Evidence for collective structure in ^{214}Po

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From $\gamma\gamma$ and $\gamma\gamma(\theta)$ coincidence studies the second excited state of ^{214}Po has been identified at 1015.0±0.3 keV, with a most probable $J^{\pi}=4^{+}$. Transitions from known levels at 1543.5 and 1847.4 keV to the new level have been observed. Mixing ratios of $2^{+}\rightarrow 2^{+}$ transitions and level spins deduced earlier are used to classify a number of levels below 2 MeV in terms of the vibrational model. A level in ^{214}Po at 1743.0 keV has unambiguously been assigned a $J^{\pi}=0^{+}$ on the basis of $\gamma\gamma(\theta)$ measurements. This 0^{+} state does not appear to be a member of a phonon multiplet.

In our previous[1] $\gamma\gamma(\theta)$ work in which mixing ratios of seven $2^{+}-2^{+}$ transitions for levels below 2.2 MeV were deduced, only the 768.4-keV transition ($\delta=+2.8\pm0.7$) and the 1401.5-keV transition ($\delta=+1.6\pm0.5$) from the 1377.7- and 2010.8-keV levels, respectively, were found to be dominantly $E2$. Each of the remaining five transitions was dominantly (>90%) $M1$. These results together with the identification of two 0^{+} states at 1415.5 and 2017.3 keV and an appropriate energy spacing between the 609.3-, 1377.7-, and 2010.8-keV levels suggested a vibrational sequence of levels in ^{214}Po. However, the higher spin members of the phonon multiplets remained unobserved mainly because of the low spin ($J^{\pi}=1^{-}$) of the parent ^{214}Bi. The purpose of the present investigation was to search for the higher spin states belonging to two- and three-phonon multiplets which might be populated through weak gamma cascades. Evidence for missing transitions between three- and two-phonon states through extensive $\gamma\gamma$ coincidence and $\gamma\gamma(\theta)$ experiments was sought also.

The coincidence experiment was performed on γ rays accompanying the β^{-} decay of ^{214}Bi using two intrinsic Ge detectors in an anticompton arrangement. Both detectors had efficiencies of about 10% and energy resolutions of 2.2 keV at 1332 keV. The coincidence spectra were obtained by sorting two parameter data associated with a large number of gating transitions. The directional correlation experiments were performed using the same two detectors and a goniometer; the source to detector distance was 5 cm. The data were obtained at four angles over a total counting time of 1520 h. The photopeak counting rate for the 405.7–609.3 keV cascade was about three counts per hour. Through the well-defined 405.7–609.3 keV coincidences and several feeding gamma transitions (832.4, 697.9, and 528 keV) all observed in coincidence with the previously[2] unassigned 405.7-keV γ ray, the new level at 1015.0 keV is established. The 697.9-keV γ ray defines a new level at 1712.9 keV, while the 832.4- and 528-keV γ rays depopulate levels established previously.[2] The details of these new placements and other levels of interest are shown in a partial level scheme of ^{214}Po in Fig. 1. Also shown is the decay of the 1743.0-keV level for which the spin assignment has been deduced from the present $\gamma\gamma(\theta)$ experiment. Because of the low intensities of the 405.7- and 1133.7-keV γ rays (0.17% and 0.26%, respectively), the correlation data for the 405.7–609.3 and 1133.7–609.3 cascades was normalized to an average of three correlations (1238–609, 1155–609, 1120–609) obtained previously.[1]

The directional correlation coefficients for the 405.7–609.3 keV cascade, corrected for finite solid angle are $A_2=0.10\pm0.05$, $A_4=-0.05\pm0.06$. The A_2 and A_4 coefficients for the 405.7–609.3 keV cascade rule out $J^{\pi}=0^{+}$, 1^{-}, 2^{-}, and 3^{-} for the 1015.0-keV level. The expected coefficients for these choices are $A_2=0.35$, $A_4=1.14$ (for $J^{\pi}=0^{+}$); $A_2=-0.25$ ($J^{\pi}=1^{-}$); $A_2=0.25$ ($J^{\pi}=2^{-}$); $A_2=-0.07$ ($J^{\pi}=3^{-}$). It is assumed that a γ transition from a negative parity level to a 2^{+} level would be $E1$. The absence of a ground-state transition from the 1015.0-keV level disfavors $J^{\pi}=1^{+}$ and 2^{+}. Of the two choices 3^{+} or 4^{+}, the latter value is supported well by the systematics of the known first 4^{+} states in the $N=130$ isotones and those of even Po isotopes as shown in Fig. 2. The theoretical correlation coefficients for a $4^{+}-2^{+}-0^{+}$ spin sequence are $A_2=0.1020$, $A_4=0.0091$. Furthermore, a 3^{-} level has already been identified at 1274.8 keV, and any 3^{+} state would be expected to be at an excitation energy significantly higher than $\sim$1.0 MeV, although no systematics of 3^{+} states are available for the mass region of concern. Level structure calculations for ^{214}Po do not exist, but a theoretical study of the structure of ^{212}Po has been carried out by Strottman,[4] in which the first 3^{+} level is predicted to have an energy 2.6 times that of the first excited state. It seems highly unlikely that the first 3^{+} level of ^{214}Po would occur at 1.7 times the energy of its first excited state.

