Lorents, and O. Heinz, Phys. Rev. 161, 31 (1967); D. Coffey, Jr., D. C. Lorents, and F. T. Smith, *ibid.* 187, 201 (1969); F. T. Smith, H. H. Fleischmann, and R. A. Young, Phys. Rev. A 2, 379 (1970); and W. Aberth, O. Bernardini, D. Coffey, Jr., D. C. Lorents, and R. E. Olson, Phys. Rev. Letters 24, 345 (1970).

[2] R. P. Feyman, Rev. Mod. Phys. 20, 367 (1948); and P. Pechukas, Phys. Rev. 181, 166 (1969).

[3] K. W. Ford and J. A. Wheeler, Ann. Phys. (N. Y.) 7, 259 (1959); and N. G. Van Kampen, Physica 35, 70 (1967).

[4] D. R. Bates and A. R. Holt, Proc. Roy. Soc. (London) A292, 168 (1966); L. Wilets and S. J. Wallace, Phys. Rev. 169, 84 (1968); R. McCarroll and A. Salin, J. Phys. B 1, 163 (1968); and J. C. Y. Chen and K. M. Watson, Phys. Rev. 174, 152 (1968).

[5] B. A. Lippmann and J. Schwinger, Phys. Rev. 79, 469 (1950).

[6] M. H. Mittleman, Phys. Rev. 122, 499 (1961); S. A. Lebedoff, *ibid.* 165, 1399 (1968); and M. L. Goldberger and K. M. Watson, *Collision Theory* (Wiley, New York, 1964).

[7] J. B. Delos and W. R. Thorson (unpublished).

[8] C. Lehmann and G. Leibfried, Z. Physik 172, 465 (1962); F. T. Smith, R. P. Marchi, and K. G. Dedrick, Phys. Rev. 150, 79 (1966); F. T. Smith, J. Chem. Phys. 42, 2419 (1965).

[9] F. T. Smith, in *Lectures in Theoretical Physics: Atomic Collision Processes*, edited by S. Geltman, K. T. Mahanthappa, and W. E. Brittin (Gordon and Breach, New York, 1969), Vol. XIC, p. 95.

[10] W. R. Thorson and S. A. Boorstein, in *Fourth International Conference on the Physics of Electric and Atomic Collisions, Abstracts of Papers* (Science Bookcrafters, Hastings-on-Hudson, 1965), p. 218.

[11] See, for example, N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Clarendon, Oxford, England, 1965), Chap XIII.

[12] R. B. Bernstein, A. Dalgarno, H. S. W. Massey, and I. C. Percival, Proc. Roy. Soc. (London) A274, 427 (1963); R. E. Olson and R. B. Bernstein, J. Chem. Phys. 50, 246 (1969).

[13] Some of the latest papers are T. A. Green and R. E. Johnson, Phys. Rev. 152, 9 (1966); M. Matsuzawa, J. Phys. Soc. Japan 25, 1153 (1968); R. P. Marchi, Phys. Rev. 183, 185 (1969); L. P. Kotova, Zh. Eksperim. i Teor. Fiz. 55, 1375 (1968)[Soviet Phys. JETP 28, 719 (1969)].

[14] E. C. G. Stueckelberg, Helv. Phys. Acta 5, 369 (1932); L. Landau, Soviet Phys. 2, 46 (1932); C. Zener, Proc. Roy. Soc. (London) A137, 696 (1933).

[15] V. K. Bykhovskii, E. E. Nikitin, and M. Ya. Ovchinnikova, Zh. Eksperim. i Teor. Fiz. 47, 750 (1964) [Soviet Phys. JETP 20, 500 (1965)].

[16] J. B. Delos, Ph.D. thesis, MIT, 1970 (unpublished).

[17] It should be noted that we have recently found that the crossing point and interaction matrix derived from the experimental data are in good agreement with the results of V. Sidis, who, from *ab initio* calculations, obtained $r_x = 1.86$ a.u. and $H_{12} = 0.096$ a.u. V. Sidis, Ph.D. thesis, University of Paris, 1970 (unpublished).

[18] H. H. Michels, NBS Technical Note 438, edited by M. Krauss (U. S. GPO, Washington, D. C., 1967), p. 115.

[19] W. A. Lester, Jr. and R. B. Bernstein, J. Chem. Phys. 48, 4896 (1968); N. F. Lane and S. Geltman, Phys. Rev. 160, 53 (1967).

