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THE ONSET OF COLLECTIVITY IN ^{196}Po

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Abstract

We have studied the in-beam γ-ray spectroscopy of ^{196}Po, which is the first Po isotope to exhibit collective vibrational structure. The onset of collective motion occurs in this isotope because of the large overlap between valence protons in $h_{9/2}$ and valence neutrons in $i_{13/2}$ orbitals.

1. Introduction

The polonium isotopes with two valence protons provide an excellent laboratory in which to study the transition between single particle and collective behavior in a nuclear system. Polonium isotopes with N ≈ 126 have structure characteristic of shell-model behavior with yrast energy spacings of a two-particle j^2 configuration. As the number of neutrons is decreased, the large number of valence particles makes a shell-model description of the low-lying structure difficult and the onset of collective structure is expected.

2. Experiment

We used the ^{172}Yb(^{28}Si,4n) reaction to study ^{196}Po at the ATLAS facility with beam energies of 141 and 145 MeV. The Argonne-Notre Dame BGO γ-ray facility which consists of 12 Compton suppressed Ge detectors and a 50-element inner BGO ball was used. Approximately 35 million γ–γ events with an inner ball multiplicity K≥3, as well as all higher fold Ge data, were recorded to tape. The data were sorted off-line into a series of matrices, of which the one with K≥5 was used for the majority of the analysis. Angular momentum assignments were determined through the use of DCO ratios. Earlier work[1] by Alber, et al., studied the delayed γ rays depopulating the 850 ns 11⁻ isomer in ^{196}Po. As summarized in Fig.1, we have extended this earlier level scheme with our prompt spectroscopy measurements and have determined spins and probable parities of the levels.

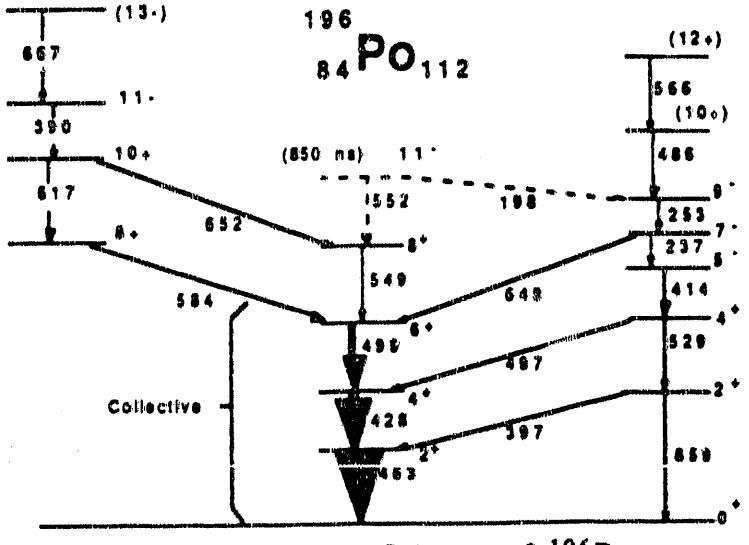

Figure 1: Level Scheme of ^{196}Po

The study of neutron deficient Po nuclei via (HI,xn) reactions is greatly hampered by competition with fission and multi-particle transfer reactions. As the number of neutrons is decreased Coulomb-enhanced fission becomes the prefered channel, especially at high angular momenta. However, through the use of the higher multiplicity cut on the BGO calorimeter, we were able to filter out most of the fission as well as some of the Coulomb excitation and transfer channels. The low-lying transitions in ^{196}Po are the strongest γ-ray lines in the spectrum, after appropriate filtering, near $E_\gamma \approx 400$- 500 keV.

3. Energy Systematics

The structure of Po nuclei can be expected to be similar to that of Te nuclei, which also have two valence protons. Earlier work[2,3] by Lee, et al., and Henry on Te isotopes showed that as the neutron number decreased from singly magic ^{134}Te to ^{118}Te the structure became collective vibrational. The absolute B(E2; $2^+ \rightarrow 0^+$) values are exceptionally well-reproduced by the expectations of the vibrational limit of the interacting boson approximation (IBA) model. Also, relative B(E2) values are in better agreement with vibrational than rotational predictions.

