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To cite this article: A. C. Larsen *et al* 2020 *J. Phys.: Conf. Ser.* **1668** 012024

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Indirect, experimental constraints of (n, γ) reaction rates for the i - and r -process

A. C. Larsen¹, A. Spyrou^{2,3,4}, M. Guttormsen¹, S. N. Liddick^{2,5}

¹ Department of Physics, University of Oslo, 0316 Oslo, Norway

²National Superconducting Cyclotron Laboratory, Michigan State University, Michigan, USA

³Department of Physics and Astronomy, Michigan State University, Michigan, USA

⁴Joint Institute for Nuclear Astrophysics, Michigan State University, Michigan, USA

⁵Department of Chemistry, Michigan State University, Michigan, USA

E-mail: a.c.larsen@fys.uio.no

November 2019

Abstract. Our Universe contains a large variety of chemical elements, for which only the lightest ones were produced during the Big Bang. To make elements heavier than iron, neutron-capture processes are called for, in particular the slow and the rapid neutron-capture processes. Recently, a so-called *intermediate* neutron-capture process has received a lot of attention as more and more evidence points towards its existence. Both the intermediate and rapid neutron-capture processes involve very neutron-rich nuclei, for which there exist little or no data on their neutron-capture cross sections. Here we present an experimental method to indirectly constrain neutron-capture reaction rates needed for calculating nucleosynthesis yields for the intermediate and rapid neutron-capture processes.

1. Introduction

The element distribution we observe in the Universe, and in particular the diverse abundances of atomic nuclei, tells a fascinating story of nucleosynthesis events that have taken place throughout the 13.7-billion-year-long history starting with the Big Bang. Since the groundbreaking works of Burbidge, Burbidge, Fowler and Hoyle [1] and Cameron [2], it is known that radiative neutron-capture reactions play a major role in synthesizing elements heavier than iron. In particular, the slow (s) and the rapid (r) neutron-capture processes are known to contribute $\approx 100\%$ to the heavy-element nucleosynthesis.

In 2017, two neutron stars merging together was observed directly for the first time with the advanced LIGO and advanced Virgo gravitational-wave detectors [3]. Follow-up measurements of the electromagnetic transients revealed a “kilonova” that was fully consistent with an r process producing both light ($A < 140$) and heavy ($A \geq 140$) nuclides (*e.g.* Refs. [4, 5]). Finally, at least one r -process site was uniquely identified.



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However, many questions remain when it comes to our understanding of neutron-capture processes in various stellar environments. For the r process, it is still not clear whether neutron-star mergers are the only source or whether other sites have contributed as well (*e.g.*, Côté *et al.* [6]). Moreover, huge uncertainties in the nuclear input parameters to r -process nucleosynthesis calculations lead to a wide spread in the predicted yields [7]. Neutron-capture rates represent one of the major sources of uncertainty, as also demonstrated in Ref. [8].

Moreover, there is increasing evidence that an intermediate (i) neutron-capture process [9] takes place in some peculiar stars, such as a sizable fraction of the carbon-enhanced metal-poor stars in the Galactic halo [10] and Sakurai's Object [11]. Again, neutron-capture rate uncertainties hamper our understanding of this process, as they largely blur the predicted abundance patterns [12, 13, 14].

As both the intermediate and rapid neutron-capture processes involve moderate to very neutron-rich nuclei, direct measurements of their neutron-capture rates are currently not feasible. Therefore, nucleosynthesis network calculations rely to a large extent on theoretical neutron-capture rates, which can vary by orders of magnitude for nuclei far away from stability. In this contribution, we present a way to obtain indirect, experimental constraints of these rates by means of the Oslo method [15, 16, 17] and the β -Oslo method [18], with the ultimate goal of reducing the present uncertainties in r - and i -process reaction-network calculations.

2. Input for calculating neutron-capture rates

Within the Hauser-Feshbach formalism (in the statistical regime) [19], the radiative neutron-capture cross section is proportional to the neutron transmission coefficient (determined from the neutron optical potential of the target nucleus), and the γ -ray transmission coefficient and nuclear level density of the residual nucleus. The astrophysical reaction rate is calculated from the cross section assuming thermodynamic equilibrium at the nucleosynthesis site. In general, the level density ρ is a function of excitation energy E_x , angular momentum J and parity π : $\rho = \rho(E_x, J, \pi)$. Furthermore, the γ -ray transmission coefficient $\mathcal{T}_{XL}(E_\gamma)$, with electromagnetic character X and multipolarity L , is directly connected to the corresponding γ -ray strength function $f_{XL}(E_\gamma)$ (abbreviated γ SF in the following) by $\mathcal{T}_{XL}(E_\gamma) = 2\pi E_\gamma^{2L+1} f_{XL}(E_\gamma)$.

