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Colloquia: COMEX7

The pygmy dipole resonance in Sn isotopes studied with the Oslo method

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Summary. — The evolution of bulk properties of the low-lying electric dipole response (LEDR) in $^{111-113,116-122,124}$Sn has been studied on the basis of the γ-ray strength functions extracted from particle-γ coincidence data with the Oslo method and from Coulomb excitation data. The LEDR was found to be concentrated at $\approx$ 8.0–8.3 MeV and exhausts $\approx$ 2–3% of the Thomas-Reiche-Kuhn sum rule in all isotopes. No clear increase of the strength from the lightest ^{111}Sn to the heaviest studied ^{124}Sn, predicted with the majority of theoretical approaches, was observed.

1. – Introduction

The electric dipole response in nuclei has always been in focus of experimental and theoretical studies in search for answers to fundamental questions regarding nuclear structure and nucleon interaction involved. Besides the well studied isovector giant dipole resonance (IVGDR), the concentration of the $E1$ strength in the vicinity of the neutron threshold, often referred to as the pygmy dipole resonance (PDR), still poses numerous questions regarding its origin. Within the macroscopic approach, this feature is expected to be linked to oscillations of excess neutrons, or neutron skin, *versus* the proton-neutron saturated core [1]. This potentially provides the experimental constraints on the neutron skin thickness in neutron rich nuclei and parameters of the symmetry energy term of the equation of state for the description of dense, neutron rich matter of neutron stars [2]. Moreover, since the PDR strength is expected to be especially large in relatively heavy nuclei with large neutron excess, the PDR is expected to have a considerable impact on the neutron capture rates in the astrophysical s and r processes [3]. For this reason, systematic experimental studies of the PDR in different isotopic chains are highly desired.

Such study has been performed for eleven Sn isotopes, $^{111-113,116-122,124}$Sn, investigated at the Oslo Cyclotron Laboratory (OCL) in light-particle-induced reactions with the so-called Oslo method [4]. The Sn isotopic chain is one of the best experimentally and theoretically studied cases and, thus, the Oslo results can be directly compared to other experimental data below and above the neutron threshold.

2. – Experiments at the Oslo Cyclotron Laboratory

The low-lying electric dipole response (LEDR) was studied in terms of the γ-ray strength function (GSF), or average, reduced transition probability. The core idea of the Oslo method is a simultaneous extraction of the GSF and the nuclear level density (NLD) from particle-γ coincidence data. Isotopes $^{111-113,116-122,124}$Sn were studied in $(p,p'\gamma)$, $(p,d\gamma)$, $(d,p\gamma)$, (^{3}He, ^{3}He$'\gamma$), (^{3}He, $\alpha\gamma$) reactions with 20 and 16 MeV protons, 11.5 MeV deuterons and 38 MeV ^{3}He. The setup at the OCL comprises the particle Si telescope SiRi and γ scintillator detector array OSCAR (see [4] and [5] for more details). OSCAR consists of 30 large-volume $LaBr_3$(Ce) scintillator detectors, surrounding the target chamber and mounted on a truncated icosahedron frame. The particle telescope exploiting the $E-\Delta E$ was mounted either in the forward or backward position, cowering azimuth angles from 36° to 50° or from 126° to 140°, respectively. Such configuration of the setup allows to collect particle-γ coincidence events and, thus, the γ-spectra at each excitation energy of the nucleus below the neutron separation energy. These spectra were unfolded to correct for the detector response. At the final stage of the coincidence event analysis, the first generation photons for each cascade at each excitation energy E_x are singled out to form a so-called primary matrix $P(E_x, E_\gamma)$. This matrix is the main input of the Oslo method, providing a decomposition of the primary matrix into the transmission coefficient $\mathcal{T}(E_\gamma)$ and the NLD $\rho(E_x - E_\gamma)$ (for more details see [4]):

$$P(E_x, E_\gamma) \propto \mathcal{T} \cdot \rho(E_x - E_\gamma), \tag{1}$$

where $\mathcal{T}(E_\gamma)$ is independent of the initial and final excitation energies, according to the Brink-Axel hypothesis [4] and proportional to the GSF $f(E_\gamma)$ as $\mathcal{T}(E_\gamma) = 2\pi E_\gamma^{2L+1} f(E_\gamma)$. In the Oslo analysis it is assumed that the extracted GSF is predominantly of the dipole $L = 1$ nature.

This decomposition provides only the functional forms of the NLD and GSF, and some additional experimental data are required to constrain the absolute values of these functions. The slope and the absolute value of the NLD are fixed with the discrete low-lying states and the value of the NLD at the neutron separation energy, obtained from the average s-wave neutron resonance spacing available from neutron resonance experiments. The GSF shares the same slope with the NLD and its absolute value is fixed with the total average radiative width obtained in the same neutron resonance experiments. For those nuclei, where these experimental data are unavailable, they were extracted from the systematics available for other stable Sn isotopes [6]. The details of the data analysis and normalization for all isotopes can be found in refs. [6-11].

3. – Experimental results

The Oslo GSFs provide the mixed $M1 + E1$ dipole response in nuclei only up to the neutron threshold energy. To describe the IVGDR region, these results have to be combined with the results of (γ, n) and Coulomb excitation (p, p') experiments [12]. The latter are available slightly below the neutron threshold, which allows to compare the slopes of the (p, p') and Oslo GSFs. For all studied isotopes they agree well within the uncertainty bands, as, for example, shown for ^{112}Sn and ^{124}Sn in fig. 1.

