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Article · February 2009

Source: arXiv

Excitation energy and strength of the pygmy dipole resonance in stable tin isotopes ⋆

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Abstract

The ^{112,120}Sn(γ,γ') reactions have been studied at the S-DALINAC. Electric dipole (E1) strength distributions have been determined including contributions from unresolved strength extracted by a fluctuation analysis. Together with available data on ^{116,124}Sn, an experimental systematics of the pygmy dipole resonance (PDR) in stable even-mass tin isotopes is established. The PDR centroid excitation energies and summed strengths are in reasonable agreement with quasiparticle-phonon model calculations based on a nonrelativistic description of the mean field but disagree with relativistic quasiparticle random-phase approximation predictions.

Key words: ^{112,120}Sn(γ,γ'); deduced E1 strength distributions. Systematics of the PDR in stable Sn isotopes; QPM and RQRPA calculations.

The electric pygmy dipole resonance (PDR) in nuclei is a topic of high current interest (for a recent review, see [1]). It is expected to occur at energies well below the isovector giant dipole resonance (IVGDR) and may exhaust a considerable fraction of the total electric dipole strength in nuclei with a very asymmetric proton-to-neutron ratio. Based on an analysis of transition

⋆ Work supported by the DFG under contract SFB 634.

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densities, most microscopic models qualitatively agree on its nature as an oscillation of a neutron skin - emerging with an increasing N/Z ratio - against an approximately isospin-saturated core. However, quantitative predictions of the centroid energy and strength of the PDR as a function of neutron excess differ considerably, in particular between models based on a relativistic and a nonrelativistic description of the mean field, respectively.

While data in very neutron-rich heavy nuclei are scarce, the mode has been investigated extensively utilizing the (γ, γ') reaction in stable even-mass nuclides (see e.g. Refs. [2,3] and references therein), in particular at the shell closures $Z = 20$ [4], $N = 50$ [5], $Z = 50$ [6], $N = 82$ [7,8,9] and in ^{208}Pb [10]. Although the PDR is much weaker excited in these nuclei, detailed spectroscopy provides important insight into a possible interpretation of the mode as a neutron-skin oscillation, the role of collectivity and single-particle degrees of freedom and its isospin nature [11]. However, the connection of these results to the PDR in nuclei with very large N/Z ratios still remains a subject of debate [1].

In this respect, a systematic investigation of the PDR in the tin isotope chain is of special interest. Recently, measurements of the E1 response below the IVGDR in the exotic isotopes ^{130,132}Sn has been reported [12]. Combined with results on the stable isotopes, for the first time a set of data spanning a large range of N/Z ratios from 1.24 to 1.64 is thus available, which can serve as a benchmark test for the validity of various theoretical approaches. Indeed, the Sn isotopes have been a favorite case in the model calculations to systematically investigate the features of the PDR as a function of neutron excess [13,14,15,16,17,18,19,20].

Experimental information on the PDR in ^{116}Sn and ^{124}Sn is available from Ref. [6]. Here we report results from new (γ, γ') experiments on ^{112}Sn and ^{120}Sn, which allow the systematics of the PDR over the range of stable tin isotopes to be established. These are compared to calculations within the framework of the quasiparticle-phonon model (QPM) using a nonrelativistic mean-field description and with the quasiparticle random-phase approximation (QRPA) based on a relativistic mean-field (RMF) description.

The experiments on ^{112}Sn and ^{120}Sn were performed at the superconducting Darmstadt electron linear accelerator S-DALINAC with the nuclear resonance fluorescence (NRF) technique using electron energies of 5.5, 7.0 and 9.5 MeV for ^{112}Sn and 7.5 and 9.1 MeV for ^{120}Sn to generate bremsstrahlung. The maximum photon energies were chosen below the neutron separation energies of both nuclides to avoid the production of neutrons from $(\gamma$,n) reactions, which would lead to a significant increase of the background in the spectra. A detailed description of the experimental setup can be found in Ref. [21] and experimental details in Ref. [22]. Targets consisted of about 2 g highly enriched ($> 90\%$) ^{112}Sn and ^{120}Sn sandwiched between two layers of boron. Well known transitions in ^{11}B were used to determine the photon spectrum and for the energy calibration. Figure 1 presents (γ, γ') spectra for ^{112}Sn at $E_0 = 9.5$ MeV (top) and for ^{120}Sn at $E_0 = 9.1$ MeV (bottom) taken at an angle of 130° with respect to the incident beam. Significant differences are suggested by the data as the strength in ^{120}Sn is much more fragmented.

