Nuclear Magnetic Moment of ^{207}Tl

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(Received 23 July 1985)

The magnetic moment $1.876(5)\mu_N$ of 4.77-min ^{207}Tl, the only heavy nucleus with a doubly magic core plus a single $s_{1/2}$ particle or hole, was measured from the hfs by collinear fast-beam laser spectroscopy at ISOLDE (isotope separator at the CERN synchrotron). The result is of theoretical importance as a test case for core polarization since the nuclear structure is relatively simple and the orbital part of the magnetic moment, including strong pion-exchange contribution, is expected to be zero.

PACS numbers: 21.10.Ky, 21.60.Cs, 27.80.+w, 31.30.Gs

Magnetic moments, along with $M1$ transition probabilities, of nuclei with closed shells of protons and neutrons ± one nucleon provide relatively clean tests for theories of nuclear magnetism. For these nuclei, the effective operator can be written as[1]

$$\boldsymbol{\mu}_{\text{eff}} = (g_s + \delta g_s)\mathbf{s} + (g_l + \delta g_l)\mathbf{l} + g_p[\mathbf{s}\times\mathbf{Y}^2]^{(1)}. \quad (1)$$

The spin and orbital gyromagnetic ratios g_s and g_l are the free-nucleon values; δg_s and δg_l are caused by both core polarization and meson exchange. The last term, arising from the dipole-dipole interaction, is a rank-one tensor product of the spherical harmonic of order two, Y^2, and the spin operator. The influence of core polarization has been studied beginning with the work of Blin-Stoyle, Arima, and Horie,[2] and that of meson exchange with the work of Miyazawa.[3] The latter has been discussed extensively more recently.[4] The extreme cases of doubly magic nuclei plus a single particle or hole that has either a large or a zero orbital angular momentum can distinguish the separate contributions δg_l and δg_s. This was brought to light in the case of $l=5$ for ^{209}Bi (single proton in $h_{9/2}$ orbit), where the pion-exchange contribution with $\delta g_l \approx 0.1$ largely explained the experimental magnetic moment $4.11\mu_N$, the Schmidt limit contributing $2.62\mu_N$, and core polarization[5] (first-order configuration mixing), $0.79\mu_N$, accounting for most of δg_s. For $l=0$, it is seen from (1) that the orbital-moment contribution vanishes. The tensor term is also zero.[4] For this case Arima[1] emphasized the necessity of measuring the magnetic moment of ^{207}Tl, the only known isotope, except ^{3}H and ^{3}He, which is doubly magic with the one particle or hole in an s ground state. Its moment has been deduced indirectly from the $(\pi 3s_{1/2}^{-1}\,\nu 3p_{1/2}^{-1})1^- \to 0^-$ transition rate[6] in ^{206}Tl, and from a decomposition[7] of the g value of the 5^- level in ^{206}Hg which is predominantly $\pi(3s_{1/2}^{-1}\,1h_{11/2}^{-1})$. Here we report a direct measurement from the atomic hfs spectrum.

The major experimental problem for an atomic hfs measurement is production of a sufficient quantity of this 4.77-min radioisotope and preparation of a sample of free atoms suitable for spectroscopy. While this might be done "off-line"[8] from a decay chain starting at ^{227}Ac, a more effective way was sought by "on-line" work at ISOLDE (isotope separator at the CERN synchrocyclotron). The direct spallation yield of thallium isotopes from uranium or thorium targets is low[9] and has its maximum of about 10^6 atoms/s around mass number 190. On the other hand, ^{207}Tl might be accessible via the decay chain

$$^{219}\text{Fr (21 ms)} \xrightarrow{\alpha} {}^{215}\text{At (0.1 ms)}$$

$$\xrightarrow{\alpha} {}^{211}\text{Bi (2.17 min)} \xrightarrow{\alpha(84\%)} {}^{207}\text{Tl (4.77 min)},$$

provided that the mother products remained within the target during their half-lives. With an estimated ^{219}Fr production of 10^9 atoms/s in the 2-μA 600-MeV proton bombardment of a 55-g/cm^2 ThC$_2$ target, we obtained a ^{207}Tl flux of about 10^8 atoms/s, which is largely sufficient for measurements with the use of collinear laser fast-beam spectroscopy.[10]

