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Electromagnetic Transitions and Branching Ratios as a Tool for Investigating the Fine Structure of Nuclear Excitations

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Abstract. The electromagnetic multipole response of atomic nuclei at extreme isospin is investigated by energy-density functional (EDF) and three-phonon quasiparticle-phonon model (QPM) theory with special emphasis on electric and magnetic dipole and quadrupole excitations below the neutron threshold. Of special interest is the dipole photoabsorption cross-section of ^{206}Pb. From theoretical and experimental studies of this nucleus additional low-energy dipole strength associated with pygmy dipole resonance is found. Furthermore, a stringent comparison of the EDF+QPM theory with recent measurements of lifetimes and branching ratios of 2^+ states in ^{112,114,124}Sn hints at the occurrence of a low-energy quadrupole mode of unique character which could be interpreted as pygmy quadrupole resonance.

KEY WORDS: branching ratios, electromagnetic transitions, energy-density functional theory, quasiparticle-phonon model, pygmy resonances

1 Introduction

The study of new excitation modes in atomic nuclei called pygmy resonances [1, 2] play an important role in the nuclear structure physics. These low-energy nuclear excitations are found to be a common feature of isospin-asymmetric stable and exotic nuclei. The spectral distributions and transition densities of pygmy resonances of dipole and quadrupole multipolarity show special features being compatible with oscillations of a neutron skin against the isospin-symmetric nuclear core [3–6]. Understanding the nature of nuclear skin excitations is an important step in the spectral dynamics of atomic nuclei at the limits of the existence.

Typically, the pygmy dipole resonance mode (PDR) appears as an additional dipole strength component around the neutron threshold sitting on top of the low-energy tail of the giant dipole resonance (GDR) which is classically represented by a Lorentzian shape [1, 7]. However, the PDR is a nuclear quantum effect. The detailed systematic analysis of pygmy dipole strengths in different nuclei shows that standard strength functions based on Lorentz curves, currently widely used for the calculation of nucleon-capture cross-sections by statistical reaction model codes, do not describe the dipole strength distribution below the (γ,n) threshold correctly and need to be improved [7]. Another interesting aspect of the low-energy excitations and in particular of the PDR is that they all incorporate interactions resulting from multi-particle-multi-hole couplings and core polarization effects induced by the GDR [6, 8]. In this sense, it is clear that in order to account for the complexity of phenomena in the PDR region, an extended theoretical approach which explicitly accounts for the interactions among multi-quasiparticle configurations is required. For that purpose a theoretical microscopic approach based on energy-density functional (EDF) methods [9] and multi-phonon techniques of the quasiparticle-phonon model (QPM) [10] was developed [3,4]. The latter is used for predictions and systematic investigations of nuclear ground and excited states [6].

One of the recent achievements of the EDF+QPM theory is the state-of-the-art theoretical prediction of a new mode of nuclear excitation, called pygmy quadrupole resonance (PQR) [5] which was also experimentally confirmed in ^{124}Sn nucleus by three independent experiments performed at Legnaro National Laboratory, Italy [11], Kernfysisch Versneller Instituut in Groningen, the Netherlands and at the S-DALINAC in Darmstadt, Germany and the University of Köln, Germany [12]. Recently, two (p,p'γ) Doppler-shift attenuation (DSA) coincidence experiments were performed at the SONIC@HORUS setup [13]. In these experiments 2^+ states of ^{112,114}Sn isotopes with excitation energies up to 4.2 MeV were populated. Lifetimes and branching ratios allowing for the determination of E2 transition strengths to the ground state were measured and compared to EDF+QPM calculations [13]. The obtained results hint at the occurrence of a low-energy quadrupole mode of unique character which could be interpreted as pygmy quadrupole resonance in these nuclei.

The precise knowledge of the nuclear response on external electromagnetic field is of crucial importance for the determination of nucleon-capture reaction rates of key elements of stellar nucleosynthesis [8, 14, 15]. The procedure requires the estimation of a huge number of nuclear reaction cross-sections which in the most cases are unknown, as far as they are related to experimentally unexplored mass regions of nuclei. Even more, when approaching the limits of existence of atomic nuclei which are characterized by a very short life time, the presently available experimental methods and techniques are not able to provide such data. Recent studies of nuclear reactions of astrophysical interest show that the reaction cross-sections strongly depend on the low-energy part of the electromagnetic strength function which is connected to the dipole photoabsorption cross-section [8, 14, 15]. In this respect, when dealing with experimentally inaccessible nuclei, reliable microscopic calculations become of prime interest for such astrophysics applications.

