Spin-Echo-Based Magnetometry with Spinor Bose-Einstein Condensates

Yujiro Eto, Hayato Ikeda, Hirosuke Suzuki, Sho Hasegawa, Yasushi Tomiyama, Sawako Sekine, Mark Sadgrove and Takuya Hirano

Department of Physics, Gakushuin University, Tokyo 111-8588, Japan

(Dated: May 7, 2014)

PACS numbers: 07.55.Ge, 03.75.Mn

We demonstrate detection of a weak alternate-current magnetic field by application of the spin-echo technique to \( F = 2 \) Bose-Einstein condensates. A magnetic field sensitivity of 12 pT/\( \sqrt{\text{Hz}} \) is attained with the atom number of \( 5 \times 10^5 \) at spatial resolution of 99 \( \mu \text{m}^2 \). Our observations indicate magnetic field fluctuations synchronous with the power supply line frequency. We show that this noise is greatly suppressed by application of a reverse phase magnetic field. Our technique is useful in order to create a stable magnetic field environment, which is an important requirement for atomic experiments which require a weak bias magnetic field.

Characterization of the inhomogeneity of the ambient magnetic field is an important task in many experiments which utilize atomic systems with spin degrees of freedom. Such experiments include fundamental physics such as tests of symmetries and identification of the ground state in spinor condensate systems as well as important applications such as optical lattice clocks and long-lived coherence. In all of these cases, the experimental accuracy is directly related to the inhomogeneity of the magnetic field. Recently, high sensitivity magnetometers have been made using both superconducting quantum interference devices and atomic systems. Although the former are known to provide ultra-high spatial resolution of about \( 99 \times 10^3 \) \( \mu \text{m} \), our observations indicate that a sensitivity of 8 pT/\( \sqrt{\text{Hz}} \) could be achieved using an \( F = 1 \) spinor BEC in Ref. [3].

All of the atomic systems mentioned above detect constant magnetic fields. However, specialized magnetometers also exist for detecting alternating current (AC) magnetic fields. Such devices have high sensitivity for an AC field within a certain frequency band and are useful for the characterization of temporal fluctuations of the magnetic field. Such magnetometers can be constructed using the spin-echo technique, as originally demonstrated in experiments on single nitrogen vacancy centers [8,9]. In this Letter, we perform a similar type of spin-echo AC magnetometry using \( ^{87}\text{Rb} F = 2 \) BECs. We attain a magnetic field sensitivity of 12 pT/\( \sqrt{\text{Hz}} \) with the spatial resolution of about 99 \( \mu \text{m}^2 \). To the best of our knowledge this is the first realization of spin-echo based magnetometer using an atomic gas. In addition, we observe magnetic field noise synchronous with the power supply line at frequencies of 50 and 100 Hz using our AC magnetometer, and reconstruct the amplitude and phase of the AC magnetic field noise. By applying a magnetic field with opposite phase, we can suppress this noise to 1 nT order. We anticipate that the clean magnetic field environment created by this technique will be useful in applications requiring low ambient magnetic fields such as the search for magnetic ground states in systems with spin greater than 1/2 [2,3] since a temporally fluctuating magnetic fields can cause undesired spin rotations, seriously affecting such experiments.

Figure 1(a) shows the outline of the experimental setup. A BEC of \( ^{87}\text{Rb} \) is created using radio frequency (RF) evaporative cooling in a magnetic trap [11,12]. The BEC is then loaded into a crossed far-off-resonant optical trap (FORT) with axial and radial frequencies of 30 Hz and 100 Hz, respectively. After 300 ms hold time in the crossed FORT, typically \( 3 \times 10^5 \) atoms remain in the \( |F = 2, m_F = -2 \rangle \) state. A bias magnetic field along the \( z \) axis \( (B_z) \) shown in Fig. 1(a) is applied to define...
In the detection of the weak AC magnetic field using the spin echo technique \cite{8}, the RF Hahn-echo pulse sequence is applied to the initial \(|\langle S_z \rangle = -2\rangle\) state of the spin-2 BEC. \(\langle S_z \rangle\) was observed, and we found that the irradiation of 21.8 ms (filled circles) and 15 ms (empty circles) was needed in the presence of an AC magnetic field of amplitude \(b_{AC}\). Figure 3 shows the measured value of \(\langle S_z \rangle\) versus \(b_{AC}\) at \(\tau = 5\) ms (filled circles) and 15 ms (empty circles), where \(b(t) = b_{AC}\sin(2\pi t/\tau)\) and the Hahn echo sequence is also applied. The solid curves in Fig. 3 are cosine functions fitted to the data where the amplitude, period and initial phase were the fitting parameters. The cosinusoidal variation shown in Fig. 3 means that the phase variation in the \(S_x-S_y\) plane accumulated by the AC magnetic field was successfully observed. The period at \(\tau = 15\) ms is three times shorter than that at 5 ms due to the longer phase accumulation time.

