EVOLUTION OF THE PYGMY DIPOLE RESONANCE IN Sn ISOTOPES*

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The $^{111-113,116-122,124}$Sn isotopes were studied in light-particle-induced reactions to obtain the low-lying γ-ray strength functions (GSFs) with the Oslo method. These data were further combined with the inelastic relativistic proton scattering GSFs to study the evolution of the pygmy dipole resonance (PDR) with an increasing neutron number. The PDR was found to be centered at ≈ 8 MeV in all isotopes. The fraction of the energy-weighted sum rule for dipole transitions exhausted by the PDR in these isotopes ranges from $\approx 1.5\%$ to 3%, being the maximum for ^{120}Sn.

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1. Introduction

The electric dipole response of a nucleus is widely dominated by the isovector giant dipole resonance (IVGDR), appearing between ≈ 10 and 20 MeV in nuclei across the whole nuclear chart. However, a certain fraction of electric dipole transitions gives rise to the pygmy dipole resonance (PDR), clearly observed in the vicinity of the neutron separation energy in relatively neutron-rich nuclei [1]. As numerous theories link the strength of the PDR to the presence of excess neutrons forming a neutron skin, gaining more knowledge on the PDR, especially in neutron-rich nuclei, can provide an important insight into the nuclear structure in general. Moreover, the PDR is expected to play a role in the astrophysical r-process by increasing the radiative neutron capture rates and, thus, contributing to the production of heavy, neutron-rich nuclei. In addition, the neutron skin thickness of exotic nuclei, constrained by the PDR strength, might further provide constraints for the equation of state applied to the dense neutron-rich matter and, hence, such astrophysical objects as neutron stars [1].

Experimental information on the evolution of the PDR in different isotopic chains is crucial for making predictions for very neutron-rich, exotic nuclei of astrophysical interest. In this work, the $^{111-113,116-122,124}$Sn

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isotopes were studied with the Oslo method in order to obtain γ-ray strength functions below the neutron threshold S_n and obtain the systematics of the PDR in the Sn isotopic chain.

2. The Oslo method

Eleven Sn isotopes, $^{111-113,116-122,124}$Sn, were studied in light-particle-induced reactions $(p,p'\gamma)$, $(p,d\gamma)$, $(d,p\gamma)$, (^{3}He,^{3}Heγ), and (^{3}He,$\alpha\gamma$) with 16 and 25 MeV proton, 11.5 MeV deuteron, and 38 ^{3}He beams at the Oslo Cyclotron Laboratory. The newest experimental setup comprises of the scintillator detector array OSCAR [2], consisting of 30 $LaBr_3$(Ce) detectors surrounding the target chamber, and the particle telescope, covering the range of 126°–140°. The experiments on $^{111-113,116,118,121,122}$Sn were performed with the older NaI(Tl) detector array [3], while ^{117,119,120,124}Sn were studied with the newest setup. The particle–γ coincidence events collected with this setup are used to obtain first-generation spectra of a nucleus at each excitation energy below S_n, which serve as the main input for the Oslo method [3]. The main objective of the method is to extract the functional forms of the nuclear level density, the number of levels per excitation energy unit, and the γ-ray strength function (GSF), or the average, reduced γ-transition probability. These functional forms are normalized with the discrete low-lying states as well as the level spacings and average total radiative widths at the neutron separation energy, obtained from neutron resonance experiments (see Ref. [3] for more details).

The Oslo method provides the dipole GSFs only up to the neutron threshold S_n, and in order to complete the nuclear dipole response up to higher γ energies, these data had to be combined with the strengths from the Coulomb excitation in a forward-angle inelastic proton scattering experiment [4] and available (γ,n) data.

To parametrize the low-lying E1 part of the nuclear response, the experimental information on the M1 component from Ref. [4] was used for ^{112,116,118,120,124}Sn. The simplest Lorentzian function was found to be satisfactory for the description of an overall shape of the M1 resonance. For the rest of the isotopes, we interpolate the parameters of the Lorentzian function based on the systematics built with the available experimental data. The generalized Lorentzian function reproduces the best the IVGDR, while the remaining E1 component in the vicinity of S_n was parametrized with the Gaussian peaks. For the lighter $^{111-113,1116,117}$Sn isotopes, the low-lying GSF is rather smooth, and a single Gaussian peak was sufficient to describe the potential PDR in these nuclei. However, both the Oslo and relativistic (p,p') data reveal a double-peaked structure of the PDR in the rest of the isotopes. For this reason, they were described with double Gaussian peaks, a smaller, low-lying and a larger, higher-lying components. The examples of the decomposition of the total E1+M1 GSFs into the IVGDR, PDR and the M1 part are shown for the lightest ^{111}Sn (a) and the heaviest studied ^{124}Sn (b) isotopes in Fig. 1.