2 Theoretical Approach

Successful description of the low-energy γ-strength functions and branching ratios connecting ground and excited states of the PDR and PQR can be achieved in our microscopic theoretical approach which incorporates self-consistent EDF theory and the three-phonon QPM [3,4,6]. Of major importance for these investigations is the reliable treatment of nuclear ground state properties like determination of nuclear surface regions, where the formation of a skin takes place [6]. This is found of genuine significance for extrapolations of QRPA and QPM calculations into unknown mass regions.

2.1 Model Hamiltonian

The QPM model Hamiltonian [10] is given by:

$$H = H_{\text{MF}} + H_{\text{res}}\,, \tag{1}$$

where H_{MF} is a mean-field part and H_{res} stands for the residual interaction.

The mean-field (MF) part H_{MF} is treated by self-consistent Skyrme Hartree-Fock-Bogoliubov (HFB) theory described in [6,9]. The pure HFB picture is in fact extended beyond MF by dynamical self-energies, hence incorporating a more detailed spectral description of nuclear spectra. The procedure allows us to account in a self-consistent manner for nuclear binding energies and other ground-state properties of nuclei like the charge radii and the neutron skin thickness [4,6,9].

The nuclear excited states are calculated with a residual interaction which is based on the QPM formalism [10]:

$$H_{\text{res}} = H^{\text{ph}}_{\text{M}} + H^{\text{ph}}_{\text{SM}} + H^{\text{pp}}_{\text{M}}\,, \tag{2}$$

where effective forces are implemented to account for the interaction between the quasiparticles. The terms H^{ph}_{M}, $H^{\text{ph}}_{\text{SM}}$ and H^{pp}_{M} are taken as a sum of isoscalar and isovector separable multipole and spin-multipole interactions in the particle-hole $(p - h)$ and multipole pairing interaction in the particle-particle $(p - p)$ channels, respectively [10]. The model parameters are fixed empirically in such a way that the properties of the lowest-lying collective states and giant resonances are described accurately [16]. An exception is the isovector spin-dipole coupling constant, which is obtained from experimental M1 data [17,18] or self-consistent QRPA calculations using the microscopic EDF of Ref. [9].

2.2 Wave function

An important advantage of the EDF+QPM approach is the description of the nuclear excitations in terms of QRPA phonons as a building blocks of the three-phonon QPM model space [10, 19] which provides a microscopic way to multi-configuration mixing. Thus, the QPM formalism allows for a further expansion of QRPA $p-h$ excitations to multi-particle-multi-hole states in terms of coupling between quasiparticles and phonons [10].

Thus, for spherical even-even nuclei the model Hamiltonian is diagonalized on an orthonormal set of wave functions constructed from one-, two- and three-phonon configurations [19]:

$$\Psi_\nu(JM) = \Bigg\{ \sum_i R_i(J\nu) Q^{+}_{JMi} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^{+}_{\lambda_1 \mu_1 i_1} \times Q^{+}_{\lambda_2 \mu_2 i_2} \right]_{JM} + \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2 \\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(J\nu) \Big[\left[Q^{+}_{\lambda_1 \mu_1 i_1} \otimes Q^{+}_{\lambda_2 \mu_2 i_2} \right]_{IK} \otimes Q^{+}_{\lambda_3 \mu_3 i_3} \Big]_{JM} \Bigg\} \Psi_0 \,, \tag{3}$$

where R, P and T are unknown amplitudes, and ν labels the number of the excited states.

The electromagnetic transition matrix elements are calculated for transition operators including the interaction of quasiparticles and phonons [20] where exact commutation relations are implemented which is a necessary condition in order to satisfy the Pauli principle.

