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Spectroscopy of ^{194}Po

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Abstract

Prompt, in-beam γ rays following the reaction ^{170}Yb + 142 MeV ^{28}Si were measured at the ATLAS facility using 10 Compton-suppressed Ge detectors and the Fragment Mass Analyzer. Transitions in ^{194}Po were identified and placed using γ-ray singles and coincidence data gated on the mass of the evaporation residues. A level spectrum up to J≈10$\hbar$ was established. The structure of ^{194}Po is more collective than that observed in the heavier polonium isotopes and indicates that the structure has started to evolve towards the more collective nature expected for deformed nuclei.

27.80.+w, 23.20.Lv, 21.60.Ev, 25.70.-z

The onset of collective motion in nuclei near shell closures and the mechanism by which this collectivity evolves towards deformation continue to be open questions in nuclear physics. While nuclei with valence particles of only one type, such as Sn (Z=50) or Pb (Z=82) isotopes, are not expected to become deformed in their ground states, we now recognize that the structure of these nuclei as a function of excitation energy and angular momentum can be associated with a wide variety of shapes. At moderate temperatures two-particle, two-hole (2p-2h) proton excitations [1] across the shell gap give rise to rotational structures in these nuclei. At moderate angular momenta, superdeformed shapes[2] have been identified in Pb isotopes. In nuclei with two valence proton holes, such as the Cd and Hg isotopes, a similar coexistence between spherical vibrations, 4h-2p deformed bands, [1] and superdeformed rotational bands (in Hg) [2] are observed. In contrast there is less evidence [3] for the corresponding 4p-2h excitations in Te isotopes, and relatively little is known about the collective motion in the Po isotopes with two valence protons. [4]

Recently we reported on the first in-beam measurements in the N=112 ^{196}Po isotope [5]. Delayed γ-rays in ^{196}Po had been initially studied by Alber, et al. [6], who made spin and parity assignments based only on systematical behavior. In ref. [5] we discussed ^{196}Po as a good example of a harmonic vibrator. The evidence includes evenly-spaced energy levels up to the 8^+ state, nearly degenerate members of the 2- and 3-phonon multiplets, and branching ratios for the deexcitation of non-yrast levels which are consistent with a simple vibrational picture. However, the energy ratio R(4/2) = E(4^+)/E(2^+) is 1.92 in ^{196}Po, and is essentially constant for several isotopes. Since R(4/2) is expected to be 2.0 for a harmonic vibrator, the N>112 Po isotopes are only weakly collective. The present work was proposed to investigate any possible change in shape in the lighter Po isotopes. By extending the systematics to a more neutron-deficient isotope, we also hoped to confirm the vibrational character of the non-yrast excitations in ^{196,198}Po.

The formation and subsequent study of the spectroscopy of such a neutron-deficient, heavy nucleus is very difficult. The statistical evaporation code PACE [7] predicts that the most favorable reaction, ^{28}Si + ^{170}Yb, at $\approx$ 142 MeV yields only a $\approx$ 10 mb cross section for

^{194}Po, which competes with a 170 mb fission cross section. Furthermore, approximately 50% of the γ-ray intensity populating the low-lying states of ^{196}Po in a similar reaction [5] goes through an 850-ns 11^- isomer. If similar conditions hold in ^{194}Po, any prompt spectroscopy experiment would miss about half of the already small cross-section, as well as suffer from intense competition from fission. Any successful measurement of ^{194}Po would, therefore, require some additional selection criteria to enhance the channel of interest.

