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Evolution of the structure of the 4_1^+ states in Po isotopes

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Abstract. The lifetime of the 4_1^+ state in ^{208}Po has been measured using $\gamma - \gamma$ fast-timing technique with $LaBr_3$(Ce) Detectors. The experiment was performed at the FN Tandem facility at the University of Cologne. The preliminary results are discussed in the scope of the systematic behavior of the transition strengths between yrast states in polonium isotopes.

1. Introduction

The nuclear shell-model represents the most fundamental concept in nuclear structure physics. The shell model, in combination with pairing correlations, provides an easy way for understanding low-energy spectra of semi-magic nuclei. In fact, the generalized seniority scheme [1] represents a truncation of the shell-model and is manifested by some very clear experimental signatures for the yrast states of even-even nuclei, close to magic number. The excited yrast states follow an energy pattern that is equivalent to the one for j^2 configuration in which the energy spacing between the states decreases towards the state with maximum angular momentum. The $E2$ transition strength of seniority changing transitions, such as the $2_1^+ \to 0_1^+$ transition, increases in a parabolic way with increasing the number of valence particles and reaches a maximum at the middle of the j-shell. For the other transitions of the yrast sequence, which are seniority-preserving transitions, we observe the opposite behavior : the B($E2$) values follow a parabolic behavior with a minimum at the middle of the j-shell [2].

In a recent study [3], an increased strength for the seniority-changing $2_1^+ \to 0_1^+$ transition in ^{206}Po has been reported, leading to the conclusion that the 2_1^+ state of ^{206}Po has a predominantly collective character. However, it has to be noted, that both the energy level pattern of the lower yrast states of ^{206}Po and the hindered transition probability of the $8_1^+ \to 6_1^+$ transition indicate that seniority-type structure is preserved to a certain extent.

In this paper, we focus on Po isotopes, which are in the vicinity of the double-magic nucleus ^{208}Pb. For those nuclei,it is already known that the 8_1^+ states are isomers with wave functions dominated by the $\pi(h_{9/2})^2$ orbital, thus suggesting a typical single particle (seniority-like) energy pattern for the yrast states. We can expect that collective behavior would appear by adding also valence neutrons. It is still not clear when and how this would happen. We started our investigation from ^{212}Po, where we had observed an extremely low collectivity. It was shown that the latter originated from the low B($E2$) value of the 2_1^+ state in ^{210}Po [4]. To investigate further the evolution of the structure in lighter Po isotopes, we have measured the lifetime of the 4_1^+ in ^{208}Po, thus to show the transition between single-particle and collective excitations.

2. Experiments

The experiment was performed at the FN-Tandem facility of the university of Cologne. The excited states of ^{208}Po were populated using the ^{204}Pb(^{12}C,^{8}Be)^{208}Po transfer reaction at a beam energy of 62 MeV. The beam energy was chosen to be about 2 MeV below the Coulomb barrier. The target was a self-supporting 23 mg/cm^2 thick Pb foil. The reaction took place in the reaction chamber of the Cologne plunger device [5] in which an array of solar cells was mounted at backward angles, in order to detect the recoiling light reaction fragments. The solar cell array consisted of six 10 mm x 10 mm cells placed at a distance of about 15 mm between their centers and the target, and covered an annual space between 116.7° and 167.2°. In order only α-particles from ^{8}Be to be detected, we have installed 80 μm Al foil in front of the solar cells. The γ rays from the decay of the excited states were registered, without trigger condition, by 11 HPGe detectors and 7 $LaBr_3$(Ce) scintillators at 90° (hereafter called LaBr), each with dimensions ø1.5 × 1.5 in. Time-to-Amplitude Converters (TAC's) recorded the time differences between the timing signals for each unique LaBr detector-detector combination.[6] The detector energy signals and the TAC amplitudes were recorded using 80-MHz synchronized digitizers in a triggerless mode.

