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Spin-polarized hydrogen maser

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Maser action on the hydrogen hyperfine transition has been achieved at a temperature of 0.3 K in a liquid-helium-lined resonator. Polarized atoms are provided by magnetic ejection from a low-temperature discharge in a high magnetic field. The maser demonstrates the feasibility of a proposed low-temperature frequency standard. Operation of the atomic hydrogen source represents an essential step toward magnetic trapping of hydrogen at very low temperatures. Operated continuously, the source provides 5×10^{12} atoms/sec to the maser. In a 1-sec single pulse it can provide up to 2×10^{13} polarized atoms.

The techniques of spin-polarized hydrogen[1] offer attractive possibilities for a new type of hydrogen-maser frequency standard[2] that operates in the subkelvin regime and employs a liquid-helium film, rather than teflon, to suppress the effects of wall collisions on the radiating atoms. The systematics of such a maser have been analyzed by Berlinsky and Hardy[3] who pointed out advantages including a highly reproducible wall frequency shift, higher power due to the diminished spin-exchange cross section at low temperature, inherently lower noise at low temperature, and the enhanced ability to control environmental factors which affect the maser's stability such as the ambient magnetic field and drift of the resonator frequency.

We report here the operation of a hydrogen maser at a temperature of 0.3 K that demonstrates the feasibility of such a device, but which is not itself intended for clock purposes. Our efforts were directed primarily at creating a new type of low-temperature atomic hydrogen source to be used in forthcoming experiments on pure magnetic confinement of spin-polarized hydrogen.[4] Hyperfine resonance was chosen as the most reliable diagnostic for the source's operation. Radiation damping was observed, and as the source's performance was improved, a point was reached where the device would spontaneously break into continuous oscillation when the source was turned on.

Spin-polarized hydrogen research has almost exclusively employed hydrogen atoms in the "high-field-seeking" states, *a* and *b* ($m_S=-\frac{1}{2}$, $m_I=+\frac{1}{2},-\frac{1}{2}$, respectively). However, only atoms in the "low-field-seeking" states, *c* and *d* ($m_S=+\frac{1}{2}$, $m_I=-\frac{1}{2},+\frac{1}{2}$, respectively) can be trapped magnetically without any confining walls. Spin-polarized hydrogen is normally created by allowing unpolarized atoms to flow into a high magnetic field: Atoms in states *a* and *b* are strongly attracted by the field; atoms in states *c* and *d* are strongly repelled. We have reversed the procedure. A low-temperature ($T\approx0.5$ K) discharge dissociates molecular hydrogen inside of a 3-T solenoid. *c*- and *d*-state atoms are magnetically ejected from the solenoid: *a*- and *b*-state atoms are confined and either recombine or undergo spin-flip transitions to be finally ejected.

The apparatus is shown in Fig. 1. The discharge is based on a design by Hardy, Morrow, Jochemsen, and Berlinsky.[5] The source of hydrogen is a film of molecular hydrogen frozen to the walls of a copper cell. The hydrogen is covered with a thick film of superfluid helium. A 180-MHz pulsed radio frequency discharge evaporates and dissociates the hydrogen. The discharge assembly cools rapidly, restoring the superfluid film which serves as an inert thermalizing surface for the atomic hydrogen. Adequate cooling of the dissociator is a critical factor, for the atoms must thermalize before they diffuse to the end of the solenoid. To remove heat generated by the discharge, the source is coupled to an intermediate cooling stage of a dilution refrigerator at a temperature of 0.5 K. The ejected atoms hit a number of thermalizing baffles as they pass through a thermal gradient to the resonator chamber. The latter is thermally coupled to the mixing chamber of the dilution refrigerator.

