Electromagnetic properties of isomers in ^{210}Pb

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The lifetimes and magnetic moments of the $J^{\pi}=8^+$ and 6^+ isomers in ^{210}Pb have been measured using the gamma-ray perturbed angular distribution technique. The levels were populated with the ^{208}Pb(t,p)^{210}Pb reaction. The g factors of the 8^+ and 6^+ states are found to be $-0.312(8)$ and $-0.312(15)$, respectively. The magnetic moment, $\mu=-1.42(7)\ \mu_N$, is deduced for the $2g\frac{9}{2}$ neutron orbital. Mean lifetimes are 290(25) ns for the 8^+ state and 71(9) ns for the 6^+ state. We find $\langle g\frac{9}{2}||M(E2)||g\frac{9}{2}\rangle=-39(2)\ e\ \mathrm{fm}^2$ and an effective charge of 0.88(5) e for the $2g\frac{9}{2}$ neutron orbital.

[NUCLEAR REACTIONS ^{208}Pb(t,p) $E_t=16$ MeV. For ^{210}Pb $E_x=1279$ keV, $J^{\pi}=8^+$, measured $\tau_m=290(25)$ ns, $g=-0.312(8)$; for $E_x=1195$ keV $J^{\pi}=6^+$, measured $\tau_m=71(9)$ ns, $g=-312(15)$. Deduce for $\nu(2g\frac{9}{2})$, $\mu=-1.42(7)\ \mu_N$, and $e_{\mathrm{eff}}=0.88(5)\ e$.]

I. INTRODUCTION

The low-lying levels of the nucleus ^{210}Pb, with just two neutrons outside the ^{208}Pb core, are well described as members of the $\nu(g\frac{9}{2})^2$ configuration. The energies of the high spin members of this configuration are separated by less than 100 keV with the result that the 8^+ and 6^+ levels have lifetimes of the order of 100 ns. Lifetimes of this magnitude are ideally suited for pulsed-beam gamma-ray measurements from which accurate g factors and $B(E2)$ values can be determined. Because these high spin states are quite pure one can use simple additivity rules to extract the magnetic moment and effective charge for the $2g\frac{9}{2}$ neutron orbital from the results of these measurements. Up to now the electromagnetic properties for the $2g\frac{9}{2}$ neutron orbital have been derived from studies of the isomeric states of the $\pi(h\frac{9}{2})\nu(g\frac{9}{2})$ configuration in ^{210}Bi (Refs. 1 and 2) and therefore they are subject to uncertainties in the larger $\pi(h\frac{9}{2})$ values and in the corrections for the many small admixtures in the wave functions of this odd-odd nucleus. Measurements on the isomeric states in ^{210}Pb should give more direct information on the electromagnetic properties of the $2g\frac{9}{2}$ single particle orbital.

The members of the $\nu(g\frac{9}{2})^2$ configuration in ^{210}Pb have been identified by charged particle studies using the ^{208}Pb(t,p) (Ref. 3) and ^{210}Pb(t,t′) (Ref. 4) reactions. These levels are shown in Fig. 1. The first attempts to study ^{210}Pb with in-beam gamma-ray spectroscopy utilized the ^{208}Pb(^{7}Li,αp) (Ref. 5) and ^{208}Pb(^{18}O,^{16}O) (Ref. 6) reactions. Both of these studies observed the 297-keV $4^+\rightarrow 2^+$ transition as well as the 799-keV $2^+\rightarrow 0^+$. Previous charged

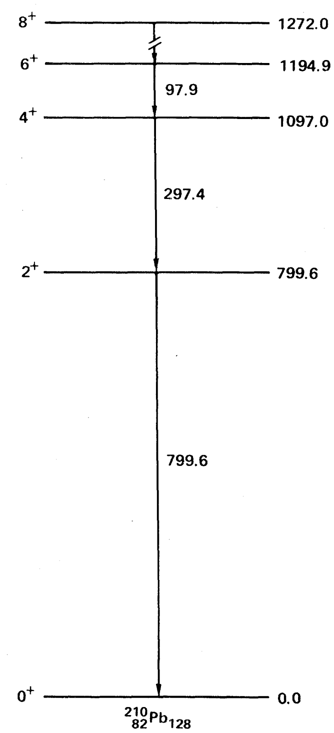

FIG. 1. The members of $\nu(g\frac{9}{2})^2$ configuration in ^{210}Pb. The gamma-ray energies are from the present work. The energy of the 8^+ level is taken from the (t,p) and (t,t′) reaction studies of Refs. 3 and 4.

