Spin-Orbit Coupling in Ultracold Fermions

1 Introduction, Motivation & Background

The use of ultracold atoms to mimic condensed matter systems, while still relatively in its infancy, has garnered much attention and achieved much success. Among the many reasons for this are the extreme tunability and precision that are attainable when working with lasers and fields controllable over wide ranges and short timescales. This allows cold atom researchers to explore a wide range of parameter space relatively easily and very precisely. In stark contrast, condensed matter systems are often fixed in parameter space and extracting the desired information out can prove difficult or impossible. Perhaps the only limit so far is human ingenuity. As has been said, cold atom Hamiltonians of this kind only contain what the experimenter puts into them by hand and as research progresses to more and more complex phenomena scientists must come up with ever more clever ways to engineer Hamiltonians.

A great example of recent progress in this regard comes in spin-orbit coupling (SOC). To any physicist, there is really no need to emphasize the importance of SOC across the field. From the fine structure of atoms to topological insulators to semiconductors, SOC is a ubiquitous phenomenon responsible, at least in part, for a great number of interesting physical problems. In the past three years researchers have succeeded in engineering a spin-orbit coupled Hamiltonian in ultracold atoms for both bosons and fermions. In 2011 Lin, Jimenez-Garcia and Spielman of the Joint Quantum Institute realized SOC in a Bose-Einstein condensate. This represented the first experimental realization of spin-orbit coupling in any cold atom system and the researchers observed a spatial ordering phase transition for atoms in two different spin states [3]. Perhaps even more excitingly, in 2013 two groups (Wang et al. and Cheuk et al.) independently and concurrently realized a SOC Hamiltonian for a fermionic system [2, 1]. The Pauli Exclusion Principle forces fermions to occupy a large number of states, as opposed to bosons which condense to occupy only one or two at ultracold temperatures. As such, fermionic systems have the potential to exhibit a much wider array of interesting phenomena like topological insulator states and exotic superfluidity.

This work focuses on the experiments of Cheuk et al. at MIT. Although technically Wang et al. of Tsinghua University achieved the first experimental realization of SOC in fermionic ^{40}K, the work of the MIT group is especially noteworthy for several reasons to be discussed shortly. The experiments of Cheuk et al. were performed using ^{6}Li, the hyperfine structure of which is detailed in Figure 1. The states used in these experiments are found by applying a small Zeeman field which removes the energy degeneracy of the m_F-states the two $2^2S_{1/2}$ hyperfine states.

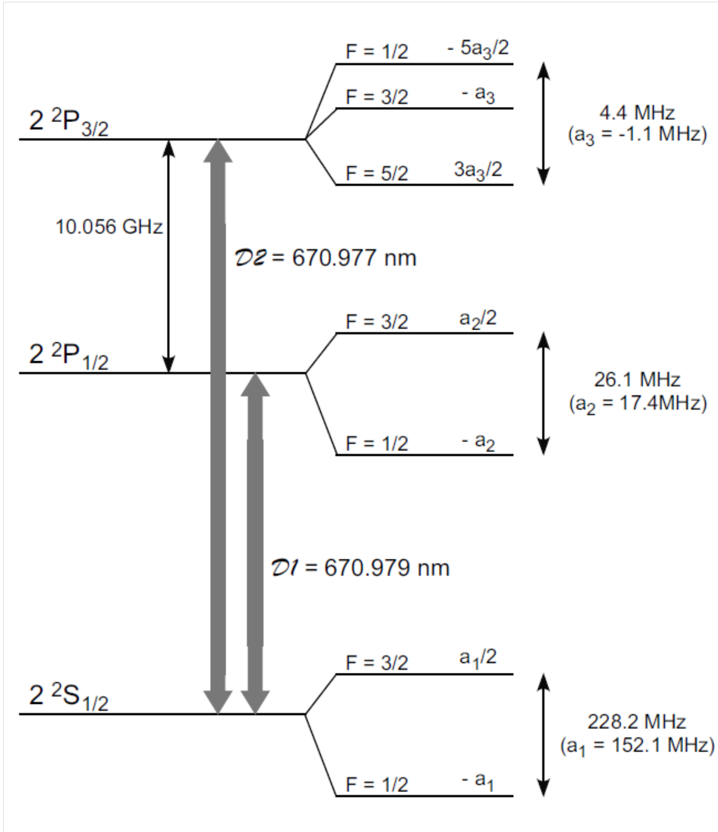

Figure 1: Energy level diagram of the ground and lowest excited states of ^{6}Li, showing fine and hyperfine structure [4].