[20] D. Secrest and B. R. Johnson, J. Chem. Phys. 45, 4556 (1966).

[21] J. B. Delos (private communication).

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Production and Detection of the Orientation of Ions by Spin-Exchange Collisions with Optically Pumped Rubidium

H. M. Gibbs and G. G. Churchill
Bell Laboratories, Murray Hill, New Jersey 07974

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Radio-frequency spectroscopy of ions has been performed on the $(\mathrm{Sr}^{87})^+$, $(\mathrm{Cd}^{111})^+$, and $(\mathrm{Cd}^{113})^+$ ground states utilizing spin-exchange collisions with optically pumped rubidium atoms for both producing and detecting the orientation.

I. INTRODUCTION

The ion ground-state orientations reported here are the first to be both produced and detected via spin-exchange collisions with polarized atoms. This technique requires no ion resonance radiation, which is often difficult to produce. Conceivably, the technique could be applied to negative ions, most of which have no resonance radiation. Also, only small quantities of material are required, making feasible an extension to rare isotopes. The technique is rather general, since no resonant collisions are required for detection. However, the precision of the technique is not competitive with the ion-storage collision technique,[1] because of the short relaxation times in the unconfined high-density discharge; this may also restrict the method to S states. The possible extension of the technique to a measurement of g values and hyperfine structures of any S-state ion is suggested by the observation of Zeeman resonances in Sr$^+$ (which is representative of the group-II A ions) and Cd$^+$

(which is representative of the group-II*B* ions).

The technique is identical in concept to Dehmelt's sodium-electron spin-exchange experiment, with ions replacing the electrons.[2] Radio-frequency spectroscopy has now been performed on several ions with various techniques. Magnetic resonances have been observed by the polarization of fluorescence from Cd^+ and Zn^+ excited states produced and aligned by electron impact.[3] Alignment of H_2^+ has been produced and observed by selective photodissociation.[4] Orientation of He^+ has been achieved by spin exchange with optically pumped Cs and detected using the nearly resonant spin-dependent charge-exchange reaction between Cs and He^+.[5] Resonances in Sr^+ and Ba^+ ions have been seen by direct optical pumping.[6] Electron-impact alignment of $Xe^+(^2P_{3/2})$ has been detected via spin exchange with optically monitored and electronically aligned $Xe(^3P_2)$ metastable atoms.[7] Nuclear resonance in Rb^+ has been observed by charge exchange with optically pumped Rb.[8] Orientation of Hg^+ has been produced by electron-impact ionization of electronically excited and optically oriented $Hg(^3P_2)$ metastable atoms and detected by optical absorption.[9] Orientation of ions produced by Penning collisions with optically pumped He metastable atoms has been detected by the polarization of the fluorescence of excited group-II atoms or by optical absorption by ground-state group-II*A* atoms.[10] The present technique involving no ion resonance radiation or resonant collisions should then make new ions accessible for study. If previously published signals are representative of the other techniques, the present method should be highly competitive whenever the discharge conditions can be tolerated.

II. TECHNIQUE AND APPARATUS

Ion spectroscopy by spin exchange is described simply as follows: The Rb is oriented optically by its resonance radiation in the usual manner.[11] Ions are produced by a weak discharge in a sidearm. The ions are oriented in spin-exchange collisions with Rb and with exchange-oriented electrons. If the electron density is comparable to the ion density, as in the case of ions and electrons produced by Penning collisions of ion parent atoms with metastable He atoms, the ion-electron and atom-electron spin-exchange times are much shorter than the ion-atom time because of the much higher electron velocity.[12] The electrons then serve as messengers between the Rb and ions. Such is believed to be the case for Cd^+ and Sr^+ (large electron signals are seen for either polarity of the discharge). When the rf field is swept through the resonant frequency, the ion orientation is destroyed. By means of the spin-exchange process, the Rb orientation is reduced slightly also; this change is detected as a decrease in Rb pumping light transmitted through the cell.

The apparatus consists of the following: source of Rb 7800- and 7947-Å resonance radiation,[13] circular polarizer,[14] interaction cell, 7947-Å interference filter, silicon photovoltaic cell,[15] Princeton Applied Research HR-8 lock-in amplifier, PDP-8 data-averaging system,[16] Helmholtz coils for producing a static magnetic field of a few G, and an rf coil to transmit the amplitude-modulated output of a General Radio 1164 synthesizer.[16] The interaction cells, evolved from the one used in the optical pumping of Sr^+, are sketched in Figs. 1 and 2.[6] A dc discharge of a few mA in He at a pressure of a few Torr produced an ion density in the interaction region estimated to be about 10^{10} ions/cm^3 from Sr^+ optical-absorption measurements at a Sr density of about 3 mTorr.