3 Discussion and Results

3.1 Dipole response of ^{206}Pb

Recently the EDF+QPM approach was implemented in the description of the fine structure of nuclear electric and magnetic excitations below the neutron threshold, S_n = 8.087 MeV in ^{206}Pb. In Figure 1 is presented the theoretical dipole photoabsorption cross-section of ^{206}Pb in comparison with recent experimental measurements carried out up to the neutron threshold at the High-Intensity γ-Ray Source (HIγS) facility at Duke University and GDR data from [8]. The impact of the PDR on the dipole photoabsorption cross-section below the neutron threshold is investigated. For this purpose two QRPA calculations

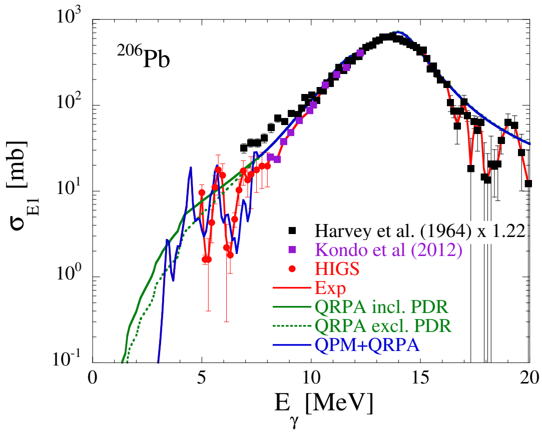

Figure 1. Dipole photoabsorption cross-section obtained from EDF+QPM calculations (blue solid line) in comparison with experimental data (red line) below (red circles) and above (black and violet squares) the neutron threshold in ^{206}Pb which are taken from Ref. [8] and Refs. therein. In addition, QRPA results included (solid green line) and excluded (dashed green line) the PDR contribution are shown.

which include or exclude the PDR states are made. The results indicate a strong influence of the PDR on the low-energy part of the dipole strength function. In addition, in three-phonon QPM approach the effect of the multi-particle-multi-hole coupling on the low-energy dipole photoabsorption cross-section is studied. A separation between E1 and M1 contributions is done. More details about the results can be found in Ref. [8].

The microscopic structure of low-energy E1 and M1 spectral distributions in ^{206}Pb is investigated [8]. From the EDF+QPM calculations is found that the fragmentation of the E1 strength is due to the interaction of the QRPA PDR states with those from the GDR tail and also with multi-phonon configurations with different spin and parities. The detailed EDF+QPM analysis of the E1 transition matrix elements strongly suggests that the PDR dominates the distribution of the dipole strength up to about 7 MeV, at which point the tail of the GDR starts making an important contribution. Also significant is the impact from multi-phonon states to the total E1 strength and to a lesser extent to the M1 strength. Based on the microscopic structure of the individual transitions, we compute experimental and theoretical cumulative strengths below the neutron threshold [8]. The theoretical results are compared to HI$\vec{\gamma}$S data in Figure 2 and discussed in detail in Ref. [8].

Furthermore, the presence of PDR mode in ^{206}Pb affects strongly the ^{205}Pb radiative neutron capture cross-section, a reaction of relevance to the destruction of ^{205}Pb during the s-process [8]. Such studies could provide key information on the formation of the solar system [8].

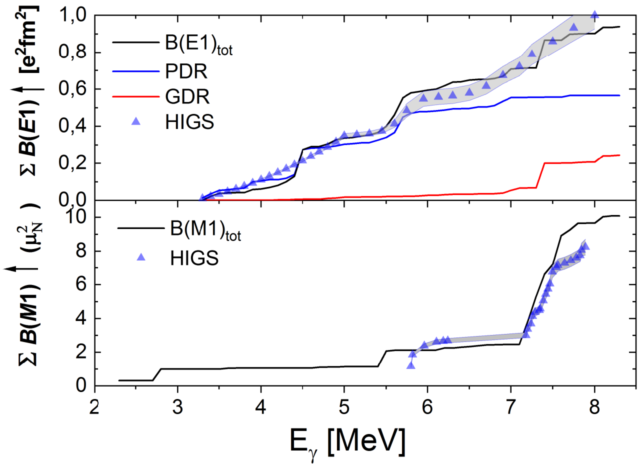

Figure 2. Cumulative B(E1) (top) and B(M1) (bottom) strength in ^{206}Pb obtained from integrating the corresponding distribution of strength up to an energy $E_\gamma \leq S_{1n}$=8.087 MeV from Ref. [8].

