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TECHNIQUE FOR PRECISION MEASUREMENTS OF NUCLEAR MOMENTS IN FREE ATOMIC IONS*

Jerry K. Mitchell† and E. Norval Fortson
University of Washington, Seattle, Washington
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The first accurate measurements of nuclear moments in free atomic ions are now possible using an optical-pumping, exchange-collision method. In an experimental application of the method to Rb^+, linewidths of a few hertz have been obtained.

We report here on the first observed nuclear resonances in free atomic ions. The nuclear moments of Rb^+ ions (electronic configuration $^1S_0$) have been oriented by charge-exchange collisions with optically pumped Rb atoms in the presence of an inert He buffer gas. Linewidths of a few hertz indicate long nuclear spin relaxation times in the buffer gas. The technique employed is a simple and a general one, which should permit precise measurements of many nuclear moments, for example, an accurate determination of the free-proton moment without the necessity of any shielding or other electronic corrections.

This technique should also have applications outside the field of resonance physics: in the production of beams of polarized nuclei and in the study of charge-exchange collisions at thermal energies, e.g., H^+ on H and H^- on H collisions.

Outline of the experiment. – The atomic-ion method that we have developed is related to earlier studies of free electrons and paramagnetic atoms which used spin-exchange collisions with optically oriented alkali atoms.[1-5] In our method charge-exchange collisions between the atomic ions and their parent atoms are utilized to establish and detect an orientation in the ions. The experimental arrangement for Rb^+ is shown in Fig. 1. In the usual manner for optical pumping,[6] circularly polarized Rb D_1 resonance radiation passes parallel to an external magnetic field through a cell containing Rb vapor and He buffer gas at 30-Torr pressure. By the process of absorbing and re-emitting the resonance radiation, the Rb atoms become polarized, with both the nuclear and electron spins acquiring orientation. A change in the orientation of the Rb atom may be detected as a change in the intensity of light transmitted through the cell.

A discharge is maintained in a side arm of the cell to produce Rb^+ ions. The nuclei in the Rb^+ ions become polarized by the Rb-Rb^+ charge-exchange reaction. A resonant disorientation of the Rb^+ nuclei by an applied oscillatory magnetic field may be detected by the consequent depolarizing effect on the Rb atoms through the same

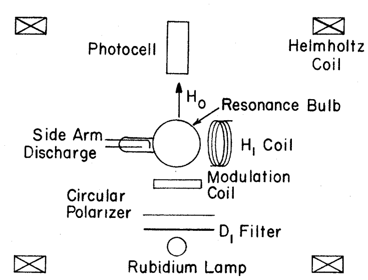

FIG. 1. Basic optical-pumping arrangement showing special side-arm discharge for producing ions and electrons in the resonance cell.

Rb-Rb$^+$ charge-exchange reaction. A competing effect results from the spin-exchange reaction between the Rb atoms and the free electrons invariably present in the plasma as a result of the discharge.

In a magnetic field of about 5 G, we have observed magnetic resonance transitions as summarized below.

System	Resonant frequency (Hz)	Relative signal height
$(Rb^{85})^+$	$1.700(5)\times10^3$	1/1200
$(Rb^{87})^+$	$5.760(50)\times10^3$	1/3000
Electron	$1.164(10)\times10^7$	$\frac{1}{3}$
Rb^{85} atom	$1.9405(5)\times10^6$	1

The ratios of these resonant frequencies agree, within the allotted errors, with other measurements of these same moments.[7] Greater accuracy will result from larger applied magnetic fields. The signal heights indicate the relative difficulty of observing the Rb$^+$ signals. With a simple lock-in system, however, these nuclear resonances were quite apparent with a signal-to-noise ratio of about 10:1 with a lock-in time constant of 10 sec. Fig. 2 shows a typical recorder trace.

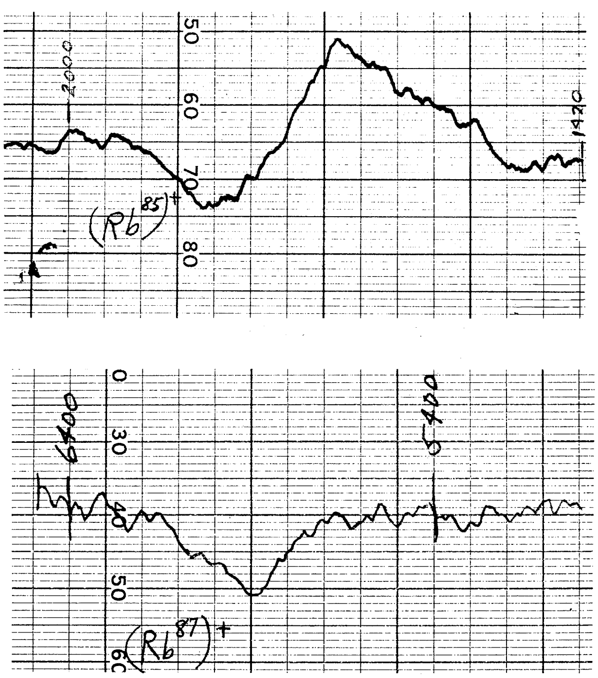

FIG. 2. $(Rb^{85})^+$ and $(Rb^{87})^+$ nuclear resonance curves. The $(Rb^{85})^+$ curve shown here was obtained for small magnetic field modulation causing it to look like a dispersion curve. The $(Rb^{87})^+$ curve was obtained with a larger modulation.

