Reinforcement Learning for Quantum Sensing

Morten Hjorth-Jensen

Department of Physics, UiO, Norway

Quantum Machine Learning: from Fundamentals to Applications, Nordita, February 2-13, 2026

Inspiration and aims

Aims

I will try to give you an overview on how we can model systems of relevance of quantum sensing, using machine learning and many-body methods. Slides and jupyter-notebooks at `https://github.com/mhjensenseminars/MachineLearningTalk/tree/master/doc/src/QuantumSensing`

Inspiration

- **Reinforcement Learning for Quantum Technlogy**, by Marin Bukov and Florian Marquardt, arXiv:2601.18953
- **Model-aware reinforcement learning for high-performance Bayesian experimental design in quantum metrology**, by Federico Belliardo, Fabio Zoratti, Florian Marquardt, and Vittorio Giovannetti, Quantum 8, 1555 (2024)

Thanks to many

Many good friends and colleagues

Jane Kim (ANL), Patrick Cook (MSU), Danny Jammooa (MSU), Dean Lee (MSU), Bryce Fore (ANL), Alessandro Lovato (ANL), Stefano Gandolfi (LANL), Francesco Pederiva (UniTN), Arnau Rious (Barcelona), Giuseppe Carleo (EPFL), Niyaz Beysengulov (EEROQ), Johannes Pollanen (EEROQ, MSU), Zachary Stewart (MSU), Jared Weidman (MSU), Angela Wilson (MSU), Francesco Massel (USN, UiO), Gunnar Lange (UiO), Viktor Svensson (UiO), Cecilie Glittum (UiO), Jonas Flaten (UiO), Oskar Leinonen (UiO), Øyvind Sigmundson Schøyen (UiO), Stian Dysthe Bilek (UiO), and Håkon Emil Kristiansen (UiO). Excuses to those I have omitted.

Di Vincenzo criteria

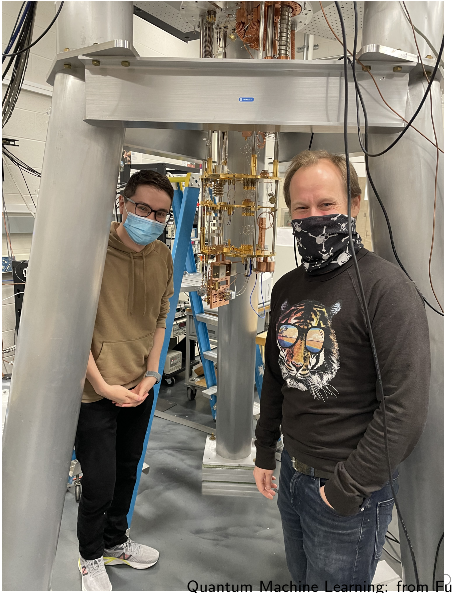
Quantum computing requirements

1. A scalable physical system with well-characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant quantum coherence times longer than the gate operation time
4. A universal set of quantum gates
5. A qubit-specific measurement capability

Our platform, electrons on helium

EEROQ and MSU

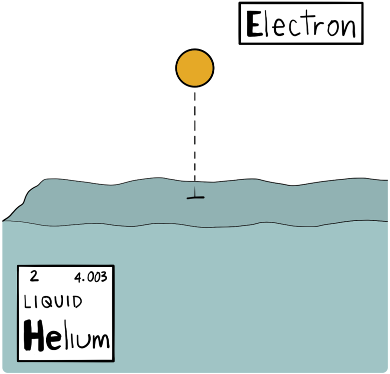
1. Long coherence times
2. Highly connect qubits
3. Many qubits in a small area
4. CMOS compatible
5. Fast gates



Single electrons can make great qubits

Electrons on helium

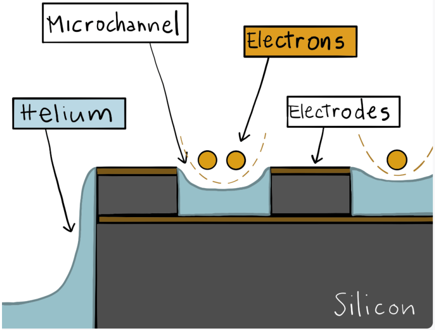
At the heart is the trapping and control of individual electrons floating above pools of superfluid helium. These electrons form the qubits of our quantum computer, and the purity of the superfluid helium protects the intrinsic quantum properties of each electron. The ultimate goal is to build a large-scale quantum computer based on quantum magnetic (spin) state of these trapped electrons.