3.2 Systematic studies of PDR and PQR in Sn isotopes

Systematic QRPA and QPM calculations of electric dipole and quadrupole excitation modes in neutron-excess Sn isotopes are recently performed. The theoretical findings indicate the presence of a genuine PDR mode in the energy range $E_x \approx 6 \div 8$ MeV and PQR mode in the energy range $E_x \approx 2 \div 5$, respectively. The QRPA spectral distributions of E1 excitations up to 25 MeV and E2 excitations up to 35 MeV in ^{114,118,122}Sn are shown in Figure 3.

The closer examination of the proton and neutron dipole transition densities in ^{114,118,122}Sn presented in Figure 4 (left panel) reveals the dominance of neutron skin oscillations of the PDR modes. The unique character of the low-energy 2^+ states at $E_x \approx 2 \div 5$ in these nuclei is evident from the behavior of proton and neutron quadrupole transition densities shown in Figure 4 (right panel). Similarly to the dipole case, QRPA transition density of 2^+ states between 2 MeV and 5 MeV reveal neutron oscillations at the nuclear surface. The results are in agreement with our previous results [4, 6, 11–13].

In order to describe the observed fragmentation pattern of the skin modes, one must go beyond QRPA and allow anharmonicities. That is achieved by the multi-phonon QPM approach, introduced in Section 2. In addition to the strong fragmentation, the multi-phonon coupling lead to induced interactions by which states from higher-energy regions are shifted in energy downward. The theoretical calculations of cumulative QRPA and QPM B(E1) and B(E2) strengths in ^{114,118,122}Sn show that the cumulative QPM B(E1) and B(E2) strengths are larger $\approx 1.5 \div 3$ times than the corresponding QRPA strengths. The QRPA

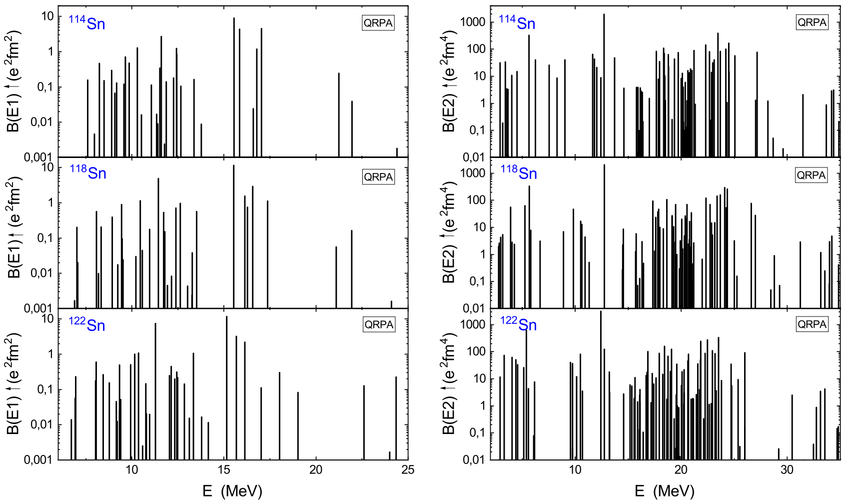

Figure 3. QRPA $J^\pi = 1^-$ (left) and $J^\pi = 2^+$ (right) multipole response functions of the Sn isotopes.

and QPM calculations show also a significant correlation of the PDR and PQR strengths with the skin thickness: the spectral strengths of the skin modes follows closely the evolution of the nuclear skin.