For exotic nuclei with $\sim 5 - 10$ neutrons extra relative to their stable counterparts, the neutron optical potential is fairly well known and does not introduce a large uncertainty in the cross section [20]. However, available models for the level density and γ SF give vastly different predictions for (n, γ) cross sections; even close to stability the variation in the calculated cross section can be up to a factor $\sim 5 - 10$ [21]. This is illustrated in Fig. 1 for the case of $^{154}\text{Sm}(n, \gamma)$ reaction rates calculated with the reaction code TALYS-1.8 [22, 23]. Here, with unconstrained level-density and γ SF models that are not tuned to reproduce *e.g.* directly measured (n, γ) data, the calculated reaction rates have a spread of a factor of ~ 10 .

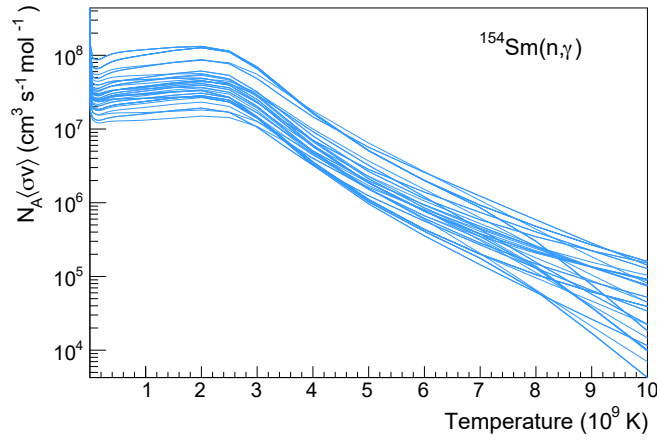
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Figure 1. Calculated radiative neutron-capture rates for the $^{154}\text{Sm}(n, \gamma)$ reaction. Each line represents one combination of a specific level density and γSF model, with six different level-density models and eight different γSF models as implemented in TALYS-1.8.

3. The Oslo and β -Oslo methods

The main purpose of the Oslo method is to extract the nuclear level density and γSF *simultaneously* from a set of excitation-energy tagged γ -ray spectra. Traditionally, such data sets were obtained by measuring charged ejectiles from light-ion inelastic or transfer reactions in coincidence with γ rays, such as $(^3\text{He}, \alpha\gamma)^{163}\text{Dy}$ [24] and $(p, p'\gamma)^{56}\text{Fe}$ [25]. The charged particles are measured with the Silicon Ring (SiRi) particle-telescope system [26], while the γ rays have previously been measured with the NaI(Tl) array CACTUS [27], now replaced with the large-volume $\text{LaBr}_3(\text{Ce})$ array OSCAR [28]. From the reaction kinematics, one can determine the initial excitation energy E_x of the residual nucleus. The Oslo-type analysis consists of four main steps:

1. Prepare an excitation-energy versus γ -ray energy matrix.
2. Deconvolute (unfold) the γ -ray spectra [15] utilizing the known detector response.
3. Obtain the *distribution* of the first-generation γ rays of all decay cascades [16].
4. Perform a simultaneous fit of the first-generation γ -ray spectra within a selected E_x range to extract the functional form of the level density and γSF [17].
5. Normalize the level density and γSF to auxiliary data and evaluate systematic errors [17, 29].

Published data and references can be found at <http://ocl.uio.no/compilation/>, and the data-analysis codes are available on Github: <https://github.com/oslocyclotronlab/oslo-method-software>. Having the experimental level density and γSF at hand, the (n, γ) cross section and the corresponding reaction rate are calculated as shown in Refs. [30, 31, 32, 33, 34, 35].

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The discovery of a low- γ -energy enhancement in the γ SF extracted at high excitation energies [36] has received a lot of attention. From a theoretical perspective, such an enhancement was not expected at all. Wiedeking *et al.* [37] confirmed the existence of the low-energy enhancement in ^{95}Mo with a new, independent technique. Soon after, new theoretical approaches came up with the first explanations of what could cause such an enhancement [38, 39]. As of today, we know that the multipolarity of the enhancement is dominantly dipole [25, 40, 41]. However, the electromagnetic character of the low-energy enhancement is not known, and the various theory predictions disagree on this point. Ref. [38] suggests it to be due to electric dipole transitions, whereas numerous shell-model calculations indicate a magnetic-dipole dominance at low transition energies [39, 42, 43, 44, 45, 46, 47, 48]. A recent study by Ngwetsheni and Orce [49] also support an $M1$ nature of the low-energy enhancement. In terms of neutron-capture reaction rates, it has been shown [50] that if the low-energy enhancement is present in *e.g.* neutron-rich Fe, Mo and Cd isotopes, it could boost their (n, γ) rates significantly. To address this experimentally, one must measure the γ SF of neutron-rich nuclei.