The magnetometer sensitivity for a single measurement is given by \(\delta b_{min} = \delta\langle S_z \rangle/(d\langle S_z \rangle/db_{AC})\), where

\[
\langle S_z \rangle = -2 \cos\left\{\frac{gF_{\mu_B}B_{AC}}{\hbar}\int_{0}^{\tau/2} b(t)dt - \int_{\tau/2}^{\tau} b(t)dt\right\}. \tag{1}
\]

In the case that \(b_{AC} = 0\) (shown by dotted arrows in the top panel of Fig. 1(b)), the spin direction returns to the \(|2, -2\rangle\) state (\(\langle S_z \rangle = -2\)). One can thus detect the weak AC magnetic field by measuring the \(\langle S_z \rangle\). In addition, the effect of undesirable inhomogeneities such as magnetic field gradients and slowly fluctuating magnetic fields is reduced due to spin-echo \cite{14}.

The techniques of the Stern-Gerlach separation and time-of-flight absorption imaging are used to obtain \(\langle S_z \rangle\). The atomic density distributions of each \(m_F\) component are measured by shining the imaging beam from the \(x\)-direction after a time of flight of 15 ms. The atom number in each \(m_F\) component, \(N_{m_F}\), is calculated over a small region in the center of the BEC (66 \(\mu\)m and 47 \(\mu\)m in the \(y\)- and \(z\)-direction) in order to extract the peak atomic number. Using \(N_{m_F}\), we calculate \(\langle S_z \rangle\) from the following equation:

\[
\langle S_z \rangle = \sum_{m_F=-2}^{2} m_F N_{m_F}/\sum_{m_F=-2}^{2} N_{m_F}. \tag{2}
\]

In the first experiment, we observed Rabi-type oscillations of the spin-2 BEC in order to determine the RF pulse durations for \(\pi/2\) and \(\pi\) pulses. Instead of the Hahn echo sequence, a single RF pulse with various irradiation time was applied to \(|2, -2\rangle\) state. Figure 2(a) and 2(b) show the population of each \(m_F\) component \((N_{m_F}/\sum_{m_F=-2}^{2} N_{m_F})\) and \(\langle S_z \rangle\) as a function of the RF irradiation time, respectively. The clear spin 2 rotation was observed, and we found that the irradiation of 21.8 and 43.6 \(\mu\)s correspond to the \(\pi/2\) and \(\pi\) pulse.

