Improved frequency stability of the dual-noble-gas maser

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We report improved frequency stability of the dual-noble-gas maser. This recently developed device can measure very small changes in the Zeeman transition frequencies of cohabitating ensembles of ^{129}Xe and ^{3}He atoms, and thus may be useful for symmetry tests and precision measurements such as a search for a permanent electric dipole moment of the ^{129}Xe atom. Using the dual-noble-gas maser, we measured the frequency stability (i.e., the Allan deviation) of the ^{3}He Zeeman transition to be approximately 100 nHz in 6000 s of data acquisition. This Zeeman frequency stability is an order of magnitude improvement over our previous report [R. E. Stoner *et al.*, Phys. Rev. Lett. **77**, 3971 (1996)]. [S1050-2947(98)07006-1]

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Precision measurement of the Zeeman splitting in a two-state system is important for magnetometry [1,2], as well as for searches for new physics such as a permanent electric dipole moment (EDM) of the neutron [3] or atoms and molecules [4–7]. Such EDM searches serve as stringent tests of time-reversal symmetry (T) in elementary particle interactions [8]. Currently, two-species differential EDM experiments are being performed to search for leptonic T violation (using ^{205}Tl and Na) [9], and to search for T violation in neutrons (using a ^{199}Hg comagnetometer) [10]. The advantage of differential measurements is that they are insensitive to common-mode systematic effects such as uniform magnetic-field variations [11]. We previously reported operation of a dual (or two-species) noble-gas maser [12], the first device to sustain simultaneous active maser oscillations on distinct transitions in two cohabitating atomic species. The dual-noble-gas maser (DNGM) allows sensitive differential measurements of the ^{3}He and ^{129}Xe nuclear spin-1/2 Zeeman transition frequencies. Here we report on a significantly improved DNGM frequency stability. We measured the frequency stability (i.e., the Allan deviation) of the ^{3}He Zeeman transition to be approximately 100 nHz in 6000 s of data acquisition. This Zeeman frequency stability is an order-of-magnitude improvement over our previous report [12]. The improved DNGM frequency stability is a result of better system design and engineering (better temperature control, mechanical stability, etc.), and a technique to compensate for unwanted interactions of the ^{129}Xe and ^{3}He magnetizations by appropriate detuning of the two maser resonators. We expect that the improved DNGM performance will enable a high-sensitivity search for a ^{129}Xe EDM.

The DNGM contains dense, cohabitating ensembles of ^{3}He and ^{129}Xe atoms. Each ensemble performs an active maser oscillation on its nuclear spin-1/2 Zeeman transition at its particular Larmor frequency: $\sim$4.9 kHz for ^{3}He and $\sim$1.8 kHz for ^{129}Xe in a static magnetic field of 1.5 G. The maser population inversions for the ^{3}He and ^{129}Xe ensembles are created by spin-exchange collisions between the noble-gas atoms and optically pumped Rb vapor [11,13]. The DNGM 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 ^{3}He and ^{129}Xe maser oscillations with good frequency stability. In the DNGM, one noble-gas species serves 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 DNGM has an additional important feature: active maser oscillation permits long coherent measurements of the noble-gas Zeeman frequencies (on time scales of a few hours). 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 [14].

Predicted EDM's for ^{129}Xe and ^{3}He arise from hadronic and tensor electron-nuclear interactions containing terms proportional to Z^2 and higher order in Z [8], so that a ^{3}He 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. However, regardless of which maser is phase locked and which is free running, the non-common-mode frequency instability of both masers is convolved in the free-running maser data. When the ^{3}He maser is phase locked, a possible ^{129}Xe EDM–electric-field coupling would induce a frequency shift in the free-running ^{129}Xe maser. When the ^{129}Xe maser is phase locked, a ^{129}Xe EDM–electric 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 proportional frequency shift in the free-running ^{3}He maser.