In Fig. 2a we display a simple qualitative indicator[4] of the transition between shell-model and collective structure in Te isotopes. The ratio, R(6/4), of the energies of the yrast 6^+ to 4^+ states are plotted as a function of the R(4/2) ratio of the energies of the yrast 4^+ to 2^+ states. Such a plot can be divided into four regions. The portion of the plot with R(4/2) $\geq$ 2.0 and R(6/4) $\geq$ 1.5 can be labeled as collective, with the lower limits the expectations for a simple harmonic vibrator. The quadrant with R(4/2) < 2.0 and R(6/4) < 1.5 is indicative of shell-model structures. The remaining two quadrants are "forbidden" in the sense that although one of the two energy ratios is characteristic of collectivity, the other is associated with single-particle behavior.

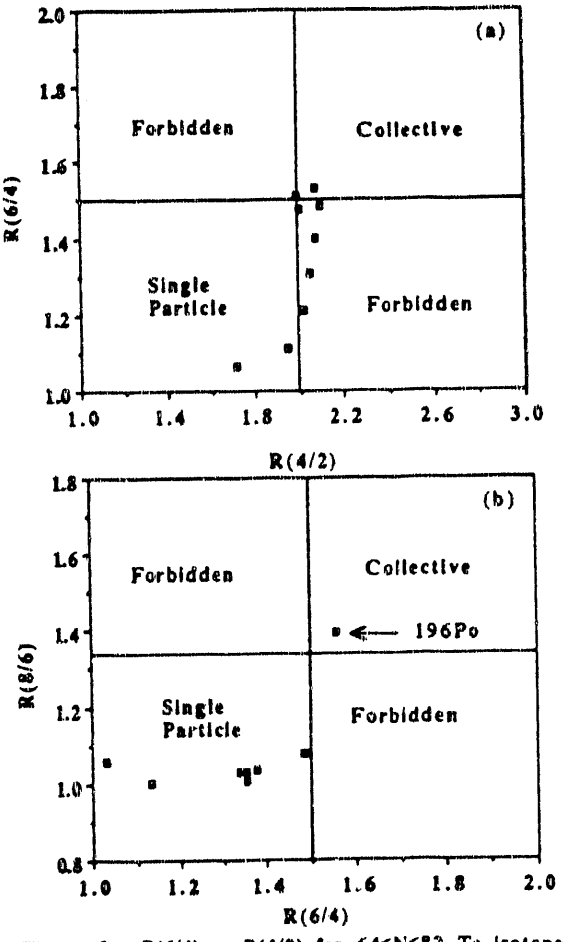

Figure 2a: R(6/4) vs R(4/2) for 64≤N≤82 Te Isotopes
Figure 2b: R(8/6) vs R(6/4) for N≤126 Po Isotopes
Data taken from ref. 1,3,5 and present work.

The ratios of various yrast energies can be used to determine the collective versus single-particle behavior. However, one needs to be judicious in the choice of the ratios plotted. Te nuclei have their valence protons in the $g_{7/2}$ orbital; therefore, the maximum angular momentum of two $g_{7/2}$ protons is 6. In Po the valence protons are in the $h_{9/2}$ orbital, with a maximum angular momentum of 8. To show the comparison between Te and Po more clearly we have plotted in Figure 2b the R(8/6) vs R(6/4) ratios, where again the solid lines demarcate the boundaries between collective (R(8/6) $\geq$ 1.33) and non-collective structures. Although the Te nuclei show a gradual tracking from the single-particle to the collective regimes, the behavior of the Po nuclei is radically different. The Po R(8/6) ratio stays tenaciously in the shell-model region from 0 to 12 valence neutrons (corresponding to ^{210}Po to ^{198}Po) and does not enter the collective area until it has 14 valence neutrons. However, ^{196}Po is clearly inside of the collective region of the plot.

