Mixing parameters of gamma transitions in ^{214}Po

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Directional correlation measurements with a Ge-Ge(Li) coincidence spectrometer were made on thirteen gamma ray cascades in ^{214}Po, the levels of which were excited by the β^- decay of 19.7 min ^{214}Bi. Spins were deduced for twelve levels in ^{214}Po and the mixing ratio, δ, determined for eleven transitions.

The study of the γ radiation emitted by 19.7 min ^{214}Bi (Ra,C) goes back to the early days of nuclear physics. More than 50 papers[1–4] have appeared on the subject since 1930; they have provided detailed information on energies, intensities, and placements of about 200 γ rays emitted following β^- decay of ^{214}Bi to about 50 levels in ^{214}Po. Nevertheless, some of the more subtle properties such as spin-parity assignments, γ ray multipolarities, and mixing ratios have not yet been finalized. Several internal conversion measurements exist,[5–8] but these fail to give precise mixing ratios. Directional correlation measurements have been reported using scintillation detectors[9,10] and a combination of scintillation and Ge(Li) detectors,[11] but only a few gamma cascades were studied. The ^{214}Po nucleus is one of a number of nuclei whose levels have not been reached by any nuclear reaction available to date. The sole source of level data, above the first excited state, has come from the study of the β^- decay of ^{214}Bi.

Using a pair of high resolution Ge detectors, we have undertaken the present measurements to extend J^π information on levels in ^{214}Po and to provide an independent determination of mixing ratios. For practical reasons the measurements were limited to 14 levels below 2200 keV and to γ rays of intensity $>0.5\%$.

The ^{214}Bi source material obtained from the Chalk River Nuclear Laboratory was 7.8 ± 0.5 μCi of ^{226}Ra sealed into a stainless steel cylinder. The active material was confined to a cylindrical region 1.5 mm in diameter and 0.8 mm in length inside the steel cylinder. The cylinder was mounted on a vertical post at the center of a goniometer and rotated about its symmetry axis at 0.7 rpm to compensate for any source decentering.

Two detectors, one hyperpure Ge and the other Ge(Li) were mounted horizontally on the goniometer table with their symmetry axes passing through the position of the active material. Each detector had an efficiency of about 10% relative to a NaI(Tl) detector and a resolution of about 2.5 keV at 1.33 MeV. One detector was kept fixed and the other rotated about the source from $-90°$ to $+90°$ relative to the fixed detector. The source-to-detector distance was 5 cm for each counter.

The timing distribution (resolving time $\simeq$15 ns) of the conventional coincidence system was observed with a time-to-analog converter. The window of a single-channel analyzer was placed on the 609-keV peak of the spectrum obtained with the Ge detector. A 4096-channel pulse-height analyzer was used to record the coincidence spectrum with the angle between the detector axes set at the values 90°, 115°, 130°, 145°, 160°, and 180°. The experiment took about three months to complete. The counting rates of 13 γ ray lines in the coincidence spectra were determined as functions of the angle (θ) between the detector axes. After correction for chance coincidences which were less than 2%, these distributions were least squares fitted to the equation

$$W(\theta)=\sum_k A_k P_k(\cos\theta)$$

with $k=0,2,4$. In order to cope with the uncertainties of the detector geometry and to normalize the counting times, a known $0^+\rightarrow2^+\rightarrow0^+$ cascade (1408γ-609γ) was selected as a normalizing correlation. The correction factors Q_2 and Q_4 obtained from normalizing the observed correlation function for the 1408γ-609γ cascade to the theoretical function for the $0^+\rightarrow2^+\rightarrow0^+$ spin sequence were 0.85 and 0.70, respectively. Since these factors change by less than 3% over the energy range of this experiment[12] (600–1600 keV), the same values were applied to the measured correlation functions for the other γ-ray cascades.

