Quantum Decoherence

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Outline

- Introduction
- Double Slit and Decoherence
- Mathematical Formalism
- Preskill’s Channels
- Experimental Measurements

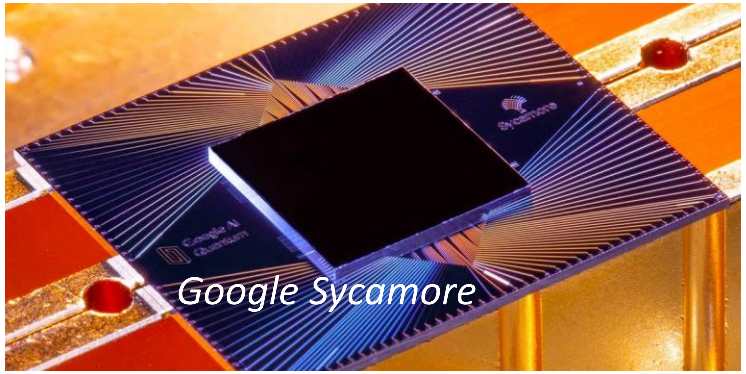
Ref: M. Schlosshauer (2019)
J. Preskill (1998)
W.H. Zurek (1986)

Introduction

- "Hilbert space is a vast and seemingly egalitarian place"
    - Why then are some "nonclassical" states more fragile than others?
- Definitions of quantum decoherence:
    - "Entangling interactions with the environment influence the statistics of future measurements on the system" – Schlosshauer
    - "The decay of quantum information due to the interaction of a system with its environment" – Preskill
- Not strictly the same as classical energy dissipation
    - Relaxation vs. decoherence times: $\frac{\tau_r}{\tau_d} \sim \left(\frac{\Delta x}{\lambda_{th}}\right)^2$

Why Care about Decoherence?

- Quantum information and computing
  - Qubit lifetimes often limited by decoherence processes
- Fundamentally interesting threshold between classical and quantum descriptions
- Historically has sparked philosophical interpretations of quantum mechanics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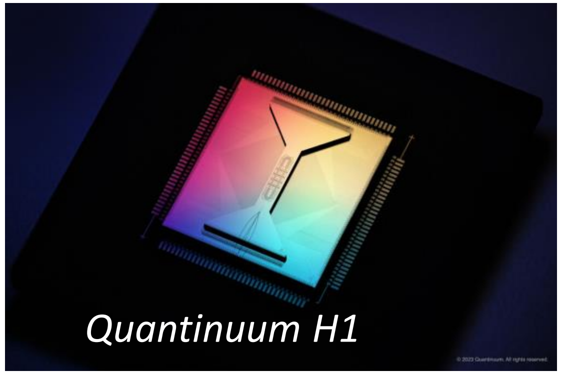
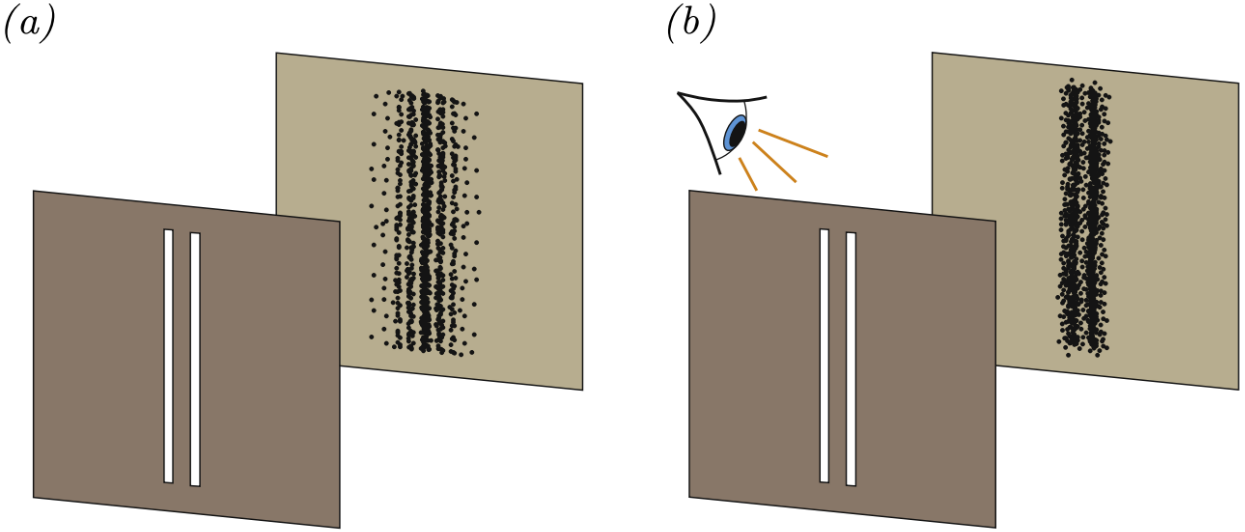

Quantinuum H1

Ref: M. Schlosshauer (2019)

Double Slit and Decoherence

- Situation A: particles pass through either slit undisturbed
- Situation B: observer monitors which slit each particle takes
- Can there be something in between?



