Chin. Phys. B Vol. 30, No. 9 (2021) 090303

Preparation of a two-state mixture of ultracold fermionic atoms with balanced population subject to the unstable magnetic field[*]

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(Received 24 December 2020; revised manuscript received 13 February 2021; accepted manuscript online 15 March 2021)

We report a novel method to prepare a mixture of ^{40}K Fermi gas having an equal population of the two ground magnetic spin states confined in an optical dipole trap, in the presence of an noisy quantization (magnetic) field. We realize the equal population mixture by applying a series of RF pulses. We observe the dependence of the population distribution between two spin states on the number of the applied RF pulses and find that the decoherence effects leading to the population fluctuations are overcome by the high number of RF pules. Our demonstrated technique can be potentially used in the precision measurement experiments with ultracold gases in noisy environments.

Keywords: Fermi gas, balanced mixture, RF-pulses, precision measurement

PACS: 03.75.Ss, 32.30.Bv, 03.65.Yz

DOI: 10.1088/1674-1056/abee6e

1. Introduction

Ultracold atomic gases provide an exceptional experimental platform to simulate the different problems found in high energy physics and condensed matter,[1] enabled by its high degree of controllability. Physical parameters in such a quantum simulator can be precisely manipulated, including the number of atoms, the temperature of the ultracold gases, the shape of external trapping potential, the dimensionality of the system and the interaction strength between different spin states.[2–6] In particular, mixtures of ultracold atoms are essentially used in studies such as those involving the mixture of Bose and Fermi superfluids,[7] thanks to the availability of a variety of atomic species and the additional degree of freedom related to the hyperfine structure.[8,9] Also, one can prepare multicomponent quantum gases with different hyperfine states, different lattice well depth and geometry, as well as different isotopes or atomic species.[7,10–12] Using an equal mixture of different spin states of the same atomic gas, many interesting physical phenomena have been researched, including the production of the spin squeezing,[13,14] the study of spin oscillations in ultracold Fermi sea[15,16] and spin dynamics.

During the preparation of such a mixture of different spin states of the same atomic species, ideally the decay time of Rabi oscillation is infinite, and an equal mixture is prepared by applying a $\pi/2$ RF pulse[17] in the presence of a quantization magnetic field. Actually, the environmental noise during the preparation of the ultra-cold atoms will influence the accuracy of preparation of a certain spin state population (and hence the measurements afterwards) in the experiment. The noise in the magnetic field comes from the change of temperature of the coils, noisy power supplies, the ion pumps and other electronic devices used in the experiment. Various methods have been developed for reducing this noise, including dynamic feedback[18,19] and the use of μ-metal enclosures.[20] For ultracold atom experiments, it is often difficult to shield an entire system due to the inherent complexities (e.g. the enclosure will limit the optical access to the atoms). In such a platform, an incoherent mixture with equal populations in each spin state can be prepared by frequency-sweeping an RF field dozens of times across the hyperfine transition.[21–23] The mixture of spin states produced is usually intended to be used for precision measurements using ultra-cold atoms not only in the laboratory but also in the outdoor.[24,25] However, the level of magnetic field noise especially in the outdoor is hard to limit due to the open environment.

In this article, we develop a novel strategy to prepare a stable two-state mixture with balanced population subject to a non-stabilized magnetic field. We measure the relative population of the two spin states of the ^{40}K Fermi gas as a function of the number of the RF pulses applied. Our employed scheme circumvents the problem of environmental noise in the magnetic field and is suitable for production of spin mixtures in the outdoor.

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[*] Project supported by the National Key Research and Development Program of China (Grant Nos. 2016YFA0301602 and 2018YFA0307601), the National Natural Science Foundation of China (Grant Nos. 12034011, 92065108, 11704234, 11804203, 11974224, 12022406, and 12004229), and the Fund for Shanxi "1331 Project" Key Subjects Construction.