2.1. Lifetime measurement

For lifetime extraction, the Generalized Centroid Difference method (GCDM) was applied. The method is discussed in detail in Ref.[7] (and the references within). In this method, two independent time spectra are obtained, defined as the time difference between two signals generated by two γ rays that interconnect an excited state. If the transition that feeds the state provides the start signal to the TAC and the decay transition from this state - the stop signal, the Delayed (D) time distribution is obtained. In the reverse case, the Anti-delayed (AD) time distribution is obtained. Assuming no background contributions, the difference between the centroids of both time spectra is expressed as :

$$\Delta C(E_f, E_d) = C^D - C^{AD} = 2\tau + PRD(E_f, E_d), \tag{1}$$

where τ is the mean lifetime of the given state and E_f and E_d are the energies of the feeding and the decaying transition, respectively. PRD stands for Prompt Response Difference and describes the mean time walk characteristics of the experimental setup. The PRD is used as a single correction for the lifetime determination and one of the main tasks is to determine its energy dependence. For calibration of the PRD curve, ^{152}Eu and ^{133}Ba sources were used. Two time spectra were produced by selecting a feeder-decay combination for a state with known lifetime. Measuring the centroid difference ΔC and using Eq.(1), the PRD is obtained. The data points are fitted using the function

$$PRD(E_\gamma) = \frac{a}{\sqrt{eE_\gamma^2 + b}} + cE_\gamma + d. \tag{2}$$

The final result of the PRD-curve is presented in Figure 1. The precision of the the PRD fit

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is defined as two times the standard root-mean-squared deviation (2σ), corresponding, in this case, to 17 ps.

2.2. ^{208}Po

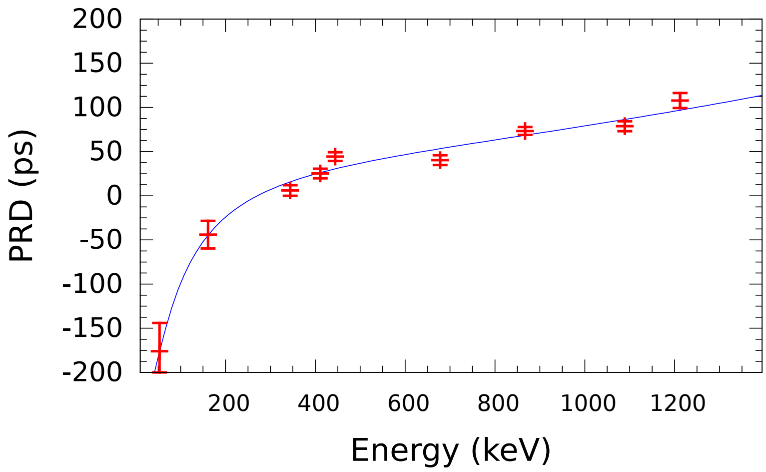

Figure 1. The PRD, measured with a ^{152}Eu and ^{133}Ba sources.

In the offline analysis, triple Solar-LaBr-LaBr coincidences were constructed. Here, instead the signal from the Ge detectors - as it is described in Ref.[8], the signal from the Solar cells was used to clean the spectrum and to select a reaction channel. By placing the first LaBr gate on the decay transition and the second on the feeding transition, the delayed and anti-delayed time distributions were obtained. Measuring the difference between the centroids of these time distributions and using Eq.(1), the lifetime can be determined. However, a correction has to be applied, related to the contribution of the time-correlated background underneath the two full energy peaks (FEP's) of the γ_{feeder} - γ_{decay} cascade. Due to this, ΔC_{exp} is corrected with this formula [9] :

$$\Delta C_{FEP} = \Delta C_{exp} + \frac{1}{2}\left(\frac{\Delta C_{exp} - \Delta C_f^{BG}}{(p/b)_f} + \frac{\Delta C_{exp} - \Delta C_d^{BG}}{(p/b)_d}\right) \quad (3)$$

