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g factors of the 9^- and 12^+ isomeric states in ^{200}Pb[†]

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The g factors of the 9^- state (2.236 MeV, $\tau = 694$ nsec) and the 12^+ state (~3.1 MeV, $\tau = 228$ nsec) in ^{200}Pb have been measured as $g(9^-) = -0.030(3)$ and $g(12^+) = -0.157(6)$ by a time-differential perturbed-angular-distribution technique. The states were populated by ^{197}Au(^{7}Li, $4n$)^{200}Pb(9^-) and ^{197}Au(^{6}Li, $3n$)^{200}Pb(12^+) reactions with pulsed lithium beams. An in-beam superconducting magnet supplied a field of ~60 kG. The 9^- state g factor is in agreement with the additivity value obtained from empirical single-particle g factors for a $(i_{13/2}{}^{-1}, f_{5/2}{}^{-1})9^-$ configuration and consistent with a small anomalous orbital contribution δg_l for the neutron. The g factor for the 12^+ state in ^{200}Pb is in surprisingly good agreement with those for the $(i_{13/2})^{-2}12^+$ state in ^{206}Pb and the $i_{13/2}{}^{-1}$ state in ^{205}Pb, in view of the possible existence of number-dependent effects.

[NUCLEAR REACTIONS ^{197}Au(^{7}Li, $4n$)^{200}Pb(9^-), ^{197}Au(^{6}Li, $3n$)^{200}Pb(12^+) $E_{\text{Li}} = 34$ MeV, pulsed beam, measured spin rotation in $B = 60$ kG, deduced g.]

INTRODUCTION

Considerable progress has been made from magnetic-moment studies of high-spin states in the Pb region towards the understanding of effective magnetic-moment operators for single nucleons which include the core polarization and mesonic contributions.[1] This information is often not obtainable from single-particle states but must be extracted from multiparticle states using the additive properties of the magnetic operators. Thus, in this respect, additivity and any violations thereof are important in addition to their intrinsic interest. The mesonic contribution to the proton magnetic moment has been shown to manifest itself by an anomalous orbital g factor of $g_l = 1.13(2)$.[2] The corresponding mesonic contribution for the neutron is not well determined. The g factor of the 9^- level ($\tau = 694$ nsec) in ^{200}Pb is expected to be particularly sensitive to the orbital δg_l for the neutron since the level is believed to be a rather pure $(i_{13/2}{}^{-1}, f_{5/2}{}^{-1})9^-$ two-neutron configuration[3,4]; for such a level the spin-related contributions nearly cancel because of the $(j_1 = l_1 + \frac{1}{2},\ j_2 = l_2 - \frac{1}{2})\ J = l_1 + l_2$ stretched configuration.[2] In ^{200}Pb, the g factor of the $(i_{13/2})^{-2}12^+$ level ($\tau = 228$ nsec) also allows a good test of the additivity relation for neutrons when compared with the $i_{13/2}$ hole moments determined in ^{206}Pb[5] and ^{205}Pb.[6] The present paper reports on a measurement of these g factors using pulsed Li beams and an in-beam superconducting magnet together with (Li, xn) reactions. Because these neutron g factors are small, the high field of this magnet is important for the required precision. A brief report of these results has been made previously.[7] Recently, an independent measurement of the 9^- state g factor employing the ^{198}Hg(α, $2n$)^{200}Pb reaction has been published.[8]

EXPERIMENTAL

To measure the g factors of the ^{200}Pb 12^+ and 9^- states, time-differential perturbed-angular-distribution measurements were made with pulsed lithium beams from the Stony Brook tandem accelerator which were incident on a thick gold target placed in a superconducting magnet, as shown in Fig. 1. The magnet, which has been described elsewhere,[9] is a split solenoid design with a Nb-Ti winding capable of 62-kG fields when operated at 4.2 K. The target, however, was at room temperature. The field strength has been calibrated to ±0.5% by flip coil measurements and also by observing the spin precessions of the 8^+ state in ^{210}Po [$g = 0.910(5)$] and the $\frac{5}{2}^+$ state in ^{19}F [$g = 1.442(3)$]. A collimator close to the target restricted the region of the target exposed to the beam to the homogeneous central region of the field. The orbit of the projectiles was determined by numerically integrating their equation of motion in the fringe field of the magnet. Two Ge(Li) detectors (12% relative efficiency) were placed at ± 45° to the calculated final beam direction. The time resolution of these detectors relative to the beam pulse signal was ~ 6 nsec full width at half maximum in the region of the 777-keV peak. The pulsed beam had a repetition time of 2 μsec with a width of < 2 nsec.