The present experiment to study ^{194}Po was carried out at the Argonne Tandem Linac Accelerator System (ATLAS) using the Fragment Mass Analyzer [8] (FMA) to mass-select the evaporation residues. A beam of 142 MeV ^{28}Si ions interacted with an enriched (70%) 500 μg/cm^2 ^{170}Yb target. Prompt γ rays were recorded using an array of 10 Compton-suppressed Ge detectors located at the target position. The recoiling evaporation residues were analyzed by the FMA, a triple-focusing mass separator which disperses recoils by their mass/charge ratio. A position-sensitive parallel-plate avalanche counter (PPAC) located at the FMA focal plane was used to determine the position and flight time of the recoils. A large area silicon detector behind the PPAC provided further energy information on the recoil products. The FMA was tuned so that both 14^+ and 15^+ charge states of A=194 recoils could be detected at the focal plane. Single γ-ray events were recorded to tape only when they occurred in coincidence with a signal in the PPAC. The energy and time information of the Ge detectors were recorded to tape, together with the position (x_{PPAC}), energy, and time-of-flight information measured at the focal plane. All double and higher fold γ-ray events were also written to tape, without the requirement of a coincidence with a residue. In total 71 x 10^6 γ-ray events were recorded, of which only about 1% occurred in coincidence with a recoil at the PPAC.

The data were first sorted into an $x_{PPAC} - \gamma$ matrix which was used to identify γ rays from A=194 nuclei. Contamination from the scattered primary beam products was reduced by setting an additional two-dimensional gate on a recoil energy vs. time-of-flight matrix. Figure 1 shows the projection of this $x_{PPAC} - \gamma$ matrix onto the position axis. A portion of the γ-ray spectrum corresponding to the A=194 mass gate with charge states 14^+ and

15^+ is shown in Fig. 2a. When similar cuts were carried out on the other mass bins, contamination from A≠194 in the A=194 gate was found to be negligible. Discriminating between the different A=194 isobars was a more difficult task. Since the FMA resolution cannot distinguish A=194 isobars and the predicted cross sections [7] for ^{194}Po and ^{194}Bi are roughly comparable, as many as half the recoils in the A=194 bin could correspond to Bi residues. However, the strongest lines assigned to ^{194}Po are observed to be in coincidence with Po x-rays. We observe only one line, at 632 keV, strong enough to be clearly seen in coincidence with Bi x-rays and assign this transition to ^{194}Bi. That only one strong line could be assigned to ^{194}Bi is not unexpected since it is an odd-odd nucleus and the γ-ray strength is expected to be fragmented over many decay paths.

The data were then sorted into a γ-γ matrix gated on the A=194 $x_{\rm PPAC}$ mass gate. Because of the poor statistics, this matrix was only used to confirm coincidences between transitions clearly visible in the A=194 gated γ-ray spectrum. Eight transitions were identified and assigned to ^{194}Po. Five of these, the 318.6(2), 365.7(2), 461.0(3), 544.6(3), and 600.7(4) keV lines, were strong in the mass-gated γ-ray spectrum, mutually coincident in the mass-gated γ-γ matrix and were, therefore, taken to be part of the ground state quasi-band. They were ordered according to their intensity in the recoil-gated γ-ray spectrum. The sum of coincidence spectra gated on these γ rays is shown in Fig. 2b. The remaining three transitions - 340.3(3), 525.1(3), and 329.2(3) keV - were placed using the γ-γ data. No angular information could be extracted from the data due to poor statistics and, possibly, to loss of alignment following de-excitation through short-lived isomers. Therefore, spin assignments were inferred from systematics. The deduced level spectrum for ^{194}Po in Fig. 3 summarizes our results.

The (2_2^+) and (4_2^+) assignments to the non-yrast levels at 659 and 1209 keV, respectively, are based on the systematical behavior of the levels in the heavier isotopes. These states are too low in excitation to be negative-parity levels, but their energies are consistent with the positive-parity non-yrast levels seen in ^{196,198}Po. A 659-keV transition cannot be assigned from our data displayed in Fig. 2a. This is consistent with the branching ratio for the deexcitation of the (2_2^+) state in ^{196}Po, as reported in ref. [5]. Similarly, from the decay pattern in ^{196}Po [5], it would be difficult to observe a transition between the (2_2^+) and (4_2^+) states in ^{194}Po.