Trapping electrons in microchannels

Microchannels

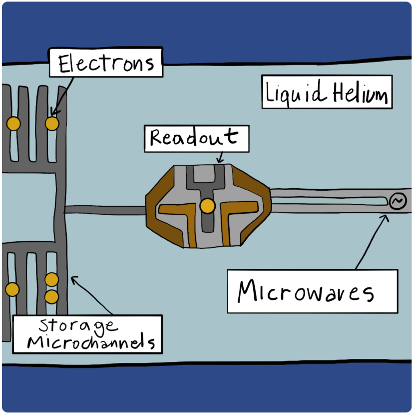
Microchannels fabricated into silicon wafers are filled with superfluid helium and energized electrodes. Together with the natural electron trapping properties of superfluid helium, these allow for the precision trapping of individual or multiple electrons. The microchannels are only a few micrometers in size, or about five times smaller than the diameter of a human hair.



Control and readout

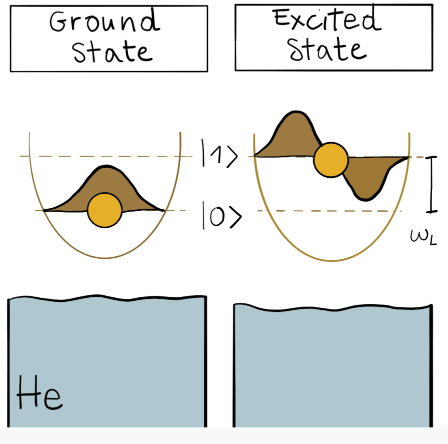
Electron control

Microchannel regions can store thousands of electrons, from which one can be plucked and transported to the single electron control and readout area. In this region, microwave signals will interact with the electron to perform quantum logic gate operations, which will be readout via extremely fast electronics.

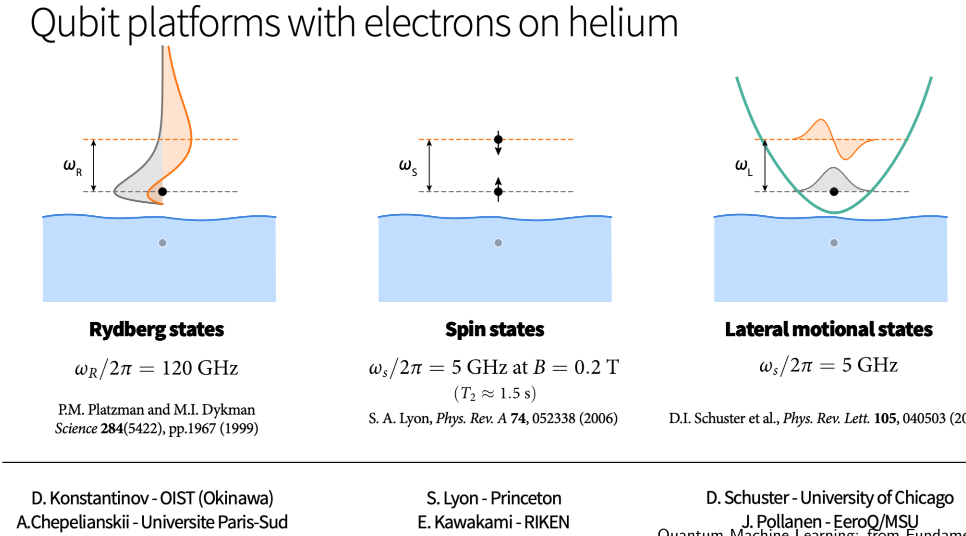


Electrons on helium

Quantum information can be encoded in a number of ways using single electrons. Currently, we are working with the side-to-side(lateral) quantum motion of the electron in the engineered trap. This motion can either be in its lowest energy state, the ground state, or in a number of higher-energy excited states. This electron motion also provides the readout capabilities for the ultimate goal of building a large-scale quantum computer based on the electron's magnetic moment (spin).