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2. Experimental setup and preparation of the spin state

We start the experiment by the preparing a degenerated Fermi gas of ^{40}K atoms in the state $|9/2,9/2\rangle$ in a crossed optical dipole trap (Fig. 1(a)) by sympathetically cooling it with the help of ^{87}Rb atoms as discussed in our previous experiments.[26,27] Around 3×10^6 atoms are prepared at a temperature $T\approx0.3T_{\rm F}$ in the crossed 1064 nm optical dipole trap with mean trapping frequency $\varpi\simeq2\pi\times80$ Hz, where $T_{\rm F}=\hbar\varpi(6N)^{1/3}/k_{\rm B}$ is the Fermi temperature and $k_{\rm B}$ is the Boltzman constant. Then, the Fermionic atoms are transferred to the $|9/2,-9/2\rangle$ state by driving the Landau–Zener transition with the RF field. The transfer efficiency is nearly 100% in the presence of the external magnetic field B of 5 G. The magnetic field is then ramped up to the final value of $B=202.2$ G in 30 ms. Figure 1(b) shows the RF field generation, amplification and delivery schematics. This RF field is applied perpendicular to the atomic quantization axis.

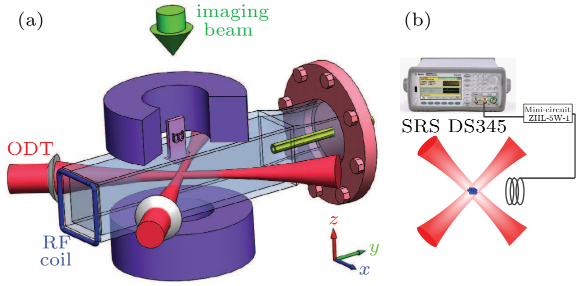

Fig. 1. The experimental setup for (a) the production of the quantum degenerate gas of ^{40}K in an optical dipole trap. A homogeneous bias magnetic field along the z axis (gravity direction) is applied by through a linear ramp. (b) The schematic for the RF signal generation by a function generator (SRS DS345). After amplification by a power amplifier (mini-circuit ZHL-5W-1), the RF power is delivered to the atoms through a three-turns circular loop antenna perpendicular to the quantization axis.

3. Results and analysis

As a prerequisite for the creation of a two-state spin mixture, both the RF resonance frequency and the π-pulse length time are calibrated by means of RF spectroscopy and Rabi-oscillation time measurement, respectively. For this purpose, choose two magnetic sub-levels $|F=9/2,m_F=-9/2\rangle$ and $|F=9/2,m_F=-7/2\rangle$ of the $F=9/2$ hyperfine level of the ^{40}K atomic electronic ground state, where F denotes the total spin and m_F is the magnetic quantum number, as shown in Fig. 2(a). The atoms already transferred to the $|9/2,-9/2\rangle$ state, we calibrate the resonant frequency by driving the transition with $\Delta m=1$ between the two Zeeman sub-levels with the RF pulse inside the dipole trap. The applied RF pulse possesses a temporal Gaussian envelope. To measure the population of the transferred atoms after the RF pulse, we then release the atoms from the dipole trap and subsequently expose them to the Stern–Gerlach field. Then we image the atoms using a resonant probe light and extract the number of atoms in each of the magnetic spin state. Figure 2(b) shows the contrast value η between $|9/2,-9/2\rangle$ and $|9/2,-7/2\rangle$ as a function of the RF pulse frequency, where η is defined as $\eta=(N_{-7/2}-N_{-9/2})/(N_{-7/2}+N_{-9/2})$ and N_i are the populations of the magnetic spin states i. The maximum η value corresponds to the resonance RF frequency.

