Investigation of the mixed-symmetric one-quadrupole phonon $2^+_{1,ms}$ state of the heavy nucleus ^{204}Hg

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Abstract. Low-energy quadrupole-collective excitations of isovector character, the so-called states with proton-neutron mixed-symmetric character (MSS), have been investigated in ^{204}Hg which is the sole stable nucleus in the straight vicinity of ^{208}Pb exhibiting a $2\pi - 2\nu$ structure. A $^{12}\mathrm{C}(^{204}\mathrm{Hg},^{204}\mathrm{Hg}^*)^{12}\mathrm{C}$ projectile Coulomb-excitation experiment at 890 MeV was performed at Argonne National Laboratory using the ATLAS accelerator. γ-rays originating from the decay of the excited states of ^{204}Hg were detected using the GAMMASPHERE spectrometer. The measured Coulomb-excitation yields provide the $B(M1)$ and the $B(E2)$ strength distributions which unambiguously reveal the 2^+_3 state at 1948 keV as the one-phonon MSS of ^{204}Hg.

1. Introduction

The appearance of collectivity from basic nuclear properties is of interest in contemporary nuclear structure research. Atomic nuclei can be considered as mesoscopic two-fluid quantum systems, which physics is determined notably by the many-body aspect, the quantum nature as well as the two-fluid character. Nuclear phenomena emerging from these properties are collectivity, shell structure and isospin. The Interacting Boson Model-2 [1, 2] formalizes this picture and predicts the appearance of two fundamental one-phonon quadrupole excitations in nuclei. Both are mixtures of the underlying proton and neutron quadrupole excitations. In weakly collective nuclei the in-phase combination of proton and neutron contributions form the so-called fully-symmetric state (FSS), whereas the anti-symmetric combination is known as mixed-symmetric state (MSS) [1, 3]. By their origin the MSSs are sensitive to the effective pn correlations in the valence shell. MSSs are uniquely identified experimentally [4, 5, 6, 7, 8] by their strong isovector $M1$ decay to the low-lying FSS. This is of importance because $M1$ transitions are forbidden between FSSs and thus are a suitable observable for unambiguous identification of MSSs. The fundamental MSS in weakly collective vibrational nuclei is the one-phonon $2^+_{1,ms}$ state [3]. The best examples of such MSSs in stable nuclei are found in the mass $A \approx 90$ region [5, 9, 10]. Recently a large number of quadrupole MSSs have been identified in the mass $A \approx 130$ region [11, 12, 13, 14, 15, 16].

Recently new experimental evidence for the formation mechanism of fully-symmetric and mixed-symmetric low-lying quadrupole-collective states was found [17]. This mechanism involves

coupling of the lowest 2-quasiparticle proton and neutron excitations to the Giant Quadrupole Resonance (GQR) [17]. The $E2$ strength in the decay of FS and MS states is dominated by the GQR contributions while the $M1$ properties are determined by the valence-shell configuration. Due to normalization of the wave function this concept demands that with increasing collectivity the GQR contribution also increases, resulting in a decrease of the $M1$ strength. Thus the strongest $M1$ transitions should occur in weakly collective vibrational nuclei, which are only two proton and two neutron holes away from doubly-magic nuclei. To improve the understanding of the formation of low-lying isovector excitations cases of MSSs in the vicinity of doubly-magic nuclei have to be identified. However, the number of such nuclei which can be studied by conventional experimental methods is low. The sole stable nucleus exhibiting two proton and two neutron holes in the region around ^{208}Pb is ^{204}Hg. Preliminary results of the search for a MSS in this nucleus are presented in this contribution.