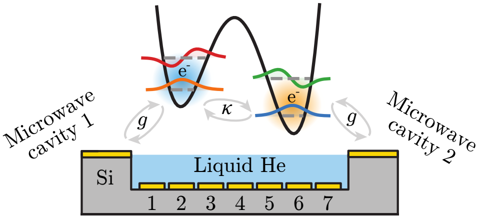


Qubit platforms



Final experimental and theoretical setup for Coulomb entanglement

1. Microdevice where two electrons are trapped in a double-well potential created by electrodes 1-7. The read-out is provided by two superconducting resonators dispersively coupled to electron's in-plane motional states.
2. Coupling constants from each individual electrode beneath the helium layer.
3. The electron's energy in a double-well electrostatic potential.
4. Screened Coulomb interaction



Recent work

- **Coulomb interaction-driven entanglement of electrons on helium**, Niyaz R. Beysengulov, Johannes Pollanen, Øyvind S. Schøyen, Stian D. Bilek, Jonas B. Flaten, Oskar Leinonen, Håkon Emil Kristiansen, Zachary J. Stewart, Jared D. Weidman, Angela K. Wilson, Morten Hjorth-Jensen, PRX Quantum 5, 030324 (2024).
- **Design and Dynamics of High-Fidelity Two-Qubit Gates with Electrons on Helium**, Oskar Leinonen, Jonas B. Flaten, Stian D. Bilek, Øyvind S. Schøyen, Morten Hjorth-Jensen, Niyaz R. Beysengulov, Zachary J. Stewart, Jared D. Weidman, Angela K. Wilson, arXiv:2509.13946, and PRA, in press.
- **Electrons on Helium and Entangled Quantum Sensors for Particle Physics**, Niyaz R. Beysengulov, Antoine Camper, Jonas B. Flaten, Morten Hjorth-Jensen, Gunnar F. Lange, Oskar Leinonen, Jan Malamant, Francesco P. Massel, Johannes Pollanen, and Heidi Sandaker, in preparation for Communications Physics.

Digression I, PINNs and quantum PINNs

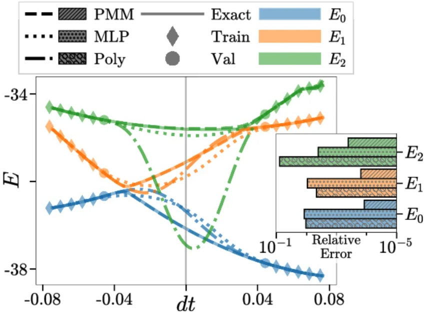
Quantum Neural Networks and PINNs

N	ω	DMC	PINN+BF	% err	PINN+CTNN	% err
2	0.001	—	0.0137948(8)	—	**0.013778(1)**	—
	0.01	—	0.69125(2)	—	**0.69036(1)**	—
	0.10	3.55385(5)	3.5549(1)	+0.0295	**3.55388(5)**	+0.0008
	0.50	11.78484(6)	11.7895(4)	+0.0395	**11.7847(2)**	−0.0000
	1.00	20.15932(8)	20.1610(6)	+0.0083	**20.1585(3)**	−0.0041
12	0.001	—	0.515823(3)	—	**0.515365(4)**	—
	0.01	—	2.48620(5)	—	**2.47363(4)**	—
	0.10	12.26984(8)	12.2731(2)	+0.0160	**12.2718(1)**	—
	0.50	39.1596(1)	39.1786(8)	+0.0485	**39.1604(3)**	+0.0018
	1.00	65.7001(1)	65.717(1)	+0.0257	**65.69556(5)**	−0.0069
20	0.001	—	—	—	**1.293033(6)**	—
	0.01	—	—	—	**6.14645(5)**	—
	0.10	29.9779(1)	—	—	29.9888(2)	+0.0364
	0.50	93.8752(1)	—	—	**93.8789(5)**	+0.0040
	1.00	155.8822(1)	—	—	**155.8738(7)**	−0.0024