The cascades chosen for the present study are shown in the partial level scheme in Fig. 1 by heavy lines. The uncorrected correlation functions for 12 cascades are shown in Fig. 2. The 1408γ-609γ correlation chosen for normalization is not included in Fig. 2. The corrected and normalized coefficients A_2/A_0 and A_4/A_0, deduced J^π values, and mixing parameters are given in Tables I and II. For comparison, the results of three previous[9–11] $\gamma\gamma(\theta)$ experiments are also included, together with the deduced J^π's and mixing parameters from internal conver-

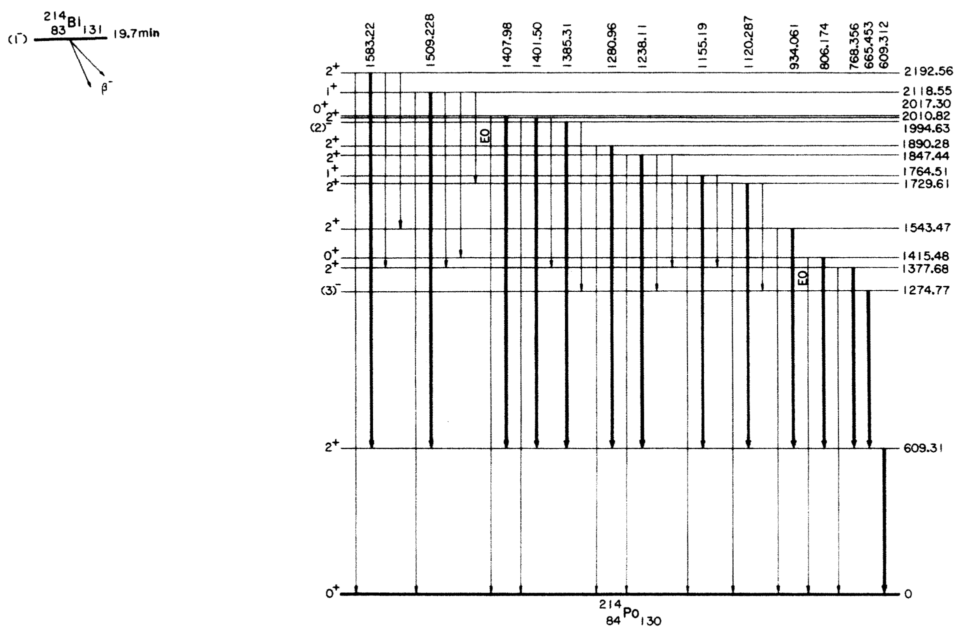

FIG. 1. Partial decay scheme of ^{214}Bi from Ref. 2. The gamma-ray cascades studied are shown in boldface. The spin-parity assignments are from the adopted values given in Table I.

TABLE I. Results of directional correlation measurements on ^{214}Po.

Gamma ray cascade[a]	A_2	A_4	Initial level (keV)	J^π from conversion data (Refs. 5–8)	J^π present work[b]	J^π adopted
665-609	-0.08_5	0.10_6	1274.77	$1^-,2^-,3^-$	$1^-,3^-,2^-$	$(3)^-$[g]
768-609	-0.29_6	0.36_{10}	1377.68	2^+	2^+	2^+
	(-0.22_7)[c]	(0.38_{13})[c]				
	(-0.28_{10})[e]	(0.45_{17})[e]				
806-609	0.22_3	1.27_4	1415.48	0^+	0^+	0^+
	(0.39_7)[d]	(0.91_9)[d]				
934-609	0.41_4	0.06_8	1543.47	$1^+,2^+$	2^+	2^+
	-0.07_3[d]					
1120-609	0.109_6	0.011_{11}	1729.61	2^+	2^+	2^+
	(0.21_4)[d]	(-0.00_5)[d]				
	(0.16_2)[e]	(0.00_2)[e]				
1155-609	-0.54_3	-0.02_6	1764.51	1^+	1^+	1^+
	(-0.23_6)[e]	(-0.04_8)[e]				
1238-609	0.272_9	-0.00_2	1847.44	$1^+,2^+$	2^+	2^+
	(0.17_3)[d]	(0.02_4)[d]				
	(0.24_3)[e]	(0.03_5)[e]				
1281-609	0.30_8	0.08_{12}	1890.28	$1^+,2^+$	$1^+,2^+$	2^+[h]
1385-609	0.19_{10}	-0.21_{19}	1994.63	$1^-,2^-,3^-$	$1^-,2^-,3^-$	$(2)^-$[i]
1401-609	-0.37_2	0.25_4	2010.82	$1^+,2^+$	2^+	2^+
1408-609[f]			2017.30	0^+		0^+
1509-609	-0.19_2	0.01_4	2118.55	1^+	1^+	1^+
	(-0.10_2)[d]	(0.00_2)[d]				
1583-609	0.38_3	0.10_6	2192.56	$1^+,2^+$	2^+	2^+