Next we find the π-pulse duration time T_π from the Rabi oscillations of the population between the two spin states. We assume a two-level configuration with the wave function $|\psi\rangle=c_1(t)|1\rangle+c_2(t)|2\rangle$, where c_1 and c_2 are the time dependent probability amplitudes. Since all atoms are initially prepared in the state $|9/2,-9/2\rangle$ at $t=0$, we have $c_1(0)=1$ and $c_2(0)=0$. When the driving RF field frequency is close to the resonance, the population difference between the two states is given by[28]

$$\begin{aligned}W(t)&=|c_2(t)|^2-|c_1(t)|^2\\&=\frac{\Omega^2-\delta^2}{\tilde{\Omega}^2}\sin^2\left(\frac{\Omega t}{2}\right)-\cos^2\left(\frac{\Omega t}{2}\right),\end{aligned}\tag{1}$$

where Ω is the Rabi frequency, $\delta=\omega-\omega_0$ denotes the detuning of the applied RF field and the generalized Rabi frequency $\tilde{\Omega}=\sqrt{\Omega^2+\delta^2}$. From Eq. (1), a resonant RF pulse ($\delta=0$) with a duration of $t=\pi/\Omega$ is needed to fully transfer the atoms into the $|9/2,-7/2\rangle$ state, referred to as the π-pulse.

To demonstrate the feasibility of our protocol, we prepare the two-state spin-mixture in both the strongly and weakly interacting regimes.[29,30] We apply a variable number $N_{\rm p}$ of resonant RF π-pulses (square shaped in time domain) during each measurement cycle prior to the time of flight imaging (TOF). We define the total measurement cycle duration $T_{\rm t}$ as $(T_\pi+T_{\rm f})\times N_{\rm p}$, where $T_{\rm f}$ is the separation between the neighboring π-pulses, as depicted in Fig. 2(c). In this work, the T_π and $T_{\rm f}$ are 120 µs and 4 µs, respectively.

Figure 3 shows the contrast value η between $|9/2,-9/2\rangle$ and $|9/2,-7/2\rangle$ as a function of the number of π-pulses $N_{\rm p}$ under different bias magnetic fields. The normalized population in the state $|9/2,-7/2\rangle$ experiences a modulated exponential decay as

$$\eta(x)=\exp(-\beta t)\sin\left(2\pi\cdot\frac{1}{2}x-\pi/2\right),\tag{2}$$

where $\exp(-\beta t)$ is the decay factor of the oscillation, and x corresponds to the number of π-pulses $N_{\rm p}$. As can be seen from the figure, η approaches zero when $N_{\rm p}>50$. Ideally, single $\pi/2$ RF pulse should be enough to obtain the equal mixture state given a stable magnetic field is present. However, the current running through coils will typically generate a static bias magnetic field and the fluctuation of the current will generate noise as well. The fluctuating magnetic field (the change of temperature of the coils) in the experiment induces a mismatch between the applied RF field frequency and the time dependent Larmor frequency of the two level system, causing the mixture to suffer from decoherence resulting in the exponential decay seen in Fig. 3. From these comparison of the three cases in Fig. 3, we find that an equal and stable symmetric mixture can be prepared with the same procedure, no matter whether we are working in the strongly or weakly interacting regime. This greatly relaxes the experimental restrictions put on the strength of the magnetic field we are allowed to use. For comparison to our previous work,[31] which needed three RF frequency sweeps each of 6 ms duration to overcome the environmental decoherence, the procedure reported in the current work only takes about 6 ms, as shown in Fig. 3(a).

