

Demonstration of a Two Species Noble Gas Maser

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We have demonstrated the first two species maser. Ensembles of ^3He and ^{129}Xe gas, co-located in a double-chamber glass cell, performed simultaneous maser oscillations on their nuclear spin- $\frac{1}{2}$ Zeeman transitions. This new device may be used for experiments requiring precision magnetometry combined with frequency measurement of a second free-running species operating in the same volume. For example, the ^3He maser may serve as a magnetometer, while the ^{129}Xe maser may be used to search for a permanent electric dipole moment of the ^{129}Xe atom as a test of time reversal symmetry. [S0031-9007(96)01584-0]

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Precision measurement of the Zeeman splitting in a two-state system is the basis for searches for permanent electric dipole moments (EDMs) in the neutron [1] and in atoms [2–5]. Such EDM searches serve as stringent tests of time reversal symmetry in elementary particle interactions [6]. Currently, two species differential EDM experiments are being performed to search for leptonic T -violation (using ^{205}Tl and Na) [7], and to search for T -violation in neutrons (using a ^{199}Hg comagnetometer) [8]. The advantage of differential measurements is that they are insensitive to common-mode systematic effects [9]. Here we report the operation of a two species noble gas maser, the first device to simultaneously sustain active maser oscillations on two distinct transitions in different atomic species (^3He and ^{129}Xe). The two species noble gas maser allows sensitive differential measurements of the noble gas Zeeman splittings. Thus one noble gas species can serve as a precision magnetometer to stabilize the system's static magnetic field, while the other species is used as a sensitive probe for new physics such as an EDM. The two species noble gas maser has an additional important feature: active maser oscillation permits arbitrarily long coherent measurement of the noble gas Zeeman frequencies. A coherent frequency measurement can achieve greater precision than the incoherent average of a set of shorter measurements made during an equivalent period of time.

Predicted ^{129}Xe and ^3He EDMs arise from hadronic and tensor electron-nuclear interactions containing terms proportional to Z^2 and higher order in Z [6], so that a ^3He EDM is expected to be much smaller in magnitude than a ^{129}Xe EDM. Our planned EDM search will entail sequential applications of an electric field parallel, and then antiparallel, to a static magnetic field. The electric field's coupling to a ^{129}Xe EDM would produce a maser frequency shift linear in the magnitudes and signs of both the ^{129}Xe EDM and the electric field. The static magnetic field can be feedback stabilized by phase locking one species' maser to a stable frequency standard. The other [free-running] maser will be monitored for electric-field-proportional frequency shifts. Either maser can be phase

locked. When the ^3He maser is phase locked, a possible ^{129}Xe EDM/ E -field coupling would induce a frequency shift in the ^{129}Xe maser. When the ^{129}Xe maser is phase locked, a ^{129}Xe EDM/ E -field coupling would change the magnetic field required to maintain a constant ^{129}Xe maser frequency: this EDM-induced alteration of the magnetic field would cause a frequency shift in the free-running ^3He maser.

The two species noble gas maser consists of dense, co-habiting samples of ^3He and ^{129}Xe atoms oscillating on their nuclear spin- $\frac{1}{2}$ Zeeman transitions at audio frequency. The maser population inversions are created by spin exchange collisions between the noble gas atoms and optically pumped Rb vapor [9,10]. The two species noble gas maser has two chambers, one acting as the spin exchange "pump bulb" and the other serving as the "maser bulb." This two chamber configuration permits the combination of physical conditions necessary for a high flux of spin-polarized noble gas atoms into the maser bulb, while also maintaining ^3He and ^{129}Xe maser oscillations of exceptional frequency stability. In a previous Letter [11] we reported the operation of spin-exchange-pumped Zeeman masers using a single noble gas species (^3He or ^{129}Xe); we also described a Bloch equation model appropriate for both the single and two species masers. In the present Letter we report the operation of the first two species noble gas maser, and a summary of our measurements to date with this new device.

A schematic diagram of the two species noble gas maser is given in Fig. 1, with typical operating parameters listed in Table I. The pump and maser bulbs contain a dense sample of ^3He , ^{129}Xe , and N_2 gas. The pump bulb also contains a small amount of Rb and is maintained at a temperature of approximately 120 °C. Thus there is a moderate density of Rb vapor ($\approx 10^{13} \text{ cm}^{-3}$) present in the pump bulb. In the maser bulb, the Rb vapor density is low ($\approx 10^{10} \text{ cm}^{-3}$) because of the relatively cool temperature ($\approx 40 \text{ °C}$) of this chamber. The low Rb density in the maser bulb prevents unwanted Rb-induced spin exchange relaxation and frequency shifts