III. DATA

A. Preliminary Studies

The detection of the orientation of the even isotopes of Sr^+ by spin exchange with Rb was attempted first by monitoring the absorption of the Rb^{85} 4215-Å output of the Rb lamp by the Sr^+ ions.[17,18] But it is extremely difficult to distinguish such a Sr^+ signal from the electron-exchange signal which changes the absorption of Rb^{85} 4215-Å light by Rb^{85} atoms. Direct optical pumping[6] was then observed with a Sr^+ lamp,[19] and spin-exchange orientation of the even isotopes of Sr^+ was verified by monitoring the transmission of the circularly polarized 4077-Å D_2 line of Sr^+ which is not absorbed by the Rb. The signal disappeared with either lamp blocked; the 4215-Å and 4077-Å signals were of opposite sign. Optical-pumping transients were observed and might be used to measure the spin-exchange cross sections for the dominant collision processes, probably Rb-e^- and Sr^+-e^- collisions.

A hurried attempt to see a direct pumping signal with Ne replacing He was unsuccessful. Direct observation of optical absorption indicated that He is about five times more effective than Ne or Ar in producing Sr^+ ions. Since He and Ne metastables are probably equally effective in producing Sr^+ ions in Penning collisions,[20] the excitation rate must be slower in Ne than in He at comparable discharge current and pressure.

B. Exchange Orientation and Detection

After the preliminary absorption and optical-detection experiments, the spin-exchange orientation of $(Sr^{87})^+$ was detected by spin-exchange collisions with Rb. Sr^{87} is 7% abundant in natural Sr and has nuclear spin $I=\frac{9}{2}$. In spite of these handicaps, the $(Sr^{87})^+$ resonance was clearly seen; see Fig. 1(b). Its g value of $\frac{1}{5}$ is easily distinguished from the Rb and electron resonances, unlike the $g\approx 2$ of the

