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Measurements of the g_J factors of the 6s $^2S_{1/2}$ and 6p $^2P_{1/2}$ states in $^{198}Hg^+$

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Measurements of $^{198}Hg^+$ g_J factors by two methods are reported. The first method was based on optical wavelength measurements of the Zeeman components of the 6s $^2S_{1/2}$ (ground state) to 6p $^2P_{1/2}$ transition at 194 nm. The lines were observed by the absorption of tunable 194-nm radiation by Hg^+ ions created in a rf discharge. The results were $g_J(6s\ ^2S_{1/2}) = 2.0036(20)$ and $g_J(6p\ ^2P_{1/2}) = 0.6652(20)$. The second method was based on microwave-optical double resonance of ions confined in a Penning trap. They were optically pumped by the 194-nm source, which was tuned to a particular Zeeman component. An increase in the resonance-fluorescence intensity was observed when the microwave frequency was tuned to the ground-state Zeeman resonance. The result is $g_J(6s\ ^2S_{1/2}) = 2.003\ 174\ 5(74)$.

INTRODUCTION

Few measurements of g_J factors in Hg^+ have been made. Measurements made with optical precision (typically a few parts in 10^3) are useful for determining the purity of the configurations and coupling schemes. Van Kleef and Fred[1] measured the g_J factors of the 7s $^2S_{1/2}$, 6p $^2P_{3/2}$, and $5d^96s^2$ $^2D_{5/2}$ states by optical spectroscopy. The values agree with those calculated for *LS* coupling to within the accuracy of the measurements. No measurements of the 6p $^2P_{1/2}$ state have been published previously. The present results for this state agree with the *LS* coupling value.

Measurements made with higher precision, usually by microwave-resonance techniques, are sensitive to relativistic and many-body effects and test calculational methods. Schuessler and Hoverson[2] observed a ground-state magnetic resonance in $^{199}Hg^+$ by spin exchange with optically pumped Rb and derived a value for the ground-state g_J factor. The results of the present study are in considerable disagreement with this value but are in agreement with a recent calculation by Dzuba *et al.*[3]

EXPERIMENTAL METHOD

Two different methods of measuring g_J factors were used in this study. The first relied on optical wavelength measurements of the Zeeman components of an absorption line. The ions in this case were created in a rf discharge. The second method used microwave-optical double resonance. This method had much higher resolution than the first but could be applied only to the ground state. The ions in this case were contained in a Penning ion trap.[4]

A narrow-band, tunable, cw 194-nm radiation source was used in both methods. This source was described previously.[5] The 194-nm radiation was generated by sum-frequency mixing 257- and 792-nm radiation in a potassium pentaborate crystal. The 257-nm radiation was generated by frequency doubling the output of a single-mode cw 514.5-nm Ar^+ laser in an ammonium dihydrogen phosphate crystal. The 792-nm radiation was generated by a single-mode cw dye laser, which provided the tunability. Ring cavities were used to increase the circulating powers at the input frequencies at both the frequency-doubling and frequency-mixing stages. The linewidth of the 194-nm radiation was about 2 MHz, and the output power was a few microwatts. The Ar^+ laser was frequency stabilized to a saturated-absorption feature of known wavelength in the $^{127}I_2$ spectrum. The wavelength of the dye laser was measured with an interferometric wavemeter of the lambdameter type.[6]

For the optical g_J factor measurements, the Hg^+ ions were created in a cell with fused-silica windows containing Ne at a pressure of about 800 Pa (6 Torr) and a droplet of ^{198}Hg. A discharge was excited by applying a few watts of power at a frequency of approximately 150 MHz to a coil surrounding the cell. The cell was placed in the gap of an electromagnet. The magnetic field of approximately 1.3 T was measured with a nuclear magnetic resonance (NMR) probe.

The intensity (after attenuation) of the 194-nm radiation transmitted through the discharge was measured as a function of the dye-laser frequency with a photomultiplier tube (PMT). The detected signal was normalized to the incident power in order to reduce noise and to eliminate sloping baselines owing to variations of the power as a function of frequency or time. The results of a typical laser scan are shown in Fig. 1. The width of the scan, approximately 6.5 GHz, was calibrated with a Fabry–Perot interferometer of 250-MHz free-spectral range. The wavelength of the dye laser was measured at a point near the resonance center with the lambdameter.

For the microwave-optical double-resonance measurements, the Hg^+ ions were confined in a Penning trap. The trap apparatus and the optics for introducing the light and detecting the fluorescence were similar to those described previously for use with Mg^+ ions[7] except that the trap electrodes were made from Mo rather than Cu. The characteristic inner dimensions were $r_0 = 0.417$ cm and $z_0 = 0.254$ cm. The magnetic field was approximately 1.3 T, and the potential between the ring electrode and the end-cap electrodes was approximately 1 V for trapping Hg^+ and about 6 V for trapping electrons. Ions were created inside the trap by ionization of neutral ^{198}Hg, introduced through a leak valve,