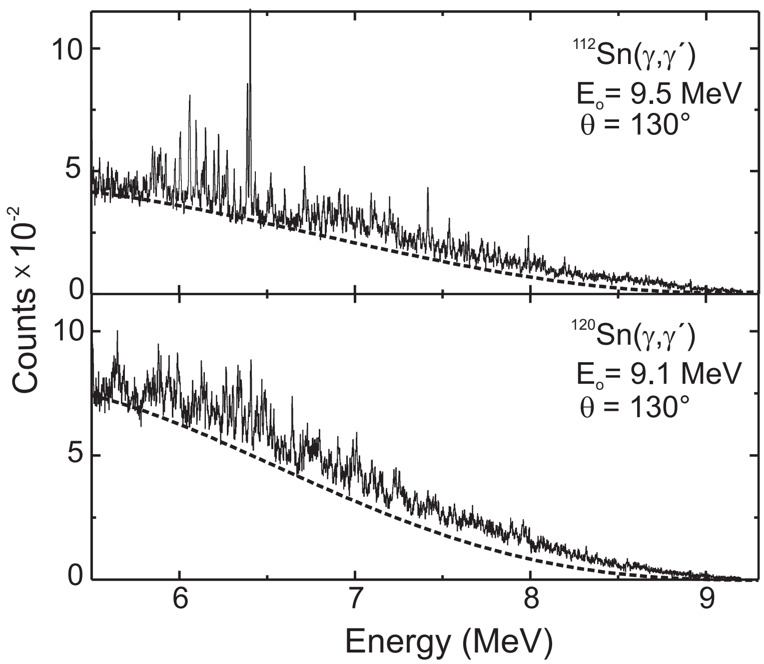

Fig. 1. Spectra of the (γ, γ') reaction at $\Theta = 130°$ on ^{112}Sn and ^{120}Sn at $E_0 = 9.5$ MeV and 9.1 MeV, respectively, measured at the S-DALINAC. The dashed lines show the nonresonant part of the spectrum deduced by a fluctuation analysis described in the text based on $J^\pi = 1^-$ level densities taken from the model of Ref. [30].

Reduced transition strengths were extracted for ^{112,120}Sn as explained e.g. in Ref. [2]. By analyzing the γ-ray angular distributions the spins of all previously unknown states was found to be $J = 1$; however, the parity was not determined. Thus all dipole transitions were assumed to have E1 character based on experimental findings in a large number of heavy semimagic nuclei [5,6,23,24,25]. A branching ratio $\Gamma_0/\Gamma = 1$ was assumed because no decay branch into excited states was observed. Feeding effects [2] were corrected for by utilizing the comparison of results obtained at different endpoint energies.

On the l.h.s. of Fig. 2 the B(E1) distributions extracted in ^{112,120}Sn are shown between 4 and 9 MeV and compared to those in ^{116,124}Sn measured previously by Govaert et al. [6]. (Note that the prominent transitions resulting from the population of the $[2^+ \otimes 3^-]_{1^-}$ two-phonon states [27,28] lie below 3.5 MeV and are therefore not shown). All distributions exhibit a concentration of strength between 6 and 7 MeV believed to represent the main part of the PDR. However, there is also sizable strength at higher energies which varies from isotope to isotope. Furthermore, a different fragmentation pattern with smaller individual strengths in ^{120}Sn already indicated by the spectrum (Fig. 1) is clearly visible.