The 12^+ state was populated by the ^{197}Au(^{6}Li, $3n$)-^{200}Pb reaction, although rather weakly, using a 34-MeV pulsed lithium beam. The γ-ray energy spectra and the ^{200}Pb decay scheme are shown in Fig. 2. The 777-keV $10^+ \rightarrow 9^-$ transition was used to measure the 12^+ state g factor, since the highly converted, low-energy $12^+ \rightarrow 10^+$ transition was not observed. The time-delay spectra of the 777-keV photopeak and an appropriate Compton background that was subtracted, were measured simultaneously for both detectors. The usual ratio $R(t) = [N(-45°) - N(+45°)]/[N(-45°)+N(+45°)]$ and the least-squares fit to the data are shown in the upper part of Fig. 3. The fit yielded a g factor for the ^{200}Pb 12^+ state of $g(12^+) = -0.157(6)$; the estimated diamagnetic and Knight-shift corrections of $(0.0 \pm 1.0)\%$ have been included in the error. The observed γ-ray anisotropy $A_2 \approx 0.07$ was substantially less than the value of 0.29, which corresponds to full alignment.

The 9^- state was populated by the ^{197}Au(^{7}Li, $3n$)-^{200}Pb reaction (see Fig. 2) using a 34-MeV pulsed ^{7}Li beam. This reaction provides less feeding from the 12^+ state than the (^{6}Li, $3n$) reaction because, while the angular momentum available is about the same, the former reaction has a $|Q|$ value which is 7.2 MeV greater and therefore favors the population of the lower energy 9^- state. Time spectra were obtained for the 420-, 462-, and 1026-keV γ rays in the stretched cascade following the unobserved $9^- \rightarrow 7^-$ transition. The $R(t)$ for the 462-keV $4^+ \rightarrow 2^+$ transition is shown in Fig. 3 with a least-squares fit to the data. For all observed transitions the $R(t)$ of the 9^- state is influenced by the unknown precession of the 7^- state ($\tau = 63$ nsec). A careful study of the influence of this precession shows that the amplitude and phase of $R(t)$ can be affected, but that the frequency in the observed time region is not appreciably changed.[10] The fit thus yields $|g| = 0.030(3)$ for the g factor of the ^{200}Pb 9^- state. Using the experimentally measured phase and assuming a small negative $g(7^-)$ which is consistent with a $(i_{13/2}{}^{-1}, p_{1/2}{}^{-1})7^-$ configuration[3] and with the measurement $g(7^-$ in $^{206}\text{Pb}) = -0.0217(4)$,[11] the deduced sign is negative, giving $g(9^-) = -0.030(3)$. This result is in agreement with an independent measurement[8] made via the ^{198}Hg(α, $2n$)^{200}Pb reaction; for that measurement, a liquid target provided near maximum anisotropy although the magnetic field was lower than that of the present experiment.

