Measurement of the ground-state g_J factor of ^{23}Na

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The technique of spin-exchange optical pumping was used to measure the ratio $g_J(^{87}\mathrm{Rb})/g_J(^{23}\mathrm{Na})$ for the alkali metals in their $^2S_{1/2}$ ground states. Zeeman hyperfine splittings were produced in a magnetic field of 43 G, the $\Delta F = 0$ transition frequencies measured, and the g_J and g_I/g_J ratios evaluated by means of a best fit to the Breit-Rabi expression for the alkali-metal energy levels. The resonance lines were collected and displayed by a minicomputer programmed for repetitive-scan signal averaging. Possible systematic effects of pumping light, buffer pressure, etc., were considered in obtaining the final results $g_J(^{87}\mathrm{Rb})/g_J(^{23}\mathrm{Na}) = 1.000017771(7)$ and $g_J(^{23}\mathrm{Na}) = 2.00229563(16)$. The measured value for $g_I/g_J(^{23}\mathrm{Na})$ is in good agreement with results from atomic-beam experiments.

INTRODUCTION

The structure of the alkali-metal atoms has been extensively studied for many years with a number of spectroscopic techniques. The interest arises from the relative simplicity of the spectra as well as the ease with which the alkalis may be experimentally handled. In particular, radio-frequency spectroscopy using optical pumping techniques is very conveniently applied to the alkalis and has yielded a wealth of data on alkali hyperfine structure, including zero-field hyperfine splittings, nuclear g_I factors, g_J factors, and collision cross sections. Measurements to very high precision have been reported in the last few years, and the ground state g_J factors of the commonly occurring isotopes of hydrogen,[1] potassium,[2] rubidium,[1] and cesium[3] have been directly or indirectly measured to precisions of better than ±0.1 ppm.

This paper extends the g_J measurements to sodium using the techniques of spin-exchange optical pumping. The general procedure consists of analysis of the radio-frequency spectrum of the weak-field Zeeman effect in sodium. The work is an extension of the work on ^{39}K reported in Ref. 2, where a very detailed description of apparatus and technique has been given. Only a brief outline of the method will be given here; for a general review of optical pumping theory and experimental technique, including spin exchange, the review paper by Happer[4] may be consulted.

EXPERIMENTAL METHOD

The experiment used a magnetic field of 43 G in which a glass cell containing rubidium and sodium was situated. The rubidium was optically pumped and ground-state Zeeman resonances induced by an alternating field H_x perpendicular to the main field H_z. The sodium was polarized by spin-exchange collisions with rubidium and its ground-state Zeeman resonances were also observed with a resonant rf field at right angles.

The sample cells were 1-in.-long, 3/4-in.-diam cylindrical Pyrex cells which contained sodium in the main body of the cell and rubidium in a sidearm. The cells were prepared by first evacuating a Pyrex blank to a high vacuum, then distilling sodium metal into and evenly around the main cell body. Next, rubidium was distilled into a sidearm provided with a check valve to prevent any rubidium entering the main cell body. Finally the cell was buffered with research-grade argon and removed from the vacuum system.

Figure 1 shows a sample cell in the center of the main field Helmholtz coils. Circularly po-

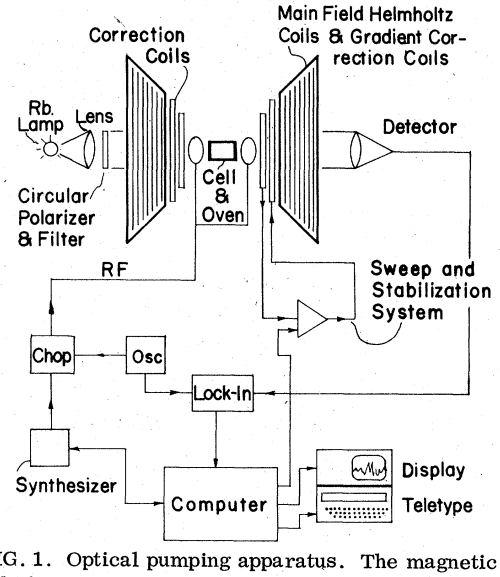

FIG. 1. Optical pumping apparatus. The magnetic field of 43 G is provided by a Helmholtz coil pair; a Rb lamp, polarizer, and lens provides the pumping light, the rf is chopped at a low frequency and the signal synchronously detected at the same frequency.

larized rubidium D_1 optical pumping light from an rf discharge lamp was passed thru the sample cell and its transmitted intensity monitored with a PIN diode sensor and current amplifier. The main body of the cell was heated to approximately 130 °C while the sidearm containing the rubidium was maintained at a lower temperature so that the alkali densities in the main volume were approximately the same.