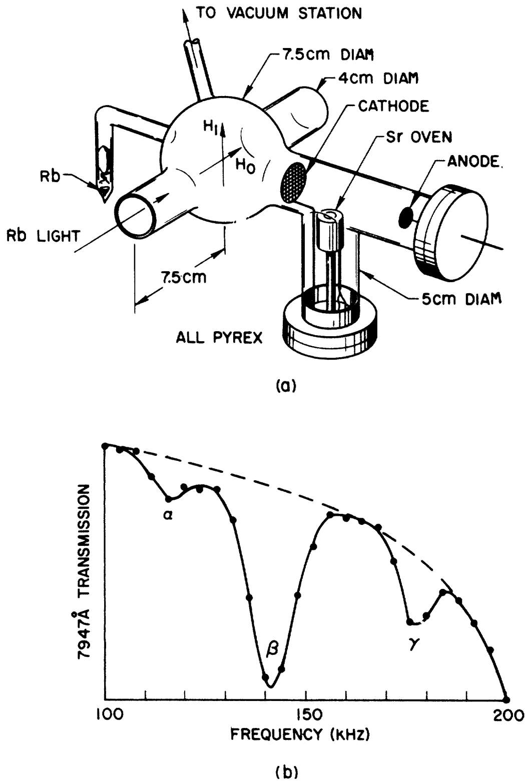

FIG. 1. (a) Rb-Sr$^+$ spin-exchange apparatus. Discharge and Sr oven tubes were wrapped with heater tape and maintained at 500 °C; Sr oven was needed to plate the walls of the discharge tube with the highly reactive Sr metal, but the wall temperature controlled the vapor pressure. The anode was a 1.3-cm-diam stainless-steel disk, and the cathode was 0.5-mm-diam Nichrome screen on a 3-cm-diam molybdenum ring. The Sr stainless-steel oven was heated by an American Standard Aerorod BXA06-B12-6M noninductive heater. (b) Transmission of Rb 7947-Å D_1 line through Rb vapor undergoing spin exchange with Sr$^+$ ions as the rf is tuned from 100 to 200 kHz in a static field of 0.5 G; a smooth curve has been sketched through the experimental points. The three resonances are superimposed on a curved background (dashed) which is the side of the Rb^{85} resonance at 233 kHz, which was 2500 times larger than the (Sr^{87})$^+$ resonance. Resonances α and γ are at the half-frequencies of the Rb^{85} and Rb^{87} resonances and result from second-harmonic components in the rf or double quantum transitions. The resonance labeled β is the (Sr^{87})$^+$ resonance with $g_F \approx \frac{1}{5}$ and $I = \frac{9}{2}$; it occurs only when the discharge is on. This resonance represents 1363 up-down cycles of 20 sec per cycle or about 7.6 h total integration time; three-to-one signal-to-noise ratios were obtained in 5–10 min total integration. Other conditions: 10-Torr He, Sr at 500 °C (about 0.3 mTorr), 8-mA discharge current from 300 V across discharge tube and 14 700-Ω series limiting resistor, rf modulation at 87 Hz, lock-in-amplifier time constant 0.1 sec, 0.4-sec-per-channel integration per cycle. Under these conditions 22% of the 4077-Å resonance radiation from a Sr flow lamp was absorbed, suggesting a Sr$^+$ ion density of about 10^{10} ions per cm^3.

even Sr$^+$ isotopes which coincides with the electron g value.

The technique was then applied to (Cd^{111})$^+$ and (Cd^{113})$^+$, both with $I = \frac{1}{2}$ and together constituting about 25% of natural Cd. No Cd resonance radiation at 2265 or 2144 Å was employed for optimizing the Cd density; in fact, those lines are not transmitted by the Pyrex end-windows. Instead, the conditions of the Sr$^+$ experiment were approximated: about 5 mTorr of Cd and 5 Torr of He. Large resonances were seen as in Fig. 2(b) using the simplified apparatus of Fig. 2(a). The Cd$^+$ resonance vanished at low (< 1 mTorr) and high (> 30 mTorr) Cd densities, with no discharge, or with no Rb circular polarizer. Good signals were seen

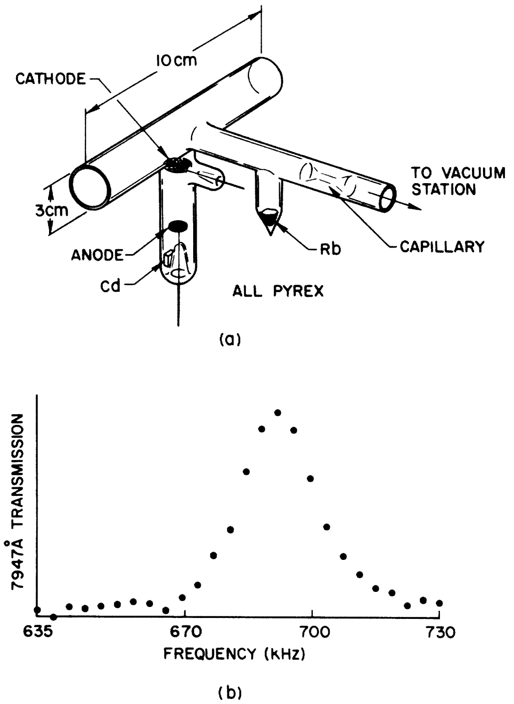

FIG. 2. (a) Rb-Cd$^+$ spin-exchange apparatus. The 1-cm-long × 1-mm-diam capillary retards the loss of Rb. AEROROD noninductive heaters prevented condensation of Cd on the cell end-windows and controlled the Cd vapor pressure in the discharge side-arm. (b) Transmission of Rb 7947-Å D_1 line through Rb vapor undergoing spin exchange with Cd$^+$ ions as the rf is tuned from 635 to 730 kHz in a static field of intensity slightly less than 0.5 G. The resonance for Cd^{111} and Cd^{113} with $I = \frac{1}{2}$ occurs for $g_F \approx 1$ as expected for $^2S_{1/2}$ ionic ground states. This curve is only one upward scan with a lock-in–amplifier time constant of 1 sec and 4 sec per channel, i.e., this curve could have been taken in 100 sec with a lock-in–amplifier time constant of 4 sec and no additional averager. Other conditions: 10-Torr He, Cd at about 253 °C (about 6 mTorr), 6-mA discharge current from 300 V across tube and resistor, and rf modulation at 88 Hz.

from 3- to 10-Torr He but not below 1 Torr; a quick signal search under similar conditions, but with Ne replacing He, yielded negative results. Under the conditions of Fig. 2(b) the relative signals for Rb^{87}: Rb^{85}: e^-: Cd^+ were 1.0: 0.67: 0.27: 0.013.[21] The discharge reduced the Rb signals by 30–40%. A Rb pumping time of 0.2–0.3 msec was measured from the recovery transient after the application of rf at the Rb^{85} or Rb^{87} resonant frequencies.