Thus the 1015.0-keV level is assigned a most probable

J^{π} of 4^{+}. However, one problem remains with this interpretation; there is a gamma intensity imbalance of 0.10±0.02 per 100 decays of the parent, ^{214}Bi. No direct β^{-} decay is expected from the $J^{\pi}=(1^{-})$ parent state of ^{214}Bi to the 4^{+}, 1015.0-keV level of ^{214}Po. Any such transition would be third forbidden with $\Delta J=3$ (yes) with a predicted $\log ft \sim 18$. Using the γ-ray intensity imbalance as indicative of a β^{-} transition we obtain $\log ft = 9.6\pm0.1$ which is strongly at variance with theory. We conclude that the 1015.0-keV level may possibly be populated by several unobserved γ rays which individually are too weak to be detected and thus produce an apparent β^{-} feeding. Our present $\gamma\gamma$ coincidence data for the energy range 240–2600 keV cannot resolve this issue. No peaks were observed below 480 or above 1875 keV in the spectrum with the gate on the 405-keV peak.

Besides the two 0^{+} states at 1415.5 and 2017.3 keV known from previous $\gamma\gamma(\theta)$ work,[1] another 0^{+} state has been identified at 1743.0 keV through the directional correlation of the weak 1133.7–609.3-keV cascade. The measured correlational coefficients are $A_2=0.54\pm0.10$, $A_4=1.1\pm0.2$. The theoretical correlation coefficients for a $0^{+}-2^{+}-0^{+}$ spin sequence are $A_2=0.3571$, $A_4=1.143$. As a further check on the interpretation of the data, the intensity ratio of the 1133.7- and the 1408.0-keV peak in the directional correlation experiment [the latter due to a transition from a known 0^{+} state at 2017.3 keV (Ref. 2)] was found to be independent of angle to within an uncertainty of 4%.

Finally, it is noteworthy that the 1712.9-keV state does not decay to the ground state but only to states with spins 2^{+} (609.3 keV) and 4^{+} (1015.0 keV). The most probable spin assignment, which is consistent with the observed modes of decay, and its β^{-} feeding from the 1^{-} parent state, is 3^{+} and we have tentatively assigned this J^{π} to the 1712.9-keV level.

