Nuclear level densities and γ-ray strength functions of ^{120,124}Sn and their application in astrophysics

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Abstract. Nuclear level densities (NLDs) and γ-ray strength functions (GSFs) of ^{120,124}Sn have been extracted with the Oslo method and additionally constrained with the novel Shape method. The GSFs were found to be in excellent agreement with the strengths from the inelastic relativistic proton scattering experiment. This comparison suggests the validity of the Brink-Axel hypothesis used as one of the key assumptions in astrophysical calculations. The extracted NLDs and GSFs were further used as experimental inputs to constrain the Maxwellian-averaged cross sections (MACS) for the radiative neutron capture process ^{119,123}Sn $(n,\gamma)^{120,124}$Sn using the the nuclear reaction code TALYS.

1 Introduction

The concepts of the nuclear level density (NLD) and γ-ray strength function (GSF) are two essential tools for the statistical description of excited nuclei and their $\gamma-$decay, used in numerous large-scale astrophysical calculations of abundances of elements in the universe [1]. One of the widely used experimental techniques, the Oslo method [2] allows for the simultaneous extraction of both these nuclear properties from γ-decay of excited states within the quasi-continuum populated in light particle induced reactions. One of the key assumptions adopted in the Oslo method is the validity of the generalized Brink-Axel hypothesis (gBA) stating an independence of the GSF of excitation energies, spins and parities of initial and final excited states involved. The same assumption is usually adopted for calculations of different reaction rates, including those of astrophysical importance, using the nuclear reaction codes, *e.g.* TALYS [3].

Comparison of the Oslo method GSFs with strengths obtained with other experimental methods allows to address the question on the validity of the gBA hypothesis below the neutron separation energy for studied nuclei. With this assumption being valid, the experimental GSFs and NLDs can be used to constrain the radiative neutron capture rates and Maxwellian-averaged cross sections (MACS), essential for the astrophysical s- and r-processes. In the present work, the Oslo method was applied to the ^{120,124}Sn isotopes to extract the GSFs and NLDs to be further constrained by other experimental techniques and exploited as the nuclear input for astrophysical purposes.

2 Nuclear level densities and γ-ray strength functions

The ^{120,124}Sn were studied in the ^{120,124}Sn $(p,p'\gamma)$ reaction with the 16 MeV proton beam, performed at the Oslo Cyclotron Laboratory. The setup comprises of the particle silicon tele-

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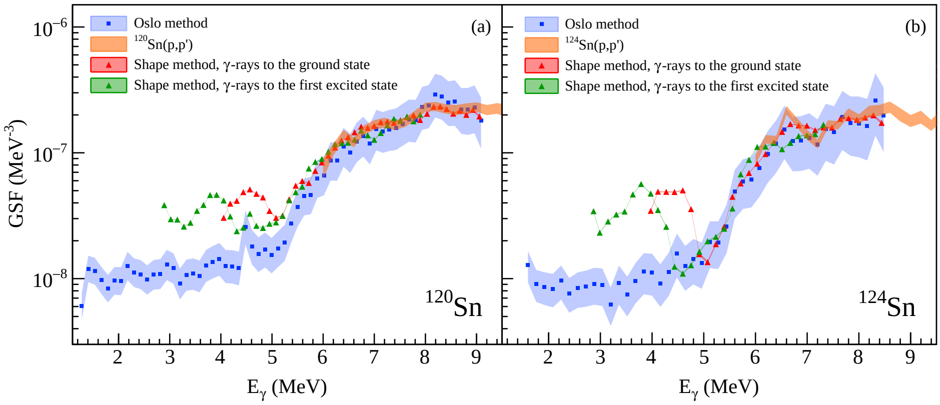

Figure 1. GSFs of ^{120}Sn and ^{124}Sn obtained with the Oslo method (blue band), the Shape method for γ-decays to the ground state (red band) and to the first excited state (green band) and the inelastic proton scattering experiment (orange band) [5].

scope SiRi placed in the backward position and the scintillator detector array OSCAR (see Ref. [2]). The setup is made to record the particle-γ coincidence data used as an input for the Oslo type of analysis. The raw coincidence data were processed to extract the primary matrix, consisting of the first generation photons in each cascade stemming from a nucleus at excited states below the neutron separation energy. The core idea behind the Oslo method is the decomposition of this primary matrix into the functional forms of the NLD and the GSF. However, these forms require external experimental data, such as low-lying discrete states, neutron resonance spacings and radiative widths, to constrain the slope and the absolute values of the NLD and GSF, *i.e.* to perform the normalization (see Ref. [2] for further details). Unfortunately, these normalization parameters are unavailable for ^{124}Sn and one has to rely on systematics of the total average radiative widths and NLDs at the neutron separation energies for other Sn isotopes. To account for errors of estimation of the normalization parameters from these systematics, the novel Shape method was additionally used to constrain the slope shared by the NLD and GSF [4]. This method allows to reconstruct the slopes of the strength from γ-decays to the ground and the first excited states in ^{120,124}Sn obtained in the same $(p, p'\gamma)$ reaction. Both the Shape and the Oslo method assume a predominant contribution of dipole transitions at sufficiently high excitation energies, which is supported by the experimental evidence [2], and, therefore, yield the dipole GSFs.