2 Theory

The main theoretical underpinning of these experiments is the creation of a spin-orbit Hamiltonian using Raman dressing of atomic hyperfine states. At the most basic level, Raman dressing produces SOC because when an atom absorbs and emits photons of different wavelengths it receives a momentum kick as it changes hyperfine state. Thus the spin (atomic state) and orbit (momentum) are coupled. In these experiments only the x-direction momentum is coupled to the spin. This section serves as an overview of the basic physics involved and more details can be found in Cheuk et al. [1] as well as in similar literature [2, 3].

When absorbing a photon from one Raman beam and emitting a photon into the other, the atom receives an impulse of $\pm\hbar Q\hat{x}$. In this setup, changing from spin-up ($|\uparrow\rangle$) to spin-down ($|\downarrow\rangle$) the impulse is negative and when changing from $|\downarrow\rangle$ to $|\uparrow\rangle$ the impulse is positive. This allows one to define a quasimomentum $q = k_x \pm \frac{Q}{2}$ for $|\downarrow\rangle$ and $|\uparrow\rangle$ respectively. Now substituting in for the quasimomentum in the Hamiltonian results in a spin-orbit Hamiltonian with equal parts Rashba and Dresselhaus coupling.

Several parameters are important when thinking about these SOC experiments. The relevant energy scale is the recoil energy $E_R = \hbar^2 Q^2/2m$ which is the energy a stationary atom would have after undergoing the stimulated Raman transition. This is determined experimentally by the frequency difference between the two beams as well as their relative propagation angle. The Raman beams intensity (via the associated Rabi frequency) determines the z-component of an effective, internal Zeeman field ($B_z^{(Z)}$) and the two-photon detuning sets the y-component of the same field ($B_y^{(Z)}$).

When no Zeeman field is present there is no mixing of the spin states and the dispersion relation of each is simply parabolic and shifted from $q = 0$ by $\pm\frac{Q}{2}$. However for a non-zero $B_z^{(Z)}$ the spin states are coupled and a gap opens in the spectrum as the eigenstates become a mixture of $|\uparrow\rangle$ and $|\downarrow\rangle$. Both bands in the new dispersion can be said to have spin texture in that the relative weights of the $|\uparrow\rangle$- and $|\downarrow\rangle$-components of the eigenstate depend on the momentum.

3 Procedure

A major reason this work is intriguing and ground-breaking is the ingenious methods employed to overcome the experimental difficulties. The fine structure and absorption properties of ^{6}Li are unfavorable for this type of experiment, and thus new techniques had to be developed to reduce inelastic light scattering and resonant heating.

The ^{6}Li atoms were first cooled sympathetically using ^{23}Na in a magnetic trap. In this method, laser cooling methods are applied to the Na atoms which in turn cool the Li atoms via collisions that exchange energy between the two. This process cools the Li atoms to well below the Fermi temperature. The Na atoms are then removed and the Li atoms are transferred to an optical dipole trap consisting of two orthogonal 1064nm laser beams. To separate the hyperfine states, an external magnetic field of 11.6G is then applied. As described above, Raman beams with a relative angle of 38° are used to induce the spin-orbit coupling. In this experiment the coupled states are the second and third lowest hyperfine states, labeled $|\downarrow\rangle$ and $|\uparrow\rangle$ respectively.

