Atomic spin orbit coupling synthesized with gradient magnetic fields

Xinyu Luo\textsuperscript{1}, Lingna Wu\textsuperscript{1}, Ruquan Wang\textsuperscript{2,3}, and L. You\textsuperscript{1,3}

\textsuperscript{1} State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084, China
\textsuperscript{2} Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China
\textsuperscript{3} Collaborative Innovation Center of Quantum Matter, Beijing, China

E-mail: lyou@mail.tsinghua.edu.cn

Abstract. Spin orbit coupling (SOC) for neutral atoms can be synthesized with pulsed or time modulating gradient magnetic field (GMF). This is confirmed through the studies of collective dipole oscillations for a spin-1 atomic condensate in a harmonic trap after abruptly turning on SOC and adiabatically adjusted equilibrium states when SOC strength is slowly ramped up. Further measurements reveal that SOC can be enhanced when the GMF modulation frequency approaches harmonic trap frequency. Additionally, we discuss how the technique of pulsed GMF can be used to synthesize space-period magnetic fields, or magnetic lattices.

1. Introduction

Spin-orbit coupling (SOC) constitutes one of the most important interactions in quantum condensed matter physics. Its ubiquitous existence is often revealed by a linear coupling between the internal (spin) state of a particle and its motional (orbital) degree of freedom, which locks the spin state of a particle to its direction of motion. The resulting correlation becomes essential in many condensed matter phenomena, such as topological insulator [1,2], spin Hall effect [3,4], and spintronics [5], where SOC naturally arises by the orbital motion of an electron inside a crystal’s intrinsic electric field. In recent years, systems based on atomic quantum gases have emerged as potential simulators for quantum condensed matter studies. Atomic SOC consequently assumes an essential role in the increasing list of desired ingredients for quantum simulations. In contrast to electrons inside a crystalline solid, atoms in simple spatial motion over surrounding charge neutral atoms do not generate SOC. Instead, synthetic or artificial atomic SOC is often engineered relying on its interaction with external laser fields [6–9].

According to the symmetries of the specific linear coupling form, SOC is often distinguished into Rashba [10] and Dresselhaus [11] types. The first experimentally synthesized atomic SOC [12], is an equal superposition of Rashba and Dresselhaus type. It’s realized by the Spielman group with Raman scheme, where two counter-propagating laser beams Raman couple the same excited state to two atomic ground (internal) states, which form a pseudo-spin 1/2 system. When an atom makes a transition from one ground (internal) state to the other, atomic spin flips, accompanied by a momentum shift to its center of mass (orbital) motion. Therefore, the Raman interaction causes different atomic internal states (or spins) to be associated with different orbital momentum, or equivalently, it can be viewed as an artificial SOC. Since its first
demonstration, the Raman scheme has essentially become the choice default for all atomic SOC experiments [13–17], with reports using both bosonic [12, 13, 15–18] and fermionic [14, 19, 20] alkali atomic species. More general forms of SOC are pursued actively [21–24], including a recent effort which observed 2D SOC [25]. Collectively, these studies raise significant hope for quantum simulations of quantum many body physics using ultracold atoms with synthetic gauge fields [18–20, 26–33], which promise exciting opportunities for observing novel quantum phenomena with ultracold atoms [34–44].

As pointed out by several authors [7, 9, 45], the main obstacle preventing further progress in the spin-flip Raman scheme is atomic spontaneous emission. It cannot be suppressed with increased detuning at a fixed effective Rabi frequency, as the effective spontaneous emission rate (heating rate) and the effective Rabi frequency for the Raman spin flip process both scale as the ratio of laser power to detuning squared [7, 9, 45]. To circumvent this problem, alternative ideas are proposed. For instance, one can seek out other atomic species, where strong SOC can be generated via Raman coupling on narrow-line transitions in high spin atoms such as Dy. Compared to alkali atoms, the heating rate becomes significantly reduced due to the small nature linewidths of the associated transitions in these atoms [46, 47]. A second approach would synthesize SOC without involving atomic spin flip, which can be implemented using far-off-resonant lasers with spontaneous emissions effectively suppressed. In an optical lattice tilted by a static gradient magnetic field, atomic states with distinct magnetic moments experience different tunneling matrices, which can be utilized to create a spin-dependent vector potential [45]. Apart from heating and loss of atoms from atomic spontaneous emission, the strength of SOC realized in the Raman scheme is difficult to tune continuously in a given experiment as it is fixed by the photon recoil momentum and the intersection angle between the two Raman laser beams, although an interesting idea for tuning SOC strength through periodic modulation of the effective Rabi frequency [48] is realized recently [49] which can reduce and change the sign of the synthesized SOC strength.