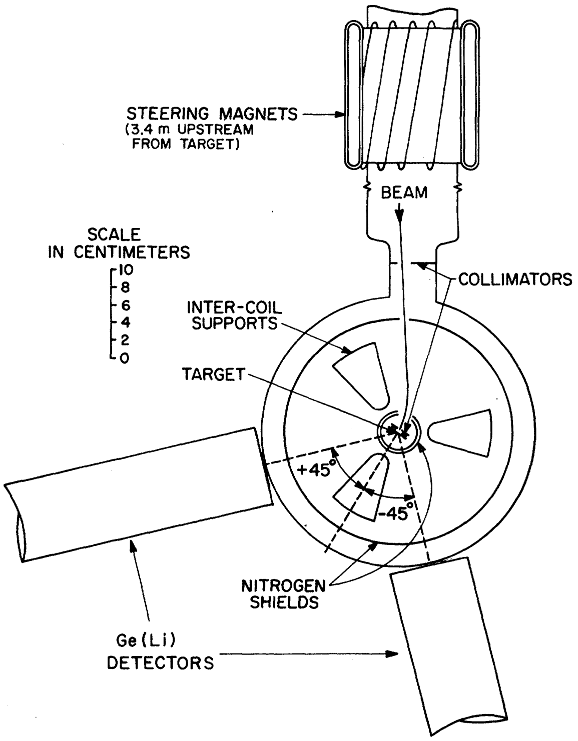

FIG. 1. Experimental arrangement for the pulsed beam-γ perturbed-angular distribution measurements as viewed in the mid-plane of the superconducting magnet.

DISCUSSION

12^+ state

From single-particle additivity considerations, the g factors of $(\nu i_{13/2})^{-n}$ states [specifically, $|(\nu)^{-m}0^+, (\nu i_{13/2})^{-n}J^+\rangle$ configurations] in Pb nuclei should equal the g factor of the $i_{13/2}$ neutron-hole state. Although core-polarization contributions[12] are expected to be mainly of renormalized character and thus additive, they can change for the various Pb nuclei because the $\nu i_{13/2} \rightarrow \nu i_{11/2}$ core polarization decreases with an increase in n (similar to blocking for holes) and because other neutron-hole orbitals $(\nu)^{-m}0^+$ allow additional $(j = l + \frac{1}{2}) \rightarrow (j = l - \frac{1}{2})$ core excitations. This is often referred to as the core-polarization number dependence. The 12^+ state in ^{200}Pb, which is dominantly $(\nu i_{13/2})^{-2}$, has six additional neutron holes ($m = 6$) compared to the same state in ^{206}Pb ($m = 0$). An exact calculation of the core-polarization difference between ^{200}Pb and ^{206}Pb is difficult because of the uncertainty in the orbital populations of these $m = 6$ holes. Nonadditive effects such as seniority- and J-dependent contributions to the core polarization may be possible.[13]

A summary of g factor measurements for $(\nu i_{13/2})^{-n}$ states in Pb nuclei is given in Table I. These g factors, which would equal the $i_{13/2}$ neutron-hole g factor for perfect additivity, are surprisingly constant over a wide range of neutron-hole number $(m + n)$, although the above nonadditive effects are expected to exist. This result is very similar to the constancy of the g factors which has been observed for the $(\pi h_{9/2})^2$ states [specifically, $|(\nu)^{-m}0^+, (\pi h_{9/2})^2(J = 8)^+\rangle$ configurations] in Po nuclei from ^{204}Po ($m = 6$) to ^{210}Po ($m = 0$).[14] This situation for the Pb and Po isotopes indicates that the contribution from excitations of the neutron holes is smaller than the experimental error of the g factors; and it suggests, although, rather weakly, since the dominant configuration for ^{200}Pb is $(\nu i_{13/2})^{-2}$, that the n dependence of the $\nu i_{13/2}$

$\rightarrow \nu i_{11/2}$ core-excitation contribution is also small. A similar situation for a larger variation in n is known for the $(\pi h_{9/2})^n$ states in the $N = 126$ nuclei where the expected n dependence or core-polarization blocking is not observed.[1,15] A quantitative evaluation of the core-polarization number dependence awaits a complete calculation of the wave functions for the Pb nuclei. Admixtures involving the collective 3^- state in ^{208}Pb such as $3^- \otimes (\nu f_{7/2})^{-1}$ should also be considered for the states that contain the $(\nu i_{13/2})^{-1}$ orbitals.