2. Experiment

An experiment was performed at Argonne National Laboratory. A pulsed (12 MHz) ^{204}Hg beam accelerated to 890 MeV was delivered by the ATLAS accelerator facility. The beam was impinging on a 1mg/cm^2 ^{nat}C target. Deexcitation γ-rays, following the projectile Coulomb-excitation reaction, were detected using the GAMMASPHERE detector array [18], consisting of 100 HPGe detectors arranged in 16 rings, at the time of the measurement. The average beam intensity was ≈ 1.3 pnA. GAMMASPHERE was used in singles mode, as no particle detector was present in the experiment. γ-ray counting rate during the experiment was $\approx 7 \times 10^3$ counts-per-second. A total of 4.4×10^8 events of γ-ray fold 1 or higher have been collected during 13 h of beam time. The excited ^{204}Hg nuclei were recoiling with $v/c \approx 8.4\%$ which was accounted for by Doppler correction of the obtained γ-ray spectra. The contribution of the room background
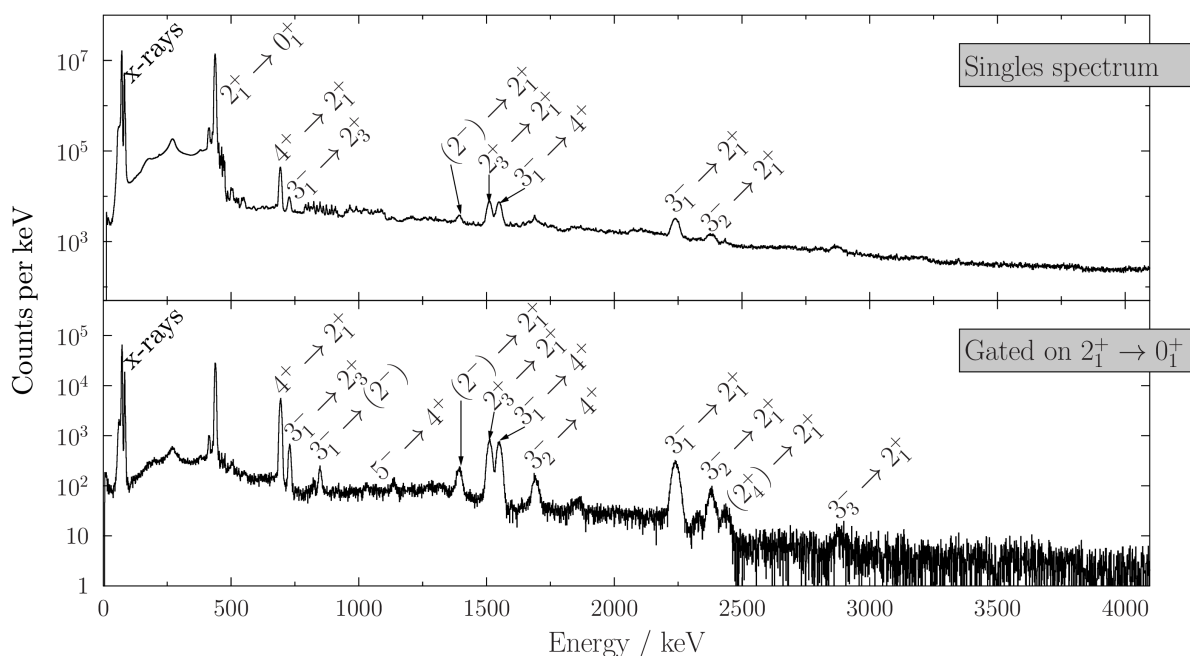
Figure 1. Doppler-corrected, background subtracted γ-ray spectra after projectile Coulomb excitation on a Carbon target. In the upper panel the singles spectrum is shown. In the lower panel a projection of the γ-γ-matrix, gated on the $2_1^+ \rightarrow 0_1^+$ transition is shown.
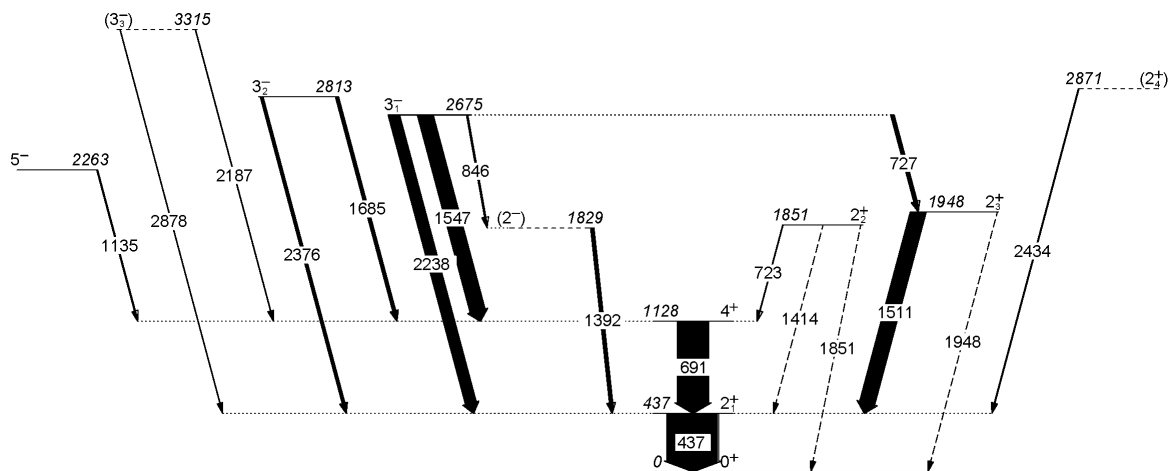
Figure 2. Deduced level scheme of ^{204}Hg. Solid lines indicate transitions observed in this experiment while dashed lines show transitions which were not observed but which intensities can be determined from beforehand known branching ratios.