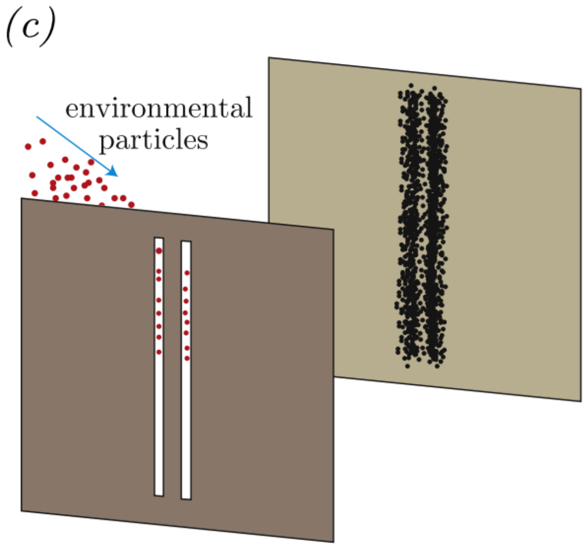
Ref: M. Schlosshauer (2019)

Double Slit and Decoherence

- Situation C: entanglement with environment
- Initial state after screen is: $|\psi\rangle = \alpha|S_1\rangle + \beta|S_2\rangle$
- Entanglement with environmental states gives:

$$|\psi'\rangle = \alpha|S_1\rangle|E_1\rangle + \beta|S_2\rangle|E_2\rangle$$

- Might expect some unrecoverable information loss into the environment. How does this impact pattern on screen?



Ref: M. Schlosshauer (2019)

Double Slit and Decoherence

- Formal treatment from reduced density matrix
  - We cannot recover environment states, so we must trace out this part of the system

$$|\psi'\rangle = \alpha|S_1\rangle|E_1\rangle + \beta|S_2\rangle|E_2\rangle$$

gives a reduced density matrix

$$\rho_S = \mathrm{Tr}_E(\rho_{SE}) = \text{populations} + \alpha\beta^*|S_1\rangle\langle S_2|(\langle E_1|E_2\rangle) + \text{c.c.}$$

- Screen interference term becomes

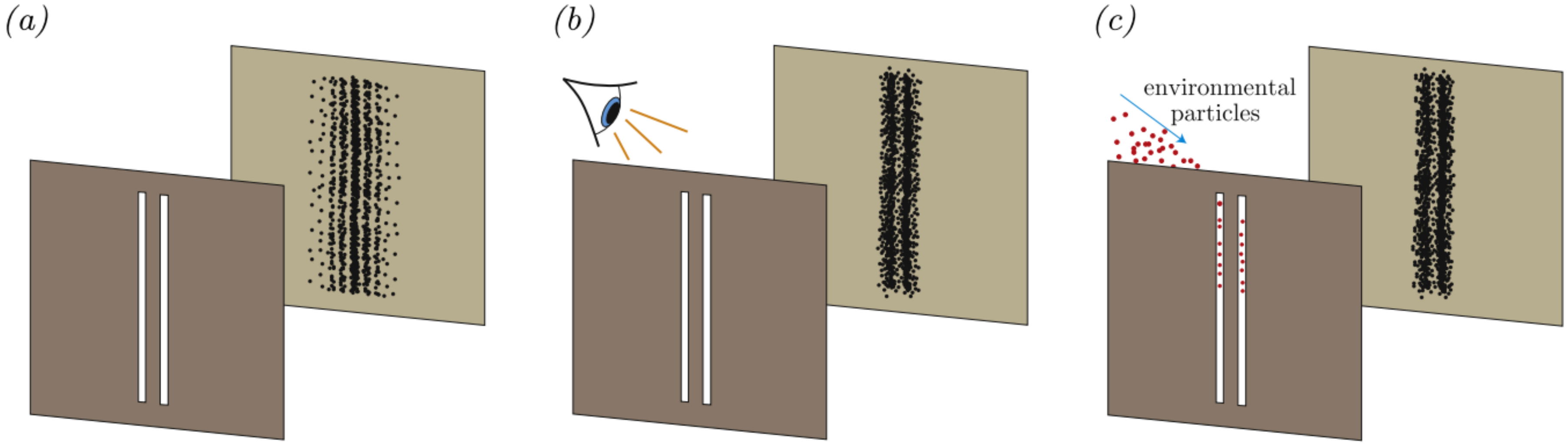
$$2\,\mathrm{Re}[\alpha\beta^*\psi_1(x)\psi_2^*(x)\langle E_1|E_2\rangle]$$