The key piece of experimental procedure is the use of all four lowest hyperfine states instead of simply using the two that are spin-orbit coupled. The highest and lowest of the four states serve as reservoir states for the $|\uparrow\rangle$ and $|\downarrow\rangle$ states respectively and are labeled $|\uparrow\rangle_R$ and $|\downarrow\rangle_R$. The atoms optically are pumped into the reservoir states, keeping very low density in the coupled states and thus causing much less resonant heating that in the traditional set-up. An important aspect of this scheme is that transitions from the $|\uparrow\rangle_R$ state predominantly populate parts of the SOC band structure with a strong $|\uparrow\rangle$ component, and vice versa. This process can be seen schematically in Figure 2.

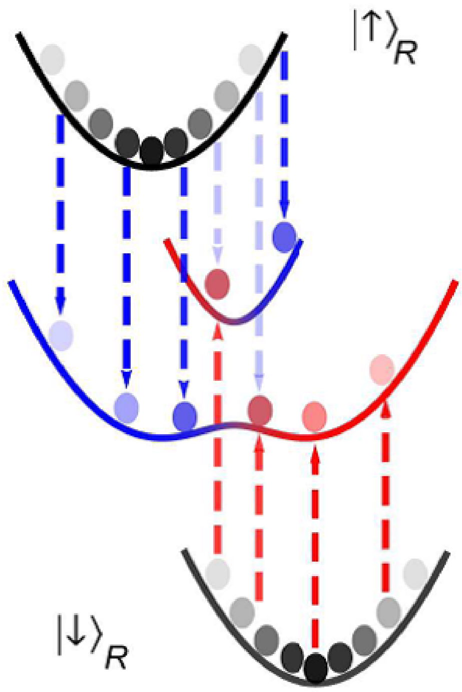

Figure 2: Schematic dispersion relation diagram showing the $|\uparrow\rangle_R$ and $|\downarrow\rangle_R$ states as well as the bands resulting from spin-orbit coupling between $|\uparrow\rangle$ and $|\downarrow\rangle$. As evidenced by the dashed lines, rf fields preferentially couple $|\uparrow\rangle_R$ to $|\uparrow\rangle$-rich parts of the dispersion and $|\downarrow\rangle_R$ to $|\downarrow\rangle$-rich parts [1].

Transitions into the SOC states are induced with radiofrequency (rf) fields of known photon energy. When this energy matches the energy difference between the reservoir state and the SOC bands the atoms are change state. Data readout is done using time of flight (TOF) imaging to measure the atoms momenta. This readout is made spin-selective by ramping the external magnetic field to a large value so that the resonant imaging frequencies of the two hyperfine states are easily distinguished.

4 Results & Discussion

The first major result of these experiments is a proof of concept that spin-orbit coupling has in face been achieved. By pulsing the Raman fields at varying duration and detuning profiles, the authors could manipulate the spin states of the atoms. A few examples are shown in Figure 3. Figure 3(d) shows momentum-dependent Rabi oscillations, a hallmark of SOC. As the Raman beams are suddenly pulsed for different amounts of time the initially homogeneously prepared spins move around the Bloch sphere with momentum dependent frequency because they are no longer eigenstates of the SOC Hamiltonian. This result also shows that the system is coherent over many cycles as evidenced by the clear oscillations seen up to at least $t = 400\mu s$. Figure 3(e) shows the precision with which momenta can be selected. After the atoms are prepared as an equal mixture of $|\uparrow\rangle$ and $|\downarrow\rangle$, a π-pulse is applied for different Raman detunings δ. Each horizontal slice shows that only a small section of atoms whose momentum and ensuing Doppler shift cause them to be resonant with the detuned Raman beams experience the π-pulse and change sign. The other atoms that are not resonant remain unaffected.