The maser resonator is a split cylinder,[6] (1.75 cm diam, 5.0 cm long), trimmed inductively to the hyperfine frequency (1420.40 MHz) with a movable, concentric cup. The Q is 590. Two small loops near one end are used to excite the resonance and to detect the radiation. The field-independent transition ($F=1$, $m=0$)$\rightarrow$($F=0$,

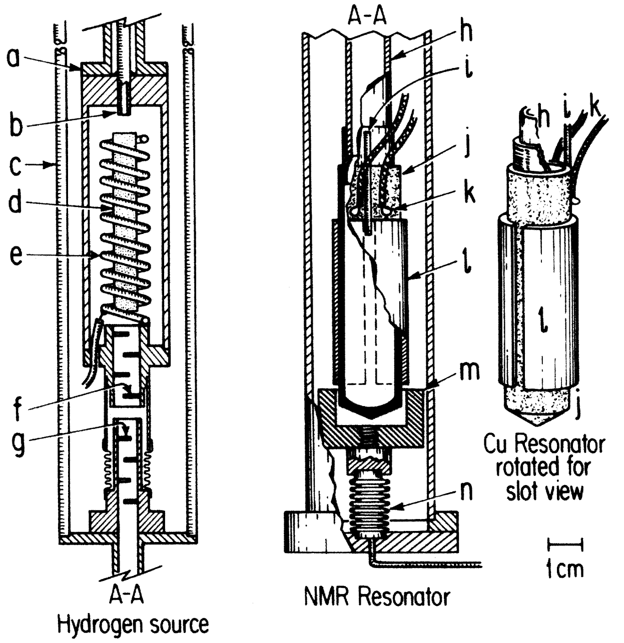

FIG. 1. Diagram of H↑ source and the 1420-MHz resonator. The source is in a 3-T magnetic field while the NMR resonator is in zero field. (a) Thermal connection to 0.5-K heat exchanger. (b) Heated H_2 filling capillary. (c) Thermal connection to mixing chamber. (d) Sapphire rod. (e) 180-MHz helical resonator. (f) 0.5-K baffles. (g) 0.3-K baffles. (h) H↑ transport tube. (i) Thermal connection to NMR resonator. (j) Epoxy container. (k) Inductive coupling loops. (l) 1420-MHz split-ring NMR resonator. (m) Inductive frequency tuning cup. (n) Frequency tuning bellows.

$m=0$), or $c \rightarrow a$ in the high-field notation, was observed. To achieve stable self-sustained maser oscillation, the Q had to be increased to 2000 by external feedback. The total system volume is 50 cm^3, approximately half of which is in the low-field region; the resonator has a sample volume[7] of 5 cm^3 and is located approximately 37 cm from the 3-T solenoid, which is compensated to reduce the field at the resonator.

In one mode of operation, a polarized population was generated by operating the source for 1.5 sec at an average power of 10 mW, using a 150-pulse sequence of 300-μsec pulses, at 10-msec intervals. Either positive or negative polarization could be observed, depending on thermal conditions. [We define the polarization as $P=(n_c-n_a)/(n_c+n_a)$. n is the atomic density.]

The initial amplitude and sign of a free induction decay following a $\pi/2$ pulse measures the instantaneous value of n_0P, where $n_0=n_a+n_c$. The dashed line indicates the time evaluation of n_0P following the fill (see Fig. 2). Immediately after the discharge ended, n_0P was observed to be -1.7×10^{12} cm^{-3}. (A stronger discharge could produce n_0P as high as -8×10^{12} cm^{-3}.) This indicated a preponderance of a-state atoms, presumably because hot atoms were escaping from the source and coming to equilibrium in the resonator. Assuming a thermal equilibrium polarization at the resonator temperature, then $P=-0.11$ and the initial density n_0 was 1.6×10^{13} cm^{-3}. The magnetic field gradients removed the a atoms, leaving an excess of c atoms in the resonator. Within one second the signal passed through zero and subsequently attained a maximum with $n_0P=7\times10^{11}$ cm^{-3}. Assuming $P=1$ at the maximum, $n_0=7\times10^{11}$ cm^{-3} and the total number of c-state atoms in the zero-field region was $N_c=2\times10^{13}$.

