Development of active nuclear spin maser with time-separated feedback scheme for Xe-EDM search

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CP violation is one of the critical requirements for generating matter-antimatter asymmetry in the Universe. It is known that the magnitude of CP violation in the Standard Model (SM) of particle physics is insufficient to explain the observed matter dominance in the Universe, and therefore the discovery of extra CP violations originating from new physics beyond the SM is much awaited. A finite permanent electric dipole moment (EDM) of a particle or a system implies the violation of time reversal and CP symmetry. The value of EDMs that are predicted by theories beyond the SM are typically many orders of magnitude larger than those predicted by the SM, and therefore the EDM is one of the most promising probes to search for new physics.

In the current study, we focus on the atomic EDM of Xe, which is sensitive to T, P-odd nucleon-nucleon and nucleon-electron interaction. The EDM is detected by measuring the Larmor frequency of a nuclear spin under the static magnetic and electric field applied at the same time. In order to improve the upper limit of the current for the Xe atomic EDM, $4.1 \times 10^{-27} e \cdot \mathrm{cm}$,[1)] which corresponds to a ~40-nHz frequency precision under a 10-kV/cm electric field, we are developing a nuclear spin maser with an active feedback scheme,[2–4)] which allows observation of a continuous spin oscillation avoiding decay of the signal. In addition, to reduce systematic uncertainties in the spin precession frequency, we are developing co-existing masers of ^{129}Xe and ^{131}Xe.[5)] By comparing the frequencies of two masers, the systematic uncertainty, which is caused by drifts in the magnetic field and in the effective field due to the Fermi-contact interaction between Xe and polarized Rb, can be reduced.

We recently found that systematic errors can be further eliminated by reducing the phase deviation between the observed signal and the actual Xe precession caused by the feedback field for masing. The spin precession of Xe is detected through the motion of Rb spins, which adiabatically follow the rotating field produced by the Xe spins. When the feedback field is superimposed on the Xe spin field, the Rb spin will follow the resultant Xe plus feedback field, and hence the Rb precession phase will be shifted from the Xe precession. The phase shift causes frequency error due to the frequency pulling effect.[2)] To eliminate the pulling effect, we adopt a new scheme for masing, the time-separated feedback (TSFB) scheme. In this scheme, the observation of spin precession and application of the feedback field are separated in time and repeated alternately. The feedback field is generated according to the precession signal, which is acquired during the period without the feedback field, so that the maser operation becomes free from the frequency pulling effect. Note that the spin precession is observed continuously, unlike the repeated free-induction-decay measurements.

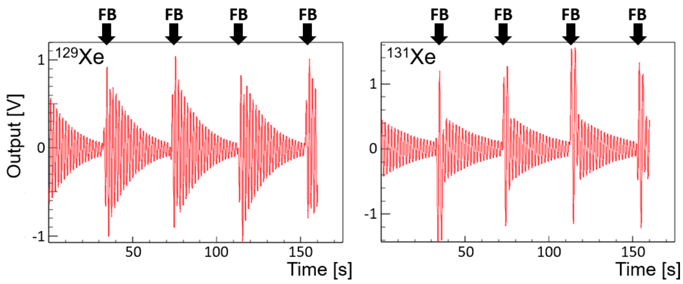

Fig. 1. Maser signals obtained for ^{129}Xe (left) and ^{131}Xe (right) with the TSFB scheme. The observation-feedback cycle is repeated every 40 s. After observation for 30 s and a margin of 2 s, a 3 s FB signal was applied to maintain the oscillation of the masers (black arrows).

A typical signal obtained from the co-existing masers of ^{129}Xe and ^{131}Xe with the TSFB scheme is shown in Fig. 1. The frequency error due to the drift in the power of the pumping light for Xe polarization was the dominant source of errors in the conventional active maser. Using the TSFB scheme, we have succeeded in reducing this error from ~1.6 μHz to below 60 nHz. A detailed study on the frequency characteristics and stability of the TSFB maser is in progress.

References
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