Fringe visibility is directly proportional to "indistinguishability" of environmental states

Ref: M. Schlosshauer (2019)

Double Slit and Decoherence

- Helpful paradigm for decoherence
  - Monitoring by observer or environment produces similar results via entanglement
  - When environmental monitoring dominates, we lose information



Ref: P. Jessen *Lecture 17* (2023)
J. Preskill (1998)

Mathematical Formalism

Review from class:

- Superoperator maps density matrix through space/time: $\rho' = \$(\rho)$ with properties
  0. $\$$ is linear

     i.e., $\$\big(\rho(\lambda)\big) = \$(\lambda\rho_1 + (1-\lambda)\rho_2) = \lambda\$(\rho_1) + (1-\lambda)\$(\rho_2)$ which fits well with ensemble preparation interpretations and seems reasonable. However, *nonlinear* evolution is not always excluded

Ref: P. Jessen *Lecture 17* (2023)
J. Preskill (1998)

Mathematical Formalism

Review from class:

- Superoperator maps density matrix through space/time: $\rho' = \$(\rho)$ with properties
  0. $ is linear
  1. $ preserves Hermiticity
  2. $ preserves trace
  3. $ is completely positive

Ref: P. Jessen *Lecture 17* (2023)
J. Preskill (1998)

Mathematical Formalism

Review from class:

- Any \$ satisfying 0-3 has a Kraus/Operator-Sum Representation

$$\$(\rho_A) = \sum_{\mu} M_\mu \rho_A M_\mu^\dagger$$

where $\sum_\mu M_\mu^\dagger M_\mu = \mathbb{I}_A$

- If superoperator has one non-zero μ-component, this is unitary evolution
  - If not unitary, this imposes an **“arrow of time”**

Ref: P. Jessen *Lecture 17* (2023)
J. Preskill (1998)

Quantum Channels

- Specific interactions between system and environment will yield different forms of superoperators
- Each form will move toward mixed states in their "preferred basis"
- Some simple categories can help build understanding
- Examples of channels:
  - Depolarizing
  - Phase-damping
  - Amplitude-damping

Ref: M. Schlosshauer (2019)

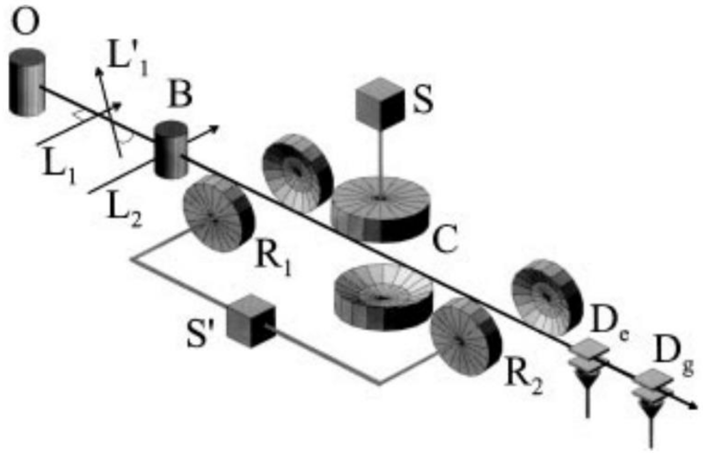
Experimental Measurements

- Quantum decoherence is no simpler experimentally!
- Explicit measurement requires
  - Ability to generate non-classical states
  - Precise measurements of quantum interferences
  - Confidence that decays are dominated by decoherence, not dissipation
- A few experimentally achieved examples
  - **Atom-photon interactions within cavity**
  - Matter-wave interferometry
  - Superconducting platforms

Ref: M. Brune, et al. (1996)
M. Schlosshauer (2019)

Decoherence in Cavity QED

- First experimental decoherence from S. Haroche group in 1996
- “System” is two-level atom. Microwave transition between Rb Rydberg states (n_g=50, n_e=51)
- “Meter” is coherent state of photons in microwave cavity



R_1: single-atom prepared in superposition of e, g
C: atom traverses microwave cavity
R_2: identical to R_1
D_e, D_g: field ionization detectors