particle and beta-decay studies[7] suggest energies for the $8^+ \rightarrow 6^+$ and $6^+ \rightarrow 4^+$ transitions as 79 keV and 99 keV, respectively. These low energy transitions are too highly converted to have been observed in the earlier in-beam gamma-ray studies. The time distributions of the 297-keV and 799-keV transitions showed the existence of two isomers in the decay. Sjoreen *et al.*[5] gave values of 225(22) and 30(10) ns for the mean lifetimes of these isomers and assigned them to the 8^+ and 6^+ levels, respectively. Bohn *et al.*[6] measured a mean lifetime of 220(19) ns for the 8^+ state but were unable to determine a value for the 6^+ isomer.

We have used the ^{208}Pb(t,pγ)^{210}Pb reaction and the time differential perturbed angular distribution method to determine the g factors of these isomers and to improve the accuracy of the lifetime measurements. As a method of populating these states the triton induced reaction is more favorable than those used previously since a large fraction ($\sim 10\%$) of the total cross section goes into the (t,p) channel. Furthermore there are fewer competing reactions than with the heavier projectiles and therefore a less complicated gamma-ray spectrum. This allowed us to measure precise values of the g factors of the 8^+ and 6^+ states and thereby determine the magnetic moment of the $2g\frac{9}{2}$ neutron orbital. Also, we used the measured $B(E2)$ values to deduce an effective quadrupole charge for the orbital.

II. EXPERIMENTS AND RESULTS

The experiments were performed at the Los Alamos National Laboratory Van de Graaff accelerator facility. A 16-MeV triton beam, which was bunched into 1-ns wide pulses with a repetition time of 12.8 μs, passed through a thin foil at the end of the beam pipe and traveled through 2 cm of air before striking the thick enriched ^{208}Pb target. The applied magnetic field at the target was 15.30(8) kG as measured by a Hall probe. Two Ge detectors, which were positioned at ± 135 degrees with respect to the beam direction and in the plane perpendicular to the magnetic field, were used to detect gamma rays. The data, which consisted of the gamma-ray energy and time relative to the beam pulse, were recorded event by event onto magnetic tape for off-line analysis. Prompt events were electronically suppressed so that the events of interest could be recorded at the maximum rate. A calibration of the time scale was based on the frequency of a quartz oscillator.

Time distributions of the 297-keV $4^+ \rightarrow 2^+$ and 799-keV $2^+ \rightarrow 0^+$ transitions were obtained by gating on the full energy absorption peaks and subtracting the time distributions from appropriate background gates. We have also observed a 97.9(1)-keV gamma ray in the delayed energy spectrum which is most likely the $6^+ \rightarrow 4^+$ transition; however, the observed intensity was not sufficient to yield a reasonable time distribution. The perturbed angular distributions were obtained by forming the ratio of the gamma-ray intensities I,[8]

$$R(t) = [I(135°,t) - I(-135°,t)]/[I(135°,t) + I(-135°,t)] .$$

The coefficient, A_2, of the Legendre polynomial expansion of the angular distribution and the Larmor precession frequency, ω_L, can be extracted from the relation, good for small A_4,

$$R(t) = [3A_2/(4+A_2)]\sin(2\omega_L t) .$$

The ratio for the 297-keV transition is shown in Fig. 2 along with a fit to the sine function. The frequency, ω_L, corresponds to a g factor of $-0.311(5)$; the A_2 value of $+0.28(4)$ is reasonable for stretched $E2$ transitions. A similar analysis for the 799-keV transition gave $g = -0.310(7)$ and $A_2 = +0.26(6)$. It is important to note that the same frequency is obtained for fits over different regions of the time distributions. Since these distributions have contributions from both the 6^+ and 8^+ isomers we can conclude that the g factors of these states are the same within $\sim 2\%$. We note that this is predicted by additivity for states with pure $(j)^n$ configurations. As a further indication that $g(8^+) = g(6^+)$ we observe no measurable phase shift in the perturbed angular distribution which would arise from two different precession frequencies. After applying a correction of -1.5% for the Knight shift of Pb in Pb (Ref. 9) and $+1.7\%$ for diamagnetic shielding[10] we obtain a value of $-0.312(8)$ for the g factor of the 8^+ state in ^{210}Pb.