In order to confirm that our system operates as an AC magnetometer, \(\langle S_z \rangle\) was measured in the presence of a purposely introduced AC magnetic field of amplitude \(b_{AC}\). Figure 3 shows the measured value of \(\langle S_z \rangle\) versus \(b_{AC}\) at \(\tau = 5\) ms (filled circles) and 15 ms (empty circles), where \(b(t) = b_{AC}\sin(2\pi t/\tau)\) and the Hahn echo sequence is also applied. The solid curves in Fig. 3 are cosine functions fitted to the data where the amplitude, period and initial phase were the fitting parameters. The cosinusoidal variation shown in Fig. 3 means that the phase variation in the \(S_x-S_y\) plane accumulated by the AC magnetic field was successfully observed. The period at \(\tau = 15\) ms is three times shorter than that at 5 ms due to the longer phase accumulation time.
The standard deviation of $\langle S_z \rangle$ is given by $\delta(S_z)$, which is calculated from the measured values as $\delta(S_z) = \sqrt{\langle S_z^2 \rangle - \langle S_z \rangle^2}$. The slope of $d\langle S_z \rangle/db_{AC}$ gives the sensitivity of our magnetometer. When we calculate $\delta(S_z)$ from the measured $\langle S_z \rangle$ values at $\langle S_z \rangle \approx 0$, $\delta(S_z)$ is found to be 0.28 and 0.48 at $\tau = 5$ and 15 ms, respectively. From these values, we find the sensitivity to be $\delta b_{\text{min}} = 0.97$ and 0.66 nT. Note that this technique can only reduce the effect of slowly fluctuating magnetic fields whose period is longer than $\tau$. However, our experiment is subject to the influence of faster fluctuations that vary for each measurement. For example, the magnetic field noise caused by the ripple of the Helmholtz coil is of order 0.1 nT.

In order to evaluate the intrinsic sensitivity, which is unaffected by the temporal fluctuation of the magnetic field, we divide the optical density distribution of each $m_F$ component for a single measurement into the three regions as shown in Fig. 4(a). We infer the value of $\delta(S_z)$ from three expectation values of $S_z$, $\langle S_z \rangle = \sum_{m_F=-2}^{+2} N_{i,m_F} / \sum_{m_F=-2}^{+2} N_{i,m_F}$, where the subscript $i = 1 - 3$ indicates which of the three regions is being considered. In our previous work [14], we theoretically and experimentally confirmed that the shape of the atomic distribution of each $m_F$ component in the optical trap is almost unchanged after a time-of-flight of 15 ms, although the distributions become more spread out. Each value of $\langle S_z \rangle_i$ thus reflects the value of $\langle S_z \rangle$ in a different spatial region of the trapped BEC. A field sensitivity of $94 \pm 9$ pT for $\tau = 15$ ms is attained with corresponding $\delta(S_z)$ of $0.069 \pm 0.006$, when we select the size of each region as $dy \times dz = 15.7 \mu \text{m} \times 6.3 \mu \text{m} = 99 \mu \text{m}^2$, where $dy$ and $dz$ represent the length along the $y$- and $z$-direction of each region. The field sensitivity for $N$ times measurement per 1 second is to be $\delta b_{\text{min}} = \delta b_{\text{min}}/\sqrt{N}/(15 \times 10^{-3}) = 12 \pm 1 \text{ pT}/\sqrt{\text{Hz}}$.

Figure 4(b) shows $\delta(S_z)$ versus atom number averaged over three regions, $N_{\text{Atom}} = \sum_{i=1}^{3} m_F = -2 N_{i,m_F} / 3$, where $N_{\text{Atom}}$ is changed by increasing $dy$. The dotted curve represents the atom shot noise limited $\delta(S_z)$. The deviation from the atom shot noise limited values has multiple origins which induce spatial distortion of the atomic distributions and the optical image: Interference fringes caused by unclean regions on the imaging optics is one well known origin of distortion in the image. Additionally, the effect of the magnetic field gradient ($\sim 1.5 \mu \text{T/cm}$), which cannot be completely removed by spin-echo [13], and spontaneous pattern formation [16] produce effective distortion of the atomic distribution. Another possible cause of the deviation is the effect of thermal atoms, whose Gaussian tails reduce the accuracy of discrimination between the $m_F$ components in the Stern-Gerlach separation. Thus the sensitivity of our AC magnetometer will be improved by reduction of the magnetic field gradient and optimization of imaging system.