[a]The 609-keV gamma ray ($2_1^+ \rightarrow 0_1^+$) deexcites the first excited state.
[b]The given spins are consistent with the observed directional correlations; partities are inferred from conversion electron data.
[c]Reference 9.
[d]Reference 10.
[e]Reference 11.
[f]Cascade used to determine Q_2, Q_4.
[g]Conversion data and $\gamma\gamma(\theta)$ rule out 2^-; see Table II. Absence of crossover transition and nuclear systematics of even-even nuclei support 3^- rather than 1^-.
[h]1^+ is ruled out by conversion data and $\gamma\gamma(\theta)$; see Table II.
[i]1^- and 3^- are ruled out since excessive $M2$ intensity would be predicted.

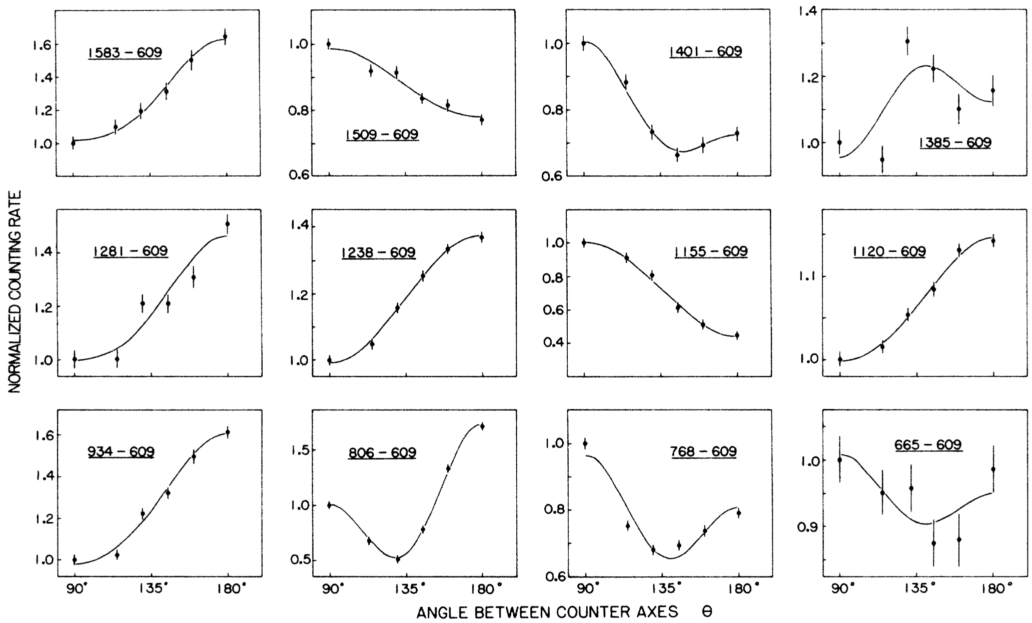

FIG. 2. Directional correlations of studied gamma-ray cascades in ^{214}Po. The solid curves depict the function $W(\theta)=\sum_k A_k P_k(\cos\theta)$, $k=0,2,4$ as it is least squares fitted to the data points.

TABLE II. Mixing ratios, δ, for selected gamma transitions in ^{214}Po.

Level (keV)	Possible J^π	Mixed gamma transition (keV)	$\lvert\delta\rvert$; multipolarity from conversion data[a]	δ $\gamma\gamma(\theta)$	δ[e] adopted
1274.77	3^-	665.45	$<0.1;E1$	$+0.00_7$	$+0.00_7$[f]
	2^-			$+0.45_{10}$	
	1^-			-0.15_7	
1377.68	2^+	768.36	$2.8_7;E2+M1$	$+2.8_{16}$	$+2.8_7$
				$(+2.6^{38}_{19})$[d]	
				$(+4.3^{45}_{18})$[c]	
1415.48	0^+	806.17	$E2$		
1543.47	2^+	934.06	$0.44_{10};M1+E2$	-0.27_{10} or -1.2_4	-0.27_{10}
				$(+0.45_5$ or $>20)$[b]	
1729.61	2^+	1120.29	$0.30_{10};M1+E2$	$+0.18_2$	$+0.18_2$
				$(+0.05_5)$[b]	
				$(+0.12_2)$[d]	
1764.51	1^+	1155.19	$<0.49;M1(+E2)$	$+0.33_4$	$+0.33_4$
				(-0.01_5)[d]	
1847.44	2^+	1238.11	$<0.13;M1(+E2)$	-0.032_{13}	-0.032_{13}
				(-0.11_4)[b]	
				(-0.02_4)[d]	
1890.28	2^+	1280.96	$<0.1;M1(+E2)$	-0.08_{12} or -1.7_6	-0.08_{12}[f]
	1^+			-0.47_{15}	
1994.63	2^-	1385.31		$+0.07_{15}$	$+0.07_{15}$[f]
	1^-			-0.40_{12}	
	3^-			$+0.4_2$	
2010.82	2^+	1401.50		$+1.6_5$	$+1.6_5$
2017.30	0^+	1407.98	$E2$		
2118.55	1^+	1509.23		-0.056_{22}	-0.056_{22}
				(-0.12_2)[b]	
2192.56	2^+	1583.22	$M1$	-0.21_8 or -1.4_2	-0.21_8