Lifetime information was obtained from decay curves formed by adding the normalized time distributions from the two detectors. [The residual $b_4 \sin(4\omega_L t)$ term has virtually no effect on the lifetime fits since b_4 is small and the period for the oscillation is short compared to the lifetimes.] The lifetime of the 8^+ state was determined by fitting the decay curve to the function $I_0 \exp(-t/\tau)$ for $t > 300$ ns. In this range the contribution from the 6^+ state should be negligible. This results in $\tau(8^+) = 290(25)$ ns, which is about 30% larger than the previously report-

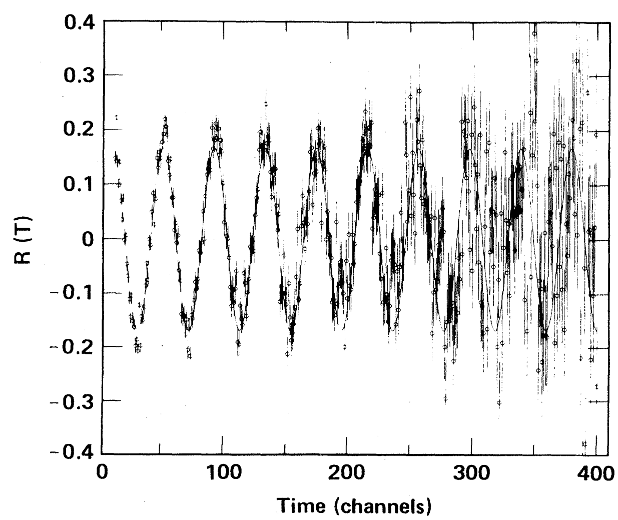

FIG. 2. The ratio function (see text) for the 297 keV transition. The time calibration is 3.44 ns/channel.

ed values, where the measuring range was limited to <500 ns. The lifetime of the 6^+ state was determined by fitting the entire time range to the function that describes successive decay through two isomers with different lifetimes. A contribution for direct population of the lower isomer was included. We find that the mean lifetime for the 6^+ state is 71(9) ns, and we also find that 35% of the delayed intensity bypasses the 8^+ state. Figure 3 shows the sum of the time distributions for the two angles for the 297-keV transition along with the fit to the function for two lifetimes.

III. DISCUSSION

A. Magnetic moments

Assuming the 8^+ state in ^{210}Pb has only the $\nu(g\frac{9}{2})^2$ configuration our measured g factor would give $-1.40(4)$ μ_N for the magnetic moment of the $2g\frac{9}{2}$ neutron orbital. Of course, the 8^+ state does contain admixtures of other configurations which change this result. The effects of these admixtures on the measured reduced matrix element can be calculated using the expression[2]

$$\langle I'||M(\lambda)||I\rangle = \sum_{I_1,I_2,I_1',I_2'} [(2I+1)(2I'+1)]^{1/2} c^{I}_{I_1I_2} c^{I'}_{I_1'I_2'} \times \left[(-1)^{I_1'+I_2'+I+\lambda} \begin{Bmatrix} I_1 & I_2 & I \\ I' & \lambda & I_1' \end{Bmatrix} \langle I_1'||M(\lambda)||I_1\rangle + (-1)^{I_1+I_2+I'+\lambda} \begin{Bmatrix} I_1 & I_2 & I \\ \lambda & I' & I_2' \end{Bmatrix} \langle I_2'||M(\lambda)||I_2\rangle \right],$$

where the two-particle state with spin I is expressed as a sum of the coupling of the states with spins I_1 and I_2 with the coefficients $c^{I}_{I_1I_2}$. The terms in brackets on the right hand side of the expression are the reduced matrix elements of the single particle states. The values for the pertinent proton and neutron orbitals, which are either known from experiment or calculated, are listed by Donahue *et al.*[11] Using the $c^{I}_{I_1I_2}$ values calculated by Kuo and Herling[12] and by Ma and True[13] for the 8^+ state in ^{210}Pb we find corrected values of $\mu(g\frac{9}{2})$ of $-1.46(7)$ and $-1.44(7)$ μ_N, respectively. The correction is mostly due to an admixture of the $\nu(g\frac{9}{2}g\frac{7}{2})$ configuration in the 8^+ state which contributes linearly in its mixing amplitude. The results of a similar analysis for the 5^- and 7^- isomers in ^{210}Bi, using the wave functions from the same authors as above, are shown in Table I. Unfortunately, shell model calculations cannot reliably predict the precise magnitude of these small components, hence the corrections introduce additional error into the extracted single particle quantities. Using our 8^+ value and the value from the 7^- state in ^{210}Bi, where the number of corrections is the fewest, we obtain $\mu(2g\frac{9}{2})=-1.42(7)$ μ_N.

