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Multipole mixing ratios of the single-neutron-hole transitions of ^{207}Pb

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Directional-correlation measurements have been made on the 1770-570 keV, 1442-897 keV, and 1063-570 keV, γ-ray cascades of ^{207}Pb, using an automated rotating-detector Ge(Li)-NaI(Tl) coincidence spectrometer. The present results imply an $E5/M4$ multipole mixing ratio $\delta(1063)=0.016(11)$ and $E2/M1$ mixing ratios $\delta(1770)=+0.082(15)$ and $\delta(897)=+0.075(25)$. The values obtained by averaging these and previous results are $\delta(1770)=+0.087(5)$, $\delta(1063)=+0.020(10)$, and $\delta(897)=+0.089(11)$. When these values are compared to the single-neutron-hole calculations made in the oscillator basis with $\hbar\omega=7.6$ meV, the best over-all agreement is obtained for the neutron-hole effective charge $\epsilon_n\simeq 0.89$.

[RADIOACTIVITY ^{207}Bi; measured $\gamma\gamma(\theta)$; deduced δ for γ rays in ^{207}Pb.]

The main interest in the ^{207}Pb nucleus is that its simplest description is one involving pure shell model hole states in the doubly magic ^{208}Pb core.[1] A more sophisticated description consists of coupling single-hole states to collective vibrations of the core[2]; however, for the description of the low lying states and the electromagnetic transitions between them, we picture these states as pure single-neutron-hole states. An accurate understanding of the properties of the transitions between these states is important to the understanding of the effective multipole operators used in the microscopic description of electromagnetic transitions in many nuclei near the doubly magic ^{208}Pb core. We hope to contribute to this understanding by our reinvestigation of the γ-γ directional correlations in ^{207}Pb using high resolution techniques, in order to extract the multipole mixing ratios of the 1770, 1063, and 897 keV transitions.

Many experimental studies of these transitions have been undertaken[3–13]; however, the mixing ratios δ are very small and extremely difficult to measure and in some cases the moderate inconsistencies between the various results which exist in the literature are important and should be clarified. The accuracy required in order to derive conclusive results is far too high for any single one of the existing measurements to suffice and, in addition, the questions are important enough so that at least one measurement involving a high resolution detector should be made in order to ensure the elimination of some of the possible experimental interferences.

One can easily obtain a simple expression for the multipole mixing ratio $\delta[E(\lambda+1)/M(\lambda)]$, in the convention of Krane and Steffen,[14] by using the definitions given in Ref. 14 and the operators as defined by Alder *et al.*[15] The indicated integrations are straightforward (see Ref. 16 for example). For transitions between single-neutron-hole states in the oscillator basis we have

$$\delta=\frac{\epsilon_n}{g_s'}\left(\frac{\hbar\omega_\gamma}{\hbar\omega_0}\right)\frac{(-1)^{\lambda+1-l}[1+(-1)^{l+l'+\lambda+1}]\sqrt{2\lambda(\lambda+2)}}{(\lambda+1)(2\lambda+1)[3\lambda(2\lambda+3)(2\lambda-1)(2j'+1)(2l+1)]^{1/2}}\begin{bmatrix} j & \lambda+1 & j' \\ \frac{1}{2} & 0 & \frac{1}{2}\end{bmatrix}\begin{bmatrix} l & \lambda-1 & l' \\ 0 & 0 & 0\end{bmatrix}^{-1}$$
$$\times\begin{Bmatrix} l & \frac{1}{2} & j \\ l' & \frac{1}{2} & j' \\ \lambda-1 & 1 & \lambda\end{Bmatrix}^{-1}\frac{\langle n'l'\|r^{\lambda+1}\|nl\rangle}{\langle n'l'\|r^{\lambda-1}\|nl\rangle}\,; \qquad (1)$$