A promising protocol using pulsed gradient magnetic field (GMF) to generate spin-dependent momentum shift, which is equivalent to SOC, was proposed by Xu et al. [50]. Similar idea in terms of time-periodic modulating GMF was discussed by Anderson et al. [51]. In this magnetic approach, a time-periodic modulating 1-dimensional (1D) GMF \( B'(t)z \) with zero average [50, 51], as illustrated in Fig. 1(a), provides a spin-dependent force \( g_{FB} F'_x z \) for an atom (with mass \( m \) and spin \( F \)), where \( \mu_B \) is the Bohr magneton, \( g_F \) is the Lande g-factor and \( F_x, y, z \) denotes the \( x-, y-, \) and \( z\)-component of spin vector \( F \). Although the net impulse over one period is zero, the accumulated distance an atom travels depends on its spin state, which implies the atom acquires a spin-dependent group velocity. Thus atomic spin and its center-of-mass (orbit) motion are coupled by the GMF. This can be understood, perhaps more straightforwardly, if we consider the extreme case where each period contains a pair of two opposite GMF pulses which enact impulses \( \pm \hbar k_{so} \) capping the ends of the free evolution over time \( T \) [50]. As illustrated in Fig. 1(b), the action of these two pulses is then equivalent to a unity transformation, which displaces the canonical momentum by a spin-dependent quantity, i.e., \( U_\pm k_z U_\pm = k_z - k_{so} F_z \), where \( U_\pm = \exp(-i k_{so} z F_z) \), leading to the effective Hamiltonian \( \hat{H}_{eff} = \hbar^2 (k_z - k_{so} F_z)^2 / 2 m \). When this momentum shifted kinetic energy term is expanded out, the cross term, which couples the spin-dependent momentum shift to the canonical momentum, is formally the same as the SOC term in the Raman scheme [12]. For a sinusoidal modulating GMF \( B'(t) = B'_{max} \sin(2\pi t/T) \), as shown in Fig. 1(a), a similar effective time-independent Hamiltonian \( \hat{H}_{eff} \) can be derived according to the Floquet theory and is given by [52]

\[
H_{eff} = \frac{\hbar^2 k_z^2}{2 m} - \frac{c_1 \hbar^2 k_{so}}{m} k_z F_z + \frac{c_2 \hbar^2 k_{so}^2 F_z}{2 m},
\]

(1)

where \( \hbar k_{so} = g_{FB} \mu_B \int_0^T B'(t) dt = g_{FB} \mu_B B'_{max} T / \pi \), \( c_1 = 1/2 \), and \( c_2 = 3/8 \). The terms
Figure 1. A schematic illustration for generating SOC by periodic modulating gradient magnetic field (GMF). (a) A modulating GMF $B'(t)z\hat{z}$ (with zero mean) exerts opposite driven forces (black arrow or gray dashed arrows) for the $|M_F = 1\rangle$ (red disk and arrow) and $|-1\rangle$ (blue disk and arrows) states of the $F = 1$ Zeeman manifold. A typical temporal profile for $B'(t)$ is shown beneath by the blue wavy line. The physical origin for the synthesized SOC can be easily understood using the extreme case of one period modulation in (b), where two opposite ultrashort GMF pulses (blue triangles) with impulse $\pm \hbar k_{so}$ cap the free evolution of duration $T$. The spatial-dependent spin rotations $\exp\{\mp i k_{so} z F_z\}$ from the two opposite GMF pulses transform momentum $k_z$ into $k_z - k_{so} F_z$ by the spin-dependent impulse, as explicitly displayed inside the blue rectangular box. (c) The associated dispersion relations for the $|M_F = 1\rangle$ (red), $|0\rangle$ (green), $|-1\rangle$ (blue) components of Eq. (1) when SOC is present. (d) Our experimental setup consists of a pair of bias (gray) and gradient (blue) coils and a crossed dipole trap (red beams), whose minimum traps an atomic condensate. The center of the gradient coils is aligned well to coincide with the crossed dipole trap in order to minimize short term fluctuations of the modulating GMF.

