

Sujet de stage de Master 2

Titre du sujet : Coherent and incoherent spin manipulations in a degenerate Fermi gas

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- Keywords : Cold atoms, quantum gases, quantum simulation, quantum metrology, dissipative engineering, photoassociation, lasers

Ultracold atoms, produced by laser cooling techniques, offer a platform to explore quantum collective effects in the regime of quantum degeneracy. We perform experiments with degenerate Fermi gases of strontium 87 atoms – an exotic fermionic system, in that its spin-9/2 degree of freedom encompasses a large number (10) of Zeeman sublevels. This is both an opportunity to explore novel many-body effects (for example, magnetic phenomena), and a “technological” opportunity to use quantum objects with a large internal Hilbert space, as a resource for quantum simulation, computation, or sensing.

We have developed original methods to manipulate and measure the atomic spins. We want now to demonstrate the production of quantum correlated states, by engineering either Hamiltonian or dissipative terms acting on the atoms. The dissipative control is counter-intuitive: it is a novel insight that couplings to an environment, typically destroying the manifestations of quantum physics, will in specific cases actually produce and stabilize quantum states with many-body correlations. This exciting point means that quantum phenomena may be harvested for quantum simulation or quantum sensing (clocks, atom interferometers) in a more robust manner than formerly thought.

Our methods rely on the original spectroscopic properties of strontium: narrow optical lines, relevant to optical atomic clocks, that we use to engineer highly selective spin manipulations. A few years ago, we developed coherent optical manipulation tools, that enable in principle taking arbitrary control over the spin state of the atoms [1]. Presently, we are working towards the dissipative manipulation of the collective spin. This results from photoassociation, controlled by laser, and the Pauli principle, that prevents identical fermions from being in the vicinity of each other. The effect is expected to pump the remaining atomic ensemble towards spin-symmetric entangled states [2]. This effect can be harvested to stabilize quantum states in quantum simulation or computation schemes (e.g., stabilizing ferromagnetic states), or to produce states of interest to metrology.

The spectroscopy of the photoassociation lines is underway. At the next stage of our research, we will need to combine the dissipative manipulation techniques being attempted presently, with the coherent manipulation schemes of [1], to demonstrate the properties of the states dissipatively engineered. In the long term, this combination of control methods is expected to foster new schemes to prepare or stabilize many-body states of interest to quantum simulation or metrology. The master's internship, in Spring 2027, will consist in developing the laser system enabling independent coherent and incoherent spin manipulations. Thus far, one single system had been modified to turn from one function to another. The new development involves implementing an injection-locked diode laser, beam shaping and controlling by active optical elements such as AOMs, fiberization, and integration of this module onto the ultracold atom platform. The internship will be an opportunity to discover the quantum gas platform as a whole, possibly as a preparatory step for longer-term integration in the team.

[1] Ahmed et al, Coherent Control Over the High-Dimensional Space of the Nuclear Spin of Alkaline-Earth Atoms, PRX Quantum 6, 020352 (2025)

[2] Foss-Feig et al, Steady-State Many-Body Entanglement of Hot Reactive Fermions, Phys. Rev. Lett. 109, 230501 (2012)