IV. DISCUSSION

A plausibility calculation can be made for the effect of the destruction of the Cd^+ polarization upon the Rb polarization (and optical-pumping signal). The Sr^+ density was calculated to be $10^{10}\ \text{cm}^{-3}$ from the 22% absorption of the 4077-Å line.[22,23] Assuming that the Cd^+ and Sr^+ production rates are identical and noting that the Cd vapor pressure was about twice the Sr pressure, one has a Cd^+ density of $2\times10^{10}\ \text{cm}^{-3}$. The combined density c of Cd^{111} and Cd^{113} ions was then about $5\times10^{9}\ \text{cm}^{-3}$. With a pressure of 10 Torr of He, ambipolar diffusion dominates, and the electron density e is about $2\times10^{10}\ \text{cm}^{-3}$.[24] Finally, the Rb density r was about $10^{11}\ \text{cm}^{-3}$ according to RCA vapor-pressure curves. The population equations can be written as

$$\dot{r}_+ = (\tfrac{1}{2}r - r_+)/T_r + (e_+ r/e - r_+)/T_{e\text{-Rb}} + (c_+ r/c - r_+)/T_{\text{Cd-Rb}} + (r - r_+)/T_p\,, \tag{1}$$

$$\dot{e}_+ = (\tfrac{1}{2}e - e_+)/T_e + (r_+ e/r - e_+)/T_{\text{Rb-}e} + (c_+ e/c - e_+)/T_{\text{Cd-}e}\,, \tag{2}$$

$$\dot{c}_+ = (\tfrac{1}{2}c - c_+)/T_c + (r_+ c/r - c_+)/T_{\text{Rb-Cd}} + (e_+ c/e - c_+)/T_{e\text{-Cd}}\,. \tag{3}$$

The Rb and Cd nuclear spins have been neglected. The + subscript refers to the spin-up state. T_r, T_e, and T_c are the nonexchange spin relaxation times, and T_p is the optical-pumping time. The remaining times are spin-exchange times; for example,

$$T_{e\text{-Rb}}^{-1} = \sigma_{e\text{-Rb}}\, e\, \bar{v}_{e\text{-Rb}}\,,$$
$$T_{\text{Rb-}e}^{-1} = \sigma_{e\text{-Rb}}\, r\, \bar{v}_{e\text{-Rb}}\,. \tag{4}$$

If one assumes all the spin-exchange cross sections are equal to $2\times10^{-14}\ \text{cm}^2$, which is typical for Rb-Rb and Rb-Cs spin exchange,[15] and if all species are thermalized to 325 °C, then we have (in msec)

$$T_{\text{Rb-}e}\approx 0.05\,,\quad T_{e\text{-Cd}}\approx 0.25\,,\quad T_{\text{Rb-Cd}}\approx 13\,,$$
$$T_{\text{Cd-}e}\approx 1\,,\quad T_{e\text{-Rb}}\approx 0.25\,,\quad T_{\text{Cd-Rb}}\approx 250\,.$$

These values emphasize the essential role of the electrons in transferring the Rb polarization to the Cd ions and vice versa. Under the assumptions $T_{\text{Rb-}e} \ll T_{e\text{-Cd}}, T_{\text{Cd-}e}, T_{e\text{-Rb}}, T_r, T_e, T_c \ll T_{\text{Cd-Rb}}, T_{\text{Rb-Cd}}$, one can show that the equilibrium Rb polarization P_r depends upon the Cd ions as follows:

$$P_r = 2\bar{r}_+/r - 1 = (1 + T_p/T)^{-1}\,, \tag{5}$$

with

$$T^{-1} = T_r^{-1} + T_{\text{Rb-}e}T_{e\text{-Rb}}^{-1}[T_e^{-1} \neg \quad {}^{-1}_{\text{Cd-}e}(1 + T_c/T_{e\text{-Cd}})^{-1}]\,. \tag{6}$$