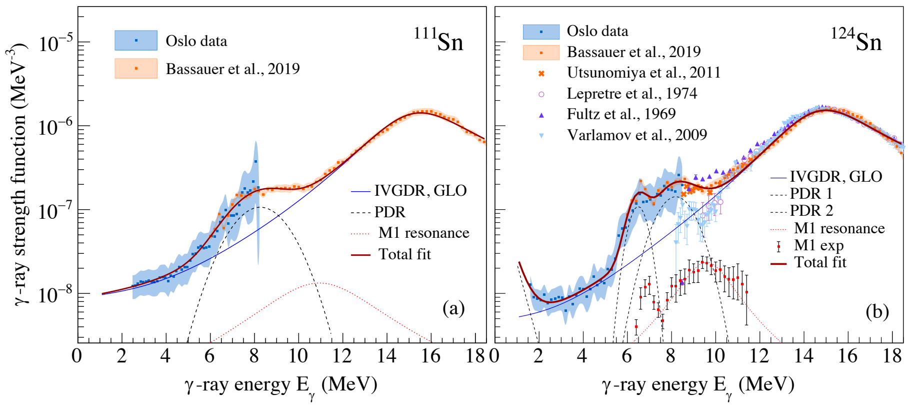

Fig. 1. The GSFs of the lightest ^{111}Sn and the heaviest studied ^{124}Sn isotopes, shown together with the (p, p') data from Ref. [4] and (γ, n) data from Refs. [5–8].

2.1. Evolution of the PDR in Sn isotopes

Given the parameters of the Gaussian peak(s), it is possible to study the evolution of the PDR characteristics with an increasing neutron number. One of the parameters to be studied is the energy centroid of the PDR, shown in Fig. 2 (a). The data points marked with circles correspond to the Gaussian peak energy for the nuclei with the single-peaked PDR ($^{111-113,116,117}$Sn) and the strength-weighted centroid of two Gaussian peaks for the rest of nuclei

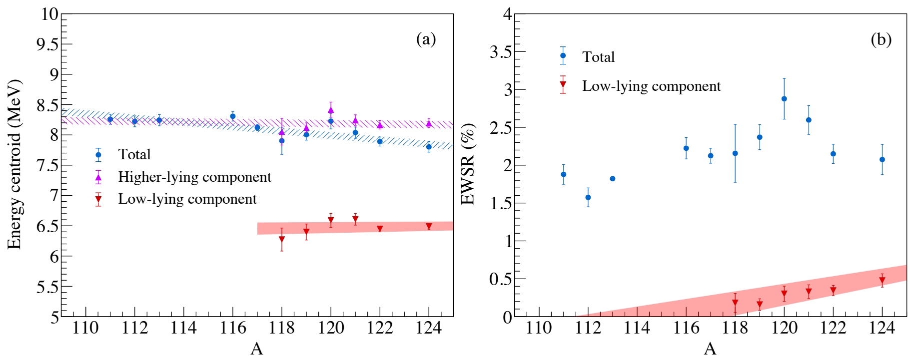

Fig. 2. (a) The energy centroid of the total PDR, the largest, and the lowest components of the PDR in studied nuclei. (b) The fraction of the EWSR exhausted by the total PDR and the smallest component in studied nuclei. Shaded and hatched bands mark the linear fits of the data points.

with the double-structured PDR. For the last group of nuclei, the peak energies of the largest and the smallest PDR components are also shown with triangles up and down, respectively.

Overall, the energy centroid tends to remain at ≈ 8.3 MeV for all studied isotopes when considering the largest component in $^{118-122,124}$Sn only and demonstrates a mild decrease in energy with the increasing neutron number when considering both PDR components in these nuclei (hatched bands in Fig. 2 (a)). The low-lying component of the double-peaked PDRs remains at ≈ 6.4 MeV, which is supported by both the Oslo and (p,p') data (see, *e.g.*, Fig. 1 (b)). This trend is in agreement with most of microscopic theoretical predictions, done with the relativistic Hartree–Bogolubov model (RHB)+relativistic quasiparticle random phase approximation (RQRPA), multiphonon quasiparticle-phonon models (QPM), and others (see Ref. [9] and references therein).

Figure 2 (b) demonstrates the fraction of the energy-weighted sum rule (EWSR) for dipole transitions exhausted by the total PDR and the low-lying component in $^{118-112,124}$Sn. The PDR increases from $\approx 1.5\%$ in the lightest Sn isotopes to $\approx 3\%$, reaching its maximum for ^{120}Sn, while the low-lying component monotonously increases in strength with the neutron number. The first trend is somewhat in accordance with the RHB + RQRPA calculations presented in Ref. [10].

2.2. Conclusion

The $^{111-113,116-122,124}$Sn isotopes were studied with the Oslo method to obtain the systematics of the PDR in the Sn isotopic chain. The PDR was found to be concentrated ≈ 8.0–8.3 MeV in all nuclei, with a relatively stable energy centroid throughout the whole chain. The largest PDR was observed in ^{120}Sn which is in accordance with the trend provided by the RHB + RQRPA calculations for Sn isotopes.

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