We measured the hyperfine spectrum of ^{207}Tl and of the stable isotopes, ^{203}Tl and ^{205}Tl (and incidentally[11] observed ^{193}Tl,^{195}Tl,^{199}Tl), in the $6p\,^2P_{3/2} \to 7s\,^2S_{1/2}$ 535.0-nm transition (Fig. 1). We used a Coherent model 599 laser in which the rhodamine-110 dye was

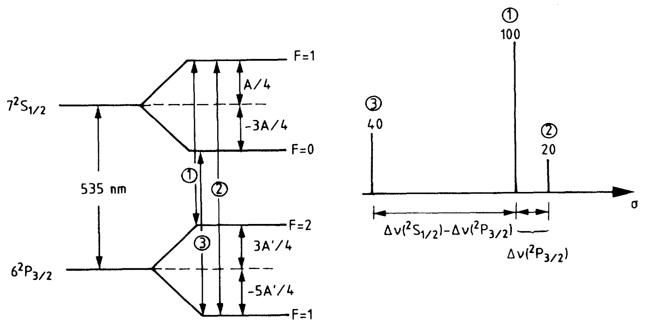

FIG. 1. Atomic levels and hfs in the thallium 535.0-nm line for isotopes with $I=\frac{1}{2}$. F is the total angular momentum quantum number. A and A' denote the magnetic dipole hfs interaction constants in the $^2S_{1/2}$ and $^2P_{3/2}$ states. The hfs splittings are $\Delta\nu = A$ and $\Delta\nu' = 2A'$. Relative intensities of the components are indicated. The dashed lines represent the centers of gravity of the levels.

pumped by the green rays of an argon-ion laser. The 60-keV thallium-ion beam, which originates in the surface ionization process on hot tungsten in the ion source, is neutralized in a sodium charge-exchange cell, leaving most of the atoms in the metastable $^2P_{3/2}$ state. Following resonant interaction with the laser radiation, exciting the metastable atoms to the $^2S_{1/2}$ state, the 377.6-nm $7s\,^2S_{1/2}$-$6p\,^2P_{1/2}$ fluorescence is detected. Appropriate filters reject the 535.0-nm laser excitation light. Light pipes to the photomultipliers, incorporated in prior experiments,[12] but not usable in the near uv, were removed without substantial loss of collection efficiency. A trace obtained of the hfs of ^{207}Tl is shown in Fig. 2. From the measurements we obtain the hfs intervals and isotope shifts given in Tables I and II. The uncertainties quoted include 1 standard deviation of the statistical errors and a systematic error or $\approx 10^{-4}$ in the voltage calibrations entering into the Doppler shifts. The data also provide a direct confirmation of the nuclear spin $I=\frac{1}{2}$ for ^{207}Tl.

TABLE I. hfs intervals, $\Delta\nu$, in the 535.0-nm transition. Values are in megahertz. Old spectroscopic results are converted by 0.001 cm^{-1} = 29.9709 MHz for air at 20 °C and 1 atm.

Isotope	$\Delta\nu(^2S_{1/2})$	$\Delta\nu(^2P_{3/2})$
203	12 172(6)[a]	524.5(1.5)[a]
	12 222(42)[b]	524.0601(2)[d]
	12 180($\sim$15)[c]	
205	12 284(6)[a]	529.9(1.5)[a]
	12 315(36)[b]	530.0766(2)[d]
	12 288($\sim$15)[c]	
207	14 070(7)[a]	607.5(3.7)[a]

[a] Laser spectroscopy (present experiment).
[b] Diffraction grating and Fabry-Perot (see Ref. 13).
[c] Fabry-Perot (see Ref. 14).
[d] Atomic-beam magnetic resonance (see Ref. 15).