[a]δ values deduced from average conversion electron intensities (Refs. 5–8) and γ intensities from Ref. 2.
[b]δ values deduced from the correlation coefficients of Ref. 10.
[c]Reference 9.
[d]Reference 11.
[e]Values are consistent with $\gamma\gamma(\theta)$ and conversion data.
[f]For adopted J^π, see Table I.

sion data.[5–8] The adopted J^π values in Table I and mixing parameters, δ, of Table II are derived from all available information including the results of the present experiment.

The spins of the 1543-, 1847-, 2011-, and 2193-keV levels have been uniquely determined as 2^+. The earlier assignments of 2^+ to the 1378- and 1730-keV levels, 1^+ to the 1765- and 2118-keV levels, and 0^+ to the 1415-keV level have been confirmed. The present data do not give unique spin choices for the 1275-, 1890-, and 1995-keV levels. The combined internal conversion and $\gamma\gamma(\theta)$ data suggest J^π assignments of $(3)^-$, 2^+, and $(2)^-$ for these levels, respectively. The mixing parameters of the 1385-, 1401-, and 1583-keV γ rays have been determined for the first time, and independent determinations are given for the 665-, 768-, 934-, 1120-, 1155-, 1238-, 1281-, and 1509-keV γ rays. We find significant disagreement for the 1155γ-609γ correlation between our results and those of Gupta and Sastry.[11] The poorer energy resolution (~ 6 keV) of the detector used in the earlier work[11] may account for this discrepancy.

The decay properties of 15 of the first 19 excited states of ^{214}Po are now fairly complete, except for lifetimes. The levels above 2200 keV are too weakly populated to be studied by the directional correlation technique. The 15 levels studied have $J^\pi=0^+$ for three levels, $J^\pi=1^+$ for two levels, $J^\pi=2^+$ for eight levels, and $J^\pi=(2)^-$ and $(3)^-$ for one level each. A straightforward application of the vibrational model can account for 8 of these 15 levels if the 609-keV level is considered to be a one-phonon state. The energy spacing and the dominant $E2$ character (refer to Table II for δ values) of the $2^+\rightarrow 2^+$ transitions from the 1378- and 2011-keV levels indicate that these levels are two-phonon and three-phonon states, respectively.

The three-phonon 2^+ state at 2011 keV should decay to the 0^+, 2^+, and 4^+ two-phonon triplet states. Only the transition to the 2^+ member of the triplet has been observed. The 596.0-keV transition has been assigned[3] tentatively to the 0^+ two-phonon state at 1415 keV. The 4^+ level of the triplet has not yet been identified.

Similarly the 0^+ three-phonon state at 2017 keV should have a γ transition to the 2^+ two-phonon state at 1378 keV. This decay has not been identified, but an unplaced 639.4-keV γ ray[2] could be the required transition.

The $(3)^-$ level at 1275 keV is most likely an octupole state. The $(2)^-$ state at 1995 keV could then be the result of coupling octupole and quadrupole phonons. The expected level energy of 1884 keV is in reasonable agreement with the observed value of 1995 keV. Furthermore, the $(2)^-$ to $(3)^-$ γ transition has a large $E2$ component ($\delta > 1$ from the internal conversion measurements[6]) as expected if the $(2)^-$ state is formed through quadrupole-octupole coupling.

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