Ref: M. Brune, et al. (1996)
M. Schlosshauer (2019)

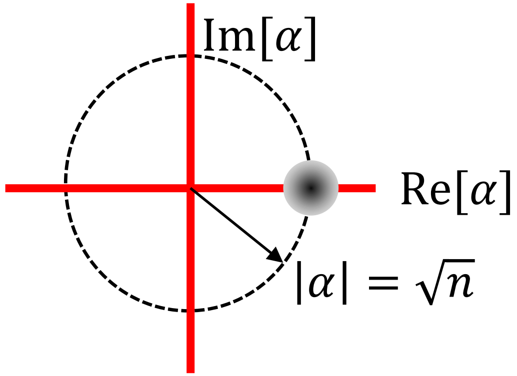
Decoherence in Cavity QED

- As atom crosses microwave cavity, it interacts with detuned coherent state field
  - No e->g transitions driven here because of detuning
  - Atom's presence imparts atomic-level-dependent phase shift to field

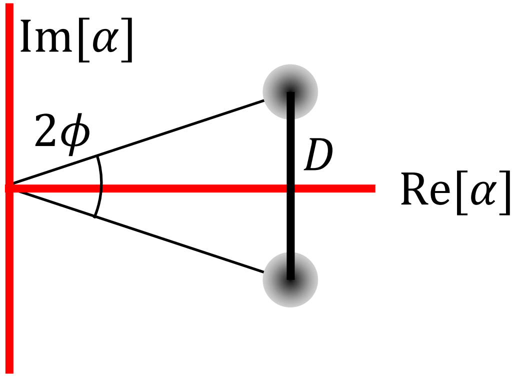
$$\phi = \frac{\Omega^2 t}{\delta}$$

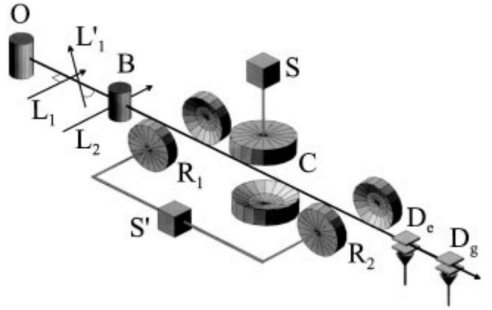
$$|\Psi\rangle = \frac{|e\rangle + |g\rangle}{\sqrt{2}} \rightarrow |\Psi'\rangle = \frac{|e, \alpha \exp(i\phi)\rangle + |g, \alpha \exp(-i\phi)\rangle}{\sqrt{2}}$$

Phase space picture



Zoom in…





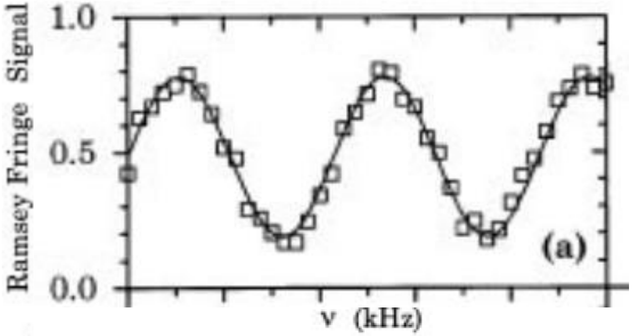
For $D = 2\sqrt{n}\sin(\phi) > 1$, we have separated "cat-state"

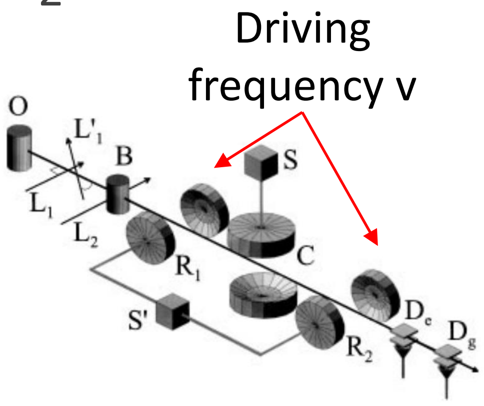
Ref: M. Brune, et al. (1996)
M. Schlosshauer (2019)

Decoherence in Cavity QED

- Decoherence rate is expected $\propto D^2$
  - "This result illustrates the basic feature of the quantum to classical transition. Mesoscopic superpositions made of a few quanta are expected to decohere in a finite time interval shorter than T_r, while macroscopic ones (n>>1) decohere instantaneously and cannot be observed in practice" – S. Haroche
- When C is empty, e->g transitions can occur in either R_1 or R_2
  - Indistinguishable paths lead to interference

Fringe contrast reduced from ideal 100% to 55% by "inhomogenieties in R_1 and R_2, finite atomic lifetime, etc."