This formula may be understood as follows. In the absence of the Cd ions and assuming the electrons are unpolarized, spin exchange with the electrons shortens the Rb relaxation to $T_{\text{Rb}}^{-1} = T_r^{-1} + T_{e\text{-Rb}}^{-1}$. If the electrons attain a polarization $P_r(1 + T_{\text{Rb-}e}/T_e)^{-1}$ as a result of competition between exchange with Rb and nonexchange relaxation then the electrons are less effective in relaxing the Rb:

$$T_{\text{Rb}}^{-1} = T_r^{-1} + [T_{e\text{-Rb}}(1 + T_e/T_{\text{Rb-}e})]^{-1}$$
$$\approx T_r^{-1} + T_{\text{Rb-}e}\,T_{e\text{-Rb}}^{-1}T_e^{-1}\,.$$

manner yielding Eq. (6).

For 10 Torr of He the Rb relaxation time is about ^{9}msec.[25] The observed recovery time of 0.25 msec after rf depolarization of the Rb without a discharge is then a measure of the pumping time T_p. The presence of the discharge reduces the signal or polarization by about 35% so the effective relaxation time T_r is about 0.5 msec [using Eq. (5)]. T_e and T_c can probably be taken equal to T_r without great error. The change in the Rb polarization upon destruction of the Cd^+ polarization by a resonant rf field is then given by

$$\frac{P_r(T_c) - P_r(0)}{P_r(T_c)} \approx \frac{T_{\text{Rb-}e}}{T_{\text{Cd-}e}\,T_{e\text{-Rb}}}\left(1 + \frac{T_{e\text{-Cd}}}{T_c}\right)^{-1}\left(\frac{1}{T_r} + \frac{1}{T_p}\right)^{-1}$$
$$\approx 2\%\ . \tag{7}$$

This agrees well with the ≈1.6% average observed for the two Rb isotopes. Clearly there are factors of 2 or more uncertainty in various densities, relaxation times, and exchange times, but this simple calculation should illustrate the magnitudes involved and the importance of the electrons. Note that a factor-of-5 reduction in electron and ion densities (as observed with Ne replacing He) decreases the polarization change to 0.04%, requiring an integration 2500 times longer for the same signal-to-noise ratio. This explains the absence of a signal with Ne.

V. CONCLUSION

Ion spectroscopy has been achieved using spin-exchange collisions with optically pumped Rb atoms both for polarizing the ions and for detecting their depolarization by a resonant rf field. The limitation on the Rb density imposed by optical-pumping requirements ($\approx10^{11}\ \text{cm}^{-3}$) results in a fairly long

Rb-ion spin-exchange time (≈10 msec). But in a weak plasma with electron and ion densities of about 10^{10} cm^{-3}, the high electron velocity at thermal energies reduces the atom-ion and ion-atom communication times to 1 msec or less. If relaxation times approaching 1 msec and pumping times less than 1 msec can be obtained, large ion signals (≈1% of Rb signals) can be observed by this technique. The advantages of this method are that no ion resonance radiation, resonant collisions, or large quantities of material are required. It should work for spectroscopy of the ground states of all the group-II ions.

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[1] H. G. Dehmelt, Advan. At. Mol. Phys. 3, 53 (1967); 5, 109 (1969).

[2] H. G. Dehmelt, Phys. Rev. 109, 381 (1958).

[3] E. Geneux and B. Wanders-Vincenz, Helv. Phys. Acta 33, 185 (1960).

[4] H. G. Dehmelt and K. B. Jefferts, Phys. Rev. 125, 1318 (1962).

[5] H. G. Dehmelt and F. G. Major, Phys. Rev. Letters 8, 213 (1962). Ultrahigh resolution hfs measurements in $(\mathrm{He}^3)^+$ are reported in E. N. Fortson, F. G. Major, and H. G. Dehmelt, *ibid.* 16, 221 (1966).

[6] H. Ackermann, G. zu Putlitz, and E. W. Weber, Phys. Letters 24A, 567 (1967); F. von Sichart, H. J. Stockmann, H. Ackermann, and G. zu Putlitz, Z. Physik 236, 97 (1970).

[7] T. Hadeishi and C. -H. Liu, Phys. Rev. Letters 17, 513 (1966); Phys. Rev. 170, 145 (1968).

[8] J. K. Mitchell and E. N. Fortson, Phys. Rev. Letters 21, 1621 (1968).