As a practical application of our magnetometer, we performed detection of the stray AC magnetic field present in our apparatus. Figure 4(a) shows $\langle S_z \rangle$ values measured as a function of $\tau$, without artificial AC magnetic field. If the stray AC magnetic field in the region occupied by the BEC fluctuates in a random manner with respect to amplitude, frequency and phase, then we would expect that the observed values of $\langle S_z \rangle$ would also...
FIG. 5: $\tau$ dependence of $\langle S_z \rangle$ values after the Hahn echo sequence. Each point represents the average over ten measurements with the error bars giving the standard deviation over those measurements. (a) $\langle S_z \rangle$ values measured without the artificial application of the AC magnetic field. (b) $\langle S_z \rangle$ values measured with application of an inverse phase magnetic field at 50 Hz, $b(t) = b_{20}\sin[2\pi t/(20 \times 10^{-3}) + \theta_{20}]$, where $b_{20} = 9.5$ nT and $\theta_{20} = -0.76 + \pi$. (c) $\langle S_z \rangle$ values measured with application of an inverse phase magnetic field at 50 Hz and 100 Hz, $b(t) = b_{20}\sin[2\pi t/(20 \times 10^{-3}) + \theta_{20}] + b_{10}\sin[2\pi t/(10 \times 10^{-3}) + \theta_{10}]$, where $b_{20} = 3.4$ nT and $\theta_{20} = 1.50 + \pi$.

exhibit a random distribution. Instead, we see that $\langle S_z \rangle$ exhibits oscillatory behavior. Such behavior indicates the existence of a stable AC stray magnetic field in our apparatus. Note that the first $\pi/2$ pulse in the Hahn echo sequence is synchronous with the power supply line of 50 Hz. It is therefore reasonable to expect that the AC stray magnetic field is mainly induced by the magnetic field arising from the electronic devices surrounding the BEC apparatus which should be synchronous with the 50 Hz supply line.

In order to quantitatively investigate the effect of AC stray magnetic field, we simulate the $\tau$ dependence of $\langle S_z \rangle$ by inserting a 50 Hz magnetic field, $b(t) = b_{20}\sin[2\pi t/(20 \times 10^{-3}) + \theta_{20}]$, into the Eq. 1. The solid curve in Fig. 5(a) represents a fit of Eq. 1 to the data assuming such a 50 Hz magnetic field, where $b_{20}$ and $\theta_{20}$ are used as the fitting parameters. The fitted curve reproduces the oscillating behavior of the data in Fig. 5(a), and the parameter values are found to be $b_{20} = 9.5$ nT and $\theta_{20} = -0.76$.

Assuming that the fitted parameter values are accurate, we should be able to remove the effects of the 50 Hz stray magnetic field along $z$-direction by application of a magnetic field with the same frequency and amplitude but inverse phase. Figure 5(b) shows $\langle S_z \rangle$ measured for the same parameters as in Fig. 5(a) but in the presence of an artificially applied 50 Hz magnetic field with $b_{20} = 9.5$ nT and $\theta_{20} = -0.76 + \pi$. The variation of $\langle S_z \rangle$ values are clearly suppressed compared with Fig. 5(a), and this suppression suggests that the 50 Hz magnetic field noise is reduced.

Nonetheless, the small remaining oscillation in Fig. 5(b) indicates that a synchronous magnetic field still remains along the $z$-direction. We assumed the existence of a 100 Hz magnetic field, $b_{10}(t) = b_{10}\sin[2\pi t/(10 \times 10^{-3}) + \theta_{10}]$, and by fitting to the data in Fig. 5(b) we obtained the parameters $b_{10} = 3.4$ nT and $\theta_{10} = 1.50$. Based on the parameter values, we further applied an inverse phase magnetic field at 100 Hz in addition to the application of that at 50 Hz [Fig. 5(c)]. As shown in Fig. 5(c), $\langle S_z \rangle$ is close to $-2$ for most values of $\tau$, particularly when $\tau \leq 10$ ms. This result indicates that magnetic field noise which is synchronous with the power supply line is strongly suppressed by the application of an inverse phase field with frequency components at 50 and 100 Hz. In particular, we note that at $\tau = 20$ ms, the value of $\langle S_z \rangle$ is $-1.7\pm 0.2$. This value is consistent with an AC magnetic field $b(t) = b_{20}\sin[2\pi t/(20 \times 10^{-3})]$ with $b_{20} = 1.1\pm 0.4$ nT, implying that the magnetic field has been suppressed by almost one order of magnitude when compared with the uncompensated case shown in Fig. 5(a).

