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Review Article

Degenerate quantum gases with spin–orbit coupling: a review

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Abstract
This review focuses on recent developments in synthetic spin–orbit (SO) coupling in ultracold atomic gases. Two types of SO coupling are discussed. One is Raman process induced coupling between spin and motion along one of the spatial directions and the other is Rashba SO coupling. We emphasize their common features in both single-particle and two-body physics and the consequences of both in many-body physics. For instance, single particle ground state degeneracy leads to novel features of superfluidity and a richer phase diagram; increased low-energy density-of-state enhances interaction effects; the absence of Galilean invariance and spin-momentum locking gives rise to intriguing behaviours of superfluid critical velocity and novel quantum dynamics; and the mixing of two-body singlet and triplet states yields a novel fermion pairing structure and topological superfluids. With these examples, we show that investigating SO coupling in cold atom systems can, enrich our understanding of basic phenomena such as superfluidity, provide a good platform for simulating condensed matter states such as topological superfluids and more importantly, result in novel quantum systems such as SO coupled unitary Fermi gas and high spin quantum gases. Finally we also point out major challenges and some possible future directions.

Keywords: quantum gases, cold atoms, spin–orbit coupling

(Some figures may appear in colour only in the online journal)

1. Introduction

The effects of SO coupling for electrons have already been extensively studied in various areas of physics. For instance, in atomic physics, it gives rise to fine structure splitting which plays a very important role in the electronic structure of atoms; in condensed matter physics, it is one of the major effects that govern electron transport in a semiconductor and recently it was found that SO coupling can give rise to novel materials such as topological insulators, the quantum anomalous Hall effect and topological superconductors.

In contrast, neutral atoms in their original state do not have the SO coupling effect. Nevertheless, by utilizing atom-light interactions recently, synthetic SO coupling was generated for ultracold atoms. In recent years, the study of SO coupled quantum gas has become one of the hottest topics in cold atom physics and much theoretical and experimental progress has been made in this direction. One question the reader may have is; since the effects of SO coupling have already been studied in several different branches of physics, why should we study this effect again in the content of cold atom systems and what new physics can we expect here? From my perspective, the main motivations for studying SO coupling effects in the ultracold quantum gases of cold atoms can be summarized as follows:

- Previously, SO coupling effects have only been studied in fermonic systems. Whereas many atomic species are bosonic, creating SO coupling in cold atomic gases provides