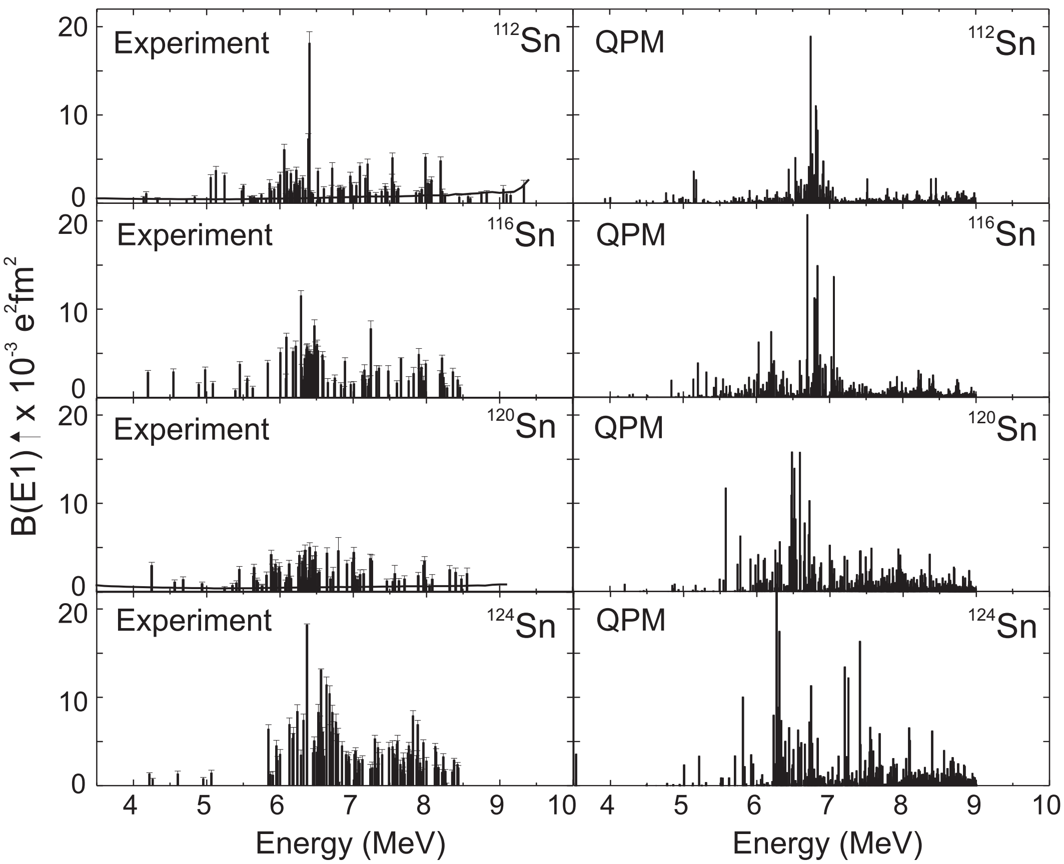

Fig. 2. L.h.s.: Experimental B(E1) strength distributions in ^{112,116,120,124}Sn. The data for ^{112,120}Sn are from the present work, those for ^{116,124}Sn from [6]. R.h.s.: QPM calculations of the corresponding B(E1) strength distributions including up to three-phonon states described in the text. The smooth lines indicate the sensitivity limits of the present experiments.

The r.h.s. of Fig. 2 shows results from calculations with the QPM, where the mean field is taken from a global parametrization [26] and levels near the Fermi surface are adjusted to experimental values. One-, two- and three-phonon states were included similar to Ref. [9], which should give a rather complete spectrum of 1^- states up to about 7 MeV. As in previous calculations within this scheme [6,9,10,23], the transition densities of states forming the PDR exhibit the features of a neutron-skin oscillation against an isospin-saturated core. Figure 2 demonstrates that good correspondence between the experimentally observed and calculated fine structure can be obtained when the coupling to complex configurations, i.e. up to three-phonon states, is taken into account.

