Searching for topological superconductors is a challenging task in physics nowadays. One of the most promising schemes is by utilizing spin-orbit (SO) coupling, a spin polarized metal proximate to an s-wave superconductor can exhibit p-wave pairing [1]. Recently, synthetic SO couplings have also been realized by two-photon Raman process in bosonic [2–9] and fermionic [10–13] cold atom systems. In cold atom systems, instead of proximity effect, s-wave pairing force originates from Feshbach resonance, in which an s-wave Feshbach molecular state is tuned to scattering threshold and resonantly couples to itinerant atoms [14]. In this work we demonstrate a dynamic process in which SO coupling can coherently produce s-wave Feshbach molecules from a fully polarized Fermi gas, and can induce a coherent oscillation between Feshbach molecules and spin polarized gas. For comparison, we also show that such phenomena are absent if the inter-component coupling is momentum-independent. This demonstrates experimentally that SO coupling does provide a finite matrix element between a singlet state and a triplet state, and therefore, implies the bound pairs of a system with SO coupling have triplet p-wave component, which can become topological superfluid by further cooling these pairs to condensate and confining them to lower dimension.

Let us consider two atoms on the positive scattering length \( a_s > 0 \) side of an s-wave Feshbach resonance. In such a system, the Feshbach molecule is in the singlet state \( |S\rangle = (|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2)/\sqrt{2} \). We assume two fermionic atoms are initially prepared in the same spin state (say \(|\downarrow\rangle\)), with different momenta \( p \) and \( q \), as represented by blue arrows in Fig. 1. The initial state under anti-symmetrization is given by

\[
|\Psi\rangle_i = \frac{1}{\sqrt{2}}(|p\rangle_1 |q\rangle_2 - |q\rangle_1 |p\rangle_2) |\downarrow\rangle_1 |\downarrow\rangle_2. \tag{1}
\]

Now let us turn on a single particle term that couples two spin states as

\[
h(k) \cdot \sigma. \tag{2}
\]

If the “effective magnetic field” \( h \) is \( k \)-independent, it represents the case without SO coupling. In that case, \( h \) acts as a uniform magnetic field and the two atoms with different momentum always rotate in the same way. Therefore, at a given time \( t \), both of them rotate to the same direction \(|\hat{a}\rangle\), as shown in Fig. 1(a). The final state wave function is then given by

\[
|\Psi\rangle_f = \frac{1}{\sqrt{2}}(|p\rangle_1 |q\rangle_2 - |q\rangle_1 |p\rangle_2) |\hat{a}\rangle_1 |\hat{a}\rangle_2. \tag{3}
\]

Since this state remains in triplet channel, \( \langle S|\Psi\rangle_f \) is always zero. Thus, there cannot be any coherent transition to the Feshbach molecular state. On the other hand, if any component of \( h \) depends on \( k \), it means that the spin and momentum are coupled. In this case, the amount of

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Spin-Orbit Coupling Induced Coherent Production of Feshbach Molecules in a Degenerate Fermi Gas

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FIG. 1: (Color online). Schematic of how SO coupling can induce transition to Feshbach molecules: Left and right column represent spins of two atoms with different momentum. (a) and (b) represent two cases in the absence (a) or in the presence (b) of SO coupling. Red arrows represent spin direction at \( t = 0 \) and the yellow arrows represent spin direction at finite time \( t \).
rotation each spin executes depends on its momentum and is in general different for different momentum. Suppose at time $t$, atom with momentum $p$ rotates to $|\tilde{n}_{p}\rangle$ and atom with momentum $q$ rotates to $|\tilde{n}_{q}\rangle$, as shown in Fig. 1f), the final state wave function can now be written as

$$|\Psi\rangle_f = \frac{1}{\sqrt{2}}(|p|_1|q|_2|\tilde{n}_{p}|_1|\tilde{n}_{q}|_2 - |q|_1|p|_2|\tilde{n}_{q}|_1|\tilde{n}_{p}|_2).$$