[9] C. -H. Liu, R. L. King, and H. H. Stroke, Phys. Rev. Letters 23, 209 (1969).

[10] L. D. Schearer, Phys. Rev. Letters 22, 629 (1969); L. D. Schearer and W. C. Holton, *ibid.* 24, 1214 (1970).

[11] R. L. deZafra, Am. J. Phys. 28, 646 (1960).

[12] $T_{\mathrm{ex}} = (\sigma_{\mathrm{ex}}\, n_2 \bar{v}_{12})^{-1}$ is the exchange time of species 1 undergoing spin-exchange collisions with cross section σ_{ex} with species 2 of density n_2. It is assumed that the thermal-energy spin-exchange cross section for atom-electron collisions is about equal to that for atom-atom collisions (see Ref. 2).

[13] R. G. Brewer, Rev. Sci. Instr. 32, 1356 (1961).

[14] Polaroid HN7 with 0.21-μm-thick quarter-wave plate.

[15] H. M. Gibbs and R. J. Hull, Phys. Rev. 153, 132 (1967).

[16] H. M. Gibbs, B. Chang, and R. C. Greenhow, Phys. Rev. 188, 172 (1969).

[17] Absorption of Rb 4215-Å light by Sr^+ ions was observed previously by J. Winocur and R. V. Pyle, J. Appl. Phys. 36, 2740 (1965).

[18] A HN38 linear polarizer and 0.075-cm Polaroid quarter-wave plate provided elliptically polarized light at 7947 and 4215 Å in the present experiment. The photocathode and first four dynodes of an RCA8575 photomultiplier tube detected the 4077- and 4215-Å light.

[19] Flow-lamp oven design of G. G. Churchill [Rev. Sci. Instr. 41, 891 (1970)] was inadequate because boron nitride disintegrates in the presence of hot Sr. A stainless-steel oven with Aerorod heater was used instead.

[20] The $\mathrm{He}(2^3S_1)$-Cd and $\mathrm{Ne}(^3P_2)$-Cd Penning cross sections are, respectively, 45 and 46 Å^2 [L. A. Riseberg and L. D. Schearer, Bull. Am. Phys. Soc. 16, 219 (1971)]. Most likely a similar equality occurs for Sr.

[21] Signals approaching 1% of the Rb signals were seen from $\mathrm{H}(^2S_{1/2})$ at $g_F = 1$ and $\mathrm{N}(^4S_{3/2})$ at $g_F = \frac{6}{5}$ and $\frac{10}{3}$ from improperly outgassed cells. Care must be taken to avoid an incorrect identification of a Zeeman resonance.

[22] Assuming the emission width to be three times the absorption width and both profiles to be Gaussian, one finds $k_0 l = 1$ [A. C. G. Mitchell and M. W. Zemansky, *Resonance Radiation and Excited Atoms* (Cambridge U. P., London, 1961), p. 323]. Then with an oscillator strength of $\frac{2}{3}$ and a length of 5 cm, Eq. (35) of Mitchell and Zemansky yields $N \approx 10^{10}$ cm^{-3}.

[23] Sr^+ density can be estimated from simple rate equations using the discharge current per unit area ($6/\pi$ mA/cm^2), approximate values of the cross sections for metastable production, Cd electron ionization, and Cd Penning ionization by He metastables, and estimates of the He metastable and Cd^+ lifetimes, yielding over 10^{12} ions per cm^3 for the interelectrode region. However, the electron cross sections assumed were for electrons above the threshold energies for metastable excitation or ionization, whereas most of the electrons are much less energetic in He at a pressure of 10 Torr. Also the density in the interaction region should be much lower than that between the electrodes.

One might also expect a high density of He^+ ions. An attempt to observe a $(\mathrm{He}^3)^+$ $g = 1$ resonance under similar conditions with 10 Torr of He^3 was unsuccessful. L. D. Schearer (Texas Instruments) suggests that the ion density and polarization may have been large but that resonant charge transfer collisions with He^3 have broadened the linewidth to many MHz.

[24] S. C. Brown, *Basic Data of Plasma Physics*, 1966 (MIT Press, Cambridge, Mass., 1967), p. 128.

[25] Estimated from the diffusion coefficient and disorientation cross section of R. A. Bernheim, J. Chem. Phys. 36, 135 (1962) and the diffusion equation for a cylindrical cell in W. Franzen, Phys. Rev. 115, 850 (1959).