The second term on the rhs of Eq. (1) denotes SOC between the canonical momentum for atomic center of mass motion and atomic spin. Its net effect can actually be altogether taken away with a suitable unitary transformation. In gauge field theories, this is often said that such a simple 1D SOC can always be gauged away, although the associated phases from the unitary transformations are real and can be observed. To prevent it from being gauged away, one can introduce additional interaction terms that do not commute with the SOC term, such as simply by introducing a detuning term reminiscent of a biased magnetic field in an
orthogonal direction \[12\] or a direct spin flip interaction as discussed in Ref. \[53\]. Alternatively, an important extension could generalize the 1D scheme to 2-dimensional (2D) systems with pulse pairs along \(x\)- and \(y\)-directions concatenated as illustrated in Fig. 2. When impulses from the respective pulses are small, the effective non-commuting actions for the \(x\)- and \(y\)-directions can be combined into the same exponent, leading to an effective 2D SOC described by the effective Hamiltonian

\[
H_{\text{eff}}^{(\text{SOC})} = \frac{\hbar^2}{2m} (k_x - \frac{1}{2} k_{\text{so}} F_x)^2 + \frac{\hbar^2 k_{\text{so}}^2}{8m} F_x^2 + \frac{\hbar^2}{2m} (k_y - \frac{1}{2} k_{\text{so}} F_y)^2 + \frac{\hbar^2 k_{\text{so}}^2}{8m} F_y^2. \tag{2}
\]

In order to enact GMF pulses along different spatial directions, the challenge lies at the required fast switch of magnetic field direction.

In addition to synthesizing SOC as discussed above, the technique of GMF can also be used to generate a space-periodic magnetic field or a magnetic lattice (ML) \[54\]. This is achieved by introducing a uniform bias field \(B_0 \hat{z}\) during the free evolution part of the previously discussed SOC protocol. As illustrated in Fig. 2, the unitary transformation from the pulse pair then gives rise to a ML described by

\[
H_{\text{eff}}^{(\text{Fig2})} = \frac{1}{2} \hbar \omega_0 [F_z \cos (k_{\text{so}} x) + F_y \sin (k_{\text{so}} y)] + \frac{1}{2} \hbar \omega_0 [F_z \cos (k_{\text{so}} y) - F_x \sin (k_{\text{so}} y)], \tag{3}
\]

in addition to turning the kinetic energy term into SOC (2). In the above \(\omega_0 = g_e \mu_B B_0 / \hbar\) is the Larmor frequency at \(B_0\). The lattice constant in our magnetic scheme is determined by the momentum impulse \(k_{\text{so}}\), or more precisely given by \(2\pi / k_{\text{so}}\). It is tunable and can be made smaller or even much smaller than the typical optical lattice constant, which is of the order of the lattice forming laser wavelength.

2. Demonstration of 1D spin orbit coupling

This section reports our demonstration of 1D SOC with GMF, more details can be found in Ref. \[52\]. Our experiment is carried out in a single chamber BEC setup previously described in
Ref. [55]. As shown in Fig. 1(d), a $^{87}$Rb BEC of $1.2(\pm 0.2) \times 10^5$ atoms in the $|F = 1, m_F = -1\rangle$ state is prepared in a crossed dipole trap. The 1D GMF is selected from a 3D quadrupole magnetic field by applying a 5.7 Gauss bias field along $z$-direction, which is generated by a pair of Helmhotz coils. In order to modulate the GMF quickly, a pair of small anti-Helmhotz coils is constructed for the 3D quadrupole field, whose center is precisely aligned with the condensate, to minimize fluctuations from the GMF at a modulation period of 1 ms. The peak gradient strength is about 50 Gauss/cm.