where ϵ_n is the effective charge of the neutron hole, $g_s'=-1.913$, $(\hbar\omega_\gamma/\hbar\omega_0)$ is the ratio of the γ-ray energy to the oscillator energy, and the radial integrals are dimensionless because we have factored out $(2\hbar/m\omega_0)^{\lambda/2}$ from the usual radial integral $\langle n'l'\|r^\lambda\|nl\rangle$. The oscillator energy commonly used in this shell[17] is $\hbar\omega_0=7.6$ MeV (see for example Ref. 17). The square angular momentum brackets are Clebsch-Gordan coefficients. The effective charge ϵ_n is a result of the polarization of the core and a value $\epsilon_n=0.5$ was commonly used earlier. More recently empirical evidence indicates that ϵ_n is from approximately 0.75 to 1.00 [18,19] and may even be state dependent.

The γ-γ directional correlations of the 1063-570, 1442-897, and 1770-570 keV γ-ray cascades were measured with an automatic directional correlation table consisting of a fixed 33 cm^3 Ge(Li) detector and a rotating 7.6 cm$\times$7.6 cm NaI(Tl) detector. A standard coincidence system was used and the coincidence logic pulse was used to gate a multichannel pulse-height analyzer. The memory of the analyzer can be split so that up to eight coincidence spectra can be stored, one corresponding to each angle between the detector axes. The moving NaI(Tl) detector was powered by a gain-stabilized power supply and its position was changed every 15 min. In addition the singles and coincidence count rates were monitored every 15 min. in order to check the stability of the system. The following angles between the detector axes were data collection angles for the 1063-570 keV correlation measurement: 90°, 112.5°, 135°, 157.5°, 180°, 202.5°, 225°, 247.5°, and 270°. For the 1770-570 keV cascade, data were collected at 90°, 135°, 180°, 225°, and 270° and for the 1442-897 keV cascade data were only collected at 90°, 180°, and 270°. For this $\frac{7}{2}(2)$-$\frac{3}{2}(1,2)$-$\frac{1}{2}$ cascade the theoretical value of A_{44} is exactly zero for all values of δ. For both weak cascades, the correlations are also weak and it was considered better to collect statistically good data at fewer angles than fit a correlation function to many more points of statistically poor data. In addition, the strong correlation of the intense 1063-570 keV cascade was measured before and after the measurement of the weak cascades which served as a check on the stability of the apparatus.

The data were corrected for chance coincidences and fitted to a function of the form $W=1+A_{22}P_2(x)+A_{44}P_4(x)$ where $x=\cos\theta$. The coefficients A_{22} and A_{44} were then corrected for finite solid angle effects using the corrections given by Yates[20] for scintillation detectors and for the other detector by the method given in Ref. 21 for Ge(Li) detectors. The corrected correlation coefficients are given along with those of earlier investigations in Table I.

The question of interest concerning the 1063-570 keV cascade is the existence of the small $E5$ mixture in the predominantly $M4$, 1063 keV transition. Of the seven previously reported values of A_{22}, only two are within error limits of the theoretical value $A_{22}=+0.2208$, for the spin sequence $\frac{13}{2}(4)$-$\frac{5}{2}(2)$-$\frac{1}{2}$, namely those of Refs. 3 and 9. All of other results imply a small $E5$ admixture. Our value of A_{22} also implies a small $E5$ admixture with $\delta(1063)=+0.016\pm0.011$. The average of the present and all previous values is $\overline{A}_{22}=+0.2281\pm0.0035$, where the error is the most probable error derived from the root mean square deviation from the average value. This value implies $\delta(1063)=+0.020\pm0.010$.

TABLE I. Directional-correlation coefficients in ^{207}Pb from this and previous investigations.