was eliminated by correlating the detected γ-rays to the ATLAS radio-frequency pulses. The final spectrum is shown in the top panel of Fig. 1.

3. Data Analysis and Results

Events featuring a γ-ray fold ≥ 2 were used to construct a γ-γ-coincidence matrix. A showcase excerpt from this matrix for all γ-rays coincident to the $2_1^+ \rightarrow 0_1^+$ transition is shown in the lower panel of Fig. 1. The combined examination of the singles spectrum as well as of the coincidence matrix results in a total of 10 states decaying via emitting γ radiation observed in this experiment. Fig. 2 presents the resulting level scheme, which is in agreement with previously reported data on ^{204}Hg [19].

All prominent γ-ray transitions originate from decays of excited states of ^{204}Hg. Most of these transitions have been observed before, besides the 727-keV transition which connects the 3_1^- and the 2_3^+ state and the transition depopulating a new state at 2871 keV. Because of the dominance of $E2$ excitations in low-energy Coulomb-excitation reactions we have assumed (2^+) for the spin and the parity of this state.

Efficiency-corrected transition intensities were deduced from the singles spectrum wherever possible. The intensities of weak transitions were derived using the γ-γ-matrix. The intensities were afterwards used to determine the yield of the states excited in this experiment. Because of the quasi-4π nature of the GAMMASPHERE array these excitation yields are proportional to the Coulomb-excitation cross-section. In the analysis, excited states population yields are compared to cross-sections calculated from Coulomb-excitation theory [20]. Additional information is obtained from analyzing the angular distributions of the $2_3^+ \rightarrow 2_1^+$ and $3_1^- \rightarrow 4^+$ transitions. The latter transition exhibits the expected dipole character while the other one is characterized by a superposition of dipole and quadrupole character. For the $2_3^+ \rightarrow 2_1^+$ transition the angular distribution in combination with the orientation tensor from Coulomb-excitation theory [20] calculated using GOSIA [21] results in a preliminary multipole mixing ratio $\delta = 0.40\,(26)$ hinting at $M1$ dominance.

