation-energy tagged γ spectra were unfolded with the known response functions of CACTUS, and the distribution of primary γ rays were extracted from the full cascades by an iterative subtraction technique. Then, the level density and γ strength were determined from a simultaneous fit of the primary γ matrix. See Ref. [11] and references therein for a full description of the method.

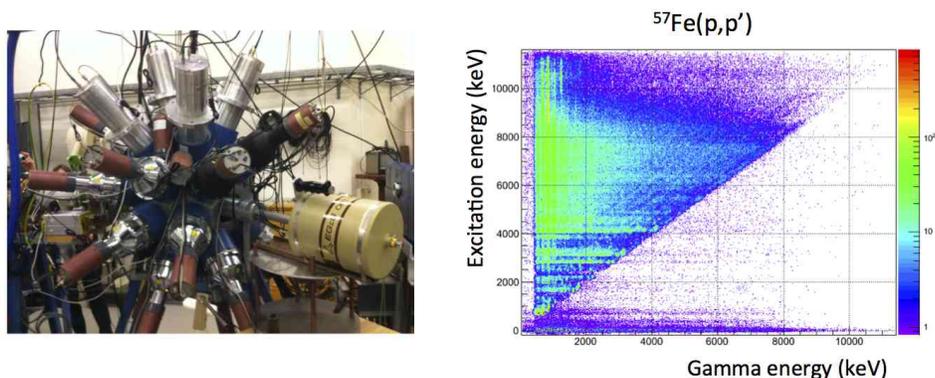


Fig. 2. Left: The γ -detector array CACTUS, including six large-volume $\text{LaBr}_3(\text{Ce})$ scintillators from the INFN Milan group. Right: Proton- γ coincidence matrix from the $^{57}\text{Fe}(p, p')$ experiment at OCL, March 2012.

3. Discussion

It has been demonstrated in Ref. [8] that if this increase persists in exotic nuclei close to the neutron drip line, it could boost the Maxwellian-averaged neutron-capture cross sections up to two orders of magnitude (see Fig. 1, right). Very recently the existence of the upbend pattern has been independently confirmed in ^{95}Mo , see Ref. [12], but there is still no experimental data of the γ strength function in neutron-rich nuclei. It would be of utmost importance to obtain such data in order to improve on the neutron-capture rates in this region.

Also, there is a great need for a better understanding of the enhancement itself. At present, the multipolarity, the electromagnetic character, and the mechanism behind this structure is unknown. However, data on ^{60}Ni might indicate an $M1$ nature [13]. With new data on $^{56,57}\text{Fe}$, using also six $3.5'' \times 8''$ $\text{LaBr}_3(\text{Ce})$ scintillators borrowed from the INFN Milan group (see Fig. 2), one expects to be able to determine the multipolarity of the low-energy enhancement in these nuclei from angular distributions.

Also, it is not clear in which mass region the enhancement is present. New data on Cd isotopes indicate that the lighter isotopes $^{105,106}\text{Cd}$ appear to have more γ strength for $E_\gamma < 3\text{ MeV}$ than the heavier $^{111,112}\text{Cd}$. It could be that this is the transitional region for the low-energy enhancement, which has been seen for $^{93-98}\text{Mo}$ but not for ^{116}Sn and heavier nuclei. However, more data on nuclei in this intermediate mass region is needed before any firm conclusions can be drawn. The analysis of several Pd isotopes is currently ongoing.

4. Summary and outlook

The discovery of an enhancement in the γ strength function at low γ energies using the Oslo method has drawn much attention recently. It has been confirmed by an independent method, it has turned out to be potentially crucial for astrophysical neutron-capture rates, and it has initiated much theoretical activity. New data on Cd isotopes indicate that the transitional region could be around $A \sim 105$, but more data is needed to confirm this. We have proposed an experimental campaign at HIE-ISOLDE to measure the γ strength function in neutron-rich medium-mass nuclei, starting with a ^{66}Ni beam as a benchmark test. This will tell whether the low-energy enhancement is present for nuclei approaching the neutron drip line.

REFERENCES

- [1] M. Arnould, S. Goriely, K. Takahashi, *Phys. Rep.* **450**, 97 (2007).
- [2] S. Goriely, *Phys. Lett.* **B436**, 10 (1998).
- [3] A. Voinov *et al.*, *Phys. Rev. Lett.* **93**, 142504 (2004).
- [4] M. Guttormsen *et al.*, *Phys. Rev.* **C71**, 044307 (2005).
- [5] A.C. Larsen *et al.*, *Phys. Rev.* **C76**, 044303 (2007).
- [6] M. Krťicka *et al.*, *Phys. Rev. Lett.* **92**, 172501 (2004).
- [7] A. Schiller *et al.*, *Phys. Lett.* **B633**, 225 (2006).
- [8] A.C. Larsen, S. Goriely, *Phys. Rev.* **C82**, 014318 (2010).
- [9] M. Guttormsen *et al.*, *Phys. Scr.* **T32**, 54 (1990).
- [10] M. Guttormsen *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A648**, 168 (2011).
- [11] A. Schiller *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A447**, 498 (2000).
- [12] M. Wiedeking *et al.*, *Phys. Rev. Lett.* **108**, 162503 (2012).
- [13] A. Voinov *et al.*, *Phys. Rev.* **C81**, 024319 (2010).