Chapter 65

Indirect $(n, \gamma)^{91,92}\text{Zr}$ Cross Section Measurements for the s-Process

M. Guttormsen, S. Goriely, A. C. Larsen, A. G3rgen, T. W. Hagen, T. Renstr3m, S. Siem, N. U. H. Syed, G. Tagliente, H. K. Toft, H. Utsunomiya, A. V. Voinov and K. Wikan

Abstract Nuclear level densities (NLDs) and γ -ray strength functions (γ SFs) of $^{91,92}\text{Zr}$ have been extracted from particle- γ coincidences using the Oslo method. The extracted γ SF data, combined with photonuclear cross sections, cover the whole energy range from $E_\gamma \approx 1.5$ MeV up to the giant dipole resonance at $E_\gamma \approx 17$ MeV. The wide-range γ SF data display structures at $E_\gamma \approx 9.5$ MeV, compatible with a superposition of the spin-flip $M1$ resonance and a pygmy $E1$ resonance. Furthermore, the γ SF shows a minimum at $E_\gamma \approx 2\text{--}3$ MeV and an increase at lower γ -ray energies. The experimentally constrained NLDs and γ SFs are shown to reproduce known (n, γ) and Maxwellian-averaged cross sections for $^{91,92}\text{Zr}$ using the TALYS reaction code, thus serving as a benchmark for this indirect method of estimating (n, γ) cross sections for Zr isotopes.

65.1 Introduction

The playground for the nucleosynthesis is found in the interior of stars and/or in extreme cosmic events. The major contributors to creating heavier elements are the neutron capture processes [1]. The key question for these processes is whether the

M. Guttormsen (✉) · A. C. Larsen · A. G3rgen · T. W. Hagen · T. Renstr3m · S. Siem · N. U. H. Syed · H. K. Toft · K. Wikan
Department of Physics, University of Oslo, 0316 Oslo, Norway
e-mail: magne.guttormsen@fys.uio.no

S. Goriely
Institut d'Astronomie et d'Astrophysique, Universit3 Libre de Bruxelles,
Campus de la Plaine, CP-226, 1050 Brussels, Belgium

G. Tagliente
Istituto Nazionale di Fisica Nucleare, Bari, Italy

H. Utsunomiya
Department of Physics, Konan University, Okamoto 8-9-1, Higashinada,
Kobe 658-8501, Japan

A. V. Voinov
Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA

nuclear system after neutron absorption will keep the neutron and emitting γ rays to dissipate the energy, or will it eject the neutron or other particles/fragments and thereby producing other elements? For the s -process, this question is important at the so-called *branch points*, where the β^- -decay rate is comparable with the (n, γ) rate.

65.2 Experiment and Methods

Nuclear level densities (NLDs) and γ -ray strength functions (γ SFs) are essential quantities in estimating (n, γ) rates. At the Oslo cyclotron laboratory, we have extracted NLDs and γ SFs for $^{91,92}\text{Zr}$ using the Oslo method [2]. The experiments [3] were performed with 17-MeV and 28-MeV proton beams for the $^{92}\text{Zr}(p, p')^{92}\text{Zr}$ and $^{92}\text{Zr}(p, d)^{91}\text{Zr}$ reactions, respectively. The target was a 2 mg/cm² thick metallic foil enriched to 95% in ^{92}Zr . The charged outgoing particles were measured with the SiRi system of 64 $\Delta E - E$ silicon telescopes with thicknesses of 130 and 1550 μm , respectively. The Si detectors were placed in forward direction covering $\theta = 42^\circ$ to 54° relative to the beam. By setting 2-dimensional gates on the $(E, \Delta E)$ matrix, the outgoing charged ejectiles for the desired reaction were selected. Coincident γ rays for the residual $^{91,92}\text{Zr}$ were measured with the CACTUS array consisting of 28 collimated $5'' \times 5''$ NaI(Tl) detectors.

The energy distribution of first-generation or primary γ rays can be extracted from the unfolded total γ -ray spectra $U^E(E_\gamma)$ at an initial excitation energy E . Then the primary spectrum can be obtained by a subtraction of a weighted sum of $U^{E'}(E_\gamma)$ spectra for E' below E :

$$F^E(E_\gamma) = U^E(E_\gamma) - \sum_{E' < E} w_{E'} U^{E'}(E_\gamma). \quad (65.1)$$

The weighting coefficients $w_{E'}$ are determined by iteration [4]. The obtained primary spectra are organized into a matrix $P(E_\gamma, E)$. The next step of the Oslo method, is the factorization

$$P(E_\gamma, E) \propto \rho(E - E_\gamma) \mathcal{T}(E_\gamma), \quad (65.2)$$

where we assume that the decay probability is proportional to the NLD at the final energy $\rho(E - E_\gamma)$ according to Fermi's golden rule [5]. The decay is also proportional to the γ -ray transmission coefficient $\mathcal{T}$, which is assumed to be independent of excitation energy according to the Brink hypothesis [6].

65.3 Results and Conclusions

We have adopted the iteration procedure of Schiller et al. [2] in order to determine ρ and $\mathcal{T}$ by a least- χ^2 fit using relation (65.2). The transmission coefficient is connected to the γ SF by $f(E_\gamma) = \mathcal{T}(E_\gamma)/2\pi E_\gamma^3$. The results for the NLDs and γ SFs are shown in Fig. 65.1.

Fig. 65.1 Normalized NLDs of $^{91,92}\text{Zr}$ (left) and γ SFs (right) extracted from the present experiment. At low excitation energies, the NLD data are normalized to known discrete levels (solid blue line). At higher excitation energies, the data are normalized to ρ at the neutron separation energy S_n using average neutron capture resonance spacing D_0 . The γ SFs are normalized to reproduce the average γ width $\langle \Gamma_\gamma \rangle$ for neutron capture states at S_n , and photoneutron data [7, 8]

The experimental NLDs and γ SFs can now be tested on the additional experimental data relative to the radiative neutron capture cross sections $^{90}\text{Zr}(n, \gamma)^{91}\text{Zr}$ and $^{91}\text{Zr}(n, \gamma)^{92}\text{Zr}$. A comparison of the experimentally known (n, γ) cross sections with the theoretical calculations obtained with the TALYS reaction code using the measured NLD and γ SF is very gratifying. A similar comparison is made for the Maxwellian-averaged cross sections, which reveal the same agreement.

We found that our indirect method of determining the MACS is fully compatible with direct measurements, giving confidence that this approach is capable of providing reasonable cross sections for cases where direct measurements are not available.

In conclusion, the experimentally constrained NLDs and γ SFs are shown to reproduce known (n, γ) and Maxwellian-averaged cross sections for $^{91,92}\text{Zr}$ using the TALYS reaction code, thus serving as a benchmark for this indirect method of estimating (n, γ) cross sections and MACS for the Zr isotopes.

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