In conclusion we have reported the demonstration of a spin-echo based magnetometer using $^{87}$Rb $F = 2$ Bose-Einstein condensates, with which weak AC magnetic field noise is detected. We attained a field sensitivity of 12 pT/$\sqrt{\text{Hz}}$ at a spatial resolution of 99 $\mu$m$^2$. In addition we observed magnetic field noise synchronous with the power supply line. By artificial application of an inverse phase AC magnetic field, the synchronous noise at 50 Hz is suppressed down to 1 nT order. The techniques demonstrated here are use for characterizing and controlling the magnetic field environment, with particular applicability to ultracold atom experiments. By allowing the detection and creation of a stable, weak bias magnetic field we anticipate that our magnetometer will facilitate the development of fundamental research areas in atomic physics which require a weak magnetic field regime \cite{1,2,3}.

We would like to thank T. Kuwamoto for fruitful discussions. This work was supported by the Japan Society for the Promotion of Science (JSPS) through its Funding Program for World-Leading Innovation R&D on Science and Technology (FIRST Program).

---

* Electronic address: eto@qo.phys.gakushuin.ac.jp

‡ Present affiliation: Center for Photonic Innovations, University of Electro-Communications

[1] L. R. Hunter, Science 252, 73 (1991).
[2] D. M. Stamper-Kurn and M. Ueda, arXiv:1205.1888.
[3] M.-S. Chang, C. D. Hamley, M. D. Barrett, J. A. Sauer, K. M. Fortier, W. Zhang, L. You, and M. S. Chapman, Phys. Rev. Lett. 92, 140403 (2004).
[4] M. Takamoto, F.-L. Hong, R. Higashi, H. Katori, Nature 435, 321 (2005).

[5] C. Langer, R. Ozeri, J. D. Jost, J. Chiaverini, B. DeMarco, A. Ben-Kish, R. B. Blakestad, J. Britton, D. B. Hume, W. M. Itano, D. Leibfried, R. Reichle, T. Rosenband, T. Schaetz, P. O. Schmidt, and D. J. Wineland, Phys. Rev. Lett. 95, 060502 (2005).

[6] I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis, Nature 422, 596 (2003).

[7] M. Vengalattore, J. M. Higbie, S. R. Leslie, J. Guzman, L. E. Sadler, and D. M. Stamper-Kurn, Phys. Rev. Lett. 98, 200801 (2007).

[8] J. M. Taylor, P. Cappellaro, L. Childress, L. Jiang, D. Budker, P. R. Hemmer, A. Yacoby, R. Walsworth, and M. D. Lukin, Nature Phys. 4, 810 (2008).

[9] J. R. Maze, P. L. Stanwix, J. S. Hodges, S. Hong, J. M. Taylor, P. Cappellaro, L. Jiang, M. V. Gurudev Dutt, E. Togan, A. S. Zibrov, A. Yacoby, R. L. Walsworth, and M. D. Lukin, Nature 455, 644 (2008).

[10] G. Balasubramanian, P. Neumann, D. Twitchen, M. Markham, R. Kolesov, N. Mizuochi, J. Isoya, J. Achard, J. Beck, J. Tissler, V. Jacques, P. R. Hemmer, F. Jelezko, and J. Wrachtrup, Nat. Mater. 8, 383 (2009).

[11] T. Kuwamoto, K. Araki, T. Eno, and T. Hirano, Phys. Rev. A 69, 063604 (2004).

[12] S. Tojo, Y. Taguchi, Y. Masuyama, T. Hayashi, H. Saito, and T. Hirano, Phys. Rev. A 82, 033609 (2010).

[13] M. Sadgrove, Y. Eto, S. Sekine, H. Suzuki, and T. Hirano, arXiv:1303.0637.

[14] Y. Eto, S. Sekine, S. Hasegawa, M. Sadgrove, and T. Hirano, Appl. Phys. Express 6, 052801 (2013).

[15] M. Yasunaga and M. Tsubota, Phys. Rev. Lett. 101, 220401 (2008).

[16] J. Kronjäger, C. Becker, P. Soltan-Panahi, K. Bongs, and K. Sengstock, Phys. Rev. Lett. 105, 090402 (2010).