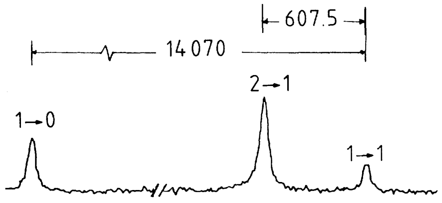

FIG. 2. Recording of the 535.0-nm line in ^{207}Tl. The F values corresponding to the ones in Fig. 1 for absorption from the P to S states are indicated. hfs separations are in megahertz.

The magnetic moment, μ, of ^{207}Tl is obtained by reference to the stable-isotope moment and hfs. The differential isotopic effect of the distribution of nuclear magnetization[17] and charge[18] on the hfs (hfs anomaly), given by

$$\Delta_{1,2} = A_1 g_2 / A_2 g_1 - 1,$$

(A is the hfs interaction constant, $g=\mu/I\mu_N$, and 1 and 2 indicate the two isotopes), should be small for isotopes with their respective unpaired protons in the same shell-model orbit. For the stable thallium isotopes, we find $\Delta_{205,203} = -0.06(4)\times 10^{-2}$ in the $^2S_{1/2}$ state (note that our systematic error cancels in the A-factor ratio), and from the literature[15,19] $\Delta_{205,203} = 0.1626\times 10^{-2}$ in the $^2P_{3/2}$ state. The relatively large anomaly of the $^2P_{3/2}$ state has been ascribed to the admixture of $6s6p7s$ into the $6s^26p\,^2P_{3/2}$ configuration.

Using our measured ratio $A(207)/A(205) = \Delta\nu(207)/\Delta\nu(205) = 1.1454$ for the $^2S_{1/2}$ state and $\mu(205) = 1.638\,2134\mu_N$, we obtain the magnetic moment $\mu(207) = 1.876(2)\mu_N$. The uncertainty represents the errors in the measurement and allows for an expected hfs anomaly of the order $\leq 10^{-3}$. However, as the magnetic moment of ^{207}Tl deviates significantly

TABLE II. Isotope shifts in the 535.0-nm transition. Values are in megahertz. The larger masses lie at the higher wave numbers.

	Isotope shifts	
Mass number	205	203
207	1783(3)[a]	3538(3)[a]
205	0	. . .
203	−1757(2)[a]	0
	−1770(120)[b]	

[a] This experiment.
[b] See Ref. 16.

from those of the lighter $I = \frac{1}{2}$ isotopes, we have chosen a more conservative estimate of the hfs anomaly effects which is based on the experimental data: The measured ratios between the A factors of the ${}^2S_{1/2}$ and ${}^2P_{3/2}$ states are summarized in Table III. For ^{203}Tl and ^{205}Tl these ratios differ by 2.3×10^{-3} because of the hfs anomalies which are opposite in sign for the two states. For ^{207}Tl, the ratio is nearly the same as for ^{205}Tl, but uncertain within 6×10^{-3}, corresponding to the error in the ${}^2P_{3/2}$ splitting. From the known hfs anomalies for the stable isotopes, about $\frac{1}{3}$ of this uncertainty has to be attributed to the anomaly between ^{205}Tl and ^{207}Tl in the ${}^2S_{1/2}$ state. Hence we obtain the final result $\mu(207) = 1.876(5)\mu_N$. We note the excellent agreement of the values $1.83(18)\mu_N$, deduced[6] from the $1^- \rightarrow 0^-$ $M1$ transition rate in ^{206}Tl, and $1.80(15)\mu_N$ for the proton in the $3s$ orbital, obtained[7] from perturbed angular distribution measurements in ^{206}Hg.