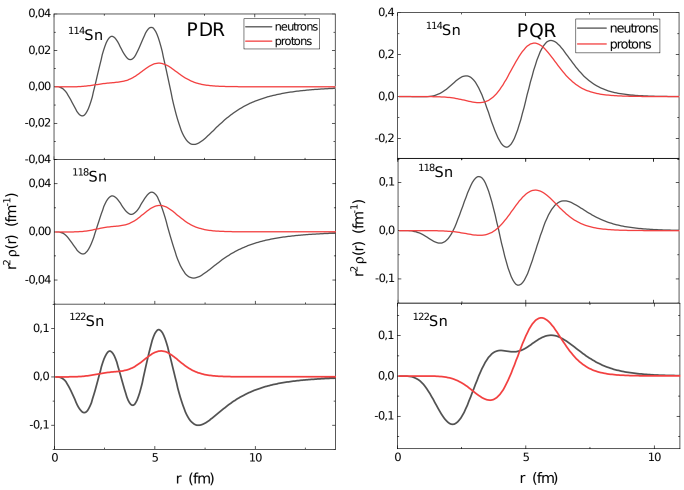

Figure 4. (Color online) Summed QRPA proton (red line) and neutron (black line) dipole and quadrupole transition densities of excited states with predominantly neutron structure related to PDR and PQR modes in ^{114,118,122}Sn nuclei.

Two recent experiments using inelastic proton-scattering followed by the coincident detection of γ-rays in ^{112}Sn and ^{114}Sn nuclei have been performed at the Institute for Nuclear Physics of the University of Cologne (Germany) to excite low-spin states in the two lightest stable Sn isotopes [13]. In these studies, lifetimes and branching ratios allowing for the determination of the reduced quadrupole transition strengths to the ground state were measured. In order to examine in detail the low-energy quadrupole strength associated with the PQR in ^{112,114}Sn, we compare the theoretical EDF+QPM and experimental B(E2) strengths, ground-state and 2_1^+ state γ-decay branching ratios to the ground state- b_0 and to excited states- b_1, respectively. We limited the considered final states in the EDF+QPM calculation of b_0 and b_1 to positive-parity final states which were also observed in the experiment. Those include states up to the 2_3^+ state as well as the 4_1^+ state [13]. The derived experimental and theoretical ground state γ-decay branching ratio b_0 have been calculated by the relations: $b_0 = (1 + \sum_i \Gamma_i/\Gamma_0)^{-1} = \Gamma_0/\Gamma$, where $\sum_i \Gamma_i/\Gamma_0$ is the intensity of all observed γ-decays to excited states and normalized to the ground-state decay intensity and $\Gamma = \Gamma_0 + \sum_i \Gamma_i$ is the total observed γ-decay width, see also the recent work on ^{124}Sn [12]. In addition branching ratios of γ-decays to the 2_1^+ state $b_1 = \Gamma_1/\Gamma$ where Γ_1 is the γ-decay width to the first 2^+ state are derived from the present theoretical and experimental investigations [13].
Commonly, the QPM PQR states have b_0 values close or above 50% and they prefer decaying to the ground state than to an excited state [12, 13]. However, there are also exceptions which mainly concern the presence of the two-phonon $\left[2_1^+ \otimes 2_1^+\right]$ component in the structure of the 2^+ states. Thus, in 2^+ states with two-phonon admixtures which contain the collective $[2_1^+]_{QRPA}$ phonon, the strong E2 transitions to the 2_1^+ lead to the reduction of the b_0 value [13]. As far as the observation of large b_0 values is a signature of the major one-phonon contribution to excited 2^+ states, the observation of large b_1 values is a clear indication for two-phonon component in these states. The obtained results emphasize that the branching ratios serve as a highly sensitive observable for distinguishing simple particle-hole type configurations and multi-phonon structures [13].

4 Conclusions

The ability of the EDF+QPM approach to deal with large configuration spaces makes it extremely valuable in the description of the fine structure of E1 and M1 spectral distributions below and around the neutron threshold. The very good agreement of the calculations with the experiment on dipole photoabsorption cross-section in ^{206}Pb is a signature that theoretical strength functions obtained within this model could be successfully applied in investigations of nuclear reactions of astrophysical significance. Furthermore, the EDF+QPM theory predicts the occurrence of a new low-energy quadrupole mode of unique character in tin isotopes which can be interpreted as pygmy quadrupole resonance. The theoretical findings are confirmed from the comparison of the theory with experimental data on B(E2) transition probabilities and branching ratios. In addition, the theoretical and experimental results of E2 transitions and branching ratios in ^{112,114,124}Sn contribute to the understanding of the fine structure of the PQR in these nuclei and give a strong evidence on the existence of multi-phonon excitations in the PQR energy region.

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