The level structure of ^{194}Po shows a clear difference from that of the heavier, weakly collective isotopes. First, the R(4/2) ratio is 2.15 in ^{194}Po, and the spacings of the other yrast levels are no longer the equal spacings characteristic of a harmonic vibrator. The systematics of the energy ratios are displayed in Fig. 4a, which clearly shows the R(6/4) ratio greater than expected for a harmonic vibrator. However, the essentially vibrational character of the lighter Po isotopes appears to be preserved in ^{194}Po. As in the heavier isotopes, the 2_2^+ and 4_2^+ states lie very close in energy to the 4_1^+ and 6_1^+ levels, respectively, as is expected with nearly degenerate members of the two- and three-phonon multiplets. If the non-yrast 2_2^+ and 4_2^+ states were members of a 4p-2h configuration, their excitation energies should have dropped as the middle of the neutron shell is approached and their energy separation should have decreased. Instead, this spacing has slightly increased, and the relative energy differences of these non-yrast states follow closely those of the corresponding member of the vibrational multiplet.

What is unexpected is that the evolution of the collectivity in the polonium isotopes is different from that of other isotopes with two valence protons. To illustrate this feature we have displayed in Fig. 4b the change in energy of the 2_1^+ states, normalized to the average 2^+ energy. The data for the Po isotopes with $N \leq 126$ are compared to those for the Cd and Te isotopes with $N \leq 82$ and the Hg isotopes with $N \leq 126$ and identical numbers of valence neutrons, N_n. For these Cd, Te, and Hg isotopes the change in the 2^+ energies as a function of N_n is within 10% over a wide range of isotopes away from the closed neutron shell. While the change for many of the Po isotopes is also relatively small, for the lightest isotopes, ^{194,196}Po, the change is very large: about 140 keV, with respect to the heavier isotope. If the 2^+ energy in ^{192}Po did drop another 140 keV with respect to ^{194}Po, the 2^+ energy would be close to the value at which the phase transition from anharmonic vibrator to deformed rotor occurs for a larger number of nuclei with $38 < Z < 82$ [9]. This would represent a rapid change to a more collective, possibly deformed structure of the N $<$ 110 isotopes, a change not seen in other regions of the periodic table.

In conclusion we have identified for the first time excited states in ^{194}Po. This nucleus has the character of an anharmonic vibrator, with non-yrast states following the expectations of members of phonon multiplets. However, the evolution of the shape seems to be much more rapid than is observed in other two-proton isotopes. The systematical behavior of the Po isotopes suggests that ^{192}Po could be a critical nucleus: it could either be deformed if the drop in 2^+ energies continues or the shape could stabilize at the moderate collectivity of ^{194}Po.

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FIGURES

FIG. 1. Projection of the recoil-γ matrix onto the position axis, x_{PPAC}. The mass assignments of the peaks are given.

FIG. 2. (a) Projection of the $x_{PPAC} - \gamma$ matrix onto the γ-ray energy axis. The insert displays the x-ray region of the spectrum from the γ-γ matrix gated on the A=194 mass and 632-keV line.(b) Sum of spectra gated on transitions from all yrast states (2^+, 4^+, 6^+, 8^+, 10^+) from a γ-γ matrix gated on the A=194 mass. The insert displays the x-ray region of the spectrum from the γ-γ matrix gated on the A=194 mass and 319-keV line.

FIG. 3. Deduced level scheme of ^{194}Po. Spin assignments are based on systematics.

FIG. 4. (a) R(4/2) and R(6/4) ratios for levels in Po (closed symbols) and Te (open symbols). The ratios for the harmonic vibrator are indicated. (b) The difference in 2^+ energies [ΔE= E(A) - E(A-2)] divided by the average 2^+ energy [$<E> = \{E(A) + E(A\text{-}2)\}/2$] as a function of the number of valence neutrons, N_n, for Po with $110 \leq N \leq 126$ (closed symbols) and Cd, Te with $66 \leq N \leq 82$ and Hg with $104 \leq N \leq 126$ (open symbols) nuclei. Data are taken from Refs. [4–6] and the present work.