2.102-MeV level in ^{206}Hg and the spin gyromagnetic ratio of the 3-s proton

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The nuclear gyromagnetic ratio, spin parity, and lifetime of the ^{206}Hg 2.102-MeV level have been measured to be $g=1.09\pm0.01$, $J^{\pi}=5^{-}$, and $\tau_m=3.1\pm0.3$ μsec, respectively. The level was populated via the ^{204}Hg$(t,p)^{206}$Hg reaction. The perturbed angular distribution technique was employed to measure g. Using known data, the spin gyromagnetic ratio for a proton in the 3s orbital has been deduced: $g_s(\pi;3s)=3.6\pm0.3$. For the 1.068-MeV level, $J^{\pi}=2^{+}$.

NUCLEAR REACTIONS ^{204}Hg(t,p), $E_t=16$ MeV. For ^{206}Hg ($E_x=2.102$ MeV), measured $\tau_m=3.1\pm0.3$ μsec, $g=1.09\pm0.01$, and $J^{\pi}=5^{-}$. For $E_x=1.068$ MeV, $J^{\pi}=2^{+}$. Deduce $g(\pi;3s)=3.6\pm0.3$.

I. INTRODUCTION

Nuclei near (and including) ^{208}Pb are an important testing ground for ideas about nuclear structure, as is well known. The predictions of spherical shell-model calculations have been very successful here. The nucleus ^{206}Hg is two proton holes away from being a doubly closed-shell nucleus, and expectations are that the spherical shell-model should give a good description of this nucleus. There are two reported measurements of level properties in ^{206}Hg: Hering, Puchta, Trautman, McGrath, and Bohn[1] used ^{18,17}O-induced reactions on ^{204}Hg and identified γ rays from states at 1.068 and 2.102 MeV in ^{206}Hg. Spin-parity values $J^{\pi}=2^{+}$ and 4^{+}, respectively, were proposed for these two states on the basis of theoretical arguments. Flynn, Hanson, Poore, and Orbesen[2] observed excited states of ^{206}Hg using the ^{204}Hg$(t,p)^{206}$Hg reaction. Reaction protons were detected with a magnetic spectrometer and differential cross sections were measured. Some 21 states were located below $E_x=4.88$ MeV with an accuracy of ±30 keV. The first two excited states were at $E_x=1.09$ and 2.12 MeV. States at 1.09 and 3.63 MeV were assigned $J^{\pi}=2^{+}$ and 0^{+}, respectively.

The assignment[1] $J^{\pi}=4^{+}$ for the 2.102-MeV level is in conflict with the shell-model prediction,[3,4] which gives for this level $J^{\pi}=5^{-}$ and a major configuration $h_{11/2}{}^{-1}s_{1/2}{}^{-1}$. We note the estimated lifetime of this level is such that its nuclear gyromagnetic ratio g can be measured using perturbed angular distribution techniques. Rough information on the orbital gyromagnetic ratio of the $h_{11/2}{}^{-1}$ proton $g_l(\pi h_{11/2}{}^{-1})$ is available from such a measurement without manipulation because the spins are antiparallel; we expect $g(5^{-})\sim g_l$ (free), where g_l (free) is the orbital g factor of the proton. Furthermore, $g(\pi h_{11/2}{}^{-1})$ has recently been measured[5]; thus the effective value of the spin gyromagnetic ratio for the $3s^{-1}$ proton $g_s(\pi s_{1/2}{}^{-1})$ can be extracted from $g(\pi h_{11/2}{}^{-1}s_{1/2}{}^{-1})$ using additivity of magnetic moments (the generalized Landé formula). To investigate these points, we have studied the 2.102-MeV level in ^{206}Hg using the ^{204}Hg(t,p) reaction and the techniques of γ-ray spectroscopy. In particular, we have employed the time-differential perturbed angular distribution technique to measure the g factor of the 2.102-MeV level.