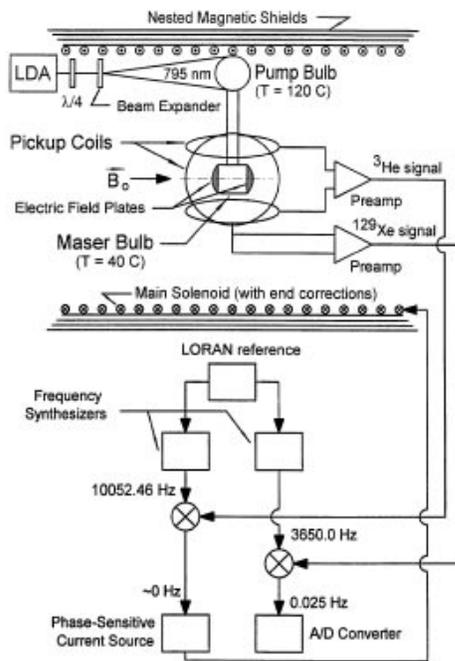


FIG. 1. Schematic diagram of the two species noble gas maser. Electric field plates were not installed in the experiments reported in this Letter.

from adversely affecting the masing ^3He and ^{129}Xe ensembles. The bulb assembly is constructed using proven techniques and materials [9,10]. The bulbs are made of borosilicate glass (Corning 7056) treated with a silane coating to minimize relaxation of the ^{129}Xe atoms at the walls [12]. The temperatures of the pump and maser bulbs are controlled to about 0.1 K by flowing heated air. A homogeneous and stable magnetic field of ≈ 3 gauss is created by a two-layer solenoid with end trim coils, together with field-gradient correction coils mounted around the maser bulb and three concentric cylindrical magnetic shields with endcaps.

Light from a high power diode laser array at 795 nm is circularly polarized and focused onto the pump bulb. Such light is resonant with the Rb D_1 transition and induces an electron spin polarization in the Rb vapor via a standard optical pumping process [13]. The N_2 buffer gas in the pump bulb promotes collisional de-excitation of the optically pumped Rb atoms, thereby preventing radiation trapping [14]. ^3He -Rb and ^{129}Xe -Rb spin exchange collisions in the pump bulb spin-polarize the noble gas nuclei and provide the population inversion necessary for continuous maser oscillation. The polarized ^3He and ^{129}Xe atoms diffuse out of the pump bulb, down the transfer tube, and into the maser bulb. The maser bulb is surrounded by two pickup coils, one part of a circuit resonant with the ^3He nuclear Zeeman transition (≈ 10 kHz for a 3 G static magnetic field), the other part of a circuit resonant with the ^{129}Xe transition (≈ 3.5 kHz in the same field). The resonant coils provide positive feedback to these noble gas transitions, and under typical

conditions the ^3He and ^{129}Xe ensembles each perform continuous and independent maser oscillations. After making radiative transitions in the maser bulb, the noble gas atoms diffuse back to the pump bulb where they are re-polarized by spin exchange. Thus active masing of both species can continue indefinitely.

The ^3He and ^{129}Xe maser signals are amplified (~ 30 dB gain) and mixed with signals generated by frequency synthesizers phase locked to a common frequency standard. The synthesizer used with the phase-locked maser is set at the desired Zeeman frequency for this noble gas species, and the resulting error signal produced by the mixer corrects the voltage driving the static magnetic field solenoid such that this maser's signal is phase-locked to the frequency synthesizer signal. As a result, magnetic field variations in the maser bulb, which could affect the frequency of the other free-running noble gas maser, are compensated for at the level of the phase-locked maser's intrinsic frequency stability. Magnetic field variations could be caused by fluctuations in the current producing the static magnetic field, by external magnetic field changes, or, in an EDM measurement, by stray currents induced by the high voltage difference between the electric field plates. The synthesizer used with the free-running maser is offset by a small amount (~ 0.01 Hz) from this noble gas species' Zeeman frequency and the resultant beat signal is digitized. A nonlinear least squares fit to a sinusoid determines the free-running maser's frequency.

Figure 2 shows plots of measured Allan deviations for the ^3He and ^{129}Xe masers as a function of measurement interval τ . The Allan deviation is the RMS spread in the set of differences between pairs of successive frequency measurements, each made over a time interval τ [15]. Figure 2(a) shows that the (phase-locked) ^{129}Xe maser's Allan deviation varies as $\sim 2 \times 10^{-3} \tau^{-3/2}$ Hz for measurement intervals from about 60 to 8,000 sec. (This behavior is similar to that reported in Ref. [11].) Figure 2(a) also shows that the (free-running) ^3He maser's Allan deviation initially varies as $\sim \tau^{-3/2}$, as is expected for a coherent frequency measurement with the dominant noise source being added thermal white phase noise from the maser's electronics [11]. For $\tau >$ a few hundred seconds, the ^3He maser's Allan deviation trends as $\sim \tau^{-1/2}$ with a value of ~ 1 μHz at 8000 sec. Similar results were obtained with a phase-locked ^3He maser and free-running ^{129}Xe maser [see Fig. 2(b)].