The sensitivity limits of the present experiment for detecting a γ-ray transition are indicated in Fig. 2 by the smooth lines. A comparison to the QPM calculations indicates that sizable strength could be missing. Furthermore, unresolved strength due to the finite energy resolution may be hidden in the spectra. A statistical analysis of the PDR in $N = 82$ nuclei [29] suggested that the level density in the region of the PDR is very high. Current level-density models based on the backshifted Fermi gas (BSFG) approach [30,31] and microscopic HF-BCS calculations [32] predict average level spacings (the inverse of the level density ρ) in the energy range of interest up to $1/\rho \approx 1$ keV in the investigated tin isotopes, i.e. values below the typical Ge detector resolution $\Delta E = 4 - 7$ keV in the γ-energy range of the present experiment. Thus some of the E1 strength is indeed expected to lie in the background of the measured spectra. Such unresolved strength can be extracted by means of a fluctuation analysis [33]. Application of this technique to (γ, γ') spectra is discussed in detail in Refs. [34,35,36]. The analysis requires either a knowledge of the 1^- level density or of the nonresonant background contributions to the spectra. Since the approach for a model-independent determination of the nonresonant background based on a wavelet decomposition [37,38] does not work in the case of the (γ, γ') spectra [1], level densities were taken from the three models discussed above . All three models [30,31,32] yield roughly the same magnitude and slope of the nonresonant background in the ^{112,120}Sn spectra. Results obtained with the level density predictions of Ref. [30] are shown as examples. Their actual slight differences (indistinguishable within the line thickness for the case of ^{112}Sn) allow to estimate the systematic uncertainties caused by the level density models in the extraction of the hidden E1 strength.

The method is applicable in the excitation region $E_\mathrm{x} = 5.5 - 7.8$ MeV. At lower energies the individual levels do not overlap while at higher energies uncertainties in the present method get too large because the fluctuation signal is too small. A comparison of the analysis of discrete transitions to the present one shows an increase of the total E1 strength of 44(6)% in ^{112}Sn and 47(12)% in ^{120}Sn, respectively, due to unresolved levels when integrating up to $E_\mathrm{x} = 7.8$ MeV. The quoted uncertainties include the model dependence of the level densities and finite-range-of-data errors.

In Fig. 3 the systematics of the E1 strength in stable tin isotopes summed in the energy interval $5 \leq E_\mathrm{x} < 9$ MeV is displayed as a function of the mass number. Two values are shown for ^{112,120}Sn investigated in the present work: full circles represent the sum of strength from discrete transitions only (which makes the result comparable to the ^{116,124}Sn data from [6]) while full squares include the unresolved strength just discussed.

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[1] Application of the technique requires a compact resonance signal and a sufficient signal-to-background ratio in the spectrum.