Cascade	Reference	A_{22}	A_{44}
1063-570	3	0.218(4)	−0.021(7)
$(\frac{13}{2}\to\frac{5}{2}\to\frac{1}{2})$	6	0.231(3)	−0.025(5)
	7	0.232(7)	−0.021(3)
	8	0.230(4)	−0.027(8)
	9	0.220(3)	−0.038(4)
	10	0.232(2)	−0.022(2)
	12	0.235(3)	−0.029(4)
	Present	0.227(3)	−0.018(8)
1770-570	13	−0.0087(89)	+0.029(14)
$(\frac{7}{2}\to\frac{5}{2}\to\frac{1}{2})$	10	−0.0094(15)	+0.0019(17)
	12	−0.003(3)	+0.010(4)
	Present	−0.012(10)	+0.018(5)
1442-897	10	−0.043(16)	+0.022(18)
$(\frac{7}{2}\to\frac{3}{2}\to\frac{1}{2})$	Present	−0.053(6)	Assumed 0.0

The main reason for the present reinvestigation of this cascade was the fact that all of the previous γ-γ directional correlation measurements were performed with NaI(Tl) detectors. This can admit the other two cascades as interference cascades which, if not corrected for, would make A_{22} nearer to the value for $\delta=0$ and would affect the implied value of ϵ_n. The use of one Ge(Li) detector allows the coincidence peak to be stripped from the continuum, eliminating the interferences due to higher energy γ rays. The present value of A_{22} is, however, very close to the average of all previous values. Since there are no significant discrepancies among the various results, we conclude that the interferences were too weak to be important and the present values, as well as the average of all the values, support the earlier conclusion that there is a small $E5$ admixture in the 1063 keV transition.

The case of the 1770-570 keV cascade has not been consistently measured which was the main motivation of its remeasurement. The two earlier measurements by Lazar and Klemma[13] and by Bargholtz, Eriksson, and Gidefeldt[10] are in good agreement; however, the more recent measurement of Kaplan and Wilson[12] is quite a bit more isotropic. The present result is in better agreement with the earlier results and implies a mixing ratio of $\delta(1770)=+0.082\pm0.015$. The average of all four measurements is $\overline{A}_{22}=-0.0083\pm0.0033$ which implies the mixing ratio $\delta(1770)=+0.087\pm0.005$. With either of these values of δ, A_{44} should be much smaller ($A_{44}\sim-0.0002$) than any of

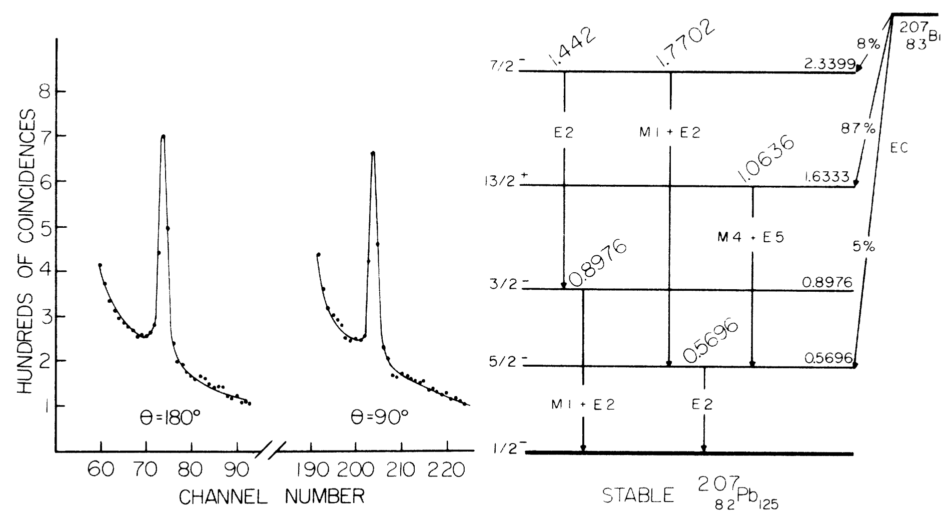

FIG. 1. The partial Ge(Li) spectrum gated by coincidences with the 1442 keV γ ray observed in the NaI(Tl) detector taken from a typical data run during the measurement of the 1442-897 keV $\gamma\gamma(\theta)$. The current decay scheme is shown on the right.

the measured values, which is somewhat indicative of the reliability of such small A_{44} coefficients. In our preliminary studies we found a subtle interference caused by real coincidences between the Compton continuum of the 1063 keV γ ray and summing of two 570 pulses, only one of which need be in real coincidence with the 1063 keV transition. This might explain the disagreement between the results of Ref. 12 and those of earlier workers.