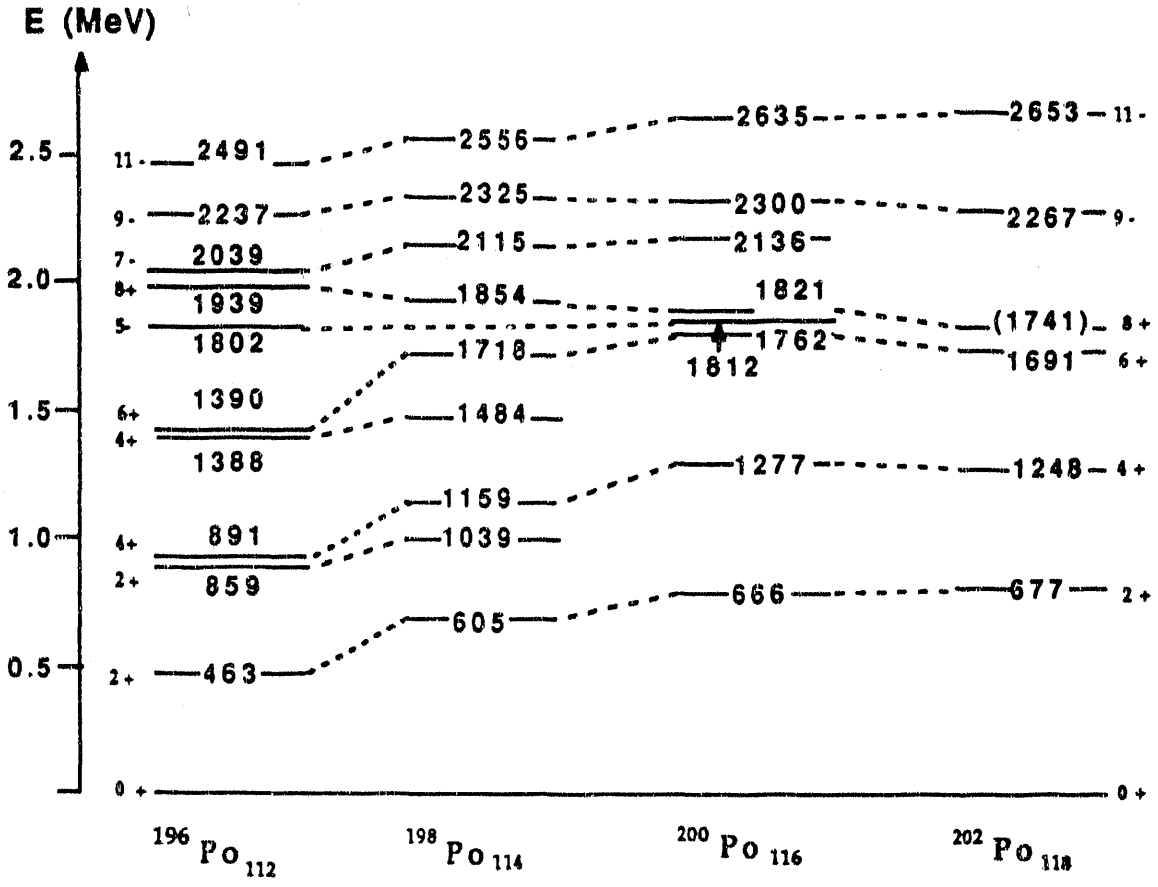

Figure 3: Even-A Polonium Systematics
Data taken from ref. 1,5 and present work

Figure 3 shows the systematics of the light Po nuclei. It is evident that as we go from ^{198}Po to ^{196}Po the energies of the yrast 2^+, 4^+ and 6^+ states decrease, whereas the energy of the yrast 8^+ state rises. It is this combination of energy spacings that signals the onset of vibrational structure in ^{196}Po. In addition, the 2_2^+ and 4_2^+ levels are now nearly degenerate with the yrast 4^+ and 6^+ states, respectively, as would be expected if these non-yrast states are members of multi-phonon multiplets.

If the low-lying structure in ^{196}Po is vibrational, then the selection rule, $\Delta N_{ph} = \pm 1$, for transitions between phonon multiplets should hold. Although no absolute B(E2) values were obtained, the ratio of B(E2) values can be calculated from the ratio of the intensities of the two transitions as seen in a gate taken on the gamma ray feeding the initial level. The comparison between experiment and the expectations of the vibrational model are given in Table 1, with the assumption that the observed transitions are of pure E2 character. The relative B(E2) ratios of the non-yrast transitions, together with the energy spacings, are a strong indication of vibrational collective structure. We propose that the last two neutron holes play a major role in the onset of collectivity in ^{196}Po.

Table 1: Ratios of B(E2) values

B(E2) ratios	Vibrator	Experiment
$B(E2;4_2 \rightarrow 2_2)/B(E2;4_2 \rightarrow 4_1)$	0.91	0.95
$B(E2;2_2 \rightarrow 2_1)/B(E2;2_2 \rightarrow 0_1)$	0	0.02

4. The p-n Interaction and Collectivity

The orderings of the single particle states for N < 126 and Z > 82 are shown in Figure 4.