II. EXPERIMENT

States in ^{206}Hg were populated with the ^{204}Hg$(t,p)^{206}$Hg reaction. Incident tritons, accelerated to an energy $E_t=16$ MeV by the Los Alamos National Laboratory Van de Graaff accelerator, struck a thick target of liquid ^{204}Hg. Typical beam currents were ~ 1 nA. Resulting γ radiation was counted in Ge solid state detectors. Data were accumulated with the data-acquisition system at the Van de Graaff facility; both direct and event-mode recording of data were utilized as required.[6] Detailed data analysis was carried out at Lawrence Livermore National Laboratory, using the data analysis system of the Nuclear Properties Group[7] and the set of integrated data reduction programs due to Stöffl.[8] The experiments were performed over a period of time with the consequence that a variety of target chambers, detectors, and experimental arrangements have been employed. Descriptions of the experimental arrangements are typical. Three distinct arrangements were used to study the reaction-produced γ radiation. First, pulse-height distributions of direct γ radiation and of γ-γ-time coincidences were recorded. Second, the decay with time of the γ radiation was studied using the pulsed-beam technique. Last, g factors of nuclear levels were measured using time-differential perturbed angular-distribution techniques.

Initially, the γ-ray pulse-height distribution was studied. A thick ^{204}Hg target was located at the center of a cylindrical target chamber, 10.0 cm in diameter. The Al chamber wall thickness was 0.5 mm and its height was 4 cm. The target was bombarded with 16-MeV tritons and the pulse-height distribution of the resulting γ radiation was measured with γ-ray spectrometers composed of Ge detectors, together with ancillary electronics. The detectors could be rotated about the center of the chamber in order to collect angular-distribution data. Based on energy measurements, most of the radiation produced in the irradiation of ^{204}Hg with 16-MeV tritons is associated with ^{205}Tl. However, two γ rays in the spectrum are associated with ^{206}Hg on the basis of their energies: E_γ (keV)$=1034.2\pm0.2$ and 1068.2 ± 0.2. These two γ rays correspond to the decay of the 1.068- and 2.102-MeV levels in ^{206}Hg, as first reported by Hering *et al.*[1] who quote E_γ (keV)$=1034\pm1$ and 1068 ± 1. The γ-ray angular distributions were parametrized by the expression

$$W(\theta)=I_\gamma[1+A_2P_2\cos(\theta)]\ ;$$

the coefficients A_2 are given in Table I. The matrix of γ-ray pulse heights in time coincidence was collected with two γ-ray detectors located at 90° and 270° with respect to the incident beam direction. The 1.034- and 1.068-MeV γ rays were found to be in prompt time coincidence. The spectrum of γ radiation in coincidence with the 1068-keV γ ray was examined for evidence of γ rays other than the 1034-keV γ ray. No evidence was found for additional γ-ray transitions in ^{206}Hg with energies $E_\gamma > 100$ keV; however, the number of counts in the spectrum was relatively small.

The pulsed beam technique was used to look for isomeric levels with mean life τ in the interval 50 nsec$\leq\tau\leq 5\ \mu$sec. Pulse-height distributions were collected with the beam on target (prompt spectra) and in the interval between beam pulses (delayed spectra). Both the 1.068- and 1.034-MeV γ rays exhibited a lifetime of a few μsec. However, the 1.034-MeV γ ray was only evident in the delayed spectrum, while the 1.068-MeV γ ray was observed in both spectra; this proves that the first two known excited states in ^{206}Hg have energies 1068.2 and 2102.3 keV. The previous result[1] was based upon the intensity of reaction-produced γ radiation.

Lastly, the g factor and lifetime of the 2.102-MeV level together with γ-ray angular distributions were measured using the time-differential perturbed angular distribution technique. The ^{204}Hg target was located in a homogeneous magnetic field, $H=3.26\pm0.03$ kG, directed normal to the incident beam direction. The target was in air, 2 cm from the end of the evacuated beam line. A pulsed triton beam of energy $E_t=16$ MeV struck the target. The beam burst width was ~ 1 nsec, and the burst interval was 12.8 μsec. The resulting γ radiation was

TABLE I. Angular distribution coefficients.

E_γ (keV)	E_i (keV)	E_f (keV)	A_2[a]	A_2[b]
1034	2102	1068	0.74 ± 0.20	0.38 ± 0.05
1068	1068	0	0.24 ± 0.13	0.22 ± 0.02

[a]Obtained from the ^{204}Hg$(t,p)^{206}$Hg reaction at $E_t=16$ MeV.