A schematic diagram of the current DNGM ("DNGM-97") is given in Fig. 1. Although the general design and

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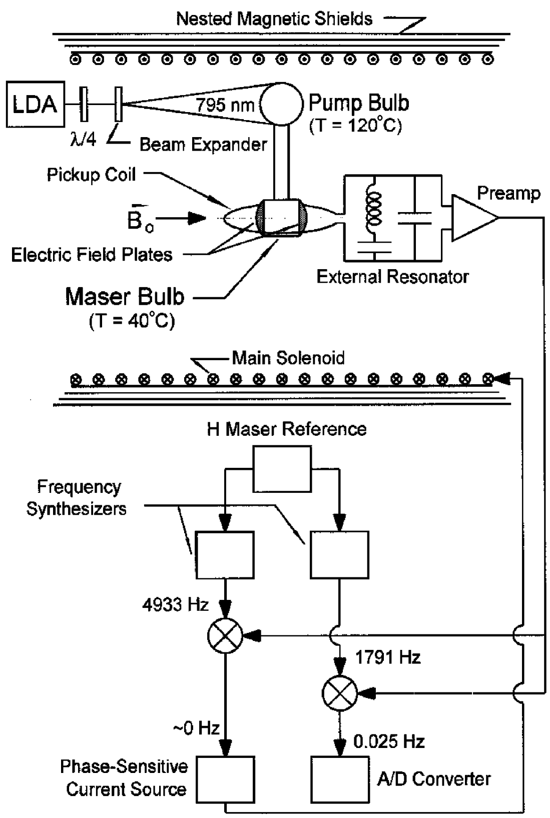

FIG. 1. Schematic diagram of the dual noble-gas maser used to make the measurements reported here. Electric-field plates were not installed in the experiments reported in this paper.

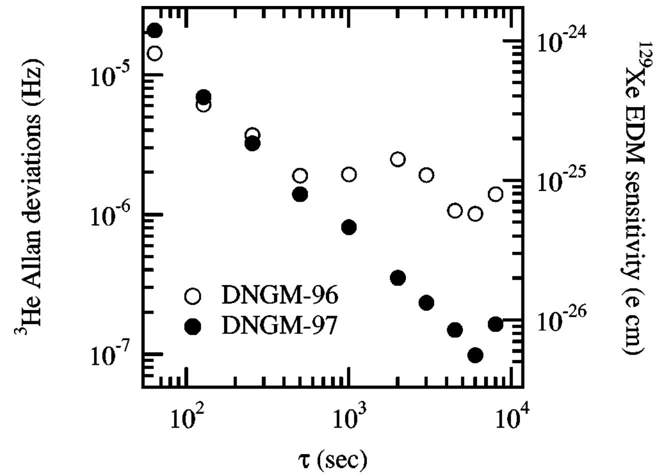

FIG. 2. Comparison of measured frequency stabilities (Allan deviations) for the free-running ^{3}He masers in the current and previously reported dual noble-gas masers. The Allan deviation of the earlier system reached a rough ''floor'' at $\sim 1-2$ μHz for measurement intervals of approximately thousands of seconds. The Allan deviation of the current dual noble-gas maser is substantially smaller, decreasing to ~ 100 nHz for measurement intervals of ~ 6000 s. Sensitivity to changes in the ^{129}Xe Zeeman frequency is given by dividing the free-running ^{3}He maser frequency stability by ~ 2.7, the ratio of ^{3}He and ^{129}Xe magnetic moments. The right ordinate axis shows the one standard deviation sensitivity to a ^{129}Xe permanent electric dipole moment, as a function of measurement interval τ, that would result from (i) a free-running ^{3}He maser frequency measurement with the Allan deviation given on the left ordinate axis; and (ii) the alternate application of electric fields of +5 kV/cm and −5 kV/cm across the maser bulb, alternating the field direction every τ seconds. (This is a simplistic sensitivity estimate, and ignores potential difficulties associated with electric fields, etc.)

operation of this device are similar to the earlier system described in Ref. [12] (''DNGM-96''), the current realization features several improvements that have enhanced its operation as a stable oscillator. These improvements include (i) better temperature control of the pump and maser bulbs, and of the resonant tank circuit (the ''maser resonator'') used to increase the effective atom-field coupling and to detect the maser signals; (ii) better mechanical stability and electronic shielding of signal extraction components; (iii) active feedback control of the current and temperature of the laser diode array [15] used in the optical pumping process, thereby leading to improved stability of the Rb magnetization in the pump cell; and (iv) installation of a newly designed maser resonator which provides for improved atom-field coupling.