The amplitude and frequency of the free-running ^3He maser during its approach to equilibrium are shown in Figs. 3(a) and 3(b), respectively. Both the amplitude and frequency exhibit damped oscillations with a characteristic system frequency of approximately 0.22 mHz. Such "start-up" oscillations are intrinsic to Zeeman masers and have been investigated previously [11,16]. However, we observed that similar oscillatory behavior persists even after a nominal equilibrium is attained. Figure 4(a) shows the free-running ^3He maser's frequency residuals (i.e., the difference of the frequency from the mean value) as

TABLE I. Two species noble gas maser operating parameters.

Bulb temperatures	120 °C (pump); 40 °C (maser)
Rb vapor density	$1.7 \times 10^{13} \text{ cm}^{-3}$ (pump) $4.2 \times 10^{10} \text{ cm}^{-3}$ (maser)
^3He density	$4.9 \times 10^{19} \text{ cm}^{-3}$
^{129}Xe density	$6.8 \times 10^{18} \text{ cm}^{-3}$
$1/\gamma_{se}$ (spin exchange collision time in pump bulb)	104 h (^3He) 0.05 h (^{129}Xe)
Rubidium polarization in pump bulb	0.6
T_1 (polarization relaxation time)	8.3 h (^3He) 0.12 h (^{129}Xe)
Q (resonator quality factor)	22.6 (^3He) 8.6 (^{129}Xe)
τ_{rd} (radiation damping time [11])	42 sec (^3He) 34 sec (^{129}Xe)
T_2 (transverse coherence time)	59 sec (^3He) 175 sec (^{129}Xe)
Operating frequencies	10,124 Hz (^3He) 3676 Hz (^{129}Xe)

a function of time, measured subsequent to attainment of a nominal equilibrium. Shown in Fig. 4(b) is the residuals' Fourier transform (frequencies were computed over 500 sec intervals). More than half of the power spectral density of the Fourier transform is in a single peak at the characteristic system frequency of 0.22 mHz. Similarly, we observed that small free-running maser am-

plitude oscillations, again at 0.22 mHz, persist after the system has reached a nominal equilibrium. The equilibrium free-running ^3He maser amplitude and its Fourier transform are shown in Figs. 4(c) and 4(d), respectively.

The persistent, near-equilibrium oscillatory behavior of the ^3He maser has a simple qualitative explanation. It

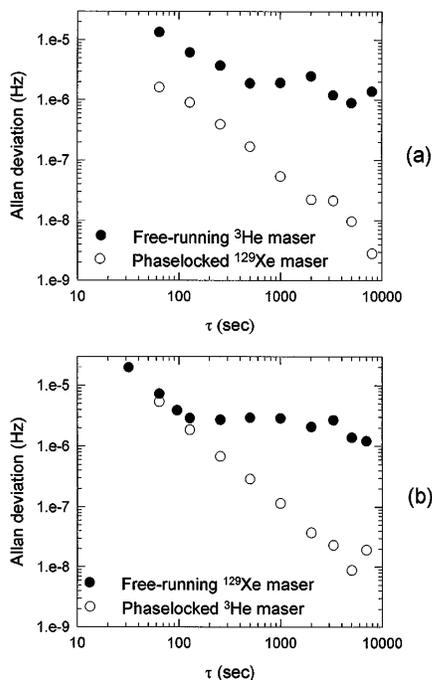


FIG. 2. (a) Allan deviations for the phase-locked ^{129}Xe maser and the free-running ^3He maser. The former shows the expected $\tau^{-3/2}$ dependence on measurement interval τ ; the latter departs from a $\tau^{-3/2}$ variation for $\tau > 500$ sec. (b) Similar results were obtained with the phase-locked ^3He maser and the free-running ^{129}Xe maser.