[b]Obtained from the time-differential perturbed angular distribution measurement.

detected in two Ge detectors located at 135° and 225° with respect to the incident beam direction and in the plane normal to the magnetic field direction. The time distribution of delayed radiation measured for the full energy absorption peak of both the 1.034- and 1.068-MeV γ radiation is illustrated in Fig. 1. Each distribution was parametrized by the expression:

$$\text{Counts}(t)=e^{-\lambda t}A_0[1+e^{-\omega' t}A_2P_2 \times(\cos(\omega_L t+\phi))] .$$

Results for A_2 are given in the last column of Table I. The positive sign of the angular distribution coefficient is taken from the results given in Table I, column 4. We found

$$\lambda^{-1}=\tau_m(2.102)=3.1\pm0.3\ \mu\text{sec} .$$

These data are consistent with the inverse relaxation time $\omega'=0$, as expected from the work of Maier et al.[9]

Spin-parity assignments for these levels will be deduced from these data, together with the result $\tau_m(1.068)<30$ nsec extracted from our coincidence data. Other data needed are the radiative widths in Weisskopf units for the 1.034-MeV γ ray, for different supposed multipolarity (Table II), and a summary of predicted angular distribution coefficients (Table III). The latter will be compared to the data contained in Table I. Assuming a Gaussian population of magnetic substates, an assignment of $J=2$ to the 1.068-MeV level is straightforward. The ground state of ^{206}Hg has $J^\pi=0^+$ because it is an even-even nucleus. Lifetime considerations restrict the spin of the excited level to $J\leq2$, and $J=1$ is eliminated by the sign of the angular distribution coefficient, which is negative for a $1\rightarrow0$ transition, while we measure $A_2(1.068)=+0.22\pm0.02$. Thus, $J(1.068)=2$, in agreement with the assignment $J^\pi=2^+$ of Flynn et al.[2]

Consider now the 2.102-MeV level. The measured lifetime, $\tau_m=3.1\pm0.3$ μsec, restricts $\Delta L(2.102\rightarrow1.068)\leq3$; the only model independent statement that can be made about $J(2.102)$ is that $J(2.102)\leq5$. The angular distribution coefficients A_2 (Table I) of the 1.034- and 1.068-MeV γ radiation are consistent with a Gaussian population of magnetic substates produced in the reaction and the γ-ray cascade spin sequence $5\rightarrow2\rightarrow0$, with no multipole mixing. The measured ratio of coefficients

$$A_2(1.068)/A_2(1.034)=0.58\pm0.09 ,$$

while, using the data of Table III,

$$A_2(2\rightarrow0)/A_2(5\rightarrow2)=0.6$$

and

$$A_2(2\rightarrow0)/A_2(4\rightarrow2)=1.0 .$$

The measured lifetime $\tau_m(2.102)$ corresponds to $\Gamma(E3)/\Gamma_W=0.18$.

The nuclear g factor of the state is obtained from the measured Larmor frequency $\omega_L=17.18\pm0.06$ μsec^{-1}, and the magnetic field measurement H (kG)$=3.26\pm0.03$. The magnetic field was measured with a Hall probe, calibrated with two standard magnets near 3 kG. This results in

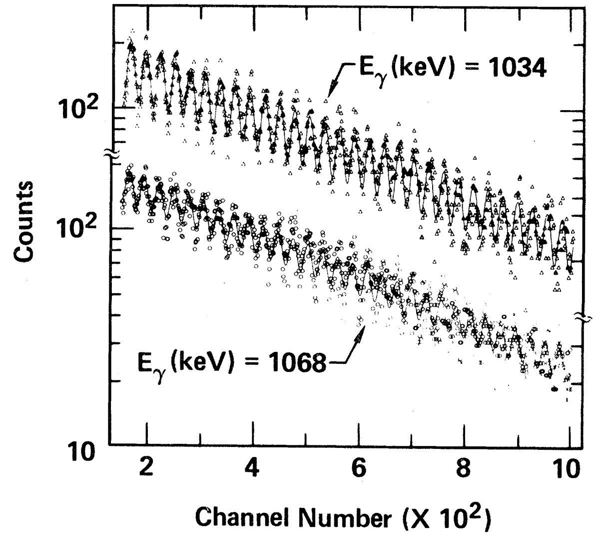

FIG. 1. Yield of the 1.034- and 1.068-MeV γ rays as a function of time. Each channel of the horizontal scale corresponds to 6.88 nsec. The smooth curve drawn through the data is the result of a least-squares fit to the expression for the decay,

$$\text{Counts}(t)=A_0e^{-\lambda t}[1+A_2e^{-\omega' t}P_2(\cos(\omega t+\phi))] .$$