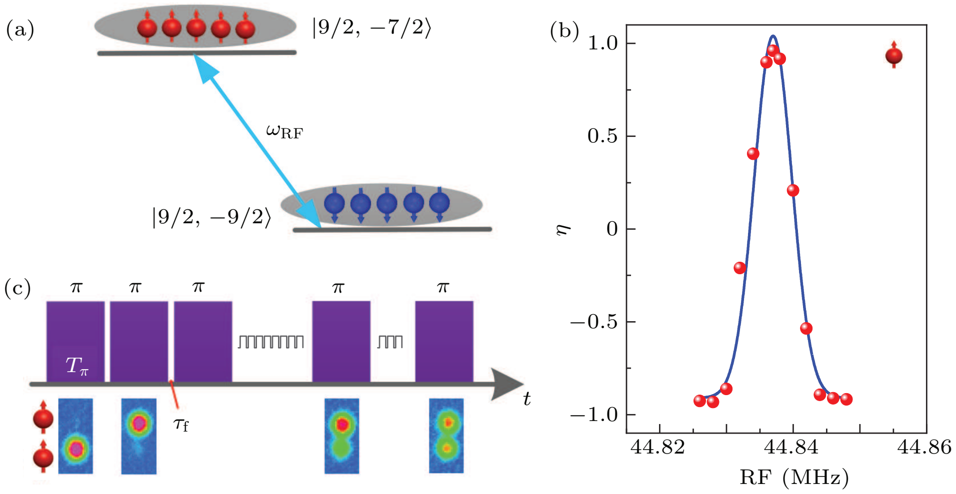

Fig. 2. Experiment procedure. (a) Two-level configuration in ^{40}K atoms. The transition between two magnetic sublevels $|F=9/2, m_F=-9/2\rangle$ and $|F=9/2, m_F=-7/2\rangle$ is driven by a resonant RF field. (b) The associated population contrast between the two states $|9/2,-9/2\rangle$ and $|9/2,-7/2\rangle$ as a function of the RF frequency ($B = 202.2$ G). Here RF spectroscopy is utilized to determine the bias magnetic field. (c) The schematic of a train of RF π-pulses (upper) and the corresponding evolution of population (lower) of the two internal states recorded with absorption imaging after 12 ms of TOF.

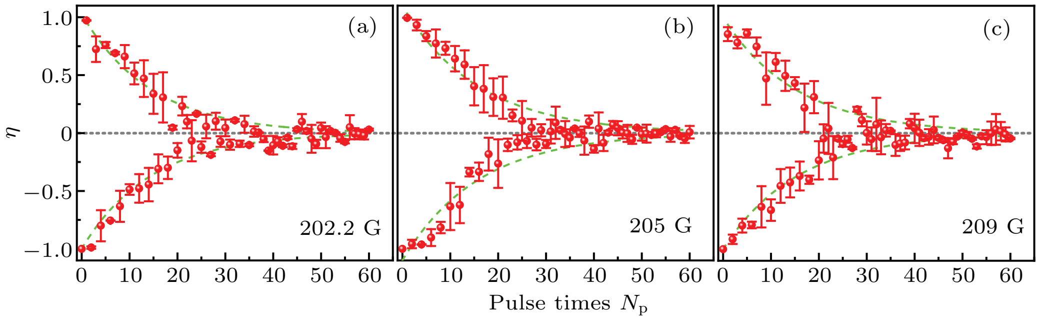

Fig. 3. Preparation of the equal and stable spin mixture in ultra-cold Fermi gases. (a)–(c) The experimentally measured values of the contrast parameter η for three different fixed magnetic-field values (202.2 G, 205 G and 209 G, respectively). The experimental data (red dots) shows the contrast value between the two internal states $|9/2,-9/2\rangle$ and $|9/2,-7/2\rangle$ as a function of the number of pulses $N_{\rm p}$ the atoms are exposed to during each experimental measurement. The error bars (standard deviation) are derived from 3 identical experiments. The green dashed lines are guides to the eyes. The gray dashed line indicates the position of the mixture with balanced state population in both states.

4. Conclusion

In summary, we have demonstrated a scheme to obtain an equal mixture of ultra-cold fermionic atoms subject to the unstable magnetic field by employing a series of π-pulses of the RF field. By exploiting the two level system model of the atom interacting with the RF field, we find the suitable resonance frequency and the Rabi oscillation time period to calibrate the π-pulse time precisely. The successive train of RF π-pulses effectively overcomes the population decay introduced by the noisy magnetic field in the form of decoherence. Since RF fields are used as ideal control tools in the ultra-cold atomic experiments, such as evaporative cooling,[32,33] adiabatic rapid passages[34] preparation of spinor BECs,[35,36] and atom lasers,[37,38] our new protocol can help facilitation in these experiments as now we are able to produce the equal mixture with initial arbitrary proportions more precisely. The use of this scheme in outdoor environment is also possible as the atomic samples are more prone to noise and hence decoherence in the outdoor.

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