Figure 2 provides a comparison of current DNGM frequency stability to our previously reported DNGM measurements. Specifically, Fig. 2 displays sample measured Allan deviations for the free-running ^{3}He masers in DNGM-96 and DNGM-97, shown as functions of the measurement interval (or averaging time) τ. The Allan deviation is the rms spread in the set of differences between pairs of successive frequency measurements, and is a commonly used statistical tool for characterizing frequency stability [16]. For DNGM-96 the free-running ^{3}He maser's Allan deviation initially varied 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 resonators and signal detection electronics [14,16]. However, for τ circa thousands of seconds, the ^{3}He maser's Allan deviation hit a rough ''floor'' of $\sim 1-2$ μHz. As discussed in Ref. [12], this frequency stability floor was caused by persistent near-equilibrium oscillations in the ^{3}He maser's amplitude and frequency due to random system perturbations in DNGM-96 (temperature variations, mechanical vibrations, etc.). Such perturbations have been greatly reduced or eliminated in DNGM-97. Thus Fig. 2 shows that the free-running ^{3}He maser's Allan deviation for DNGM-97 decreases out to ~ 100 nHz for measurement intervals of 6000 s. This frequency stability is an order of magnitude better than that of DNGM-96. For $\tau \geqslant 6000$ s, the DNGM-97 ^{3}He maser's Allan deviation begins to increase. Additional diagnostic measurements indicate this long-time Allan deviation increase results from a slow, monotonic drift of the free-running ^{3}He maser frequency. We are currently investigating long-time maser frequency drift mechanisms.

DNGM sensitivity to changes in the ^{129}Xe Zeeman frequency is given by dividing the measured free-running ^{3}He maser frequency stability by ~ 2.7, the ratio of the ^{3}He and ^{129}Xe magnetic moments. Therefore, in terms of the Allan deviation, DNGM-97 measures the Zeeman transition frequency of ^{129}Xe relative to that of ^{3}He with a precision of approximately 36 nHz in 6000 s of data acquisition. The significantly improved DNGM frequency stability reported here should allow a high-sensitivity ^{129}Xe EDM search to be performed in the near future. Shown on the right ordinate axis of Fig. 2 is the estimated ^{129}Xe EDM measurement sensitivity, as a function of measurement interval τ, that would result from (i) the free-running ^{3}He maser frequency stability given on Fig. 2's left ordinate axis; and (ii) the alternate application of electric fields of +5 and –5 kV/cm across the DNGM's maser bulb, alternating the field direction every τ seconds. Thus a ^{129}Xe Zeeman frequency sensitivity of 36 nHz in 6000 s would correspond to a ^{129}Xe EDM sensitivity of $5.7\times10^{-27}e$ cm at the one standard deviation level. Assuming one could make thirteen measurements per day at this sensitivity, one would have an integrated ^{129}Xe Zeeman frequency sensitivity of about 940 pHz in 100 days of data acquisition, with a corresponding ^{129}Xe EDM sensitivity of $1.6\times10^{-28}e$ cm. Of course, such an estimate is speculative, and ignores potential difficulties related to the application of large electric fields, etc. Note, however, that we have recently applied 5-kV/cm electric fields to noble-gas maser cells similar to those used in DNGM-97.

In conclusion, we have significantly improved the frequency stability of the dual-noble-gas maser. This device can measure very small changes in the difference between the Zeeman transition frequencies of cohabitating ensembles of ^{129}Xe and ^{3}He atoms. Measurements reported here demonstrate a ^{129}Xe Zeeman frequency stability (i.e., Allan deviation), relative to the ^{3}He Zeeman frequency, of approximately 36 nHz for 6000 s of data acquisiton, with a corresponding potential ^{129}Xe EDM measurement sensitivity of $5.7\times10^{-27}e$ cm for each 6000 s. If this performance can be maintained over several months, then the current DNGM would provide a ^{129}Xe EDM measurement sensitivity of $\sim1.6\times10^{-28}e$ cm in 100 days of data acquisition. The Zeeman frequency stability of the current DNGM (DNGM-97) is an order of magnitude better than that of our previous DNGM system (DNGM-96) [12]. This improved DNGM frequency stability is a result of improved system design and engineering. We plan to employ the DNGM in a high-sensitivity search for an EDM of the ^{129}Xe atom as a test of time reversal symmetry in elementary particle interactions. We also plan to continue our investigations of DNGM performance, with a goal of further improvements in DNGM frequency stability and hence greater utility as a tool for symmetry tests and precision measurements.

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