Digression II, Parametric Matrix Models and Trotterization

Parametric matrix models

- Parametric matrix models (PMMs) as a way to compute the Lie-Trotter formula, see Nature Communications **16**, 5929 (2025), Cook, Jammooa, MHJ, Lee and Lee
- Extrapolated Trotter approximation for quantum computing simulations. We plot the lowest three energies of the effective Hamiltonian for the one-dimensional Heisenberg model with DM interactions versus time step *dt*. All training (diamonds) and validation (circles) samples are located away from dt = 0.



Two-Electron 2D Schrödinger via DVR and CI with Slater Determinants

Key approach for identical fermions:

- We construct the two-electron basis using **Slater determinants** that include both spatial and spin degrees of freedom
- Each basis state is a properly antisymmetrized combination: $|\psi\rangle = |\phi_a\sigma_i; \phi_b\sigma_j\rangle$ where the total wavefunction is antisymmetric under particle exchange
- This naturally separates states into singlet (spatially symmetric) and triplet (spatially antisymmetric) configurations
- We include the full 2D soft Coulomb interaction and diagonalize the Hamiltonian in this antisymmetrized basis
- We compute both spin expectation values ($\langle S^2\rangle$, $\langle S_z\rangle$) and entanglement entropy for each eigenstate

Double-Well Trap Potential

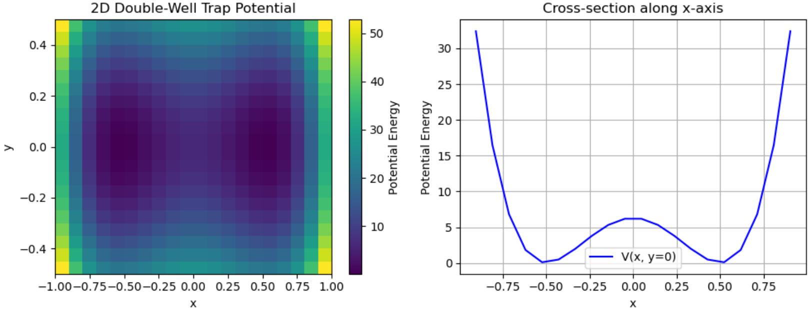
We use an arbitrary 2D potential $V(x, y)$ for the single electrons, meant to represent the electrostatic trapping potential from electrodes beneath the helium surface. For simplicity we demonstrate with an analytic double-well form:

- Quartic double well in x: $V_x = k(x^2 - a^2)^2$
- Harmonic confinement in y: $V_y = \frac{1}{2}k_y y^2$

To allow specification of a 2D electrode geometry and voltages, one would solve the 3D Laplace equation for the electrode layout to find the coupling functions $\kappa_i(x, y)$ on the helium surface. Then the total trap potential is

$$V(x, y) = \sum_i \kappa_i(x, y)\, V_i$$

Harmonic oscillator double well, no anharmonic terms



Two-Electron Slater Determinant Basis for Identical Fermions

For **indistinguishable fermions**, we must construct properly antisymmetrized two-electron states using Slater determinants. Each basis state includes both spatial orbitals $\phi_i(\mathbf{r})$ and spin states $\sigma \in \{\uparrow, \downarrow\}$.
A two-electron Slater determinant is:

$$|\phi_a\sigma_i, \phi_b\sigma_j\rangle = \frac{1}{\sqrt{2}} \begin{vmatrix} \phi_a(\mathbf{r}_1)\sigma_i(1) & \phi_b(\mathbf{r}_1)\sigma_j(1) \\ \phi_a(\mathbf{r}_2)\sigma_i(2) & \phi_b(\mathbf{r}_2)\sigma_j(2) \end{vmatrix}$$

For each eigenstate in our Slater determinant basis, we compute: 1. **Spin expectation values**: $\langle S^2 \rangle$ and $\langle S_z \rangle$ 2. **Total entanglement entropy**: Via Schmidt decomposition including both spin and spatial degrees of freedom

Why compute total (spatial + spin) entanglement?