Linewidths and exchange rates.—A plot of the measured $(Rb^{85})^+$ linewidth versus Rb atom density as measured by optical absorption in the cell is given in Fig. 3 for high atom densities, together with a plot of the free-electron resonance linewidths. The plots display a linear behavior and yield cross sections for near-room-temperature Rb$^+$-Rb charge exchange of $\sigma(Rb^+)=2\times10^{-14}$ cm^2 and for e-Rb spin exchange of $\sigma(e)=3\times10^{-14}$ cm^2. For high Rb atom densities the ratio of Rb$^+$ and electron resonance signals should be

$$\kappa\frac{Iv_{Rb}\sigma(Rb)^+}{\frac{1}{2}v_{el}\sigma(e)}\cong\frac{1}{330}$$

for $(Rb^{85})^+$, where $I=\frac{5}{2}$ is the Rb^{85} nuclear spin, v_{Rb} and v_{el} are the Rb$^+$ and electron velocities, and the factor $\kappa=0.36$ is determined by the relative isotopic abundances of Rb^{85} and Rb^{87}. This ratio is consistent with the values in the table given above. From these same data we conclude that we have ion densities in the plasma of about 10^{10} ions/cc. Further studies of ion mobilities in the plasma should improve upon the accuracy of these estimates concerning the exchange processes.

The Rb$^+$ signal height was not strongly dependent upon whether the discharge was dominantly He or Rb. It is probable that He$^+$ ions tend to convert Rb atoms to ions via the charge-exchange reaction

$$Rb + He^+ \rightarrow Rb^+ + He^*,$$

where He* is an excited He atom. For He* in the

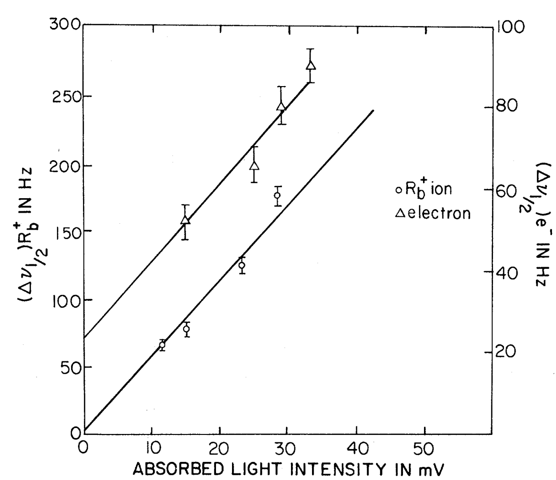

FIG. 3. $(Rb^{85})^+$ and electron linewidths for various absorbed light intensities ΔI. For small intensities, ΔI is proportional to the Rb atom density in the cell.

$^3S_1$ state, the above reaction is only a few tenths of an eV from resonant charge exchange, and hence has a sizable cross section.

As can be seen from Fig. 3, the linewidth for Rb^+ extrapolated to zero Rb atom density is about 5 Hz, which is about the width expected due to magnetic field inhomogeneities. However, further studies of the line shape at lower Rb atom pressures are needed to establish the complete validity of this extrapolation. There is no evidence at the moment of detectable broadening due to Rb^+-He collisions through nuclear quadrupole or other relaxation effects. It appears, therefore, that precision nuclear moment measurements with this technique will be limited only by the relative inhomogeneity in the applied magnetic fields. With uniform magnetic fields of a few kilogauss, accuracies exceeding 1 ppm should be possible.

Future developments.—The method here reported can in principle be applied to measuring the magnetic moment of any nucleus in an atomic ion whose neutral parent possesses a paramagnetic state suitable for orientation by either direct optical pumping or spin-exchange with optically oriented atoms. Accurate measurements of the Rb nuclear moments are planned which may resolve discrepancies between earlier measurements of these moments.[7]

Of the various ions which may be studied by this technique, the most interesting may be H^+, because of the fundamental importance attached to the proton (as well as the deuteron and triton) which have never been measured free from the influence of bound atomic or molecular electrons. Preliminary experiments with hydrogen gas in the absorption cell are now underway with a view to applying the technique to H^+. An interesting comparison should be possible with the extremely accurate hydrogen maser measurement of g_I/g_J in the neutral H atom.[8]

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INFLUENCE OF Q VALUES IN ATOMIC SINGLE COLLISIONS ON OBSERVED SCATTERING CROSS SECTIONS AND SOME Q VALUES

P. Loftager and G. Hermann
Institute of Physics, University of Aarhus, Aarhus C, Denmark
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Total differential scattering cross sections observed at 80° in the lab system versus incident energy for 12- to 100-keV P^+, Cl^+, Ar^+, and K^+ on Ar exhibit a similar characteristic structure. The structure is explained in terms of the kinematics of inelastic collisions occuring in the region of triple Q structure in the Ar-Ar case. The existence of triple Q structure in P^+-, Cl^+-, and K^+-Ar cases is further supported by a calculation of Q values involving theoretical Thomas-Fermi cross sections.

The scattering of 12- to 100-keV P^+, Cl^+, Ar^+, and K^+ on Ar in single collisions has been studied with a setup characterized by a scattering angle Ψ in the laboratory system fixed at 80° and an acceptance angle $\Delta\Psi$ fixed at approximately 0.25°. All charged particles scattered into the detector are counted irrespective of charge state. About 99 % of the scattered particles at 80° are recoils. The experimental uncertainty amounts to about 10 % except for incident ener-