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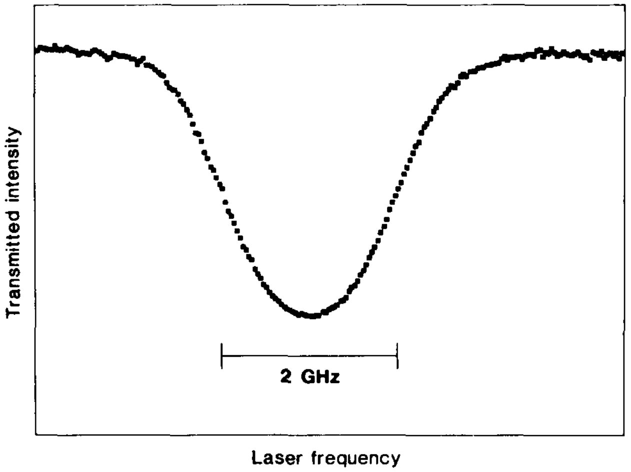

Fig. 1. Graph of the intensity of the 194-nm radiation transmitted through the rf discharge as a function of laser frequency, showing the absorption that is due to the $M_J = -1/2$ to $M_J = +1/2$ component of the ^{198}Hg$^+$ $6s$ $^2S_{1/2}$ to $6p$ $^2P_{1/2}$ transition.

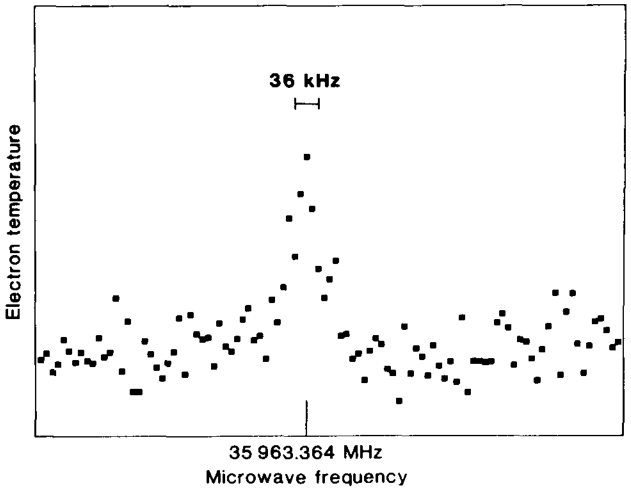

Fig. 2. Graph of the temperature of electrons in the Penning trap as a function of the applied microwave frequency, showing the cyclotron resonance.

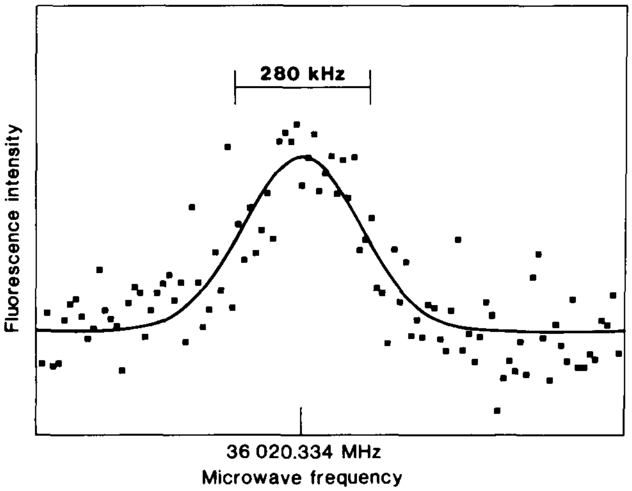

Fig. 3. Graph of the 194-nm resonance-fluorescence intensity of ^{198}Hg$^+$ ions in the Penning trap as a function of the applied microwave frequency, showing the ground-state Zeeman resonance. The curve is a least-squares fit to a Gaussian.

with an electron beam directed along the trap axis. The storage time was typically a few minutes, limited by neutral ^{198}Hg pressure. The 194-nm radiation was introduced through a hole in the ring electrode along a direction perpendicular to the trap axis. Photons scattered by the ions back through the hole in the ring electrode were counted by a PMT. The net detection efficiency (number of photoelectrons counted per photon emitted by the ions) was of the order of 0.5×10^{-4}. Microwave radiation was transmitted through a window in the vacuum envelope using a pair of horns (one as a transmitter outside the vacuum apparatus and one as a receiver inside the vacuum apparatus) and introduced into the trap through the gap between the ring and one of the end caps. The number of ions trapped was estimated by driving the axial motion of the ion cloud in the wings of the resonance with a rf electric field and measuring the induced currents. The maximum number was about 8×10^4. The magnetic field was stabilized by means of a NMR probe. The magnetic field inside the trap was calibrated by detecting the cyclotron resonance of a cloud of electrons, using the bolometric method.[8] In this method the translational motions of the electrons are detected by the currents induced in an external circuit coupled to the trap electrodes. The microwave source for the electron-cyclotron excitation was a frequency tripler driven by a frequency synthesizer. A typical cyclotron-resonance curve is shown in Fig. 2.