We compare first the magnetic moment of ^{207}Tl with those of the odd-neutron isotopes ${}^{195-205}$Tl. They all have $I = \frac{1}{2}$, and their moments increase slowly with neutron number[20] from $1.58\mu_N$ to $1.64\mu_N$. The Schmidt-limit value is $2.793\mu_N$. As meson effects are not expected[1] to modify g_s substantially, the jump in the ^{207}Tl magnetic moment may reflect a significant change in the contribution of configuration mixing:

(i) The first-order contribution of core polarization from the $\nu(p_{3/2}^{-1} p_{1/2})$ 1^+ excitation mode vanishes for ^{207}Tl because of the filling of the $\nu p_{1/2}$ orbital between ^{205}Tl and ^{207}Tl.

(ii) The collective admixtures described, e.g., by the coupling of single-hole components to the first excited 2^+ core states, as seen in the neighboring even lead isotopes, may cause appreciable second-order effects: The main contribution is expected by admixing $(2^+ \otimes \pi d_{3/2}^{-1})\frac{1}{2}^+$ to the $(0^+ \otimes \pi s_{1/2}^{-1})\frac{1}{2}^+$ principal component. This should be about the same for ${}^{195-205}$Tl, but considerably smaller for ^{207}Tl because of the jump of the lowest 2^+ state in ^{208}Pb to 4.1 MeV from the nearly constant ≈ 0.9 MeV for the lighter even-N lead isotopes.

With the rough parameters of Arima and Horie,[2] we calculate $\mu(207) \approx 1.54\mu_N$. A more realistic configuration-mixing calculation with nearly vanishing correction for one-pion exchange and coupling with vibrational states[5] gives $2.03\mu_N$. It is pointed out that the remaining second-order corrections from configuration mixing and meson exchange cannot be calculated with great accuracy. However, they largely cancel each other and are neglected. Nevertheless, including an estimation of these corrections[5,21] gives $1.80\mu_N$, in better agreement with the experimental result. An independent approach, based on the theory of finite Fermi systems and an effective magnetic-moment operator,[22] gives $1.935\mu_N$.

TABLE III. Ratios $A({}^2S_{1/2})/A({}^2P_{3/2})$. Isotopic variations give an indication of hfs anomalies.

Isotope	$A({}^2S_{1/2})/A({}^2P_{3/2})$
203	46.453(23)[a]
205	46.348(23)[a]
207	46.32(28)

[a] Using Ref. 15 for the ${}^2P_{3/2}$ hyperfine structure.

The good agreement between our direct moment measurement and the one deduced[7] from the g factor of the 5^- state in ^{206}Hg adds weight to the value of the $h_{11/2}$ proton moment obtained[23] from decoupling of the moment in ^{205m}Tl. The combinations of the $h_{11/2}$ and $h_{9/2}$ (from ^{209}Bi) proton moments isolates[23,24] the δg_l contribution. Bergström, Kerek, and Ekström[24] proposed to measure the ^{207m}Tl $h_{11/2}$ isomer by atomic-beam magnetic resonance. Our experiment has indicated a possible yield of 10^5 isomeric nuclei per second from ISOLDE, which would be above the limit of still possible experiments with the laser spectroscopy.

This work was performed with the ISOLDE Collaboration. It was supported in part by the Deutsche Forschungsgemeinschaft, by the Bundesministerium für Forschung und Technologie, and by the National Science Foundation under Grant No. PHY 8204402. One of us (H.H.S.) acknowledges seminal discussions and preliminary studies with O. Redi. He also wishes to thank B. Jonson, H.-J. Kluge, and R. Klapisch for their hospitality. We are grateful for the discussions and with E. W. Otten and the comments of A. Arima, J. Blomqvist, G. E. Brown, C. Ekström, and H. Haas. We also thank W. Klempt for valuable contributions in the early stages of the experiment, and O. C. Jonsson for his assistance with the isotope production studies.

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