The only previous measurement of the 1442-897 keV, γ-γ correlation was reported by Bargholtz *et al.*[10] This measurement was made using a 56-channel goniometer of NaI(Tl) detectors. The extremely weak 1442-897 keV cascade can be somewhat masked by the coincidences between a 1770-570 keV cascade plus a chance partial deposition of the energy of one of the other strong γ rays. We found this effect to be significant with any source strength for which reasonable count rates for the desired cascade could be obtained. The effect of this can be seen in the large continuum in the sample coincidence spectra shown in Fig. 1. It was decided that it would be better to take advantage of the high resolution of a Ge(Li) detector by suffering the interference and then stripping the peaks off of the interference continuum than to obtain better count rates while not being able to accurately evaluate this possibly serious source of interference. The resulting value of A_{22} $=-0.053(6)$ is somewhat larger than the NaI(Tl) goniometer measurement of Ref. 10; however, it is within experimental error. These two measurements taken together do not constitute a meaningful average between a number of independent measurements; however, their implied mixing ratios can be averaged with the two values deduced from Coulomb excitation data. The present

TABLE II. Experimental and theoretical multipole mixing ratios of the single-neutron-hole transitions in ^{207}Pb.

Transition energy (keV)	Experimental values δ [a]	δ [b]	Theoretical values δ [c]	δ [d]
1770 $f_{7/2} \rightarrow f_{5/2}$	+0.082(15)	+0.087(5)	+0.0457	+0.0777
1063 $i_{13/2} \rightarrow f_{7/2}$	+0.016(11)	+0.020(10)	+0.0077	+0.0131
897 $p_{3/2} \rightarrow p_{1/2}$	+0.075(25)	+0.089(11)	+0.0694	+0.1179

[a] Present results.
[b] Average of available experimental results.
[c] Calculated with $\epsilon_n = 0.5$.
[d] Calculated with $\epsilon_n = 0.85$ (see Refs. 18 and 19).

mixing ratio $\delta(897) = +0.075(25)$ was also averaged with $\delta(897) = +0.11(6)$ given in Ref. 10 and with the two values $\delta(897) = 0.096(11)$ and $\delta(897) = 0.075(25)$ quoted in a paper by Klapdor *et al.*[22] The average value $\delta(897) = +0.089(11)$ is in serious disagreement with the earlier work of Häusser and Ward[23] for which $\delta(897) = -0.31(6)$. One of the serious difficulties in this transition is that it is a member of an extremely weak cascade and in addition, the experimental value of A_{22} is in the region for which a very small change in A_{22} corresponds to a significant change in δ.

The results of all of the directional correlation coefficients are presented in Table I. The results of the present and the average multipole mixing ratios are presented in Table II together with the single-hole values calculated with $\epsilon_n = 0.5$ commonly used earlier and also with $\epsilon_n = 0.85$ suggested by Bohr and Mottelson.[18] (Also see Ref. 19.) It is interesting to note that if we ignore the possible state dependence of ϵ_n and take a weighted average of the three values of ϵ_n implied by the average values of δ for all three transitions we find $\epsilon_n = 0.89$ and that the average values of δ for all three transitions are in good agreement with the simple theory predicting these transitions to be between single-neutron-hole states with the effective charge of a single-neutron hole to be closer to unity (0.89) than the widely used value $\epsilon_n = 0.5$.

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