TABLE II. Radiative widths in Weisskopf units for the 1.034-MeV γ ray. For the 2.102-MeV level, $\tau_m=3.1\pm0.3$ μsec.

	Multipolarity			
	$M2$	$E2$	$M3$	$E3$
$\Gamma(1.034)/\Gamma_W$	3.5×10^{-4}	3.1×10^{-6}	2.09×10^{1}	1.78×10^{-1}

TABLE III. Theoretical angular distribution coefficients calculated assuming 100% population of the magnetic substate with $m=0$. Possible transitions are identified by the angular momentum label. No multipole mixing is permitted.

$J_i \rightarrow J_f$	$5\rightarrow 2$	$4\rightarrow 2$	$2\rightarrow 0$	$1\rightarrow 0$	$5\rightarrow 2\rightarrow 0$[a]	$4\rightarrow 2\rightarrow 0$[a]
$A2$	0.83	0.51	0.71	-1.00	0.48	0.51

[a]The $2\rightarrow 0$ transition is observed.

$g=\omega_L/H=1.10\pm 0.01$. The measured g factor has to be corrected for both the Knight shift and diamagnetic shielding of the magnetic field at the nucleus. The Knight shift correction[10] for Hg in Hg is 2.72% and the diamagnetic shielding correction[11] is -1.59%, resulting in a correction of -1.1% to g. Thus,

$$g(^{206}\text{Hg};2.102)=1.09\pm 0.01\ .$$

This value is in agreement with the result expected for the $J^\pi=5^-$ configuration. (See Sec. III.) We conclude that the bulk of experimental evidence and theoretical guidance[1–4] favor the J^π sequence $5^-\rightarrow 2^+\rightarrow 0^+$. The experimental results and theoretical predictions are summarized in Fig. 2.

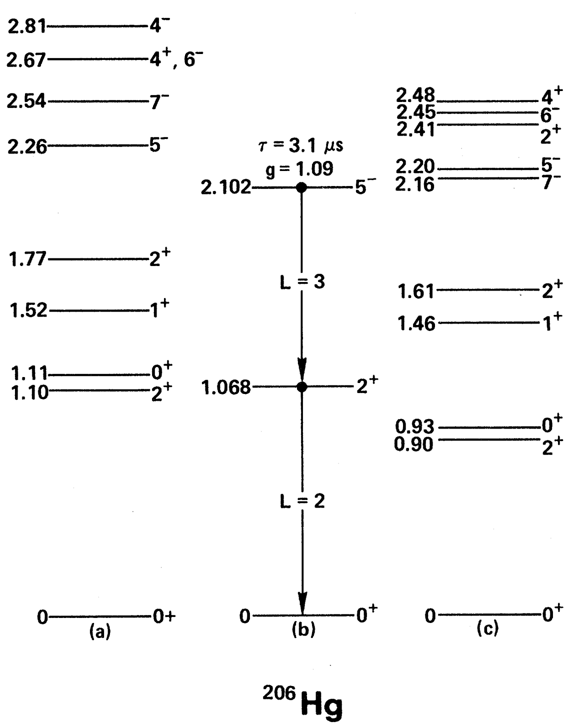

FIG. 2. The experimental level scheme of ^{206}Hg (b) compared with theoretical level schemes (a) and (c). The theoretical descriptions (a) and (c) are due to Refs. 4 and 3, respectively.