The Zeeman resonances were scanned using a fixed H_x frequency and a low-frequency main field sawtooth sweep which was provided by a potentiometer driven by a clock motor. Normally the H_x rf field was amplitude modulated (chopped) at a low frequency and the resonances observed via synchronous detection of the PIN diode current with a lock-in amplifier.

The major difference between the present apparatus and that of Ref. 2 is the use of a minicomputer for on-line data collection and analysis. The machine controlled the experiment through interface circuitry, swept the main field, switched rf frequencies as required, and accumulated and displayed the resonance signals. As each resonance was swept, the output of the lock-in amplifier was digitized with ten-bit accuracy over selected sample intervals from a few milliseconds to a few hundred milliseconds and stored in the computer memory. Either the current sweep or the accumulated sum of a number of sweeps could be displayed on a CRT and the sodium and rubidium resonances could be overlaid in the display. The computer also analyzed the data and printed out the results.

The data collection was done in a signal averaging mode because of the low signal- to-noise ratio of the sodium signals observed in spin exchange. The procedure was as follows: Using a fixed H_x frequency, the main field was swept slowly through one of the resonance frequencies for ^{87}Rb and the Zeeman line recorded digitally in the memory of the minicomputer. On the next upsweep of the field, with the H_z field the same, the H_x frequency was set to the calculated value for one of the ^{23}Na lines and the spin-exchange resonance similarly recorded digitally in the computer. By repeating the field sweep and overlaying the successive resonances appropriately the signal-to-noise ratio improves as the square root of the number of sweeps of the resonance, and the precision to which the line center can be read correspondingly improves. In a few cases as many as 200 sweeps, representing more than six hours of observation, were required for an acceptable signal-to-noise ratio on a single resonance.

Once an acceptable S/N was obtained, line centers were determined and calibrated extrapolations of measured frequency were made to allow for differing displacements of the ^{87}Rb and ^{23}Na resonances along the sweep. The scale of the sweep was calibrated in terms of frequency by a best fit of measured displacements and frequencies to a straight line.

RESULTS AND DISCUSSION

Results

The energy levels of the ground states of ^{87}Rb and ^{23}Na are $^2S_{1/2}$ electronic states split by the electron-nucleus interaction into hyperfine states labeled by (F, M_F). Since the nuclear spin I is $\frac{3}{2}$ for both atoms, the quantum number F takes on the values $F^+ = 2$ and $F^- = 1$.

In a magnetic field the energies of these (F, M_F) states are given by the Breit Rabi expression[5]:

$$W(F^{\pm}, M_F) = \frac{-\Delta W}{2(2I+1)} + g_I \mu_0 H_z M_F \pm \frac{\Delta W}{2}\left[1 + \frac{4M_F}{2I+1}x + x^2\right]^{1/2}, \quad (1)$$

where ΔW is the zero-field hyperfine splitting, H_z is the magnetic field strength, g_I is the nuclear g factor, and x is given by

$$x = (g_J - g_I)\mu_0 H_z / \Delta W. \quad (2)$$

The $\Delta F = 0$, $\Delta M_F = \pm 1$ transition frequencies are given by

$$\nu = [W(F, M_F) - W(F, M_F \pm 1)]/h. \quad (3)$$

At the rf intensities used, the S/N of the strongest Zeeman transition in ^{87}Rb for a single sweep was approximately 15/1 while for the strongest ^{23}Na transition the S/N was approximately 2/1 and for the weakest ^{23}Na transition somewhat less than 1/1.

The resonant frequencies at 43 G ranged from 19 to 21 MHz for ^{85}Rb, 29 to 31 MHz for ^{87}Rb, and from 27 to 33 MHz for ^{23}Na. The linewidth for ^{85}Rb transitions was approximately 55 Hz at low rf strength, while the ^{87}Rb and ^{23}Na signals were 80 to 85 Hz in width at low rf intensities and working spin-exchange rates. Resonances in cells containing only rubidium were stronger but linewidths were not much different from those observed in cells containing both rubidium and sodium. The linewidth arises principally from field inhomogeneity and, although spin exchange, modulation, pumping light, etc., each contribute, measurements showed that the sum of these other contributions was small compared to the field width.

Because the alkali atoms in a buffered sample are confined by the rare gas and do not motionally average the magnetic field inhomogeneities, the

resonance line shape will reflect the magnetic field distribution over the sample. The analysis used in this work checked each line for symmetry and center channel by computing the center of the line as a function of amplitude from about 10% to 90% of the total height of the resonance. The column of centers was examined for skew, corrected by adjustment of the gradient coil currents as necessary, and then the average computed and printed out. This line center program was used first in check runs on the rubidium isotopes and provided results in excellent agreement with much higher precision evacuated cell results (see Ref. 2, Sec. V).