To study the evolution of bulk properties of the LEDR, a decomposition of the total $M1 + E1$ dipole response should be performed. For this reason, the $M1$ data available from the Coulomb excitation experiments were parametrized with a simple Lorentzian

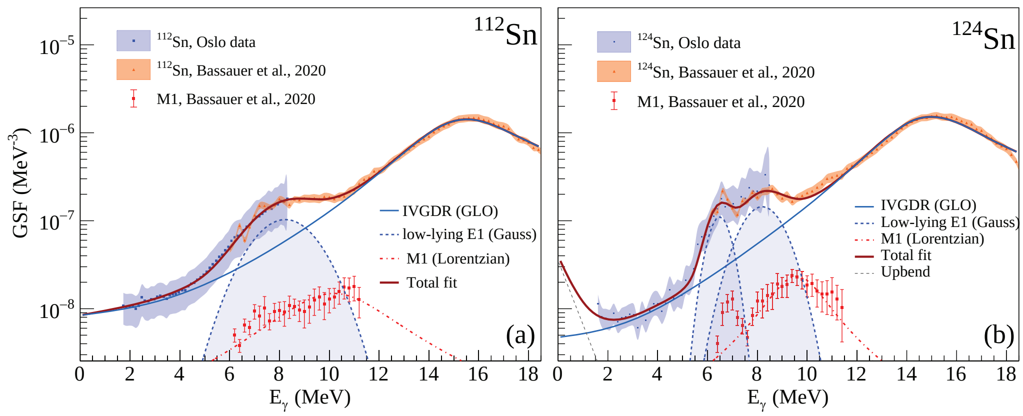

Fig. 1. – Experimental GSFs of ^{112}Sn (a) and ^{124}Sn (b) obtained with the Oslo method (blue bands) and from the Coulomb excitation (p, p') experiments (orange bands). The (p, p') $M1$ data are shown with with red squares. The IVGDR and $M1$ fits are shown with solid blue and dashed red lines. The low-lying $E1$ fits are marked with shaded blue areas. In ^{124}Sn and additional upbend feature was added to reproduce the strength at low E_γ.

function to build the systematics and estimate the $M1$ component in those nuclei where no experimental data is available. The IVGDR was parametrised with a Generalized Lorentzian function (GLO), while the LEDR component was best fitted by a combination of Gaussian peaks. Both the slope of the Oslo GSF and the (p, p') hint at a presence of a peak-like structure at ≈ 6.4 MeV, thus, two Gaussian peaks were used for the LEDR in $^{118-122,124}$Sn. The best fit in the lighter isotopes was achieved with only one Gaussian peak. All fit functions are shown together with the experimental data points in fig. 1 .

Provided the parameters of the Gaussian peak(s), it is possible to study the evolution of the LEDR characteristics with an increasing neutron number. One of the parameters to be studied is the energy centroid of the LEDR, shown in fig. 2(a). The data points marked as blue squares correspond to the Gaussian peak energy for the nuclei with the single-peaked LEDR ($^{111-113,116,117}$Sn) and the strength-weighted centroid of two Gaussian peaks for the rest of nuclei with the double-structured LEDR. For the last group of nuclei, the peak energies of the largest and the smallest LEDR components are also shown with magenta triangles down and red circles, 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 LEDR components in these nuclei. The low-lying component of the double-peaked LEDR 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. [10] and references therein).

Figure 2(b) demonstrates the fraction of the Thomas-Reiche-Kuhn sum rule for dipole transitions exhausted by the total LEDR and the low-lying component in $^{118-112,124}$Sn. The LEDR increases in strength from $\approx 1.8\%$ in the lightest Sn isotopes to $\approx 3\%$, reaching its maximum for ^{120}Sn, while the low-lying component monotonously increases

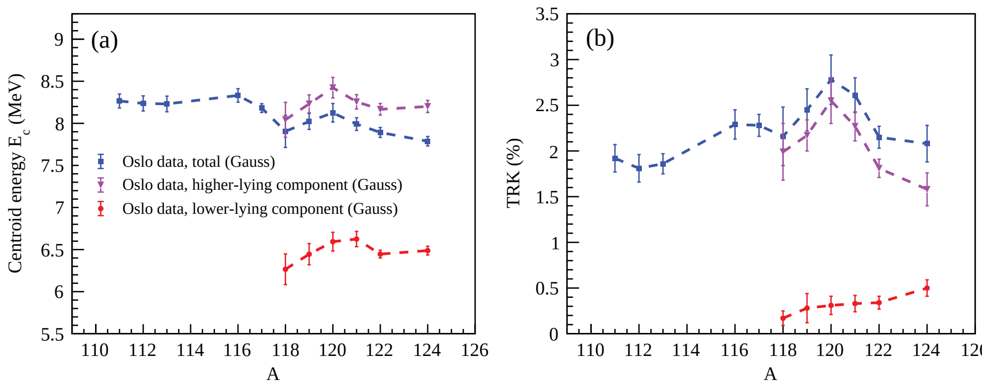

Fig. 2. – Energy centroids (a) and TRK values (b) for the total extracted low-lying electric strength in Sn isotopes (blue squares), its lower-lying (red circles) and higher-lying components (magenta triangles).

in strength with the neutron number. The first trend is somewhat in accordance with the RHB + RQRPA calculations presented in ref. [13].

4. – Conclusions

The present results provided a consistent experimental study of the evolution of the low-lying electric dipole strength in Sn isotopes. In contrast to the majority of theoretical approaches, this strength exhausts only $\approx 2-3\%$ of the TRK sum rule in the studied nuclei. The experimental results do not seem to reveal any strong increase of the strength with an increasing neutron number between ^{111}Sn and ^{124}Sn, which might still set in for more neutron rich nuclei, according to the RQRPA calculations. 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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