It is straightforward to show the wave function Eq. (4) can be rewritten as

$$|\Psi\rangle_f = \frac{|p|_1|q|_2 - |q|_1|p|_2}{2}T + \frac{|p|_1|q|_2 + |q|_1|p|_2}{2}S,$$

where $|T\rangle = (|\tilde{n}_{p}|_1|\tilde{n}_{q}|_2 + |\tilde{n}_{q}|_1|\tilde{n}_{p}|_2)/\sqrt{2}$ and $|S\rangle = (|\tilde{n}_{p}|_1|\tilde{n}_{q}|_2 - |\tilde{n}_{q}|_1|\tilde{n}_{p}|_2)/\sqrt{2}$. Therefore, a transition to Feshbach molecular state can be induced.

Nevertheless, in reality, it is known that a momentum-independent coupling, such as radio-frequency (rf) coupling, can also produce Feshbach molecules in a degenerate Fermi gas. In such a process the atoms in $|\downarrow\rangle$ first evolve to the superposition of $|\uparrow\rangle$ and $|\downarrow\rangle$ through rf coupling. Then, after decoherence, it becomes an incoherent mixture of scattering atoms in $|\uparrow\rangle$ and $|\downarrow\rangle$, and further, the inelastic collision can bring some atoms in the mixture into molecules 13. It is important to notice that decoherence process has to be involved in such a process. While in contrast, the SO-coupling-induced transition discussed above does not require any incoherent process, and is a fully quantum coherent process.

In our experiment, a pair of 774.4 nm Raman lasers is applied to spin polarized $^{40}$K gas in $|F, m_F\rangle = |9/2, -9/2\rangle$ state. Two Raman beams are linearly polarized along $\hat{z}$ and $\hat{y}$ axis, respectively, which correspond to $\pi$ and $\sigma$ polarization along the quantization axis $\hat{z}$. Thus, the Raman process couples $|9/2, -9/2\rangle$ (denoted by $|\downarrow\rangle$) to $|9/2, -7/2\rangle$ (denoted by $|\uparrow\rangle$), and the momentum transfer in the Raman process is $2k_0 = 2k_t \sin(\theta/2)$, where $k_t = 2\pi h/\lambda$ is the single-photon recoil momentum, $\lambda$ is the wavelength of the Raman beam, and $\theta$ is the angle between two Raman beams. The recoil energy $E_r = k_t^2/2m = h \times 8.36$ kHz. The relative frequency between two lasers $\omega_1 - \omega_2$ can be precisely controlled, and the detuning $\delta = h(\omega_1 - \omega_2) - \hbar \omega_z$, where $\hbar \omega_z$ is the Zeeman splitting between $|\uparrow\rangle$ and $|\downarrow\rangle$. This Raman process is described by single particle Hamiltonian 2

$$\hat{H}_0 = \frac{(p_x - k_0 \sigma_z)^2}{2m} + \frac{\Omega}{2} \sigma_x - \frac{\delta}{2} \sigma_z + \frac{k_y^2 + k_z^2}{2m}.$$

Here, $p_x$ denotes the quasi-momentum of atoms, which relates to the real momentum $k_x$ as $k_x = p_x \pm k_0$ with $\pm$ for spin-up and down, respectively, and $\Omega$ is the strength of the Raman coupling. Comparing with Eq. (2), it is clear that $\hbar = (\Omega/2, 0, -\delta/2 - p_y k_0/m)$. If two Raman beams are parallel to each other, we have $\theta = 0$ and thus $k_0 = 0$. In this case there is no SO coupling. When $\theta \neq 0$, $k_0$ becomes non-zero and there will be SO coupling effect. According to above analysis, a fully polarized Fermi gas cannot be coupled to Feshbach molecular state if two Raman beams are parallel, while coherent molecule production is allowed if they are not parallel.