The g_J ratio was obtained by comparing the ^{23}Na resonance frequencies to the ^{87}Rb resonance frequencies at a fixed magnetic field H_z. For ^{87}Rb, the strongest transitions, which were the $[(2,2)-(2,1)]$ in σ^+ light and the $[(2,-2)-(2,-1)]$ in σ^- light, were used while for ^{23}Na the $[(2,2)-(2,1)]$, $[(2,1)-(2,0)]$, and $[(1,0)-(1,1)]$ transitions were used in σ^+ light and the $[(2,-2)-(2,-1)]$, $[(2,-1)-(2,0)]$, and $[(1,0)-(1,-1)]$ transitions were used in σ^- light.

Since the constants ΔW and g_I/g_J are known very accurately for ^{87}Rb, one can take a measurement of a Zeeman transition frequency and find the product $g_J^{87}\mu_0 H_z$. Similarly for ^{23}Na one can, given a measurement of a Zeeman resonance and sufficiently accurate values for ΔW and g_I/g_J, find the product $g_J^{23}\mu_0 H_z$. If the measurements are made at the same field H_z, the ratio of these numbers then yields the desired g_J ratio.

The g_I/g_J of ^{23}Na was also measured as a check on possible systematic effects. The ratio may be evaluated by substituting Eq. (3) of Ref. 2 for ^{87}Rb in Eq. (5) of Ref. 2 for ^{23}Na. The result expresses the g_I/g_J ratio in terms of measured frequencies and known constants:

$$\frac{g_I}{g_J}(^{23}\mathrm{Na}) = \frac{g_J(^{87}\mathrm{Rb})}{g_J(^{23}\mathrm{Na})} \frac{\omega^{23}}{2\Sigma^{87}/(1+3g_I/g_J(^{87}\mathrm{Rb}))} \qquad (4)$$

where ω^{23} is the difference in frequency between the $[(2,1)-(2,0)]$ and the $[(1,1)-(1,0)]$ transitions in ^{23}Na and Σ^{87} represents the sum of the frequencies of all the transitions of the $F=2$ complex of ^{87}Rb. For σ^- light the frequency difference between the $[(2,0)-(2,-1)]$ and $[(1,0)-(1,-1)]$ transitions was used for ω^{23}.

The field stabilization technique required the main field strength to be slightly different in σ^+ and σ^- light, so all the frequencies were changed on reversing the sense of circular polarization.

The results for the g_I/g_J ratio are given in Fig. 2(a). The ratio was measured in both senses of light polarization and at two different rf field strengths. The average of the four runs is $g_I/g_J(^{23}\mathrm{Na}) = -0.000\,401\,845(17)$, in good agreement with the more precise result $g_I/g_J(^{23}\mathrm{Na}) = -0.000\,401\,840(6)$ computed from the measured μ_I (Ref. 6) and the Taylor, Parker, and Langenberg[7] value of M_p/M_e.

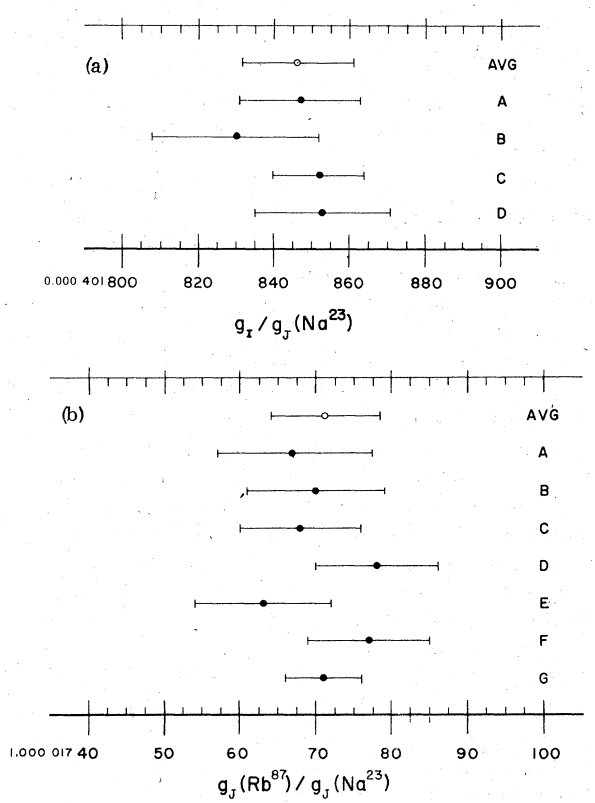

FIG. 2. (a) Results for the g_I/g_J ratio of ^{23}Na. The results (A) and (B) were taken in σ^+ light and the results (C) and (D) in σ^- light. A substantially stronger rf drive was used on runs (A) and (C). (b) Results for the rubidium to sodium g_J factor ratio. The points given correspond to the transitions: (A) $[(2,0)-(2,-1)]$ in σ^- light; (B) $[(1,-1)-(1,0)]$ in σ^- light; (C) $[(1,0)-(1,1)]$ in σ^+ light; (D) $[(2,0)-(2,1)]$ in σ^+ light; (E) $[(2,0)-(2,-1)]$ in σ^- light; (F) $[(2,-2)-(2,-1)]$ in σ^- light; and (G) $(2,2)-(2,1)]$ in σ^+ light. The point (A) was taken with reduced rf power.