For **indistinguishable fermions**, the spatial and spin degrees of freedom are fundamentally coupled by antisymmetrization:

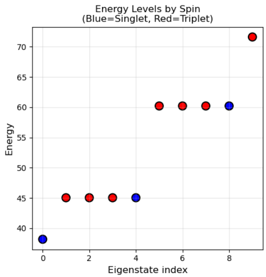
- **Singlet states**: Spatially symmetric × spin antisymmetric
- **Triplet states**: Spatially antisymmetric × spin symmetric

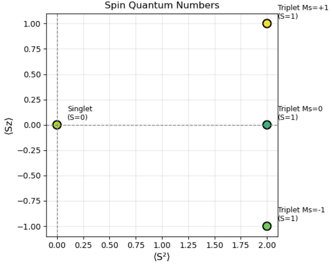
This coupling means that **pure spatial entanglement alone would often be zero** because:

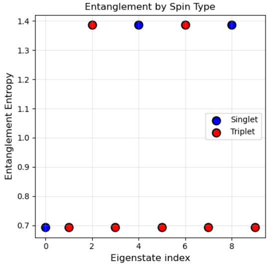
- For a pure singlet in orbital —a,a⟩, there's only one spatial configuration (both electrons in the same orbital)
- The entanglement comes from the spin antisymmetry: $(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

The **total entanglement** (including both spin and spatial) captures the full quantum correlations between the two particles and is the physically meaningful measure for identical fermions.

States and Entanglement







Time-Dependent Magnetic Field Perturbation and Quantum Sensing

We now add a **time-dependent magnetic field perturbation** $B(t)$ acting on one of the electron spins through the Pauli σ_z operator:

$$H_{\text{pert}}(t) = \frac{g\mu_B}{2} B(t)\sigma_z^{(1)}$$

where we set $g\mu_B/2 = 1$ for simplicity (can be rescaled). This perturbation:

- Acts only on **electron 1**
- Causes **Zeeman splitting** between $|\uparrow\rangle$ and $|\downarrow\rangle$ states
- Induces a **phase** $\phi(t) = \int_0^t B(t')dt'$

By acting asymmetrically on an entangled singlet, the magnetic field converts an otherwise hidden phase into a measurable singlet–triplet population imbalance, allowing the phase—and hence the field—to be inferred with enhanced quantum sensitivity.

Physical Picture:

Starting with an **entangled singlet state**:

$$|S\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

The magnetic field on electron 1 causes:

- **Phase accumulation**: $|\uparrow\rangle_1 \to e^{i\phi(t)/2}|\uparrow\rangle_1$, $|\downarrow\rangle_1 \to e^{-i\phi(t)/2}|\downarrow\rangle_1$
- **Singlet $\to$ Triplet leakage**: The singlet mixes with the triplet $T_0 = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$
- **Measurable signal**: By monitoring the triplet population, we can **measure $\phi(t)$ and thus $B(t)$**

This is a **quantum sensing** protocol where entanglement enhances sensitivity to weak fields! Here we apply (for the sake og demonstration only) a weak oscillating field: $B(t) = B_0 \sin(\omega t)$.

Quantum Fisher Information (QFI)

The **Quantum Fisher Information** $F_Q(\phi)$ quantifies the sensitivity of the quantum state to the phase ϕ:

$$F_Q(\phi) = 4 \left(\langle \partial_\phi \psi | \partial_\phi \psi \rangle - |\langle \psi | \partial_\phi \psi \rangle|^2 \right)$$

The **quantum Cramér-Rao bound** sets the fundamental limit on phase estimation:

$$\Delta\phi \geq \frac{1}{\sqrt{N_{\text{meas}} F_Q(\phi)}}$$

where N_{meas} is the number of measurements. Higher QFI $\rightarrow$ better sensitivity!