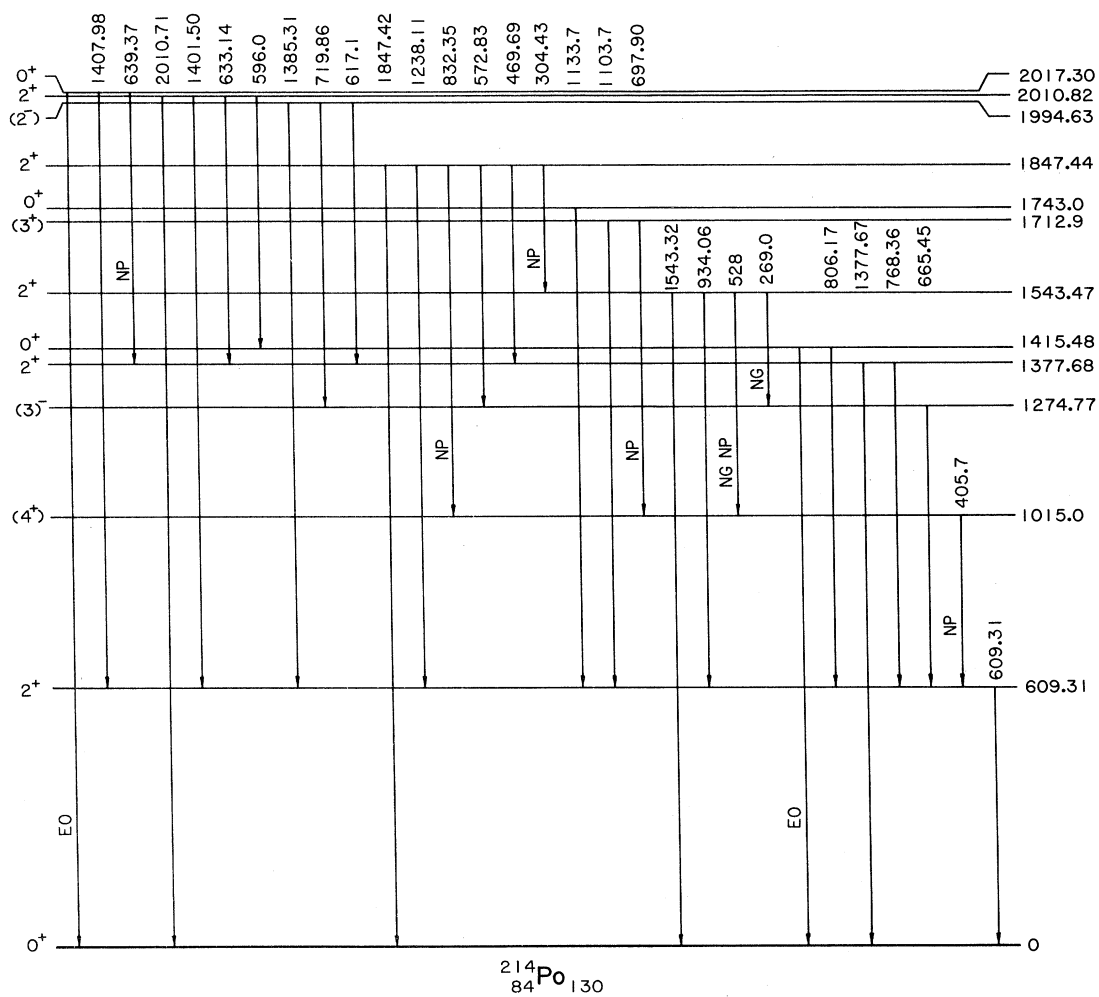

FIG. 1. Partial level scheme of ^{214}Po from β^{-} decay of ^{214}Bi, showing the new level at 1015.0 keV and new placements deduced from present $\gamma\gamma$ coincidence experiments. Besides the 1015.0-keV level and the transitions connecting this level to the other levels, only those levels are shown in this scheme which are relevant to the vibrational model.