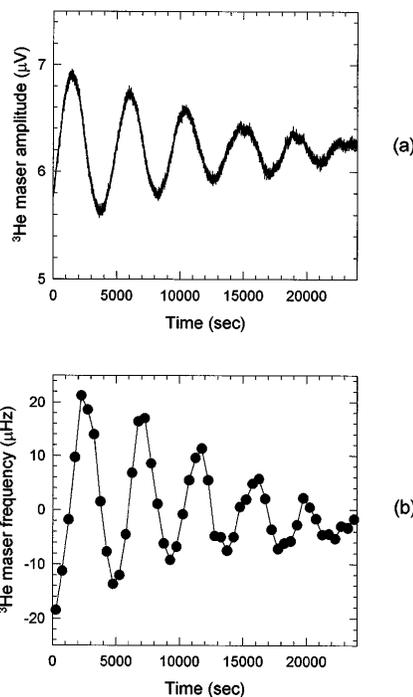


FIG. 3. (a) Free-running ^3He maser amplitude undergoing oscillations during approach to equilibrium. The oscillation frequency of 0.22 mHz is an intrinsic property of the maser near equilibrium. (b) Free-running ^3He maser frequency residuals, measured simultaneously with the data of (a). The frequency residuals also undergo a damped oscillation at 0.22 mHz which is correlated to the amplitude oscillations.

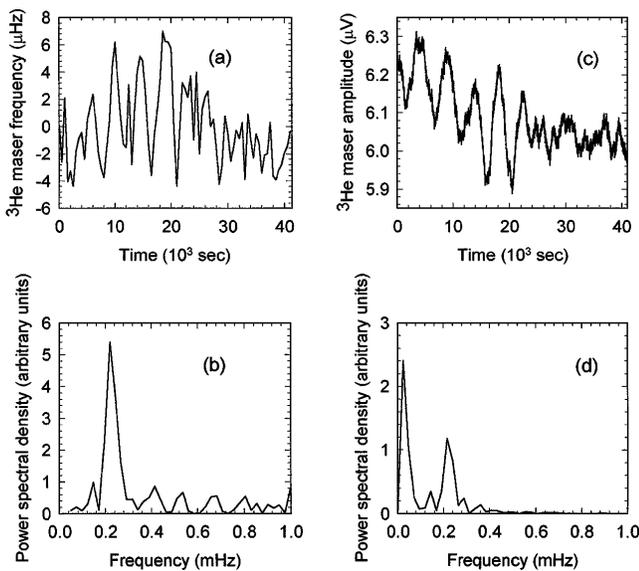


FIG. 4. (a) Free-running ^3He maser frequency residuals near equilibrium as a function of time. (b) Fourier transform power spectrum of the free-running ^3He maser frequency residuals shown in Fig. 4(a). Note the strong peak at 0.22 mHz. (c) Free-running ^3He maser amplitude near equilibrium as a function of time. (d) Fourier transform power spectrum of the free-running ^3He maser amplitude shown in Fig. 4(c). Again, note the strong peak at 0.22 mHz.

was shown previously that the longitudinal and transverse polarizations of a Zeeman maser behave near equilibrium as coupled damped harmonic oscillators [16]. An underdamped simple harmonic oscillator, when subjected to random perturbations, will respond at its resonant frequency. Thus the near-equilibrium ^3He maser amplitude and frequency manifest the effects of random system perturbations by oscillating at the resonant or characteristic system frequency of ~ 0.22 mHz. System perturbations include random fluctuations in laser power and system temperature, as well as mechanical vibrations of the cell and pickup coils. We are currently investigating the behavior of the ^3He and ^{129}Xe masers with the goal of suppressing the near-equilibrium resonant response of the maser frequencies and amplitudes to perturbations. Modification of the apparatus is under way to reduce environmental perturbations to the masers by improving the system's mechanical stability and the control of temperatures and laser power.

[Note, the observed oscillation frequency and damping rate of ^{129}Xe maser amplitude oscillations are much greater than those of the ^3He maser, because the longitudinal polarization time constants ($1/\gamma_{\text{sc}}$ and T_1 , see Table I) are much shorter for ^{129}Xe than for ^3He [16]. Thus the effects of ^{129}Xe maser amplitude oscillations rapidly average out and become negligible at measurement intervals for which ^3He maser amplitude oscillations are important.]

In conclusion, we have operated the first two species maser. Spin-exchange-pumped ^3He and ^{129}Xe Zeeman masers oscillate simultaneously and continuously, with

the two noble gas species co-located in a two-chamber glass cell. The phase-locked maser Allan deviation (either species) is currently $\sim 2 \times 10^{-3} \tau^{-3/2}$ Hz for $60 \leq \tau \leq 8000$ sec. The Allan deviation of the free-running maser (either species) currently trends as $\sim \tau^{-1/2}$ for measurement times $\tau >$ about 200 sec. Instability in the free-running maser frequency is strongly correlated with persistent near-equilibrium oscillations of the ^3He maser amplitude, which result from random fluctuations of environmental parameters. These fluctuations may be significantly reduced using standard environmental control techniques, which should greatly improve the free-running noble gas maser frequency stability.

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