Our experiment is performed at 201.4 G, below the Feshbach resonance between $|9/2, -9/2\rangle$ and $|9/2, -7/2\rangle$ located at 202.2 G, which corresponds to a binding energy of $E_b = h \times 30$ kHz (corresponding to 3.59$E_r$) for the Feshbach molecules and $1/(\hbar k_F m) \approx 0.92$ for our typical density. After applying the Raman lasers for certain duration time, we turn off the Raman lasers and measure the population of Feshbach molecule and atoms in $|9/2, -7/2\rangle$ state with a radio-frequency (rf) pulse. This rf field drives a transition from $|9/2, -7/2\rangle$ to $|9/2, -5/2\rangle$. After the rf pulse, we abruptly turn off the optical trap and the magnetic field, and let atoms ballistically expand for 12 ms in the presence of a magnetic field gradient applied along $\hat{y}$, and finally take absorption image along $\hat{z}$ to measure the population of $|9/2, -5/2\rangle$ state. For a mixture of $|9/2, -7/2\rangle$ and Feshbach molecules, as a function of rf frequency $\nu_f$, we find two peaks in the population of $|9/2, -5/2\rangle$, as shown in Fig. 2(b). The first peak (blue curve) is attributed to free atom-atom transition and the second peak (red curve) is attributed to molecule-atom transition. Thus, in the following, we...
The population of Feshbach molecules and scattering atoms in \(|9/2, -7/2\) state as a function of two-photon detuning of the Raman pulse.

The Raman coupling strength is \(\Omega = 1.3E_r\) and the duration of the Raman pulse is 15 ms. Angle of two Raman beams is \(\theta = 180^\circ\) (a), \(\theta = 90^\circ\) (b), and \(\theta = 0^\circ\) (c), respectively. The red data points are Feshbach molecular population and the black data points are population of scattering atoms in \(|9/2, -7/2\) state.

We set \(\nu_R\) to 47.14 MHz to measure Feshbach molecules.

When the two-photon Raman detuning \(\delta\) is set to \(\delta = -E_b = -3.59E_r\) \((\theta = 180^\circ)\), as shown in Fig. 2(a), we measure the population of Feshbach molecule as a function of duration time for three different angles, \(\theta = 180^\circ\), \(\theta = 90^\circ\), and \(\theta = 0^\circ\), as shown in Fig. 2(c), (d) and (e). We find for \(\theta = 180^\circ\), Feshbach molecules are created by Raman process and the coherent Rabi oscillation between atom-molecule can be seen clearly. For \(\theta = 90^\circ\), production of Feshbach molecules is reduced a little bit and the atom-molecule Rabi oscillation becomes invisible. For \(\theta = 0^\circ\), no Feshbach molecule is created even up to 40 ms, which means the transition between Feshbach molecules and a fully polarized state is prohibited if Raman process has no momentum transfer.

Fig. 3 shows the population of Feshbach molecules detected by the rf pulse as a function of two-photon detuning \(\delta\) with the fixed Raman coupling strength \(\Omega = 1.3E_r\) and the pulse duration 15 ms. For \(\theta = 180^\circ\) and \(\theta = 90^\circ\) we find that the formation of Feshbach molecules starts to appear when \(\delta \gtrsim -7.18E_r\), reaches a maximum around \(\delta \approx -2.39E_r\) (it is a little bit larger than \(-E_b = -3.59E_r\), which is probably due to the momentum recoil from the Raman beams), and gradually decreases to zero around \(\delta = +3.59E_r\), as shown by red data points in Fig. 3(a) and (b). While for \(\theta = 0^\circ\), we find no Feshbach molecule production until \(\delta \gtrsim -1.79E_r\) and a Feshbach molecular population with narrower width is only near \(\delta \sim 0\), as shown in Fig. 3(c). The peak value in (c) is also much reduced compared to (a) and (b).

