Quantum Sensing: Magnetic Flux Detection

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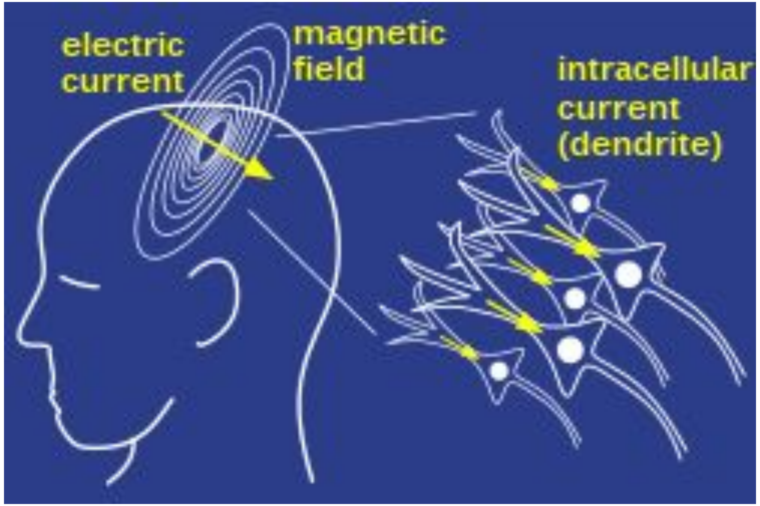
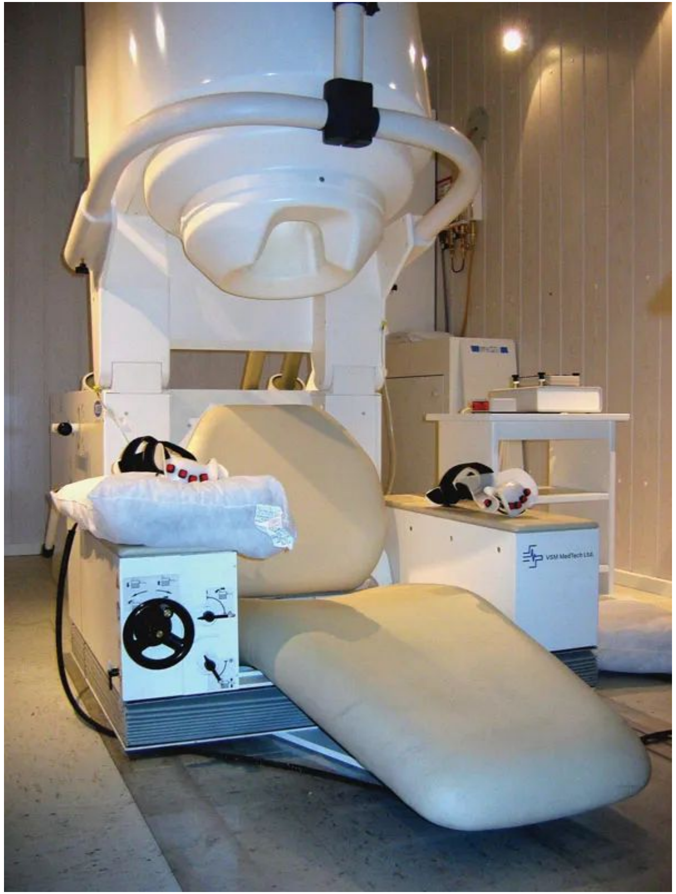
Overview

- **Magnetoencephalography (MEG)**
  - Neuroimaging technique
  - used to measure magnetic fields produced by neuronal activity in the brain
- Neurons in the brain generate electrical currents when they communicate, resulting in tiny magnetic fields being produced



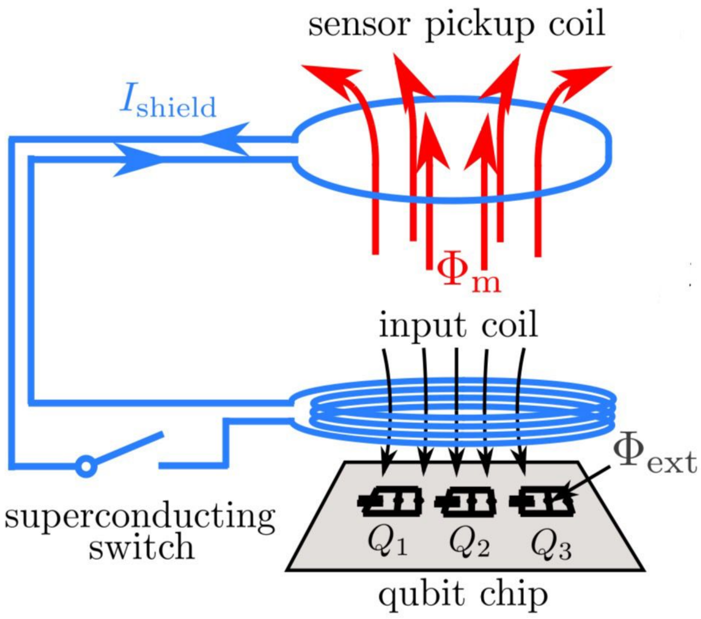
SQUIDs

- **Superconducting Quantum Interference Device (SQUIDs)** is a magnetometer that detects magnetic fields from neural activity within the brain
  - Extremely sensitive to small magnetic fields