At this stage of the analysis only a minor subset of states consisting of the 0_1^+, 2_1^+, 2_3^+, and 3_1^- states was taken into account for the Coulomb-excitation calculations. The relative yields of the 2_3^+ and 3_1^- states have been fitted to the theory [20] using the multiple CE code CLX [22]
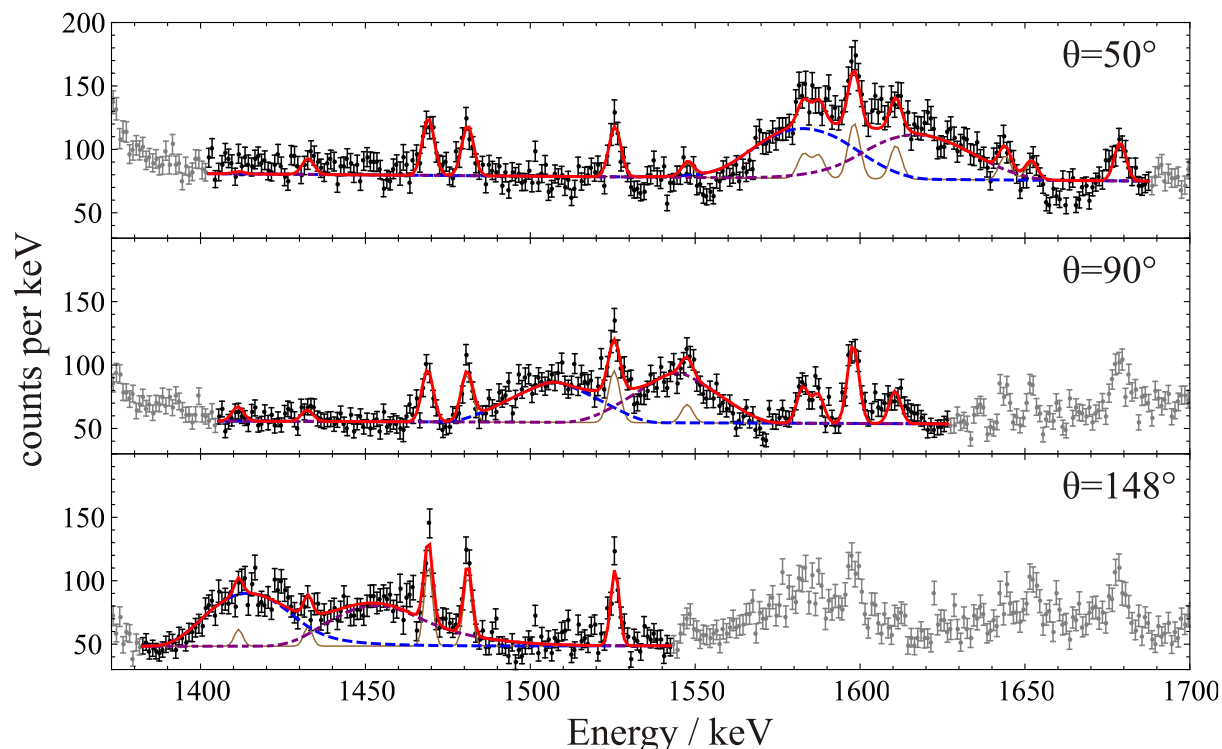
Figure 3. Example of lineshape fits in the DSAM analysis of the 1511- and 1547-keV transitions. The thick solid line shows the total fit to the spectrum, the dashed lines show the 1511-keV decay of the 2_3^+ state (blue) and the 1547-keV decay of the 3_1^- state (purple), thin solid lines show contaminants taken into account for the fit. The unshifted parts of both decays are not present under forward (top panel) and backward angles (bottom panel), indicating short lifetimes, compared to the slowing-down of the nucleus of interest in the target.

taking into account the energy loss of the beam in the target of $\approx 124\,\mathrm{MeV}$. The scale for the calculation is set by the ground-state decay $E2$ strength $B(E2; 2_1^+ \to 0_1^+) = 11.96\,(9)\,\mathrm{W.u.}$ [19]. Preliminary results from this calculation indicate an $M1$ strength for the $2_3^+ \to 2_1^+$ transition of $\sim 0.6\,\mu_\mathrm{n}{}^2$. This large $B(M1; 2_3^+ \to 2_1^+)$ value implies that the 2_3^+ state is a single isolated one-phonon MSS.

In the same experimental campaign the ^{204}Hg beam was impinging on a thick Al target for a caDSAM measurement [23]. Data was taken for about $\approx 3\,\mathrm{h}$. The preliminary analysis of this experiment yields a lifetime of the 2_3^+ state in the order of $100\,\mathrm{fs}$ in agreement with the results from the Coulomb-excitation analysis. In Fig. 3 an example of lineshape fits for the 1511- and 1547-keV transitions is presented.

4. Summary
A Coulomb-excitation experiments have been performed on the nucleus ^{204}Hg. The preliminary results from the investigations indicate the existence of a one-phonon MSS in this nucleus. This is among the first experimentally identified MSSs in the vicinity of the doubly-magic nucleus ^{208}Pb and calls for theoretical explanations about the origin of isovector states in the mass $A \approx 208$ region.

Acknowledgments

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