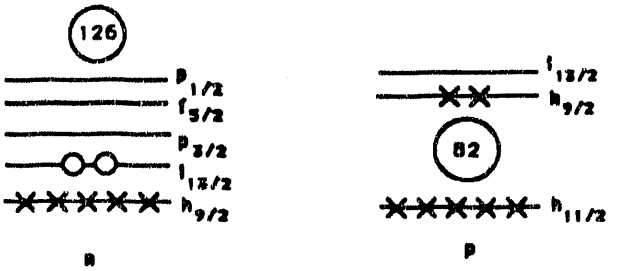

Figure 4: Shell Model levels for protons and neutrons in ^{196}Po

In a naive picture N=112 is the first Po isotope in which there are holes in the neutron $i_{13/2}$ intruder orbital, which is well known to drive the onset of deformation. In addition, Casten[6] has shown that the proton-neutron (p-n) interaction plays a major role in the onset of deformation. In particular, with the use of the parameter $P = N_p N_n / (N_p + N_n)$, which is a normalized ratio of the p-n interaction to the pairing interaction, systems with P > 4-5 are usually deformed.[7]

However, P is an incomplete representation of the p-n interaction, since it does not take into account the actual overlap of the proton and neutron orbitals. If the protons and neutrons are in states with very different quantum numbers, then it is unlikely that they will have a large interaction. If, however, there is a high degree of spatial overlap, then the p-n interaction could cause a large amount of mixing between the states and a corresponding lowering of the energy that is a signature of collectivity.

Casten has also developed a simple way to quantify the amount of overlap of single-particle wave functions with the use of a semi-classical angle. When two angular momentum vectors are added to form a resultant, the three vectors obey the law of cosines, which can be written as[6]

$$\theta_{j1,j2} = \cos^{-1}\{(J^2 - j_1^2 - j_2^2) / (2 \cdot |j_1| \cdot |j_2|)\}$$

If we replace the vectors with operators and extract the expectation value of the operators then[6]

$$\theta_{j1,j2} = \cos^{-1}\{[(J(J+1) - j_1(j_1+1)] - j_2(j_2+1)] / [2 \cdot j_1(j_1+1) \cdot j_2(j_2+1)]^{1/2}\}$$

This semi-classical angle can be viewed as the angle two single-particle states make with respect to one another in order to form a total angular momentum, J, of a given state.It gives a quantitative measure of the distribution in angles of the nucleons in a state with a particular J.

Table 2 presents the semi-classical angles of several $|(j^2,J)>$ configurations located near the Fermi surface in ^{196}Po. The angles for the neutron $(i_{13/2})^2$ and proton $(h_{9/2})^2$ configurations at moderate angular momenta are similar. This indicates that there is a larger overlap between this neutron intruder orbital and the valence proton orbital than was the case in heavier Po isotopes, in which the $i_{13/2}$ orbital is fully occupied. This large overlap means more p-n interaction, which then in turn drives the collective motion.

Table 2: Semi-classical angles (in degrees) for $|j^2,J>$ configurations

j (single particle)	J=2	J=4	J=6	J=8
$i_{13/2}$	160	144	127	108
$h_{9/2}$	152	127	99	63
$f_{7/2}$	144	111	71	-
$f_{5/2}$	131	82	-	-
$p_{3/2}$	90	-	-	-
$p_{1/2}$	-	-	-	-

5. Conclusion

The onset of collective vibrational motion has been observed in the low-lying structure of ^{196}Po. The energy spacings of the yrast 2^+, 4^+ and 6^+ states, as well as the 2_2^+ and the 4_2^+ states, are consistent with the spacings of one, two, and three phonon multiplets. The ratios of the B(E2) values for decays from the 4_2^+ and 2_2^+ states are also consistent with those for vibrational structure.

The transition at moderate angular momenta from single-particle behavior in ^{198}Po to collective behavior in ^{196}Po can be attributed mainly to the valence $i_{13/2}$ neutrons, since the $i_{13/2}$ neutrons have a large overlap with the valence $h_{9/2}$ protons. The p-n interaction causes mixing for configurations with spins less than 8, which yields collective wave functions and a lowering of excitation energies.

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