The comparison of the Oslo method with the Shape method results and the strengths deduced from spectra of relativistic Coulomb excitation in forward-angle inelastic proton scattering [5] is presented in figure 1. All GSFs agree quite well in shape within the estimated error bands above $\approx$ 5 MeV and below the neutron separation energy. The Shape method GSFs demonstrate an upward trend at low γ-ray energies due to the failure of some of the assumptions of the method at low energies. The details of the limitations of the Shape method are presented in Ref. [6]. This direct comparison of the γ-decay strength with the ground state photoabsorption strength suggests that the GSF is somewhat independent of the excitation energy below the neutron separation energy in accordance with the Brink-Axel hypothesis. An explicit study of the excitation energy dependence of the Oslo method GSF also reveals that the strengths for different initial and final excitation energies agree quite well within the error bands with the Oslo method result. The comparison of these results with the Shape method strengths above 5 MeV, where the Shape method can be considered applicable, also suggests some independence of the GSF of final spins $J = 0$ and $J = 2$ of studied transitions, corresponding to direct decays to the ground and first excited states.

The NLDs for ^{120,124}Sn are quite close in shape and absolute values to the previously studied NLDs for other even-mass Sn nuclei ^{116,118,122}Sn [6]. Moreover, the reduced Oslo method NLDs of 1^- states for ^{124}Sn agrees quite well within the error bars with the corresponding NLD from the Coulomb excitation experiment.

2.1 Maxwellian-averaged cross-sections

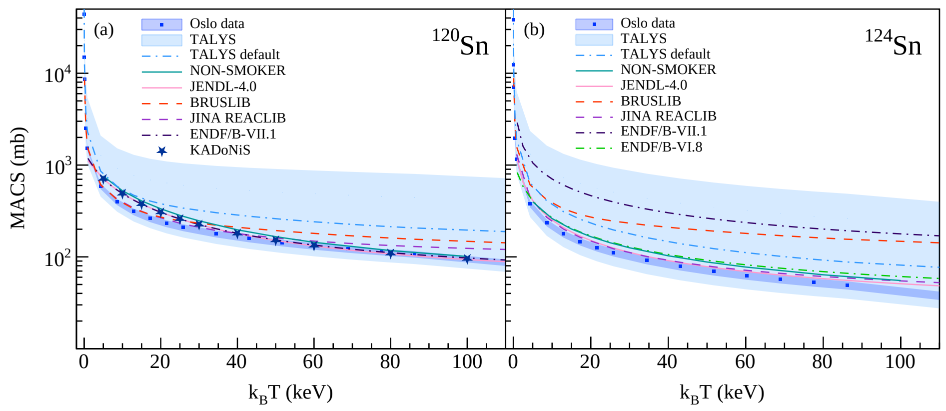

Figure 2. MACS of ^{120}Sn and ^{124}Sn obtained with the Oslo method input NLDs and GSFs compared to the span of TALYS predictions (light blue band), NON-SMOKER [7], JENDL-4.0 [8], BRUSLIB [9], JINA REACLIB [10], ENDF/B-VII.1 [11], ENDF/B-VI.8 [12], KADoNiS [13] libraries.

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The experimental NLDs and GSFs were further used to constrain the MACS of the ^{119,123}Sn $(n,\gamma)^{120,124}$Sn reactions with the TALYS code. Both results are presented in figure 2 in comparison with the span of TALYS predictions, NON-SMOKER [7], JENDL-4.0 [8], BRUSLIB [9], JINA REACLIB [10], ENDF/B-VII.1 [11], ENDF/B-VI.8 [12] and KADoNiS [13] libraries. For both nuclei the experimentally constrained MACS deviate significantly from the default TALYS prediction and lie closer to the bottom par of the span of TALYS cross-sections. In is not surprising given large deviations of the TALYS NLD and GSF models from the experimental results that might reach up to several orders of magnitude for some excitation and γ-energies correspondingly. For ^{120}Sn, the MACS agree quite well with KADoNiS, ENDF/B-VII.1, JINA REACLIB and JENDL-4.0 values. The situation is different for ^{124}Sn , where the MACS from different libraries differ significantly from each other and from the experimental result, providing relatively low estimates of MACS values.

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