9^- state

The additivity relation for the 9^- state can now be checked using the present neutron-hole $i_{13/2}$ g factor $[-0.157(6)]$ obtained for the ^{200}Pb 12^+ state together with the known neutron-hole $f_{5/2}$ g factor[16] $[+0.316(12)]$ in ^{207}Pb. For a pure $(i_{13/2}{}^{-1}, f_{5/2}{}^{-1})9^-$ neutron-hole configuration, which is expected[3,4], the calculated g factor is $-0.026(4)$, in excellent agreement with the measured value of $-0.030(3)$. Assuming that nonadditive effects are small for the 9^- state in ^{200}Pb, as was observed for the 12^+ state, the present 9^- g factor can be used to demonstrate the purity of the 9^- state. Using a wave function which includes the two energetically reasonable configurations,

$$|9^- \; {}^{200}\mathrm{Pb}\rangle = (1-\alpha^2)^{1/2} (i_{13/2}{}^{-1}, f_{5/2}{}^{-1})9^- + \alpha (i_{13/2}{}^{-1}, f_{7/2}{}^{-1})9^-$$

a value of $\alpha^2 \lesssim 0.010$ is deduced from a comparison of the calculated g factor with the experimental value.

The g factor of a $(i_{13/2}{}^{-1}, f_{5/2}{}^{-1})9^-$ state is sensitive to the anomalous orbital contribution of the neutron δg_l because the spin contributions including part of the core polarization nearly cancel when the neutrons occupy orbitals with opposing spin momenta as the $(j_1 = l_1 + \frac{1}{2},\ j_2 = l_2 - \frac{1}{2})\ J = l_1 + l_2$ stretched configurations. This sensitivity to δg_l is reflected in the equation,

$$g(9^-) = \delta g_l + \tfrac{1}{63} (g_s - \delta g_l) + \tfrac{1}{9} [\delta\mu_{1\mathrm{st}} (i_{13/2}{}^{-1}) + \delta\mu_{1\mathrm{st}} (f_{5/2}{}^{-1})] \,.$$

Arima and Huang-Lin,[17] using the matrix elements of Kuo, have calculated the first-order $M1$ core-

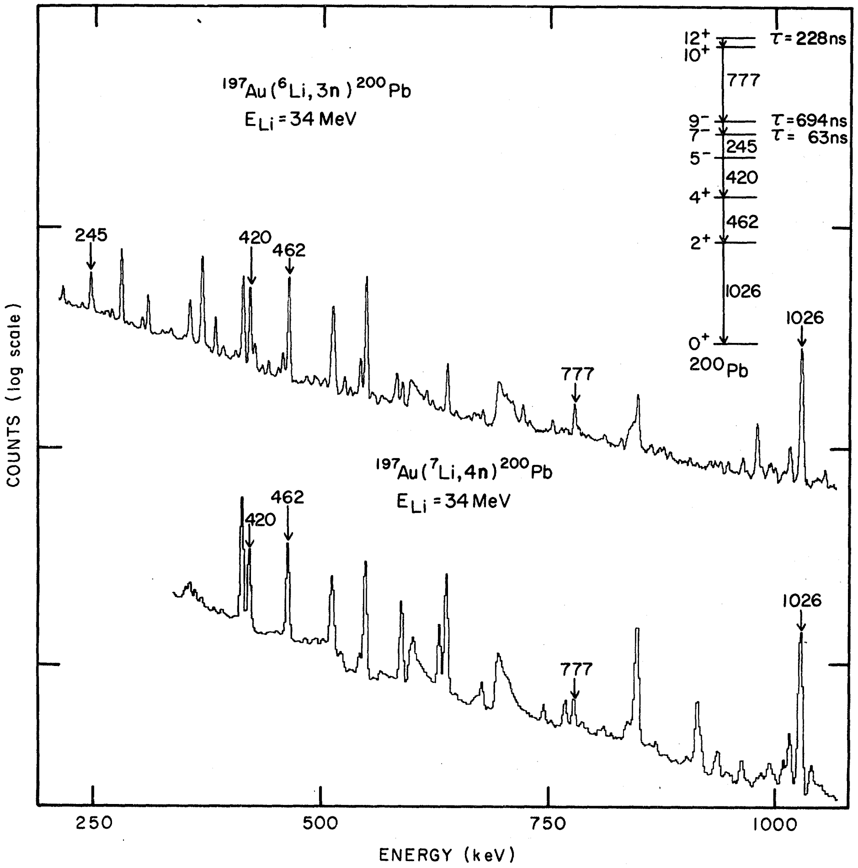

FIG. 2. Singles γ-ray spectra as observed in a Ge(Li) detector for the ^{197}Au(^{6}Li, $3n$)^{200}Pb and ^{197}Au(^{7}Li, $4n$)^{200}Pb reactions at $E_{\mathrm{Li}} = 34$ MeV. The relevant γ-ray decay scheme in ^{200}Pb is shown in the upper right corner.

