ORIENTATION OF $(He^4)^+$ IONS BY EXCHANGE COLLISIONS WITH CESIUM ATOMS*

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One of the chief experimental objectives in modern rf spectroscopy of free atomic systems is their localization for durations as long as possible under conditions minimizing undesirable interactions with the confining means. If such techniques are available, it becomes feasible on the one hand to orient the systems by a variety of collision reactions with photons,[1] atoms,[2] and electrons,[3] and on the other, to minimize line broadening, due to Doppler[4] and observation time effects, in subsequent resonance (disorientation) experiments. While, in the case of neutral atoms, considerable headway has been made through the use of inert buffer gases and container wall coatings,[5,6] small residual interactions remain which are not fully understood.[7] Charged particles, on the other hand, offer the intriguing possibility,[3] so far unexploited, of being trapped in suitable electromagnetic fields for practically unlimited periods and with vanishing side effects. Quadrupole rf[8,9] and dc[10] (magnetron) traps offer themselves as being most suitable for rf spectroscopy. An experimental program for the study of electrons and various ions based on the above considerations has been pursued in this laboratory for some years and has now yielded the first results. The polarization of trapped $(He^4)^+$ ions has been demonstrated by observing the low-field Zeeman transitions. The ions were created by a pulsed electron beam, of 120-msec duration and approximately 1-ma amplitude, which ionized the background gas, consisting mainly of He introduced through a quartz leak. They were confined by an rf quadrupole trap similar to the one described by Fischer.[11] When operated with a 1-Mc/sec rf voltage of about 175 volts peak and 7 volts dc, on the electrodes (see Fig. 1), the trap acts effectively as a parabolic potential well about 20 volts deep, with an axial oscillation frequency of 110 kc/sec for $(He^4)^+$. The resonant rf absorption signal occurring at the axial oscillation frequency of the ions was used to monitor the number of trapped ions. By varying the time interval between the creation of the ions and their detection, their mean lifetime was determined as approximately 8 seconds for a background gas pressure of about 3×10^{-8} mm Hg achieved through the use of Vacion pumps. Since the ions are presumably lost by collisions with the electrodes after repeatedly gaining energy from the trapping rf field through randomizing collisions with background atoms, it is expected that the ions remaining will retain a mean energy of about half the well depth.

The next task, namely the orientation of the ions and its subsequent monitoring, was achieved by bombarding the trapped ions with a beam of optically oriented [1,12,13] Cs atoms. The principal processes of interest occurring during the

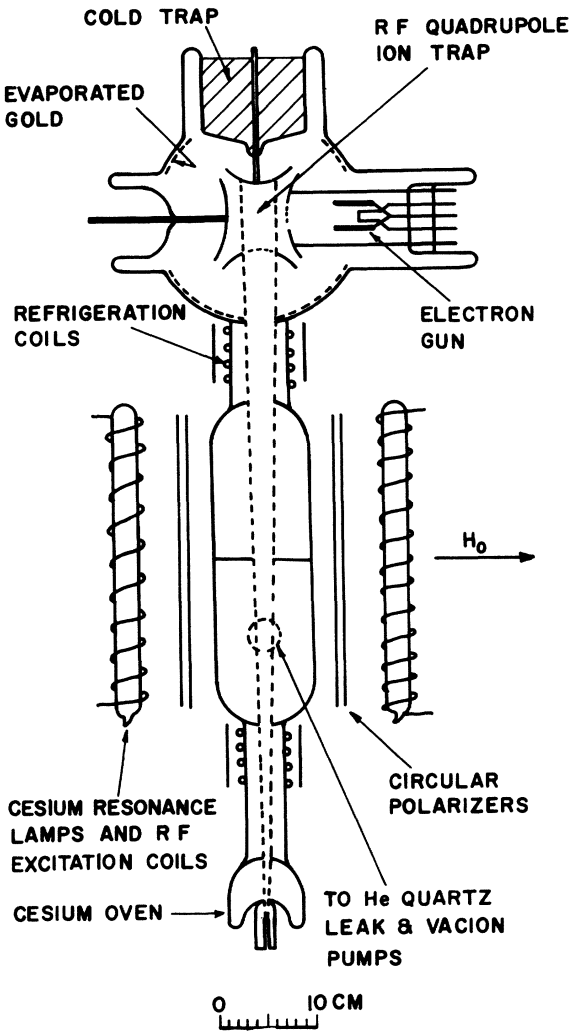

FIG. 1. Ion trap and optically pumped Cs beam apparatus for the study of He^+ rf spectra.

Cs-He^+ collisions are spin exchange,

$$Cs(\downarrow)+He^+(\downarrow)\rightarrow Cs(\downarrow)+He^+(\uparrow),$$

and charge capture,

$$Cs+He^+\rightarrow Cs^+ + He^*.$$

The excited He^* atom may either be in the $2\,^1S_0$ singlet or the $2\,^3S_1$ triplet state. Since the energy defects for these three reactions with cross sections Q_e, Q_1, and Q_3 are 0.0 ev, 0.1 ev, and 0.9 ev, respectively, one might expect approximately on the basis of the Massey criterion[14] for nearly adiabatic conditions, and other considerations, that

$$Q_e \gg Q_1 \gg Q_3.$$

This ordering of the cross sections is most effective in realizing the orientation of the ions and explains the choice of cesium. Because of it, the ions assume the electron spin orientation of the atoms, P, in a time short compared to the characteristic time for neutralization due to charge capture, T_0, and the latter process subsequently reinforces the orientation. This can easily be seen for the limiting case

$$P=1,\quad Q_3=0,\quad Q_1\neq 0.$$

By adjusting the intensity of the unoriented beam, T_0 was set at 0.4 sec, which, by comparison with the 8-sec lifetime in the absence of the Cs, indicates that He^+-Cs collisions are certainly dominant.

In order to demonstrate the polarization of the ions, use was made of the dependence of the mean lifetime of the ions, T, on the polarization of the Cs beam, P. It can readily be shown that

$$T\approx T_0(1-\tfrac{1}{4}dP^2)^{-1},$$

where

$$d\equiv(Q_1-Q_3)/Q,\quad Q=\tfrac{3}{4}Q_3+\tfrac{1}{4}Q_1.$$

From this one may deduce that the signal S, defined as

$$S\equiv[n(P)-n(0)]/n(0),$$

where $n(P)$ is the number of ions remaining when the beam polarization is P, takes the optimum value

$$S\approx\tfrac{1}{2}dP^2,$$

when the ions have been allowed to interact with the atoms for a time $2T_0$. Experimentally, the ions were created and detected periodically with a frequency of 1/sec, with the Cs beam being disoriented on alternate cycles by a frequency-modulated H_1 field applied in the optical pumping region. The experimental signal obtained in this way was $S=0.04$. This is in agreement with the reasonable estimates of $d=1$, $P=0.3$. The mean fluctuation in the ion signal was about 1% for constant beam polarization and oscilloscopic observation.

In a further experiment a second unmodulated rf H_1 field was applied at the site of the trap. It was observed that upon adjusting the frequency, the signal S was reduced to zero at 1.93 Mc/sec and 15.44 Mc/sec, which in a magnetic field of 5.5 gauss corresponds to the disorientation of the Cs atoms and the He^4 ions, respectively.

Similar work is in progress on the He^3 ion with a view to studying the $\Delta F=\pm 1$ hyperfine transitions.

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