Quantum Sensors

- Φm: general flux to be measured
- Ishield: Current representing Φm
- Φext: magnetic flux representing Φm
  - They are exposed to the Φext
    - This results in a phase shift depending on exposure time
      - Exposure time is determined by the superconducting switch
    - Phase shift is dependent on the strength of the flux and the time of exposure



Ramsey Fringes Interferometry

- Technique used to measure phase evolution of qubits as it interacts with external fields
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Sensor Output Interpretation

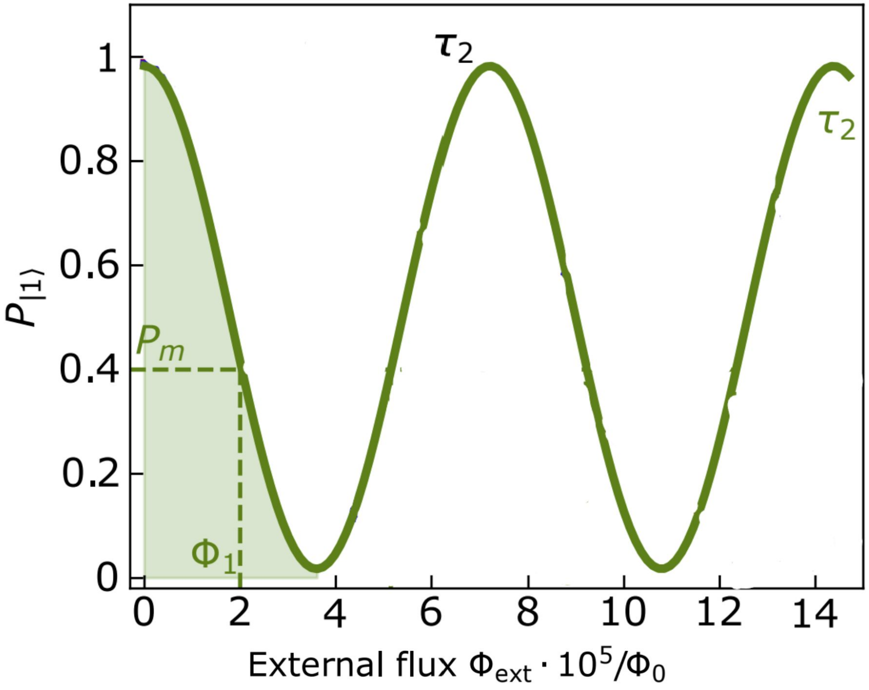
Pm is an outcome from sensing procedure

τ is the delay time

Amount of time the sensor has been

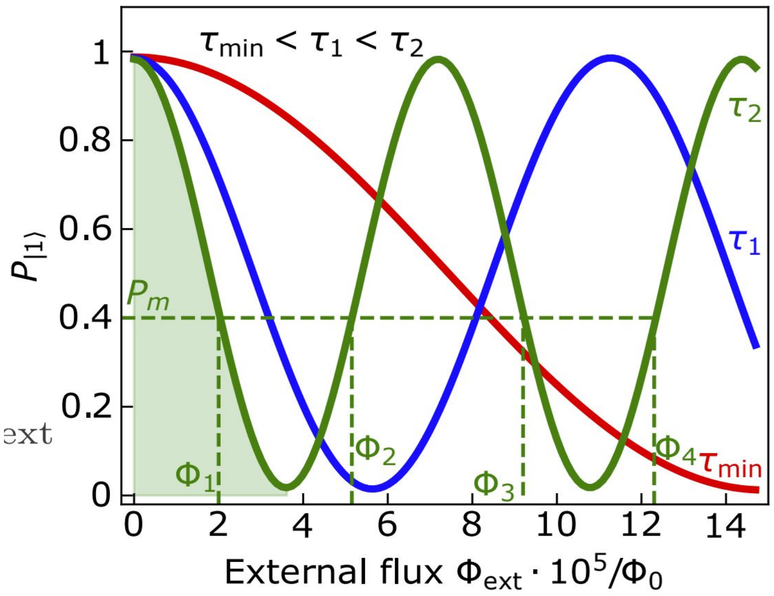
Influenced by the magnetic flux

Φ is the external flux we are measuring



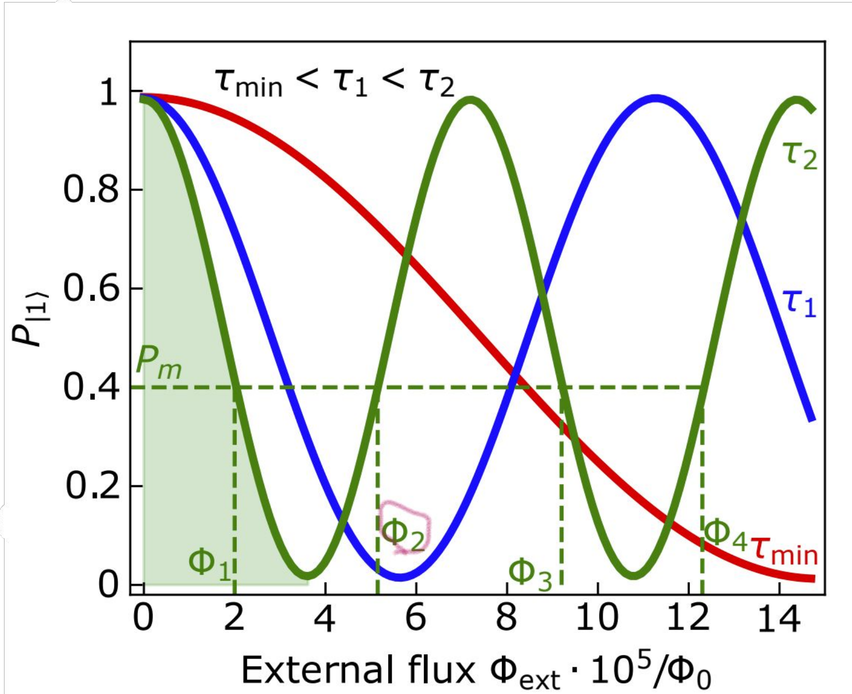
Issues

- Selecting the optimal delay time for unknown flux value.
  - Topt as large as possible
  - Larger delay times are more sensitive to flux



Issues

- For longer delay times, it is not possible to unambiguously determine the measured flux based on a single outcome
  - Φ1, Φ2, Φ3, Φ4?
  - Coherence time
    - Time qubit can maintain its state
      - Decoherence occur after
        - Energy relaxation
        - Dephasing
    - Depends on qubit



Coherence only if asked.

how long a qubit can maintain its quantum state before it is disrupted by decoherence mechanisms, such as energy relaxation and dephasing.

Solution

- For this we use PEA(Phase Estimation Algorithms) to find the optimal delay time

- One common approach is using Kitaev algorithm

- Using Kitaev’s algorithm provides both a higher accuracy and a faster runtime as will be shown next

Kitaev's Algorithm

Simulation

Create n ancilla qubits

Apply the Hadamard gate to ancilla qubits

Apply the U gate to the qubit being controlled

home > tai > Desktop > qiskit2.py > ...