where ΔC_{FEP} corresponds to the corrected centroid difference, ΔC_{exp} is the experimentally determined centroid difference including the FEP events and the Compton background. ΔC_{BG} is the time response of the background and $(p/b)_{f,d}$ are the peak-to-background ratios observed in the gated spectrum, shown in Fig.2. The subscript "feeder"(f) or "decay" (d) indicates the reference energy, thus the centroid difference is defined at the energy of the decay/feeder γ ray relative to the energy of the feeding/decaying γ ray. As ΔC_{BG} cannot be measured directly, it has to be interpolated from measuring background time spectra, generated at different energies above and below the FEP. The analysis to derive the correction for background contributions is performed for each FEP separately. Using this method, the procedure of extracting the lifetime of the 4_1^+ state in ^{208}Po is presented in Fig.2 . Here, the overlaid spectra from Ge detectors are only used to visualize that we see the correct transitions. From this procedure, we determined a preliminary lifetime of $\tau(4_1^+;{}^{208}\text{Po}) = 125(35)$ ps. In our previous experiments [13], we have determined the lifetimes of the 4_1^+ states in ^{206}Po and ^{204}Po to be $\tau(4_1^+;{}^{206}\text{Po}) = 89(7)$ps - and $\tau(4_1^+;{}^{204}\text{Po}) = 23(6)$ps. The results from the current analysis and from previous experiments are summarized in Table 1.

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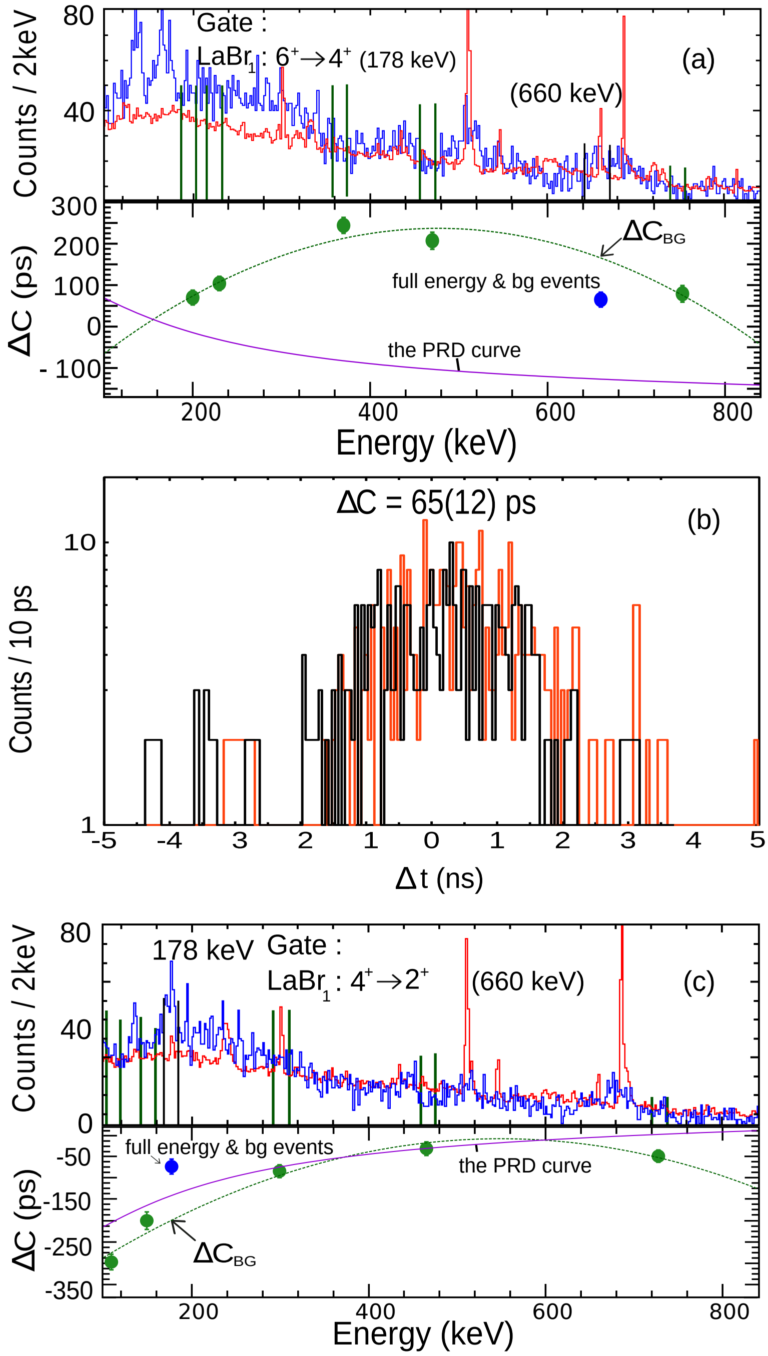