Quantum Sensing Metrics

- **Field amplitude:**

$$B_0 = 0.1$$

- **Field frequency:**

$$\omega = 2.0$$

- **Maximum accumulated phase:**

$$\phi_{\text{max}} = 0.0999$$

- **Singlet $\rightarrow$ Triplet leakage:**

$$P_{S\rightarrow T} = 0.0099$$

Physical Interpretation

This singlet–triplet leakage enables indirect measurement of the time-dependent magnetic field $B(t)$ through spin-state readout.

Quantum Metrological Advantage I

Enhanced sensitivity

- The entangled **singlet state** provides enhanced sensitivity to the time-dependent magnetic field $B(t)$ compared to separable states.

Quantum Fisher Information

For the optimized sensing protocol, the quantum Fisher information is

$$F_Q = 3107.42.$$

Quantum Metrological Advantage II

Phase Estimation Precision

- **Shot-noise limit:**

$$\Delta\phi_{\mathsf{SQL}} \sim \frac{1}{\sqrt{N}}$$

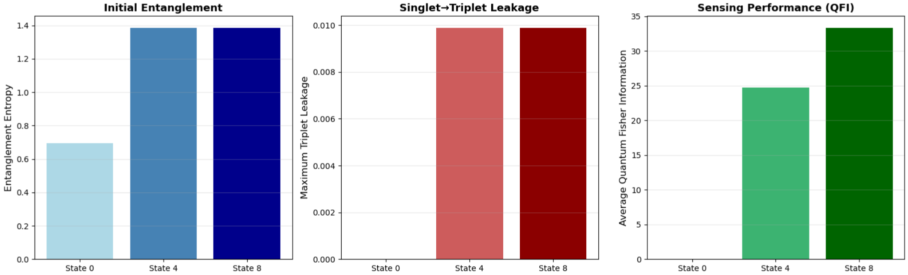
- **Heisenberg limit (ideal entanglement):**

$$\Delta\phi_{\mathsf{HL}} \sim \frac{1}{N}$$

- **Achieved sensitivity:**

$$\Delta\phi \sim \frac{1}{\sqrt{F_Q N}} = \frac{1}{\sqrt{3107.42\, N}}$$

Singlet-triplet leakage



Reinforcement Learning for Optimal Quantum Control

Finally we are implementing a **model-based reinforcement learning** approach to optimize the control sequence for quantum sensing. Since we **know the Hamiltonian**, we can simulate the quantum dynamics and use RL to find optimal control strategies.

RL Framework:

Sequential Decision Process

- **State**: $(t, |\psi(t)\rangle, \mu_\phi, \sigma_\phi^2)$ - time, quantum state, posterior mean variance of phase
- **Action**: $(B_{\text{amp}}, t_{\text{pulse}}, V_{\text{trap}})$ - magnetic field amplitude, pulse duration, trap voltage
- **Transition**: Evolve under $B(t)\sigma_z^{(1)} + V_{\text{trap}}(x, y)$ and kinetic plus Coulomb
- **Measurement**: Projective measurement in singlet/triplet basis
- **Reward**: Quantum Fisher Information of final state

Goal: Maximize cumulative QFI over multiple measurement cycles to achieve optimal phase estimation.