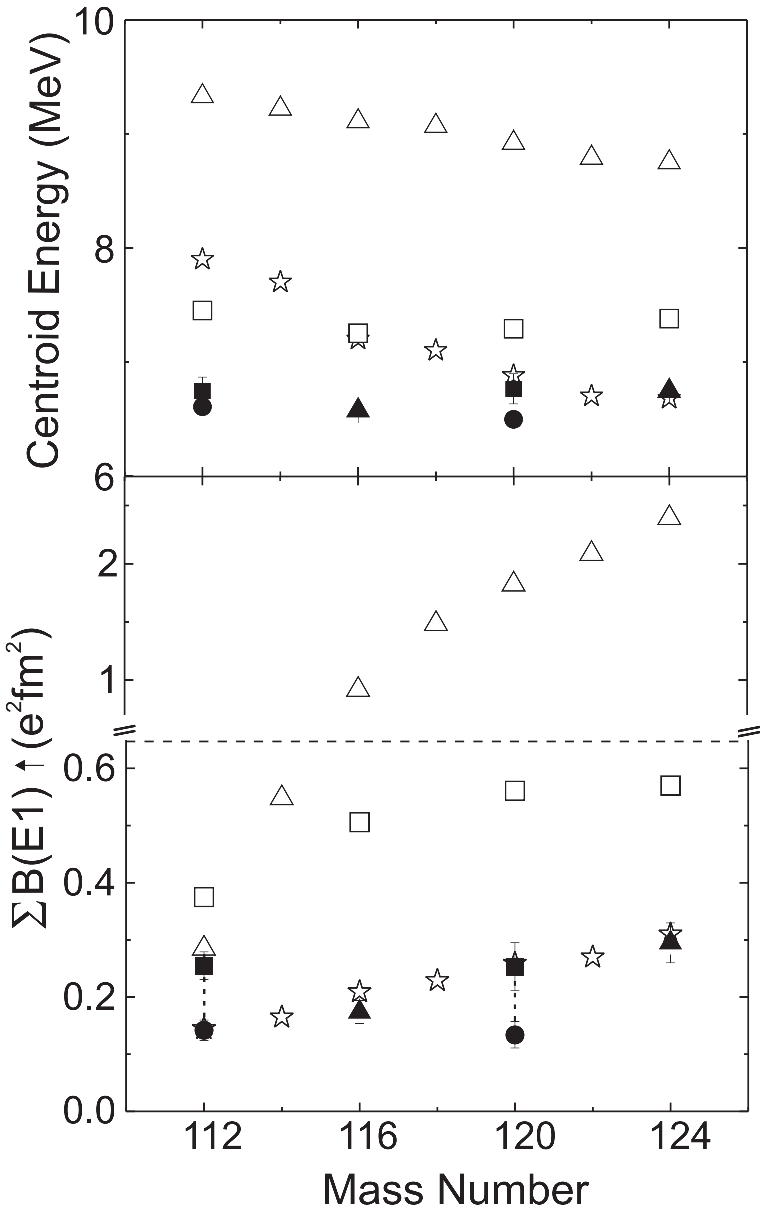

Fig. 3. Systematics of the energy centroids (top) and summed E1 strengths (bottom) of the PDR in the Sn isotope chain. Experimental results are shown as full triangles (^{116,124}Sn, Ref. [6]), circles (^{112,120}Sn, present experiment, discrete transitions only) and squares (^{112,120}Sn, unresolved strength included). Model results are shown as open stars (QPM, Ref. [20]), open squares (QPM described in the text) and open triangles (RQRPA, Ref. [16]).

The results are confronted with model predictions of the PDR centroid energies (top) and summed strengths (bottom). Starting with a discussion of the centroids, the experimental results (full circles and triangles) appear to be nearly constant at a value $E_x \approx 6.5$ MeV independent of the neutron excess. Inclusion of the unresolved strengths obtained in ^{112,120}Sn (full squares) leaves the results almost unaffected. Such a behavior is reproduced by the

QPM calculation introduced above (open squares), albeit the centroids lie systematically about 500 keV higher. The QPM approach of Ref. [20] (open stars) predicts a systematic dependence on the neutron excess. Good correspondence with the data is observed for the heavier ^{120,124}Sn isotopes but for ^{112,116}Sn the experimental centroids are significantly lower. The predictions of a self-consistent relativistic QRPA approach based on the relativistic Hartree-Bogoliubov model, using an interaction with density-dependent meson-nucleon couplings (DD-ME2) [16], are presented as open triangles. They show a weak mass dependence but the predicted centroids are about 2 MeV higher than the data.

The experimental summed E1 strengths (bottom part of Fig. 3) display the following pattern: Analyzing the discrete transitions only, an increase with increasing neutron number is observed - as predicted by all calculations shown here - but the E1 strength shows a minimum for ^{120}Sn. Including unresolved transitions raises the strength by about 50% for ^{112,120}Sn. Its magnitude depends sensitively on the 1^- level densities which are expected to vary little (typically less than a factor of two) over the range of investigated tin isotopes. Thus, the contribution from unresolved transitions in ^{116,124}Sn should be similar leaving the pattern unchanged. Comparing to the data including the unresolved strength, the QPM results of Ref. [20] are somewhat below the data for ^{112}Sn (and probably also for ^{116,124}Sn) and agree for ^{120}Sn. The QPM calculations described above give PDR strengths which are typically a factor of two larger than experiment. Finally, the relativistic QRPA (open trinagles) dramatically overpredicts the strength (note the scale change in Fig. 3) except for ^{112}Sn. A similar RQRPA calculation with a slightly different interaction has been reported by Piekarewicz [18] with almost identical results for the PDR centroids and strengths.

We note that the excitation energy intervals used for the summation in the model calculations partly differ from the experimental one since the PDR strengths are predicted in different excitation energy regions (cf. the top part of Fig. 3). In Refs. [20,16] the intervals are determined based on an analysis of the transition densities. For the QPM calculations presented above, the summation is performed over the energy range of the data. The QPM results of Ref. [20] correspond to an energy range $E_{\mathrm{x}} < 8.1$ MeV (based on the structure argument). If one would sum up to 9 MeV as in the experimental case, the E1 strengths would be significantly larger (cf. Fig. 7 in [20]). The quoted PDR properties from the RQRPA calculations correspond to a summation up to 10 MeV.