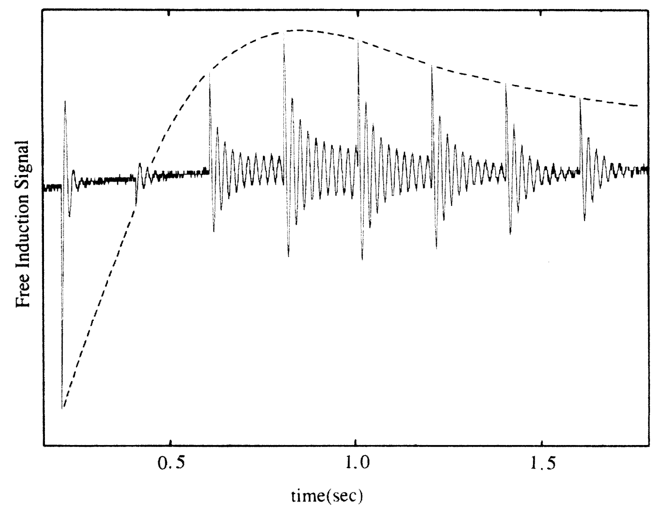

FIG. 2. Sequence of $\pi/2$ free induction decays after 1.5-sec operation of source. Horizontal axis indicates time elapsed after source was turned off. Evolution of n_0P is indicated by the dotted line. The maximum n_0P is 7×10^{11} cm^{-3}. The oscillation visible in the decay of the third through sixth free-induction signals are the initial indications of maser action.

The free-induction-decay time T_2^* at low densities was 20 msec. A magnetic field inhomogeneity of approximately 0.4 G would produce such a relaxation time. The decay times observed at high densities, following a 1.5-sec discharge, show strong effects of radiation damping (see Fig. 2). Immediately following the discharge, when n_0P was large and negative, the decay time was shorter than 20 msec. As the polarization evolved and changed sign, the free-induction-decay time lengthened beyond the low density value; when n_0P exceeded 5×10^{11} cm^{-3} the signal did not decay to zero but instead approached a constant. The free-induction signal of a small-angle tipping pulse increased with time under these conditions. These quasi-continuous oscillations occurred when the threshold condition $T_2^* > \tau_R$ was satisfied, where τ_R is the radiation damping time. The maser threshold was used in our calibration of the gas-density–polarization product. An independent estimate of n_0P based on the amplitude of a free induction decay was roughly consistent.

To achieve stable maser oscillation, the source was operated continuously but at a much reduced power in order to reduce heating effects. The discharge was excited using a continuous stream of 100-μsec pulses spaced 70 msec apart, leading to an average power dissipation in the source of 400μW. The thermal load at the low-temperature resonator was 40μW. The hydrogen flux was not adequate to sustain maser oscillations with a cavity Q of 590. However, when the Q was increased to 2000 with external feedback, the maser started spontaneously within a few seconds and oscillated continuously. Under these conditions, n_0P was found to be 2×10^{11} cm^{-3}, from free-induction-decay measurements. By studying the resonance signal as the source was turned off, the polarized steady-state flux was estimated to be 5×10^{12} sec^{-1}. The power radiated by the maser was 1.0×10^{-13} W.

The frequency of the maser was shifted typically 500 Hz above the free-space hyperfine frequency, the exact value being determined by the applied magnetic field. For average fields below 0.4 G the oscillation quenched, indicating that the field gradients were approximately this size. Because of the gradients, we did not attempt a precise measurement of the frequency. We measured a frequency fluctuation of 0.2 Hz over 40-sec intervals. This corresponds to ambient field variations of 16 μG, a reasonable value for an unshielded maser in a laboratory environment.

We hope that the results will be helpful in efforts to develop low-temperature hydrogen masers as atomic clocks. The magnetic ejection source represents a useful advance toward pure magnetic confinement of hydrogen, and it may possibly find use in other applications.

Note added in proof. Successful operation of another low-temperature hydrogen maser is described in another article.[8]

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[5]W. N. Hardy, M. Morrow, R. Jochemsen, and A. J. Berlinsky Physica B **109&110**, 1964 (1982).

[6]W. N. Hardy and L. H. Whitehead, Rev. Sci. Instrum. **52**, 213 (1981).

[7]The filling factor used for our determination of the densities (0.2) is based directly on the ratio of the sample volume to inductor volume. If the true filling factor were another factor of three smaller as suggested in M. Morrow, Ph.D. thesis, University of British Columbia, 1983 (unpublished), then the densities must be scaled up by a factor of 3.

[8]M. D. Hürliman *et al.*, following paper, Phys. Rev. A **34**, 1605 (1986).