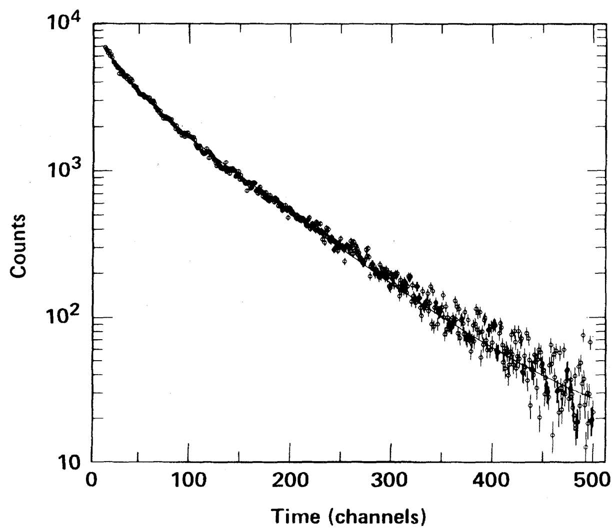

FIG. 3. The sum of the time distributions for the 297 keV transition for $+135$ and -135 deg. The time calibration is 3.44 ns/channel.

Using this value we can then calculate the magnetic moment of the 1^- ground state of ^{210}Bi. The measured moment, $-0.0440(1)$ μ_N, deviates strongly from the value of $+0.296$ expected for a pure $\pi(h\frac{9}{2})\nu(g\frac{9}{2})$ configuration and is therefore a good test of the calculated mixing amplitudes. The results are shown in the lower portion of Table I. It is clear that the wave functions of Kuo and Herling do far better than those of Ma and True. The difference is due to the large amplitude of the $\pi(f\frac{7}{2})\nu(g\frac{9}{2})$ component in the wave functions of Ma and True. We also note that our values calculated with the Ma-True wave functions are different from those given in Ref. 11. This is because we have used the complete wave functions whereas the values of Donahue *et al.*[11] were produced with the partial listing from Ref. 13.

The Schmidt value for the $g\frac{9}{2}$ neutron orbital is -1.91 μ_N. The deviation between this and the measured value can be attributed to the following: (1) magnetic core polarization from the excitation of the $\pi h\frac{11}{2}$ and $\nu i\frac{13}{2}$ core particles to their respective spin-orbit partners above the closed shell, (2) the small two-body spin-orbit interaction, and (3) any deviation in the orbital magnetic moment from the free nucleon value. Petrovich[14] has calculated the magnetic moments for several single particle orbitals in the ^{208}Pb region using an effective operator formalism. He calculates the core polarization contribution using a

TABLE I. Summary of magnetic moment calculations.

Nucleus	J^{π}	μ(exp)[a]	Extracted $\mu(2g\frac{9}{2})$ Pure configuration	Kuo-Herling	Ma-True
^{210}Pb	8^+	$-2.50(4)$	-1.40	-1.46	-1.44
^{210}Bi	7^-	$+2.11(5)$	-1.36	-1.39	-1.38
^{210}Bi	5^-	$+1.53(5)$	-1.32	-1.33	-1.40

Nucleus	J^{π}	μ(exp)[a]	Calculated moment Pure configuration	Kuo-Herling	Ma-True
^{210}Bi	1^-	$-0.0440(1)$	$+0.296$	$+0.025$	-1.01

[a]All moments in units of μ_N.

zero range force for the interaction between the valence particles and the core and assumes an anomalous orbital g factor of -0.06 for the neutron. His result of $-1.42\ \mu_N$ for the $2g\frac{9}{2}$ neutron is in good agreement with our measured value.

