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QPM Analysis of ^{205}Tl Nuclear Excitations below the Giant Dipole Resonance

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Abstract. We analysed our experimental recent findings of the dipole response of the odd-mass stable nucleus ^{205}Tl within the quasi-particle phonon model. Using the phonon basis constructed for the neighbouring ^{204}Hg and wave function configurations for ^{205}Tl consisting of a mixture of quasiparticle $\otimes$ N-phonon configurations (N=0,1,2), only one group of fragmented dipole excited states has been reproduced at 5.5 MeV in comparison to the experimental distribution which shows a second group at about 5 MeV. The computed dipole transition strengths are mainly of E1 character which could be associated to the pygmy dipole resonance.

1 Introduction

The nuclear structure of low-lying states consists of pure single quasiparticle states in odd-mass nuclei and one-phonon or two-quasiparticle configurations in even-mass nuclei. At higher excitation energy due to the high level density and to the quasiparticle-phonon interaction, the wave function is more complex [1]. Different coupling of quasi-particle and phonon states may result to different configurations with the same spin and parity. This is the case of the Pygmy states distribution which appears on the low-energy tail of the Giant dipole resonance [2]. The corresponding dipole transition strengths may increase considerably the reaction rates of elements nucleosynthesis [3]. Although the nature of the Pygmy is still under debate, the Quasiparticle-Phonon Model (QPM) [1] has successfully reproduced the general features as for instance in the lead isotopes [4],[5]. This has been complemented by the recent nuclear resonance fluorescence (NRF) measurements on the neighboring Z=81 ^{205}Tl nucleus. In this work, we report on the analysis of the results within the QPM model.

2 $(\gamma,\gamma^{'})$ measurements

The dipole response of ^{205}Tl has been investigated in Nuclear Resonance Fluorescence experiments (NRF) using a bremsstrahlung photon beam with an end-point energy of 7.5 MeV at the Darmstadt High Intensity Photon Setup (DHIPS). The NRF technique [6] is very selective to dipole transitions. Two NRF measurements have been conducted for about 80 hours with a natural Tl target (2060.0 mg) and a target enriched to 99.9% in ^{205}Tl (1938.4 mg), respectively. For the photon flux calibration both targets were sandwiched between two boron disks with a total mass of 240.8 mg (natural) and 394.3 mg (enriched to 99.5% in ^{11}B), respectively. The scattered photon intensities were measured by high-resolution HPGe γ-ray detectors positioned around the target at 90°, 95° and 130° with respect to the incident beam.

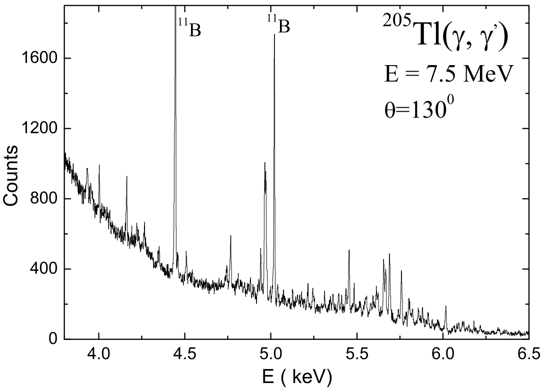

Figure 1. Photon scattering spectrum of ^{205}Tl.

From the transition intensities observed in the spectrum (Fig. 1), elastic scattering cross sections are extracted. These are proportional to the $g\cdot\frac{\Gamma_0^2}{\Gamma}$ quantity where Γ_0 is the partial decay width to the ground state, Γ is the

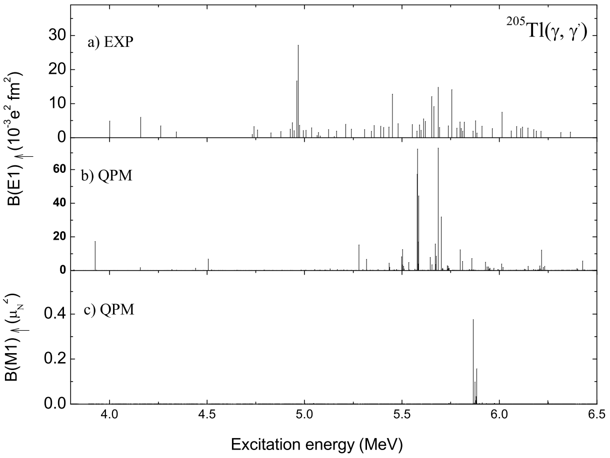

Figure 2. Extracted experimental (a) and QPM calculated electric (b) and magnetic (c) dipole strengths distributions.

total decay width and g is a spin factor. Knowing the branching transitions, the reduced transition probabilities are directly deduced. However, due to the detection limit most of the weak branching transitions are undetectable and only a lower limit of the dipole strengths can be obtained. In our case of odd- nucleus, the angular distributions of the ground-state transitions are nearly isotropic. As a consequence, it was not possible to deduce the multipolarity and therefore we assume an electric dipole character for the corresponding transitions (Fig. 2a).