The β -Oslo method [18] is a new twist of the Oslo approach, with the goal of extracting level densities and γ SFs for nuclei away from stability. Here, excited levels in the residual nucleus is populated through β^- decay instead of through a charged-particle reaction. For exotic nuclei on the neutron-rich side of the valley of stability, the Q -value for β^- decay becomes large, making a wide range of excitation energies accessible in the residual nucleus. To apply the β -Oslo method, a β^- -unstable nucleus is implanted in the center of a segmented, total absorption spectrometer; so far the Summing NaI (SuN) detector [51] has been used. The emitted electron provides a tag for the following γ decay in the daughter nucleus. The initial excitation energy is determined from the sum of segments, *i.e.*, the sum of all γ rays de-exciting levels within the populated E_x bin. Furthermore, the γ -ray spectra from each segment gives the individual γ -ray spectra for that specific E_x bin.

As of today, the β -Oslo method has been applied to determine the level density and γ SF of ^{76}Ge [18], ^{70}Ni [8, 46], ^{74}Zn [52], and ^{51}Ti [53]. A review of the method and other complementary techniques are given in Ref. [54]. The main results are that all nuclei studied so far display the low-energy enhancement in the γ SF, which is particularly intriguing in the case of the neutron-rich ^{70}Ni and ^{74}Zn . For the ^{51}Ti case, the residual nucleus was populated both through β^- decay of ^{51}Sc and through the stripping reaction $^{50}\text{Ti}(d, p\gamma)^{51}\text{Ti}$. The $E_x - E_\gamma$ matrices of first-generation γ rays from the two cases are shown in Fig. 2a and b. Within the experimental error bars, the two experiments yield the same γ SF (Fig. 2c), although the nature of the two population mechanisms is very different. This fact indicates that the γ decay is indeed taking place from equilibrated states governed by mainly statistical decay.

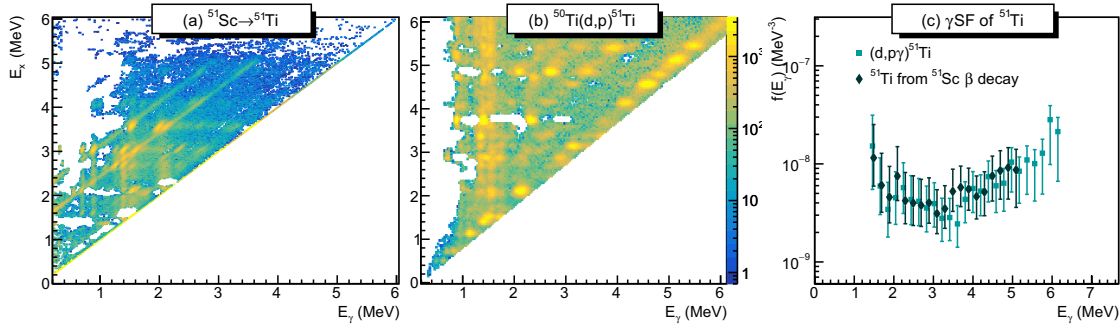
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Figure 2. First-generation matrices of ^{51}Ti from (a) β^- decay of ^{51}Sc and (b) $^{50}\text{Ti}(d, p)^{51}\text{Ti}$. The extracted γ SFs are shown in (c), where the error bars include statistical uncertainties as well as systematic errors. The data are from Ref. [53].

4. Summary and outlook

This is a very exciting time for nuclear astrophysics, as we enter the era of multi-messenger astronomy and huge leaps forward are taking place also on the nuclear-physics side. Indirect methods are called for to provide experimental constraints for (n, γ) reaction rates, with the aim of significantly improving the theoretical r -process and i -process yield estimates. In this respect, we find the β -Oslo method to be promising. More studies are underway to carefully evaluate systematic uncertainties and limitations of the method.

Acknowledgments

A. C. L. gratefully acknowledges funding through ERC-STG-2014 under grant agreement no. 637686, and support from the ChETEC COST Action (CA16117), supported by COST (European Cooperation in Science and Technology). This work was supported in part by the National Science Foundation under Grant No. PHY-1430152 (JINA Center for the Evolution of the Elements) and Grant No. OISE-1927130 (IReNA). This work was supported by the National Science Foundation under Grants No. PHY 1102511 (NSCL) and PHY 1350234 (CAREER).

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