**Optimizing, probing, and leveraging spins squeezing of cavity-mediated atom pairs** (semester project)

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GOALS

- Devise and investigate optimal strategies to generate and probe spin squeezing in cavity-mediated spin and momentum pairs (under realistic experimental conditions)

- Explore and quantify schemes for quantum-enhanced atomic interferometry

CONTENTS

1. **Preparation Stage**

* Map out many-body Hamiltonian and dissipative contributions considering realistic experimental conditions [1,2].
* Understand experimental observables, control parameters and energy scales [2]
* Reproduce mean-field dynamics [1] (e.g. parametric amplification of pairs, coherent oscillations)
* Reproduce Truncated Wigner simulations

1. **Main Tasks**

* Derive and simulate evolution of different **squeezing and entanglement criteria.**

**Three-mode case:** Relative number squeezing [3,4] and spin-nematic squeezing [5,6]

**Five-mode case:** Bipartite entanglement [7,8]

* Find optimal conditions and maximal squeezing for different criteria and finite dissipation.
* **Read-out strategies:** Can we map out the relevant ‘spin coherences’ in Refs. [5-8] to spin and momentum population after global radio-frequency spin rotations? How do we handle the momentum degrees of freedom?

1. **Further Directions**

Devise and simulate protocols for **quantum-enhanced interferometry** with squeezed pairs.

* Explore time-reversal based SU (1,1) interferometry of spinor phases [9,10]
* Explore gradient sensing with correlated momentum states [11]

METHODSFew-mode expansion of many-body system (at least 2 methods for mutual benchmarking)

* Truncated Wigner simulations [2]
* Analytic estimations for undepleted pump mode approximation
* Benchmark: Exact diagonalization simulations in QuTip for small system sizes
* Further methods: Stochastic Gross-Pitaevskii Simulations?

WORKSTYLE

* The above listed task and methods are intended as a guideline and can be adapted based on interest and feasibility.
* Document analytic calculations and scripts for numerical calculations.
* Self-contained report at the end of project

REFERENCES

**Cavity Experiment**

**[1]** <https://arxiv.org/abs/2303.11326> (preprint on spin- and momentum-correlated atom pairs)

**[2]** <https://www.research-collection.ethz.ch/handle/20.500.11850/637804> (PhD thesis of Rodrigo Rosa-Medina on the cavity experiment. It contains details on atomic pairs theory and experiments)

**Cold-atom experiments measuring relative number squeezing due to spin-changing collisions.**

**[3]** <https://arxiv.org/pdf/2004.09003.pdf>

**[4]** <https://arxiv.org/pdf/1112.4594.pdf>

**Cold-atom experiments measuring spin-nematic squeezing due to spin-changing collisions**

[5] <https://arxiv.org/pdf/1111.1694.pdf>

(First observation of spin-nematic squeezing in Spin-1 BECs)

[6]<https://chapmanlabs.gatech.edu/papers/Hamley_Christopher_Spin_Nematic%20Squeezing_in_a_Spin-1_BEC_May_2011.pdf>

(Accompanying PhD thesis on the topic: Chapter 3 discusses the mapping of an interacting spin-1 BEC to the squeezing Hamiltonian, Chapter 4 introduces theory methods to simulate spin-nematic squeezing, and Chapter 5 describes the experimental protocol and read-out)

**Bipartite Entanglement in BECs ([7],[8] are also cited in thesis of Finger)**

[7] <https://arxiv.org/pdf/1708.02480.pdf>

[8] <https://arxiv.org/pdf/2104.05663.pdf>

(Complementary theory paper discussing different criteria for probing spin)

**Quantum-enhanced interferometry with atomic pairs in BECs**

[9] <https://arxiv.org/pdf/1708.02480.pdf>

(Time-reversal based implementation of SU(1,1) interferometer using spin-changing collisions)

[10] <https://arxiv.org/pdf/2309.12980.pdf>

(SU(1,1) theory proposal using cavity-mediated momentum pairs interactions)

[11] <https://arxiv.org/pdf/2010.09168.pdf>

(Review on quantum-enhanced atomic interferometry)