Figure 2. (Color online) The procedure of extracting the lifetime of the 4_1^+ state in ^{208}Po. (a) Double-gated spectra from LaBr (blue) detectors and HPGe detectors (red) produced from triple coincidence data by imposing the indicated coincidence conditions (gates). Here, the gate on the first LaBr detector is set on the transition feeding the level of interest. The black lines indicate the gate, which was used to produce the time-difference spectra at the full energy peak (FEP) of the decay transition. The vertical green lines indicate the gates used to extract the time response of the background. The panel below presents the fitted time response of the background (dashed green line) with marked interpolated time response of the background; Together with the PRD curve (magenta line) and the obtained centroid difference (the blue circle). (b) Time-difference spectra for the 178- and 660-keV feeder-decay combination. (c) Same as (a) but the gate on the LaBr detectors is set on the decay transition.

Table 1. Lifetimes determined from the fast-timing experiments on Po isotopes and energies of the corresponding gates to obtain time-difference spectra as well as reduced transition probabilities of yrast states in those nuclei, calculated from the measured lifetimes.

Nucleus	State	E_f [keV]	E_d [keV]	α^1	τ [ps]	B(E2) [W.u.]
^{204}Po	4_1^+	426	516	0.0297	$23(6)^2$	13.0(34)
^{206}Po	4_1^+	395	477	0.0359	$89(7)^2$	4.97(40)
^{208}Po	4_1^+	178	660	0.0173	$125(35)^3$	0.7(2)

[1] From Ref. [10].
[2] From Ref. [13]
[3] From the present experiment

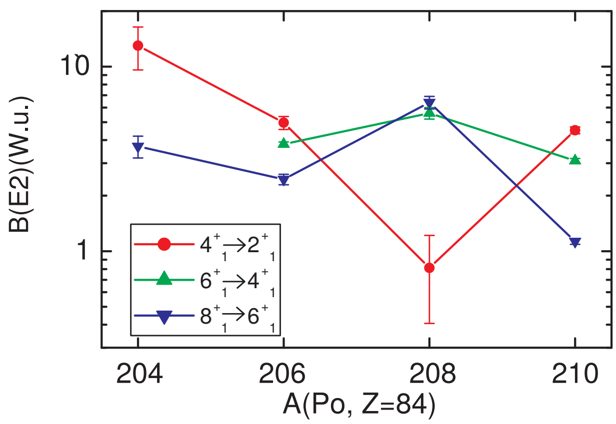

Figure 3. (Color online) The experimental $B(E2)$ values for the seniority preserving transitions for the polonium isotopes. The result for the $4_1^+ \to 2_1^+$ transitions in ^{208}Po is obtained in the present work. The results for ^{210}Po and the results for the 8_1^+ and 6_1^+ states in ^{208}Po are taken from Ref.[11]. The result for the 6_1^+ state in ^{206}Po is taken from Ref.[12]. The results for the 4^+ states in ^{206}Po and ^{204}Po are taken from Ref.[13].

On Fig.3 the experimental $B(E2)$ values for the seniority preserving transitions are plotted for the polonium nuclei as a function of the mass number A. It can be seen that the evolution of the $E2$ strengths for the $8_1^+ \to 6_1^+$ transition follows the one for the of $6_1^+ \to 4_1^+$ transition. This indicates that both 8_1^+ and 6_1^+ states have seniority character. At the same time, the behavior of the $B(E2); 4_1^+ \to 2_1^+$ is somehow opposite, indicating collective character. All together, this strongly suggests that the transition from seniority regime to collective mode has a spin dependence. However, theoretical calculations are needed to validate and understand the underlying structure for this observation.

3. Conclusion

The lifetime of the 4_1^+ state in ^{208}Po have been measured via the γ-γ fast-timing technique. The level of interest has been populated by the ^{204}Pb(^{12}C,^{8}Be)^{208}Po transfer reaction. The γ spectra were purified by a coincidence condition requiring observation of a charged particle in an array of solar cells. The evolution of the $B(E2)$ strengths for the $4_1^+ \rightarrow 2_1^+$ transitions of the polonium isotopes from $A = 204$ to $A = 210$ indicates that the transition from single-particle to collective mode occurs in this mass region.

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