To observe the Hg$^+$ ground-state Zeeman resonance, the 194-nm source was tuned to the $6s$ $^2S_{1/2}(M_J = -1/2)$ to $6p$ $^2P_{1/2}(M_J = +1/2)$ transition. The ions were pumped to the $M_J = +1/2$ ground-state sublevel and ceased scattering photons, since they were no longer in resonance. When the frequency of the applied microwave radiation matched the ground-state Zeeman resonance, the $M_J = -1/2$ sublevel was repopulated, and an increase in the resonance fluorescence was detected. Here, the microwave source was a klystron, phase-locked to a harmonic of a frequency synthesizer. Up to 100 mW of power was available at the end of the horn. A typical resonance curve is shown in Fig. 3. The linewidth was larger than for the electron-cyclotron resonance. This was probably due to magnetic-field inhomogeneities and a larger spatial extent of the Hg$^+$-ion cloud compared with that of the electron cloud.

RESULTS

Two or three optical measurements were made of each of the four Zeeman components. The centers of the absorption curves were determined by least-squares fitting to a function of the form, transmitted intensity $= C_1 + C_2 \exp(-C_3 \exp\{-[(\upsilon - C_4)/C_5]^2\})$, where υ was the dye-laser frequency and C_1–C_5 were constants. This line shape included the effect of saturation on the Gaussian Doppler profile, which tended to broaden the lines. All the line shapes were fitted with a Doppler-width parameter (C_5) corresponding to a temperature of approximately 400 K. The temperature of the rf discharge was not measured directly. The reproducibility of the line centers was ±20 MHz. The uncertainties in absolute frequencies of up to several hundred megahertz, which were due mostly to the uncertainty of the frequency of the reference laser of the lambdameter, were unimportant since only frequency differences were needed to determine the g_J factors. Similarly, perturbations that shifted all magnetic sublevels of a state equally, such as pressure shifts, could be neglected. From the four frequency measurements, there were two independent ways to obtain the S-state Zeeman splitting and two independent ways to obtain the P-state splitting. The average values were 36 033(30) MHz for the S state and 11 964(30) for the P state. The measured-proton NMR frequency in a mineral-oil sample was 54.708 MHz, corresponding to a magnetic field of 1.284 95 T. The resulting values for the g_J factor were 2.0036(20) for the S state and 0.6652(20) for the P state.

The g_J factor of the ground S state was obtained from the Hg^+ microwave-resonance frequency $\nu(Hg^+)$ and the unperturbed electron cyclotron frequency ν_c by the equation $g_J = 2\nu(Hg^+)/\nu_c$. The measured cyclotron frequency ν_c' differed from ν_c because of the electric fields of the Penning trap.[4] The correction was calculated from the axial resonance frequency ν_z, measured by the bolometric method, according to $\nu_c \cong \nu_c' + \nu_z^2/2\nu_c'$. At a particular value of the magnetic field, $\nu(Hg^+)$ was measured to be 36 020.477(48) MHz, whereas ν_c' was measured to be 35 963.345(24) MHz. The line centers were determined by least-squares fitting to Gaussians. The value of ν_z was 59.25 MHz. The result was $g_J(6s\ ^2S_{1/2}) = 2.003\ 174\ 5(74)$. The statistical error was only 1.5 parts in 10^6 (ppm), but a possible systematic error may have arisen because the Hg^+ ions and the electrons may not have sampled the same average magnetic field. We estimated this error to be no more than the half-width of the Hg^+ resonance (3.4 ppm).

DISCUSSION

The measured g_J factor of the $6p\ ^2P_{1/2}$ state is equal to the value calculated for LS coupling (0.665 89) within the experimental error. This is the first reported measurement of this quantity.

The values of the ground-state g_J factor measured by the two methods are in agreement. They are both in serious disagreement with the measurement of Schuessler and Hoverson.[2] The present measurement is, however, in good agreement with a recent calculation based on the relativistic Hartree–Fock equations and many-body perturbation theory.[3] It is probably more instructive to express these results in terms of the small deviation, $\Delta g = g_J(6s\ ^2S_{1/2}) - g_e$, of the g_J factor from the free-electron g factor ($g_e = 2.002\ 319\ 30$) than in terms of the g_J factor itself. The present experimental result is $\Delta g = 0.8552(74) \times 10^{-3}$, the experimental result of Schuessler and Hoverson[2] is $\Delta g = 14.7(1.0) \times 10^{-3}$, and the theoretical result is $\Delta g = 1.02 \times 10^{-3}$. An empirically corrected result of 0.85×10^{-3} is also given in Ref. 3. The correction is based on the difference between the experimental and theoretical values for isoelectronic Au.

In light atoms, deviations of the g_J factor of a $^2S_{1/2}$ state are due to the relativistic and diamagnetic interactions given by Abragam and Van Vleck.[9] For the alkali atoms up to K, calculations based on these interactions are in good agreement with experiment.[10] For these atoms Δg is negative. However, for the heavier alkali atoms and for Au and Hg^+, which also have $^2S_{1/2}$ ground states, Δg is positive. This is primarily due to a perturbation that is of the second order in the spin–orbit interaction and of the first order in the residual Coulomb interaction. Calculations that take this effect into account agree well with experiment.[3,11,12]

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