```python
from qiskit import QuantumCircuit
from qiskit_aer import AerSimulator
from qiskit.circuit.library import QFT
from qiskit.visualization import plot_histogram
from qiskit.utils import QuantumInstance
import numpy as np

# Define the phase for the U gate
theta = 0.5
U = QuantumCircuit(1)
U.rz(2 * np.pi * theta, 0)  # U = Rz(2*pi*theta)
U = U.to_gate()
U.name = "U"

# Kitaev Phase Estimation Circuit
tabnine: test | explain | document | ask
def kitaev_phase_estimation(U, n_bits):
    qc = QuantumCircuit(n_bits + 1, n_bits)

    # Apply H-gates to all ancilla qubits
    for i in range(n_bits):
        qc.h(i)

    # Controlled-U operations
    for i in range(n_bits):
        qc.append(U.control(), [i, n_bits])

    # Inverse Quantum Fourier Transform
    qc.append(QFT(num_qubits=n_bits, inverse=True).to_gate(), range(n_bits))

    # Measure the ancilla qubits
    qc.measure(range(n_bits), range(n_bits))
    return qc

# Number of bits for phase estimation (try increasing this value)
n_bits = 1

# Create the phase estimation circuit
qc = kitaev_phase_estimation(U, n_bits)

# Set up the AerSimulator
simulator = AerSimulator()

# Run the simulation using the QuantumInstance
quantum_instance = QuantumInstance(backend=simulator, shots=1024)
result = quantum_instance.execute(qc)
# print(result)
counts = result.get_counts(qc)

# Plot the results
plot_histogram(counts)

# Estimate the phase from the most frequent result
max_count = max(counts, key=counts.get)
estimated_phase = int(max_count, 2) / 2**n_bits
print(f"Estimated Phase: {estimated_phase}")
```

References

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[3] Tengyue Long (2023)

Suppression of Amplitude and Phase Errors in Optically Pumped Magnetometers using Dual-PI Closed-Loop Control

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[4] Sergey Danilin (2024)
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