The results for $g_J(^{87}\mathrm{Rb})/g_J(^{23}\mathrm{Na})$ are illustrated in Fig. 2(b). Six independent measurements were averaged to yield the final result $g_J(^{87}\mathrm{Rb})/g_J(^{23}\mathrm{Na}) = 1.000\,017\,71(7)$. The constants assumed in Fig. 2(b) for ΔW and g_I/g_J were $\Delta W^{87} = 6834.682\,614(3)$ MHz,[8] $g_I/g_J(^{87}\mathrm{Rb}) = -0.000\,496\,991\,47(45)$,[9] $\Delta W^{23} = 1771.626\,047(100)$ MHz,[10] and $g_I/g_J(^{23}\mathrm{Na}) = -0.000\,401\,840(6)$. The uncertainty in the ^{87}Rb g_I/g_J does not affect the g_J ratio result while the ^{23}Na g_I/g_J uncertainty results in a 1 part in 10^8 uncertainty in the g_J ratio. The uncertainties in the hyperfine transition frequencies do not affect the results at our level of precision.

The ^{23}Na g_J factor itself may be computed from

the result of Fig. 2(b) by the expression

$$g_J(^{23}\mathrm{Na}) = \frac{g_J(^{23}\mathrm{Na})}{g_J(^{87}\mathrm{Rb})} \frac{g_J(^{87}\mathrm{Rb})}{g_S(e^-)} g_S(e^-) \quad (5)$$

$$= 2.002\,295\,63(16) \quad (6)$$

using $g_s(e^-) = 2(1+a)$ and $a = 0.001\,159\,644(7)$.[11] The value of the right-hand side is computed from our result, the results of Ref. 1, and the theoretical results of Grotch and Hegstrom.[12] The usefulness of ^{87}Rb as a working standard is evident in the high precision of the vacuum cell data used. The final error was obtained by adding the individual contributions in quadrature and rounding to the nearest whole number.

Discussion

In assessing possible sources of error in the result (6), several factors which can change the observed frequencies from the free atom values should be considered.

Pumping light shifts[13] are expected to be small at the fields and lamp intensities used in this experiment, however they may be substantially eliminated by appropriate averaging of data taken in σ^+ and σ^- light (see Sec. III of Ref. 2). The results bear out the expectation of small lamp shifts since the g_J ratios taken in σ^+ and σ^- light are in good agreement.

The effects of buffer gas density on the hyperfine frequency ΔW are well known, and coefficients giving frequency shift as a function of buffer density have been measured by a number of authors, particularly Ramsey and Anderson[14] for ^{23}Na and Beatty, Bender, and Chi[15] for ^{87}Rb. For ^{23}Na the logical choice for the buffer gas is argon because the pressure shift of only 4 Hz/Torr at 130 °C is more than an order of magnitude smaller than that for any of the other rare gases. The shifts themselves may be computed either by evaluating the Breit-Rabi expression (3) for the Zeeman frequencies directly, or by expanding Eq. (3) in powers of $(g_J \mu_0 H_z/h)$.

In either case the results show that for either ^{23}Na or ^{87}Rb, the residual error after averaging the shift of the [(2, 2)-(2, 1)] transition and the [(2, −2)-(2, −1)] transition is much less than one part in 10^8 for working pressures of 36 Torr of argon. A similar conclusion holds for the averages of the other $\Delta F = 0$ transitions used so that buffer gas density shifts do not affect the results.

The influence of rf field strength on the experimental line center was also checked, as was the effect of the setting of the lock-in phase adjust and the lock-in time constant, both sources of systematic error on early runs (see Ref. 2). There were no discernible systematic effects from any of these sources at the level of precision quoted in the final result. The final error estimate is greater than statistical and, in fact, is large enough to include the results from all transitions.

The rubidium-sodium ratio has not been previously measured directly by either atomic beam magnetic resonance or optical pumping. However, by combining results of rubidium and sodium g_J factors relative to potassium the rubidium-sodium ratio may be computed. From the results of Vanden Bout *et al.*[16] the value $g_J(^{87}\mathrm{Rb})/g_J(^{23}\mathrm{Na}) = 1.000\,017\,5(4)$ is obtained while the results of Boklin *et al.*[17] may be combined to yield $g_J(^{87}\mathrm{Rb})/g_J(^{23}\mathrm{Na}) = 1.000\,017\,2(9)$, where errors are simply the sum of the errors of the two contributing measurements. The result of Fig. 2(b) is in agreement with both of these numbers.

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