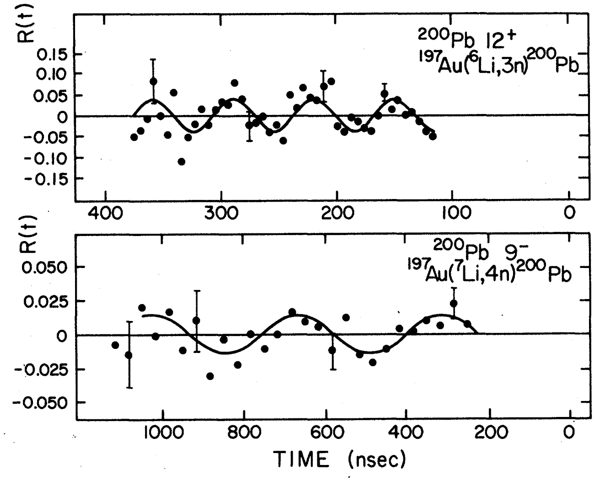

FIG. 3. Experimental results for the ratio $R(t)$ (see text) as a function of time relative to the beam pulse. The upper data represent the magnetic-moment measurement of the ^{200}Pb 12$^+$ state and the lower data that of the ^{200}Pb 9$^-$ state. The solid curves display the least-squares fits to the data.

polarization corrections $\delta\mu_{1st}$ for the $i_{13/2}$ and $f_{5/2}$ neutron-hole states in ^{207}Pb. Taking their values $\delta\mu_{1st}(i_{13/2}) = 0.85\mu_N$ and $\delta\mu_{1st}(f_{5/2}^{-1}) = -0.46\mu_N$, and using the single-particle g_s value of -3.826 for the neutron in the above equation, an anomalous orbital g factor for the neutron of $\delta g_l(n) = -0.01(1)$ is deduced, allowing for a 10% error in the calculated $\delta\mu_{1st}$. Khanna and Hausser,[18] using slightly different energy denominators and including a 3$^-$ admixture into the $i_{13/2}$ neutron-hole state, calculate $\delta\mu_{1st}$ of 1.13 and $-0.44\mu_N$ for the $i_{13/2}$ and $f_{5/2}$ holes, respectively, which leads to a $\delta g_l(n) \approx -0.046(13)$. Higher-order corrections[19] which are expected to be small have been neglected in these evaluations of δg_l.

TABLE I. Summary of the measured g factors of $i_{13/2}$ neutron-hole states in Pb nuclei.

Nucleus	J^π	Dominant neutron configuration	g factor	Ref.
^{206}Pb	12^+	$(\nu i_{13/2})^{-2}\,12^+$	$-0.155(4)$	5
^{205}Pb	$\frac{13}{2}^+$	$(\nu)^{-2}0^+,\ (\nu i_{13/2})^{-1}\,\frac{13}{2}^+$	$-0.150(6)$	6
^{200}Pb	12^+	$(\nu)^{-6}0^+,\ (\nu i_{13/2})^{-2}\,12^+$	$-0.157(6)$	Present work

The 9$^-$ g factor observed in the present experiment thus appears consistent with an anomalous orbital g factor δg_l of the neutron, which is somewhat less than the corresponding anomaly deduced for the proton of $\delta g_l(p) = +0.13(2)$.[2] The present $\delta g_l(n)$ which is consistent with information[1] from other neutron orbitals, is also less than the value adjusted for the neutron excess $\delta g_l(n) = (Z/N) \times \delta g_l(p)$ as deduced from the Fermi gas model by Wahlborn and Blomqvist.[20] It is apparent, however, that even in the very favorable case of a stretched two-neutron configuration with opposite spin moments, more reliable calculations of the core-polarization contributions are needed in order to extract the anomalous orbital moment of the neutron more accurately and to definitely establish its existence.

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