3 Quasiparticle-phonon model calculations

The ground and excited states of ^{205}Tl have been described by the wave function

$$\Psi_\nu(jm) = C_j^\nu \left\{ \alpha^\dagger_{jm} + \sum_{\lambda i j'} D_{j'}^{\lambda i}(j\nu)[\alpha^\dagger_{j'} Q^\dagger_{\lambda i}]_{jm} + \right.$$

$$\left. \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2 \\ \lambda j'}} F_{j'\lambda}^{\lambda_1 i_1 \lambda_2 i_2}(J\nu)[\alpha^\dagger_{j'}[Q^\dagger_{\lambda_1 i_1} Q^\dagger_{\lambda_2 i_2}]_\lambda]_{jm} \right\} \Psi_{g.s.}^{^{204}\mathrm{Hg}} \qquad (1)$$

where $\alpha^\dagger_j$ is an operator which creates quasi-particle (qp) on a mean field level $j = |nlj\rangle$ and $Q^\dagger_{\lambda i}$ describes phonon (ph) excitation of the core nucleus ^{204}Hg with multipolarity λ and QRPA root number i. Diagonalization of the QPM Hamiltonian on the set of wave functions (1) yields the spectrum of states for each particular j^π and coefficients C, D, and F for all of these states. We refer for details to review article [7].

In the present calculations, we have used natural parity phonons with multipolarity λ^π from 1^- to 7^- and unnatural parity 1^+ phonons. The density of configurations in ^{205}Tl is very high and to make calculations possible we have had to truncate complex $qp \otimes ph$, $qp \otimes 2ph$ configurations at 6.5 and 7.5 MeV, respectively.

4 Comparison to (γ, γ') measurements

The ground state of ^{205}Tl is $1/2^+$. In the calculations, this state is an almost pure (97%) quasiparticle state $3s_{1/2}$. We have calculated E1 transitions to the states with $j^\pi = 1/2^-$ and $3/2^-$ and M1 transitions to the states with $j^\pi = 1/2^+$ and $3/2^+$. The results are presented in Fig. 2b and c, respectively.

Although the number of components of the wave function (1) is of the order of a few thousand for each j^π, only a few of them carry noticeable dipole excitation strength. They are qp components corresponding to the valence transition $\alpha^\dagger_{3s_{1/2}} \to \alpha^\dagger_{j^\pi}$ and $qp \otimes 1ph$ components of the type $[\alpha^\dagger_{3s_{1/2}} \otimes Q^\dagger_{1^{-(+)}i}]_{j^\pi}$ which correspond to the dipole excitation of the core when the unpaired quasiparticle plays the role of a spectator. The other components of (1) provide fragmentation of the strength carried by the above-mentioned components, via interaction with them.

The main part of the E1 strength in Fig. 2b is due to the fragmentation of the strength of the $[\alpha^\dagger_{3s_{1/2}} \otimes Q^\dagger_{1^-1}]_{1/2^-(3/2^-)}$ configurations. The lowest 1^-_1 phonon in ^{204}Hg has excitation energy 5.5 MeV and B(E1) = 0.46 e^{2}fm^2. This state corresponds to the very strong 1^- ground state transition in ^{208}Pb at the same energy. Other 1^- phonons in ^{204}Hg have either very small B(E1) values or are located above 7 MeV without noticeable contribution for ^{205}Tl below 6.5 MeV. The role of the valence E1-transitions are also of marginal importance because of high energies of the $3p_{3/2}$ and $3p_{1/2}$ qp-levels.

The M1 strength in Fig. 2c is caused by almost non-fragmented $[\alpha^\dagger_{3s_{1/2}} \otimes Q^\dagger_{1^+4}]_{1/2^+(3/2^+)}$ configurations. The fourth 1^+ phonon in ^{204}Hg at 5.82 MeV corresponds to the well-known isoscalar 1^+ state in ^{208}Pb at 5.85 MeV. The other 1^+ phonons in ^{204}Hg at lower energies have much smaller B(M1) values.

We conclude from our analysis that the dipole transitions observed experimentally are mainly of E1 character. The main transitions are of $3s_{1/2} \to 3s_{1/2} \otimes 1^-_i$ nature. The fragmentation of the strength distribution is underestimated in calculation as compared to data. This is not surprising because $qp \otimes 3ph$ configurations are omitted in the wave function (1) due to a very high density of them. But in general, we may speak about a good qualitative agreement between the results of calculations and data.

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