III. DISCUSSION

We have determined the spin-parity sequence of the first two known excited states in ^{206}Hg to be $5^-(2.102)\rightarrow 2^+(1.068)\rightarrow 0^+$. The previous suggestion[1] of $J^\pi=4^+$ the 2.102-MeV level was based on a lifetime limit of the 2.102-MeV level, $\tau_m<10$ nsec. We find

$$\tau_m(2.102)=3.1\pm 0.3\ \mu\text{sec}\ .$$

Because of the good agreement between the γ-ray energies quoted here and in Ref. 1, the possibility of a doublet is unlikely. Theoretical calculations of the spectrum of the excited states have been made by Ma and True,[3] and by Herling and Kuo.[4] Partial level schemes are illustrated in Fig. 2. Predictions include a $J^\pi=2^+$ first excited state with a dominant configuration $(s_{1/2}{}^{-1}d_{3/2}{}^{-1})$, while the next state of higher spin has $J^\pi=5^-$ with the dominant configuration $(s_{1/2}{}^{-1}h_{11/2}{}^{-1})$. In approximation 2 of Ref. 4, $E_x(2^+)=1.10$ MeV and $E_x(5^-)=2.26$ MeV. We identify these with the states at 1.068 and 2.102 MeV, respectively. An estimate of the lifetime of the 2.102-MeV level can be made using the amplitudes of the Herling-Kuo calculation and assuming the transition takes place via $(h_{11/2}{}^{-1}s_{1/2}{}^{-1})_{5^-}\rightarrow(d_{5/2}{}^{-1}s_{1/2}{}^{-1})_{2^+}$ with amplitudes A_1 and A_2, respectively. The calculated $B(E3)$ value

$$B(E3)=(125/363\pi)\times e_{\text{eff}}^2\langle d_{5/2}\,|\,r^3\,|\,h_{11/2}\rangle^2(A_1)^2(A_2)^2\ .$$

With $e_{\text{eff}}=2e$, $\langle d_{5/2}|r^3|h_{11/2}\rangle=180$ fm^3 (Ref. 12), $A_1=0.95$, and $A_2=0.30$, $B(E3,5^-\rightarrow 2^+)=1157\,e^2\text{fm}^6=0.45\Gamma_W$. An adjustment in the value of the $s_{1/2}d_{5/2}$ component A_2 will produce better agreement with the experimental value $\Gamma/\Gamma_W=0.18$. Ma and True[3] predict a similar lifetime.

We report $g=1.09\pm 0.01$ for the 2.102-MeV level. This value in itself constitutes good evidence for an enhanced orbital gyromagnetic ratio for the $h_{11/2}$ proton. The 2.102-MeV level has the configuration $(h_{11/2}{}^{-1}s_{1/2}{}^{-1})_{5^-}$: Since the spins of the valence protons point in the opposite directions, the magnetic moment is due almost entirely to the orbital contribution. Thus

$$g(h_{11/2}{}^{-1}s_{1/2}{}^{-1})\sim g_l(\pi h_{11/2})\ .$$

For the free proton g_l (free) $=1$, therefore the value reported here represents a significant enhancement of the orbital magnetism presumably due to meson exchange. The situation is analogous to the value of g_l deduced from the measurement of the g factor of the ^{210}Po level at 2.80 MeV, which has the configuration $(h_{9/2}i_{13/2})_{11^-}$. Blomqvist[12] has pointed out that one must be careful in this interpretation since $\pi s_{1/2}$ has a completely different wave function compared to $\pi h_{11/2}$, and since mesonic and polarization effects may have different radial dependencies.[13]

The dominant configuration of the 2.102-MeV level is $\pi(s_{1/2}{}^{-1}h_{11/2}{}^{-1})_{5^-}$. Since $g(\pi h_{11/2}{}^{-1})$ is known,[5] $g(\pi s_{1/2}{}^{-1})$ can be extracted after correction for configuration mixing. The $(d_{3/2}{}^{-1}h_{11/2}{}^{-1})_{5^-}$ configuration is the only important admixture: Herling and Kuo calculate its amplitude and phase to lie between -0.16 and $+0.28$, depending upon the approximation employed in the calculation. We take ± 0.30 as a reasonable limit to the amplitude. If

$$g_{\exp}[\psi=0.954(h_{11/2}{}^{-1}s_{1/2}{}^{-1}) \pm 0.30(h_{11/2}{}^{-1}d_{3/2}{}^{-1})]=1.09\pm 0.01 ,$$