B. Lifetime measurements

Using the lifetimes of the 8^+ and 6^+ states, the $B(E2)$ values were calculated for the two transitions. We use transition energies of 82(5) and 97.9(1) keV and total conversion coefficients of 15.2 and 7.13 (Ref. 15) for the $8^+\rightarrow6^+$ and $6^+\rightarrow4^+$ transitions, respectively. For the energy range of the former the quantity $(1+\alpha_{\rm tot})E_\gamma^5$ is virtually a constant and therefore the uncertainty in this transition energy has little effect on the $B(E2)$ value. The resulting $B(E2)$ values are 46(5) e^2fm^4 for the $8^+\rightarrow6^+$ transition and 158(20) e^2fm^4 for the $6^+\rightarrow4^+$ transition. The reduced $E2$ matrix element

$$\langle 6^+||M(E2)||8^+\rangle=28(1)\ e\,\text{fm}^2$$

can be used to extract the reduced matrix element for the $2g\frac{9}{2}$ neutron.

Again we use the wave functions of Kuo and Herling[12] and the matrix elements given by Donahue *et al.*[11] to calculate the contributions of admixtures in the 8^+ and 6^+ states. We obtain

$$\langle g\tfrac{9}{2}||M(E2)||g\tfrac{9}{2}\rangle=-39(2)\ e\,\text{fm}^2\ ,$$

which is in good agreement with the value from ^{210}Bi of $-38(4)\ e\,$fm^2. We can also use our $B(E2)$ value to extract the quadrupole moment for the $2g\frac{9}{2}$ neutron orbital as $-29(2)$ fm^2. A similar analysis for $\langle 4^+||M(E2)||6^+\rangle$ yields $-48(6)\ e\,$fm^2 for $\langle g\frac{9}{2}||M(E2)||g\frac{9}{2}\rangle$ and $-35(6)$ fm^2 for the quadrupole moment. However, for this case the number of corrections for admixtures in the wave functions is larger, making the extracted single particle quantities more uncertain.

Using the radial matrix elements of Astner *et al.*[16] our value of the quadrupole moment, from the $8^+\rightarrow6^+$ transition, gives an effective charge of 0.88(5) e, which for this neutron orbital can be equated with the polarization charge. This is comparable to the value of 0.96(4) e obtained for the $i\frac{13}{2}$ neutron orbital. An orbital dependence is expected and can be explained in terms of a shape-vibrational model for particle-core coupling,[16,17] with the coupling term proportional to a form factor

$$k(r)=-r\,df(r)/dr$$

where $f(r)$ gives the radial dependence of the central nuclear potential. On the other hand, one finds for the proton $\pi h\frac{9}{2}$ orbital a polarization charge of only 0.53(4) e. Blomqvist[17] has shown that this feature of effective charges in the ^{208}Pb region can be explained by expressing the polarization charge in terms of both isoscalar and isovector components.

The additivity of effective charges suggests that our value of the quadrupole moment of the $2g\frac{9}{2}$ neutron orbital represents the value for the ground state of ^{209}Pb. Proetel *et al.*[2] have performed calculations of this state allowing for admixtures of the 2^+ and 3^- core states of ^{208}Pb. Their wave function

$$|^{209}\text{Pb,g.s.})\rangle=0.95\,|g\tfrac{9}{2}\rangle+0.13\,|2^+\otimes g\tfrac{9}{2}\rangle+0.24\,|3^-\otimes j\tfrac{15}{2}\rangle+\cdots$$

yields a value of $-35(3)$ $e$fm^2 for the reduced $E2$ matrix element using experimental values for the core states and zero charge for the $\nu g\frac{9}{2}$ orbital. The second term in the wave function provides almost 90% of this value. Their result is in good agreement with our measured value of $-39(2)$ $e$fm^2.

Our data on the isomers of the $\nu(g\frac{9}{2})^2$ configuration in ^{210}Pb represent the first measurements of the electromagnetic properties of this single particle neutron orbital which do not depend on measurements of proton properties. The results reinforce the applicability of the additivity of anomalous g factors and effective charges in the ^{208}Pb region. This is reflected both in the magnetic moment measurements, where we observe that the g factors of the 6^+ and 8^+ states are equal, and in the agreement between our value of the $\nu(2g\frac{9}{2})$ magnetic moment and that extracted from the $\pi(h\frac{9}{2})\nu(g\frac{9}{2})$ isomers in ^{210}Bi. A similar situation is observed in the consistency of the reduced matrix elements, $\langle g\frac{9}{2}||M(E2)||g\frac{9}{2}\rangle$, of the present work and those from ^{210}Bi. Furthermore, these results provide a good test of the shell model wave functions calculated for these "two-particle" nuclei and thereby of the nucleon-nucleon interactions used to generate them.

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