The atom-molecule transition shown in Fig. 4 contains both the SO-coupling induced coherent process and the incoherent process discussed above. For the incoherent process, sufficient population of scattering atoms in \(|9/2, -7/2\) is inevitable. In contrast, the coherent process can still exist even when the population of the scattering atoms in \(|9/2, -7/2\) is negligible at sufficient large detuning. Thus, to further distinguish these two processes, we measure the population of scattering atoms in \(|9/2, -7/2\) state for three cases with \(\theta = 180^\circ\) (a), \(90^\circ\) (b), \(0^\circ\) (c), after a Raman pulse with the same intensity and the same duration. We find in all the three cases, the population of scattering atoms in \(|9/2, -7/2\) becomes non-zero for \(\delta \gtrsim -3.59E_r\) as shown in black data points in Fig. 3. The difference between (a,b) and (c) is that for (a,b), the system mainly populate in \(|9/2, -7/2\) when \(\delta > 3.59E_r\), while for (c) the population of \(|9/2, -7/2\) vanishes when \(\delta > 2.39E_r\). This is because for the case without SO coupling (c), the resonance always takes place when two-photon detuning matches Zeeman energy, i.e. \(\delta = 0\), for atoms in all momentum. While for (a) and (b) with SO coupling, the resonance frequency is momentum dependent and spend over a much wider frequency range.

Comparing the populations of scattering atoms in the state \(|9/2, -7/2\) and Feshbach molecules in Fig. 3 we find that for \(\theta = 180^\circ\) and \(\theta = 90^\circ\) (SO coupling case), significant molecule population exists in the frequency regime \(\delta \lesssim -3.59E_r\), where almost no scattering atoms in \(|9/2, -7/2\) are found. This confirms the coherent nature of Feshbach molecular production. On the other hand, for \(\theta = 0^\circ\) (no SO coupling), no Feshbach molecule can be found where no population of scattering atoms in \(|9/2, -7/2\) can be seen (either \(\delta \lesssim -2.39E_r\) or \(\delta \gtrsim +2.39E_r\)). This shows that decoherence process is key in producing scattering atoms in the state \(|9/2, -7/2\), which is prerequisite for incoherent molecular formation.

A more direct evidence for the coherent nature of molecular production is the Rabi oscillation between Feshbach molecular state and a fully polarized Fermi gas. Previously coherent atom-molecule oscillation has only been observed in bosonic atomic gas \([19]\) and boson-fermion mixture \([20]\). In a Fermi gas the energy of atoms in scattering states spread over a wide energy range of the order of Fermi energy \((2.2E_r\) in our system), which inevitably leads to damping of Rabi oscillation. However, by tuning the laser intensity and as a result, the magnitude of the Rabi frequency, the oscillation period can be made shorter compared with damping time and can be readily observed in the experiment. In Fig. 4 we plot Feshbach molecular fraction as a function of duration time of Raman laser with two-photon detuning tuned to molecule binding energy. In Fig. 4(a-c) at least one oscillation period can be identified. While in case (d) with a smaller Raman intensity, oscillation becomes invisible. For (a-c) we take the first minimum as one period \(\tau\), and plot Rabi oscillation frequency \(\nu = 1/\tau\) as a function of Raman coupling \(\Omega\) in Fig. 4(c), and find a perfect linear relation. This is indicative of a coherent process in which the
oscillation frequency is proportional to Raman-coupling strength. Finally in Fig. 4(f) we plot Feshbach molecular fraction for various temperatures. We find when temperature increases from \( T/T_F = 0.3 \) to \( T/T_F = 0.68 \), the oscillation period is almost unchanged but the oscillation itself becomes less and less visible. This shows the increase of damping rate with the increase of temperature.

Finally, we study the creation of Feshbach molecules for different magnetic fields corresponding to different binding energies \( E_b \) of the molecules. The detuning \( \delta \) is chosen to be \( \delta = -E_b \). Here, the Feshbach molecules are dissociated by a magnetic sweep over the Feshbach resonance instead of the rf pulse. As shown in Fig. 5 we find that the Feshbach molecular population increases at the higher magnetic field, or lower binding energy \( E_b \). This is because the atom-molecule transition amplitude depends on the overlap between the wave-function of Feshbach molecule and the one of two free atoms (i.e., the Franck-Condon factor), which increases with \( E_b \).

