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


1Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
2ExtreMe Matter Institute EMMI and Research Division, GSI, 64291 Darmstadt, Germany
3Frankfurt Institute FIAS, 60438 Frankfurt am Main, Germany
4Department of Physics, North Carolina State University Raleigh, North Carolina 27695, USA
5Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA
6Department of Physics, Duke University, Durham, North Carolina 27708, USA
7Institut für Angewandte Physik, Goethe Universität Frankfurt am Main 60438 Frankfurt am Main, Germany

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 $Z=81$ $^{205}$TI nucleus. In this work, we report on the analysis of the results within the QPM model.

2 $(\gamma, \gamma')$ measurements

The dipole response of $^{205}$TI 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 $^{205}$TI (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 $\gamma$-ray detectors positioned around the target at 90°, 95° and 130° with respect to the incident beam.

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

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

$$\Psi_{\lambda}(jm) = C_{\lambda} \left( \sum_{j'q} D_{j'}^{j}(jv) [\alpha_{j'}O_{j'i}^{\lambda}]_{jm} + \sum_{s_{1}^{j^*(1)} s_{2}^{j}(1)} F_{s_{1}^{j^*(1)} s_{2}^{j}(1)}(jv) [\alpha_{s_{1}^{j^*(1)} s_{2}^{j}(1)}O_{s_{1}^{j^*(1)} s_{2}^{j}(1)}}^{\lambda}]_{jm} \right) \psi_{p.s.}^{\gamma,\gamma'}$$

(1)

where $\alpha_{j'}$ is an operator which creates quasi-particle ($qp$) on a mean field level $j = \{nlj\}$ and $O_{j'i}^{\lambda}$ describes phonon ($ph$) excitation of the core nucleus $^{204}$Hg with multipolarity $\lambda$ 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 $j'$ and coefficients $C_{\lambda}$, $D_{j'}$, 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 $\lambda'$ 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 ($\gamma, \gamma'$) measurements

The ground state of $^{205}$Tl is 1$^{+}$. In the calculations, this state is an almost pure (97%) quasiparticle state $3s_{1/2}$. We have calculated E1 transitions to the states with $j' = 1/2^-$ and 3$^2$ and M1 transitions to the states with $j' = 1/2^+$ 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 $j'$, only a few of them carry noticeable dipole excitation strength. They are $qp$ components corresponding to the valence transition $\alpha_{3s_{1/2}}^{\dagger} \rightarrow \alpha_{j}^{\dagger}$ and $qp \otimes 1ph$ components of the type $[\alpha_{3s_{1/2}}^{\dagger} \otimes Q_{j^*(1)}^{\lambda}]_{j'}$ 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 $[\alpha_{3s_{1/2}}^{\dagger} \otimes Q_{j^*(1)}^{\lambda}]$ configurations. The lowest 1$^{-}$ phonon in $^{204}$Hg has excitation energy 5.5 MeV and $B(E1) = 0.46 e^2f m^2$. 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 3$^{-}_{p(1/2)}$ and 3$^{-}_{p(1/2)}$ $qp$-levels.

The M1 strength in Fig. 2c is caused by almost non-fragmented $[\alpha_{3s_{1/2}}^{\dagger} \otimes Q_{j^*(1)}^{\lambda}]$ 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 $3s_{1/2} \rightarrow 3s_{1/2} \otimes 1_{1}^{-}$ 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.

*This work has been supported by the Deutsche Forschungsgemeinschaft under grant No. SFB 634.

References