we find

$$g(\psi=h_{11/2}{}^{-1}s_{1/2}{}^{-1})=1.066\pm 0.01 .$$

In obtaining this result we have used the measured value[14] for the 0.350-MeV ($0.350\rightarrow 0$) transition in ^{207}Tl, $B(M1,\frac{3}{2}\rightarrow\frac{1}{2})=0.025\ \mu_N{}^2$, and the calculated moment[15] $\mu(\pi d_{3/2})=0.67\ \mu_N$. The generalized Landé formula gives

$$g(s_{1/2})=13g(h_{11/2})-12g(h_{11/2}s_{1/2}) .$$

Using $g(\pi h_{11/2}{}^{-1})=1.264\pm 0.024$ (Ref. 5), we have

$$g(\pi s_{1/2})=3.6\pm 0.3 .$$

The error is large since the contribution of the $s_{1/2}$ orbital to the magnetic moment of the 2.102-MeV level is small. Nevertheless, since the 5^- level is a quite pure two-hole state, $g(\pi s_{1/2})$ is well founded. The uncertainty in $g(\pi s_{1/2})$ due to other two-hole admixtures in the wave function of the 5^- level is $\sim\frac{1}{10}$ the quoted error, as judged from the admixture amplitudes calculated by Herling and Kuo.[4] A possible wave function admixture based upon the configuration

$$[\pi d_{5/2}{}^{-2}(2^+)\otimes{}^{208}\text{Pb}(3^-)]_{5^-}$$

contributes even less; we can estimate its probability as 0.004 using the measured values $B(E3, 3^-\rightarrow 0^+)$. Corrections due to admixtures such as

$$[\pi d_{5/2}{}^{-1}\otimes(3^-)]$$

are included in the result since the experimental value[5] $g(\pi h_{11/2})$ which contains these corrections has been used in the calculations outlined above. [For comparison, the ground state magnetic moment of ^{205}Tl, 1.64 μ_N,[16] is in good agreement. The value of $g(\pi s_{1/2})$ cannot be extracted here because the wave function is uncertain.]

The measured $g(\pi s_{1/2})$ differs from the free proton or Schmidt value, $g_s=5.59$. In general, magnetic moments measured in this mass region have been reproduced with an effective magnetic moment operator. For a single proton or proton-hole state with $j=l\pm\frac{1}{2}$,

$$g(nlj)=(g_l+\delta g_l)\pm\frac{(g_s+\delta g_s(nlj))-(g_l+\delta g_l)}{(2l+1)}+g_p(nlj)\frac{1\mp(j+\frac{1}{2})}{4\sqrt{2\pi}j(j+1)} . \tag{1}$$

Compared to the Schmidt expression, (1) the gyromagnetic ratios of the free nucleon, g_l and g_s are modified by δg_l and δg_s, respectively, and (2) a tensor term with the strength parameter g_p is introduced. Important contributions to δg_s and g_p are due to core polarization and can be calculated for a given residual interaction. Petrovich[15] has determined two interaction parameters from a fit to known magnetic moments in this mass region; he then calculates core polarization explicitly with the result $g(3\pi s_{1/2})=3.46$. However, the interaction strength required to reproduce experimental magnetic moments is about twice that required to describe other nuclear properties. Another procedure is to adopt Eq. (1) and determine δg_s and g_p from a fit to the set experimental magnetic moments. Taking into account the dependence of these parameters on the valence-nucleon orbital, Moringaga and Yamazaki[10] find $g(\pi s_{1/2})=4.34$.[17] Both these values are consistent with the value reported here.

Introducing the value reported here into Eq. (1), we find

$$\delta g_s(3s_{1/2}) = g_s(\text{exp}) - g_s(\text{free}) = -2.0 \pm 0.3 \; .$$

Note that this result is independent of the expectation values of l and the tensor term (due to core polarization or otherwise), both of which are zero for an s-orbital nucleon. The result is model independent except that there is the underlying assumption that the magnetic moment can be expressed as a single particle operator. The interpretation of δg_s is an open question. A significant contribution comes from core polarization, as, e.g., the calculations of Petrovich show.

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[17] For nucleon orbits with $l \neq 0$, contributions to the magnetic moment from δg_s and g_p have opposite signs, producing a small net effect. Thus, the uncertainty associated with extracting these parameters from experimental data is large.