In conclusion, by applying SO coupling, we have demonstrated coherent production of Feshbach molecules from a fully polarized Fermi gas, as well as a coherent oscillation between them, provided that the coupling strength is strong enough. Such a coherent process reveals that, in the presence of SO coupling, the atomic triplet state is coupled to the singlet state, and thus the bound state of a system with SO coupling contains both singlet and triplet components. For symmetry reason, the triplet component should at least be a \( p \)-wave pairing. Although the temperature of our current system is still above the condensation temperature of these pairs, one may still expect some interesting physics of these noncondensed nontrivial pairs. At low temperature and lower dimension these pairs will exhibit topological superfluidity.

**Method:** This experiment starts with a degenerate Fermi gas of about \( 2 \times 10^6 \) \(^{40}\)K in the \([9/2, 9/2]\) state, which has been evaporatively cooled to \( T/T_F \approx 0.3 \) with bosonic \(^{87}\)Rb atoms in the \([2, 2]\) inside the crossed optical trap \([10, 21, 23]\), where \( T_F \) is the Fermi temperature defined by \( T_F = (6N)^{1/3}/\hbar \omega/k_B \), and \( \omega \approx 2\pi \times 80 \) Hz in our system, \( N \) is the number of fermions. A 780 nm laser pulse is applied for 0.03 ms to remove the \(^{87}\)Rb atoms in the mixture without heating \(^{40}\)K atoms. Subsequently, the fermionic atoms are transferred into the lowest state \([9/2, -9/2]\) via a rapid adiabatic passage induced by a radio-frequency field of 80 ms at 4 G. A homogeneous bias magnetic field for magnetic Feshbach resonance along the \( z \) axis (gravity direction) is produced by the quadrupole coils (operating in the Helmholtz configuration).

A pair of 772.4 nm Raman laser are extracted from a CW Ti: sapphire single frequency laser. Two Raman beams are frequency-shifted around \(-77 \) MHz and \(-122 \) MHz by two single-pass acousto-optic modulators (AOM), respectively, to precisely control their frequency difference. These two Raman beams has a maximum intensity \( I = 130 \) mW for each beam, and they overlap in the atomic cloud with \( 1/e^2 \) radii of 200 \( \mu m \).

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[1] Fu, L. & Kane, C. L. Superconducting proximity effect and Majorana fermions at the surface of a topological insulator. *Phys. Rev. Lett.* **100**, 096407 (2008).

[2] Lin, Y.-J., Jiménez-García, K. & Spielman, I. B. Spin-orbit-coupled Bose-Einstein condensates. *Nature* **471**, 83-86 (2011).

[3] Fu, Z., Wang, P., Chai, S., Huang, L. & Zhang, J. Bose-Einstein condensate in a light-induced vector gauge potential using the 1064 nm optical dipole trap lasers. *Phys. Rev. A* **84**, 043609 (2011).

[4] Williams, R. A. *et al.* Synthetic partial waves in ultracold atomic collisions. *Science* **335**, 314-317 (2012).

[5] Jochim, S. *et al.* Pure gas of optically trapped molecules created from fermionic atoms. *Phys. Rev. Lett.* **91**, 240402 (2003).

[6] At the same time we should be careful that each single beam $\omega_1$ and $\omega_2$ will not cause bound-to-bound transition.

[7] Donley, E. A., Claussen, N. R., Thompson S. T. & Wie- man, C. E. Atom-molecule coherence in a Bose-Einstein condensate. *Nature* **417**, 529-533 (2002).

[8] Olsen, M. L., Perreault, J. D., Cumby, T. D. & Jin, D. S. Coherent atom-molecule oscillations in a Bose-Fermi mixture. *Phys. Rev. A* **80**, 030701(R) (2009).

[9] Xiong, D. *et al.* Quantum degenerate Fermi-Bose mixtures of $^{40}$K and $^{87}$Rb atoms in a quadrupole-Ioffe configuration trap. *Chin. Phys. Lett.* **25**, 843-846 (2008).

[10] Cheuk, L. W. *et al.* Spin-injection spectroscopy of a spin-orbit coupled Fermi gas. *Phys. Rev. Lett.* **109**, 105301 (2012).