When SOC is present, the free atom dispersion curve will be shifted by a spin-dependent amount as depicted in Fig. 1(c). Analogous to a particle displaced from the center of a harmonic trap (in momentum space), atoms will oscillate back and forth both in coordinate and momentum space at the harmonic trap frequency, completely out of phase for the $|M_F = \pm 1\rangle$ components. This is indeed observed in the collective dipole oscillation of a single spin component condensate in a harmonic trap when the modulating GMF is suddenly turned on. Figure 3(a) shows the absorption images of the 3 spin components after 26 ms time of flight as a function of holding time in a harmonic trap, from which the momentum of each spin component can be deduced. The corresponding center of mass motions for the respective condensate spin components track their dipole oscillation trajectories, which are found to quantitatively agree with theoretical predictions, as reported in more detail in Ref. [52].

As a second confirmation, we adiabatically ramp up the SOC. According to the adiabatic theorem, if the ramping of $k_{so}$ is slow enough, atoms initially at the minimum will follow the ramp and stay at the (spin-dependent) shifted minimum. We measure the final momentum of each spin component as a function of SOC strength from the absorption images shown in Fig. 3(b). Again, we find the experimental results agree well with our theoretical predictions. This demonstrates our ability of continuously tuning the SOC strength by changing the modulation amplitude. More details can be found in Ref. [52].

2.1. Atomic loss and heating

We find heating and loss due to the parametric processes from the modulating GMF to be reasonable and acceptable. The loss for the $|M_F = -1\rangle$ component is largest. As shown in
Figure 4. (a) Measured life time of the $|m_F = -1\rangle$ component as a function of $k_{so}$ in units of one photon recoil momentum $k_L = 2\pi/\lambda$ at a laser wavelength $\lambda_L = 780$ nm. The harmonic trap frequencies are respectively $(\omega_x, \omega_y, \omega_z) = 2\pi \times (75, 68, 32)$ Hz. (b) The atomic cloud radius $R$ (fitted radius) after 24 ms free expansion (black square) for the $|M_F = -1\rangle$ component at $k_{so} = 4.9 \mu m^{-1}$ as a function of modulation frequency $\omega_{\text{mod}}$. The dashed line denotes the atomic cloud radius without SOC ($k_{so} = 0$). The trap frequencies are respectively $(\omega_x, \omega_y, \omega_z) = 2\pi \times (60, 100, 60)$ Hz.

Fig. 4(a), the measured life time for the $|M_F = -1\rangle$ component decreases with increasing SOC strength. With $k_{so}$ at approximate 0.6 photon recoil momentum, the life time is about 300 ms, which is long enough for our planned future explorations. Also shown in Fig. 4(b) is the measured cloud radius as a function of modulation frequency at a fixed SOC strength. We find the cloud radius become smaller with increasing modulation frequency, which implies smaller heating at higher modulation frequency.

3. Challenges for implementing 2D SOC

According to the proposed scheme [50], to generate 2D SOC, the GMF needs to be switched quickly between two alternating spatial directions, as otherwise atomic spins will adiabatically follow the temporally changing magnetic field. Experimentally the temporal rate of changing magnetic field is limited by the coil inductance and eddy currents. Atom chip based setups with extremely small coils will be most suitable for generating the required fast GMF pulses as is detailed in Ref. [54].

4. Conclusion

Since the idea of synthesizing atomic SOC with GMF was proposed [50, 51], rapid advances in this exciting new direction have occurred. A preliminary observation of 1D SOC for spin-1 atoms is reported [52], demonstrating the power of GMF for pure magnetically synthesized SOC and ML, and for further generalizations to higher spatial dimensions and higher spin atoms. In the GMF based scheme we implement, the strength of the synthesized SOC can be easily and continuously tuned through a simple change of the amplitude for the modulating GMF. Our early experimental results indicate that atom loss and heating due to temporal modulation of GMF is reasonable and acceptable for future experimental explorations. Together with the recent results in optical lattices from the Zurich group [56], the idea of GMF based scheme for synthesizing novel atomic gauge fields points to a promising direction for observing non-Abelian topological phenomenon in ultracold quantum gases. The immediate next step for us will be to introduce direct coupling between spin states to generate robust 1D SOC that cannot be gauged.
away. Extension to 2D SOC is also envisioned. Further studies will also uncover theoretical understanding and experimental confirmation that the strength of SOC can be enhanced making use of motional resonance associated with atomic center of mass in a harmonic trap [57].

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