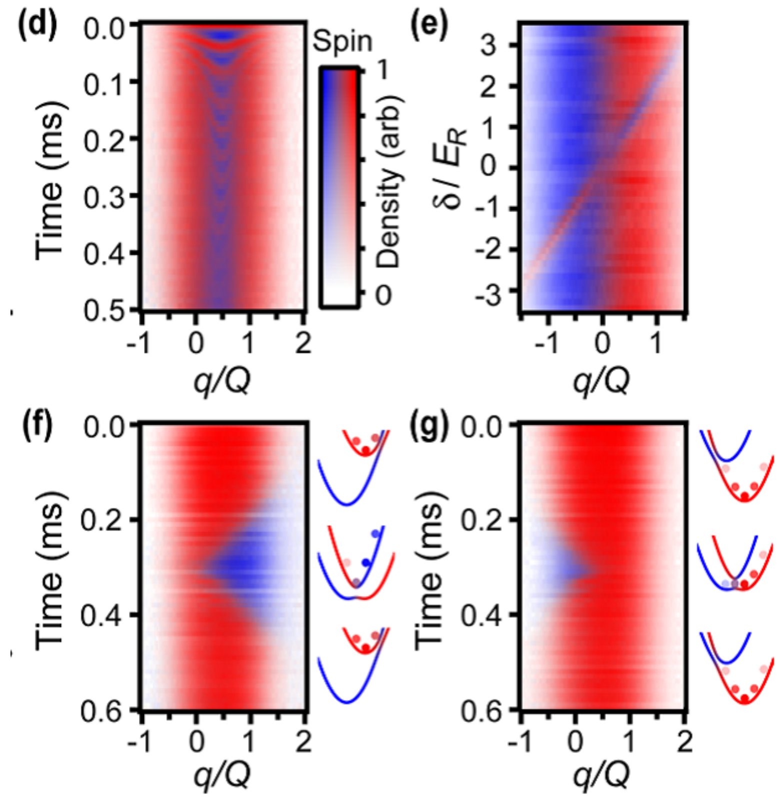

Figure 3: Evidence for spin-orbit coupling and the ability to manipulate and adiabatically load and unload atoms from the bands. (d) Momentum dependent Rabi oscillations beginning in a homogeneously prepared initial spin state. (e) Applying π-pulses to selectively flip spins with different momenta. (f) and (g) Adiabatically loading and unloading atoms into the upper and lower SOC bands [1].

The previous two results show instantaneous pulsing of the Raman fields at set detunings. This results in projection of the initial states into superpositions of the SOC band states. Figures 3(f) and 3(g) show adiabatic loading and unloading of the atoms into the upper and lower SOC bands. To do this, the Raman detuning is swept beginning at a large value compared to the two-photon recoil energy and ending at zero. In (f) the detuning is swept from below and results in loading of the upper band while in (g) the detuning begins above and the lower band is loaded. In both cases at around $t = 300\mu s$ the sweep is reversed and the atoms are returned to the state they started in.

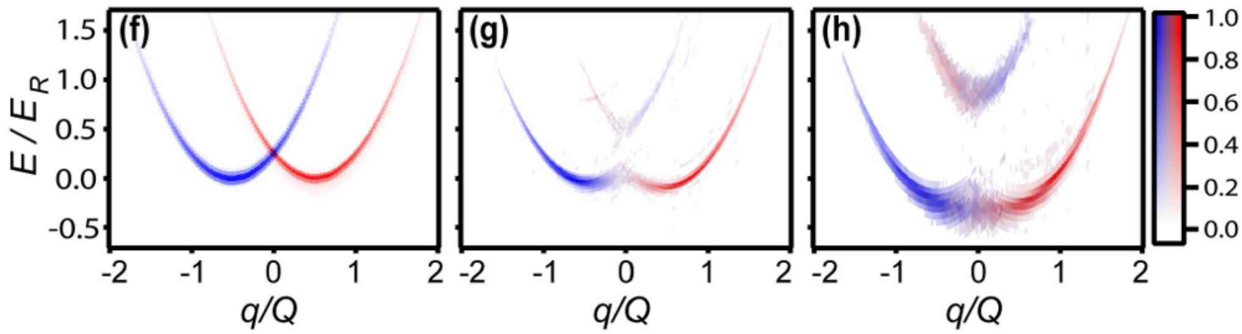

Figure 4: Reconstructed spinful dispersion relations for the two dressed state bands showing: (f) shifted parabolic dispersions for no coupling and, (g)(h) opening and widening of an energy gap as coupling is turned on and gets stronger [1].