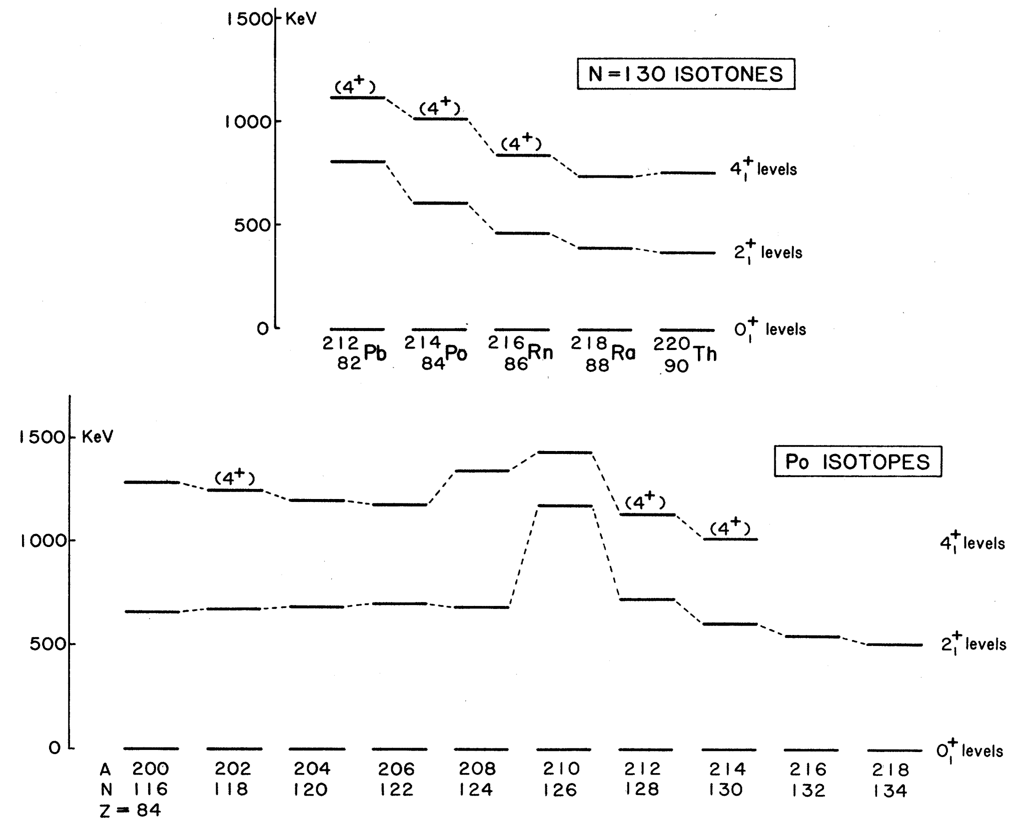

FIG. 2. Systematics of first 2^+ and 4^+ states for $N=130$ isotones (upper panel) and for even Po isotopes (lower panel). The data are from recent mass chain evaluations published in Nuclear Data Sheets except those for ^{216}Rn which are from Ref. 3. The spins shown in parentheses are the most probable choices for which strong arguments for a J^π assignment are still lacking.

On the basis of the observed spin sequences, the energy spacing of the levels and γ transitions shown in Fig. 1, the following levels can be interpreted as collective states expected from the vibrational model 609.3, 2^+ as one-phonon state; 1015.0, (4^+), 1377.7, 2^+, 1415.5, 0^+ as the two-phonon triplet; 2010.8, 2^+, 2017.3, 0^+, and 1712.9, (3^+) as three possible members of a three-phonon quintuplet of states; 1274.8, $(3)^-$ as an octupole state; and 1994.6, $(2)^-$ as an octupole+quadrupole coupled state. The assignment of 2010.8, 2^+ and 2017.3, 0^+ to the three-phonon quintuplet is based predominantly on the $E2$ character of the 1401.5-keV γ ray ($\delta=+1.6\pm0.5$)

TABLE I. Ratios of reduced transition probabilities for proposed two- and three-phonon levels in ^{214}Po. Mixing ratios for $M1+E2$ transitions from Ref. 1; γ-ray intensities are from Ref. 2.

Proposed phonon number N	Level (keV); J^π	Transitions involved (keV)	$\frac{B(E2;\gamma_1;\Delta N=2)}{B(E2;\gamma_2;\Delta N=1)}$	$X=\frac{B(E0)}{B(E2)}$	Comments
2	1015.0; (4^+)		0.0		no crossover observed
2	1377.7; 2^+	$1377\gamma/768\gamma$	0.043 ± 0.003		
2	1415.5; 0^+		0.0		no crossover observed
		$1415(E0)/806\gamma$		0.319 ± 0.011	K-shell intensity of $1415(E0)=0.39\%$[a]
3	1712.9; (3^+)	$1103\gamma/697\gamma$	0.26 ± 0.13		$1103\gamma,679\gamma$ assumed $E2$
3	2010.8; 2^+	$(1401\gamma+2010\gamma)/(596\gamma+633\gamma)$	0.084 ± 0.023		633γ assumed $E2$
3	2017.3; 0^+	$1408\gamma/639\gamma$	$1.5\ \pm0.3$		
		$2017(E0)/1408\gamma$		0.021 ± 0.004	K-shell intensity of
		$2017(E0)/639\gamma$		0.033 ± 0.006	$2017(E0)=0.0062\%$[a]

[a]Reference 6.

(Ref. 1) and the existence of 596.0- and 639.4-keV transitions observed in the present coincidence experiment with the 860- and 768-keV gates, respectively. The assignment of the 1712.9-keV level to the quintuplet is purely speculative.

The newly assigned 0^+ state [from the present $\gamma\gamma(\theta)$ experiment] at 1743.0 keV does not seem to be a member of the three-phonon multiplet since it does not decay to the 2^+ level of the two-phonon triplet. This state probably is a 0^+ intruder state, a number of which have been reported[5] for other even-even nuclides near closed shells.

As further support for these possibilities, we have compared reduced transition rates for the levels in question as shown in Table I. With but one exception, the calculated ratios tend to support the suggestion of collectivity. The 2017.3-keV level has a large $B(E2)$ ratio which might cast some doubt on its collective nature. In the absence of data on level lifetimes, etc., it is not possible to make further comments on the nature of the observed $E0$ transitions.

As a final test of the collective nature of some of the levels of ^{214}Po, we have followed the lead of Cizewski and Dieperink[7] and studied the ratio $E(4_1^+)/E(2_1^+)$ as a function of the neutron and proton boson numbers for the Po isotopes with $Z \geq 82$, and the $N=130$ isotones. The ratio is <2.0 in all cases but one; the 2.0 value is the ratio predicted for the collective spherical quadrupole vibrator. The most that one can conclude is that if collectively exists in ^{214}Po as we suggest, it will be vibrational in nature.

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