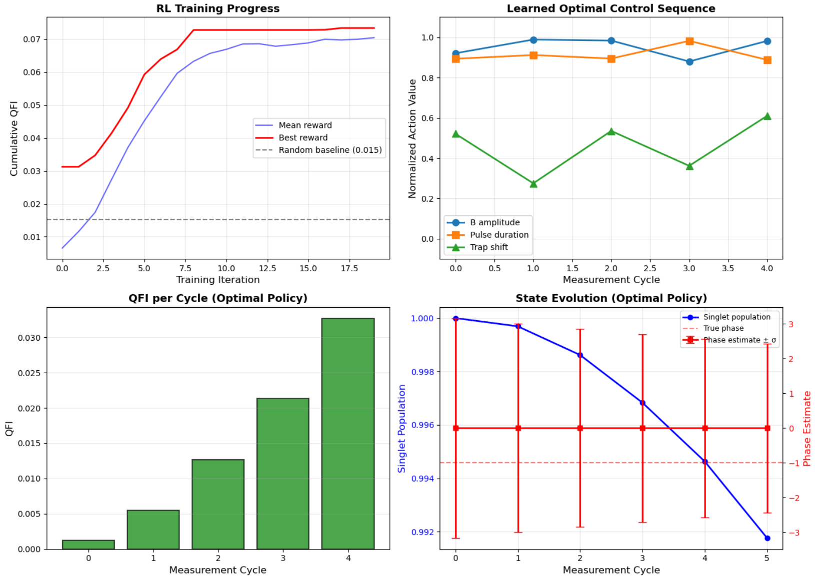
RL Agent: Cross-Entropy Method (CEM)

Cross entropy

We use the **Cross-Entropy Method**, a simple yet effective model-based RL algorithm:

- Sample action sequences from a Gaussian distribution
- Evaluate each sequence by simulation
- Select elite sequences (top performers)
- Update distribution to concentrate on elite actions
- Repeat until convergence

Reinforcement learning



Key Insights from RL-Optimized Control

The RL agent discovers strategies that:

- **Maximize QFI**: By learning optimal pulse sequences that keep the state in regimes of high sensitivity
- **Adaptive sensing**: Adjust control based on measurement history to refine phase estimates
- **Balance exploration vs exploitation**:
  - Early cycles: stronger pulses to generate detectable leakage
  - Later cycles: fine-tuned pulses to maximize information gain
- **Sequential optimization**: Each measurement cycle informs the next, leading to cumulative information gain
- **Outperform heuristics**: The learned policy significantly outperforms random or fixed control sequences

This demonstrates that **model-based RL with known quantum dynamics** can discover non-intuitive control strategies that approach fundamental quantum limits of sensing!

Physical Interpretation and conclusions I

What we've shown:

- **Singlet-Triplet Oscillations**: The magnetic field $B(t)$ on one electron causes the initially pure singlet state to oscillate between singlet and triplet components. This "leakage" is directly measurable through spin-selective detection.
- **Phase-Dependent Signal**: The triplet population depends on the accumulated phase $\phi(t) = \int_0^t B(t')dt'$, providing a way to measure the time-integrated field.
- **Quantum Fisher Information**: Quantifies how sensitive our entangled state is to the phase. Higher QFI means:
  - Better precision in estimating ϕ (and thus $B(t)$)
  - Approach to the Heisenberg limit of quantum metrology
  - Advantage over classical (separable state) sensors

Physical Interpretation and conclusions II

What we've shown:

- **Excited States vs Ground State**: We use an **excited singlet state with maximum entanglement** rather than the ground state because:
  - Higher entanglement $\rightarrow$ stronger quantum correlations
  - More sensitive response to perturbations
  - Enhanced quantum Fisher information
  - Better phase estimation precision
  - The comparison shows QFI scales with entanglement!
- **Applications**:
  - **Magnetic field sensing**: Detect weak, time-varying magnetic fields
  - **NMR/ESR spectroscopy**: Enhanced signal detection
  - **Quantum metrology**: Fundamental limits of measurement precision
  - **Quantum information**: Characterizing decoherence and noise

Physical Interpretation and conclusions III

Key result

Highly-entangled excited singlet states are superior quantum sensors compared to weakly-entangled ground states. The singlet$\rightarrow$triplet leakage provides a direct readout of the magnetic field, with sensitivity quantified by the quantum Fisher information!

Physical Insights:

This code demonstrates fundamental quantum mechanical principles:

- **Fermion antisymmetry**: Total wavefunction must be antisymmetric under particle exchange
- **Exchange interaction**: Energy splitting between singlet and triplet states arises from Coulomb exchange
- **Quantum entanglement**: Spatial and spin entanglement in two-electron systems