Clearly, none of the models provides a satisfactory reproduction of both quantities, viz. energy centroid and strength of the PDR, in the stable tin isotopes. However, the QPM calculations are generally much closer to the data. The variations between neighboring nuclei and the small total E1 strengths of less than 1% of the EWSR suggest that the transitions retain much of their single-particle character. Oros et al. [39] demonstrated for example in a schematic two-group RPA calculation that irregularities of the unperturbed one-particle one-hole (1ph) spectrum can lead to a local concentration of E1 strength well below the IVGDR. On the other hand, it is instructive to recall the important role of mixing between transitions considered to belong to the PDR and slightly higher-lying one-phonon states which lead to a shift of the low-energy single-particle continuum below the threshold (see e.g. Ref. [40]). This mechanism is also very sensitive to details of the mean-field description.

To summarize, we have presented a NRF study of the dipole strength in ^{112}Sn and ^{120}Sn up to the neutron threshold. The analysis reveals in both nuclei significant unresolved strength in the energy region $E_x = 5.5 - 7.8$ MeV which must be included when extracting integral features of the dipole strength distribution from the data. Combined with previous results on ^{116,124}Sn from Ref. [6], for the first time a systematics of the PDR in the stable tin isotopes is now available. Their global features are in reasonable agreement QPM calculations but disagree with RQRPA results which predict significantly higher centroid energies and larger collectivity. An extrapolation of the these results to the exotic ^{130,132}Sn isotopes suggests that the low-energy E1 strength observed in the Coulomb breakup experiments [12] does not represent the PDR, but rather some other nuclear effect.

The collectivity of the PDR in the stable tin isotopes predicted by the models discussed above differs substantially ranging from an interpretation as almost pure 1ph transition with a $\nu[3p_{3/2}3s^{-1}_{1/2}]$ structure [20] to a rather collective mode exhausting up to about 7% of the EWSR [16,18]. Very recently, for the first time RQRPA calculations of the E1 strength in tin isotopes including phonon coupling have been presented [41,42]. While the global characteristics of the PDR remain essentially unchanged, due to the fragmentation some strength is shifted into the energy region below 7 MeV which is claimed to be in reasonable accordance with the strengths experimentally observed in ^{116,124}Sn [6]. Still, the discrepancy with predictions of the QPM remains since the latter finds the characteristic features of the PDR (based on the structure of the transition densities [10,43]) for states below $E_\mathrm{x} \approx 7$ MeV only. Calculations of the fine structure of the E1 mode in the various models are called for, such as the ones shown in Fig. 2. This should allow to further elucidate the structure of the PDR.

Uncertainties on the experimental side remain also because of the inherent limitations of the used techniques. The Coulomb breakup experiments are restricted to energies above neutron threshold and the NRF experiments (roughly) to energies below threshold. Furthermore, some correction of the NRF results may be necessary due to unobserved decay to excited states. New experimental approaches are thus desired to determine complete E1 strength distributions from low energies up to the GDR region with good resolution. Therefore, a tagger for this energy region aiming at a resolution $\Delta E/E = 25$ keV (FWHM) is presently put into operation at the S-DALINAC [44]. Alternatively, intermediate-energy polarized proton scattering at 0° has been developed as a new spectroscopic tool for dipole strength with comparable energy resolution [45]. As demonstrated for the case of ^{208}Pb, E1 strengths extracted from such data are in good agreement with NRF studies [46]. Because of the conflicting results in the present work a case study of ^{120}Sn is presently underway [47].

Acknowledgements

Discussions with G. Colò, N. Paar and D. Vretenar are acknowledged. We are indebted to N. Paar and J. Piekarewicz for providing us with numerical results of their calculations and to Y. Kalmykov for his help with the fluctuation analysis. We thank the GSI for the loan of the enriched ^{112}Sn target. BÖ acknowledges financial support by the DAAD sandwich program.

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