Having established that spin-orbit coupling is indeed acheived, the main goal of the experiments is to use the new spin-injection technique for measuring the state and energy of the atoms at different momenta to measure the band structure and spin texture of the SOC system. Figure 4 shows the dispersion relation and spin texture for the two bands as the internal Zeeman field is applied. Figure 4(f) shows the two spin-orbit coupled bands with offset momenta as expected. Figures 4(g) and 4(h) show the band structure development as the Zeeman field is increased and the two bands mix. Using both the $|\uparrow\rangle_R$ and $|\downarrow\rangle_R$ reservoir states to measure the $|\uparrow\rangle$- and $|\downarrow\rangle$-rich sections of the bands, both the dispersion relation and spin texture can be obtained. One can clearly see the development of a SOC gap and a transition from spin-homogeneous bands to spin-mixed bands as the coupling increases.

The authors also investigated the more complex band structure of SOC in the presence of a periodic lattice potential. Although the details are complicated and not qualitatively different from the results so far, some attention is deserved. The 1-D lattice was created using an additional rf field, allowing spin flips without a Raman impulse. The resulting band structure involves multiple degeneracies which are lifted by the application of the Raman and rf fields and which create very detailed spin-injection spectra. One example of an reconstructed experimental band structure and theoretical comparison is shown in Figure 5.

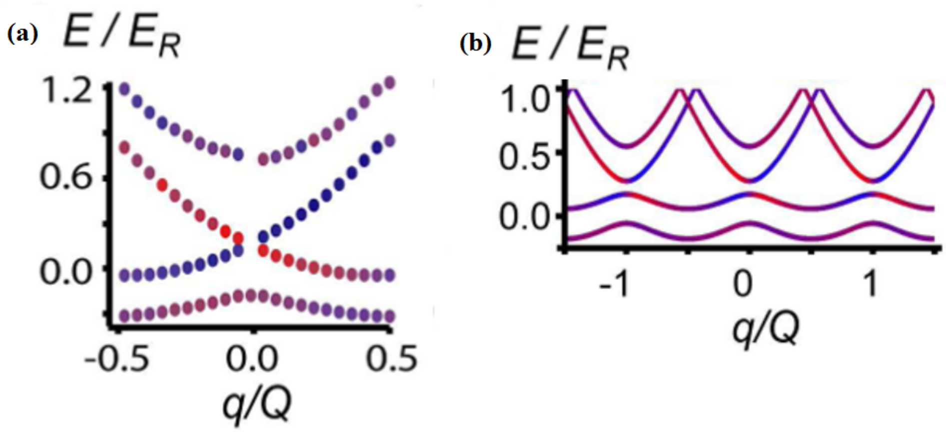

Figure 5: Comparison between (a) experimental results and (b) theory for the lowest four bands of spin-orbit coupled states on a periodic lattice.

5 Conclusion

These experiments are interesting both in themselves and as what they bring to the wider field of constructing condensed matter Hamiltonians in cold atom system. The authors introduced a new technique for studying cold atom systems that reverses the traditional thinking. Spin-injection spectroscopy keeps the populations in the states of interest low, thereby reducing negative effects such as resonant heating and uncontrolled interactions. In this scheme, the spectroscopy probes unoccupied states as opposed to the more traditional methods.

Thinking more broadly, Two-level spin-orbit coupling is an archetypal phenomena that can describe a wide variety of phenomena across physics. Even more importantly, fermionic SOC contributes to many of the most interesting condensed matter phenomena such as unconventional superconductivity and superfluidity and topological insulators. This work represents the first step towards realizing those more complex, yet just as easily tunable and precisely manipulated spin-orbit coupled systems. As a result, yet another addition has been made to the ultracold atom toolbox.

References

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