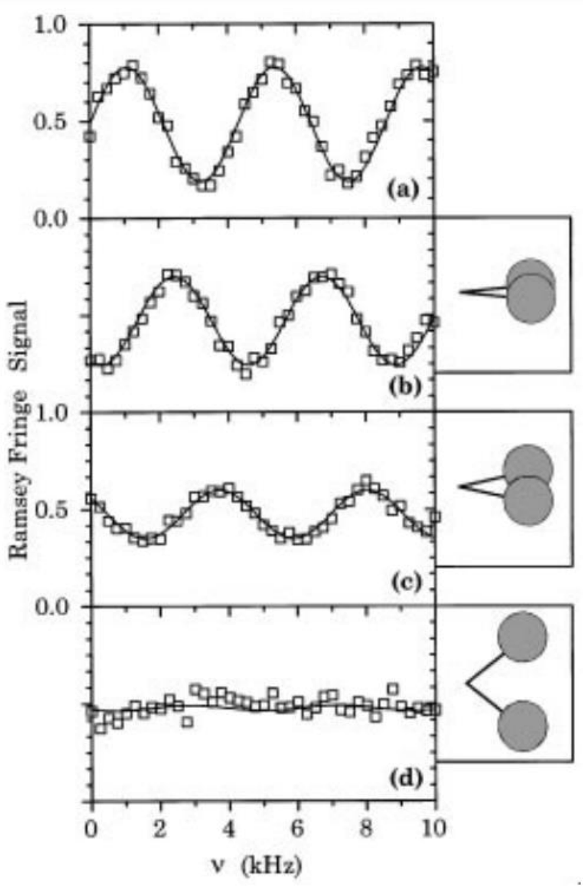



Driving frequency ν

Ref: M. Brune, et al. (1996)
M. Schlosshauer (2019)

Decoherence in Cavity QED

- When cavity has coherent state inside (n=9.5), the atom-photon interaction causes phase shifts in the cavity field that **contain information** about the atom's energy level while traversing C
- For small phase shifts (small D, large detuning), the cat-state component overlap is significant
  - "Environmental states" are mostly "indistinguishable"
- For larger phase shifts, cat-state components are more distinguishable, carrying more information away from the "system" into the "meter"



Ref: M. Brune, et al. (1996)
M. Schlosshauer (2019)

Decoherence in Cavity QED

- Increasing phase shift decreases fringe contrast and increases fringe shift in good agreement with theory
- Changing strength of interaction continuously gives confidence that we're actually seeing decoherence
- Two-atom correlation experiment
- "It does not matter that the field is actually not measured. The mere fact that the atom leaves in C information which could be read out destroys the interference" – S. Haroche

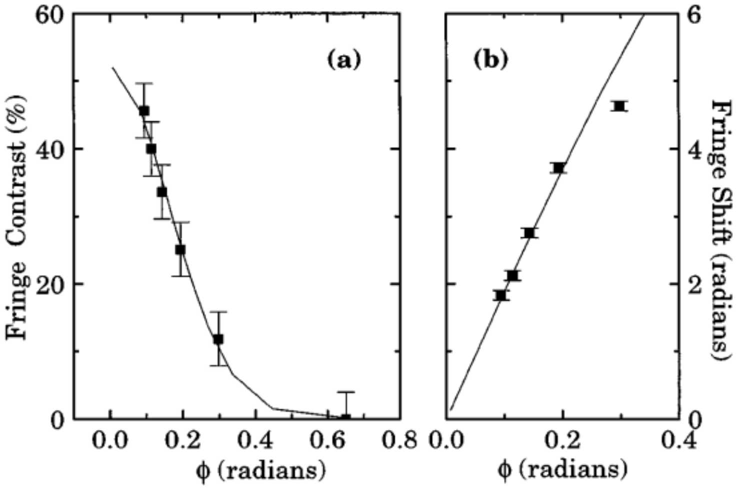
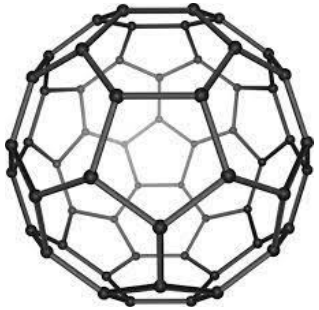


FIG. 4. Fringes contrast (a) and shift (b) versus ϕ, for a coherent field with $|\alpha| = 3.1$ (points: experiment; line: theory).

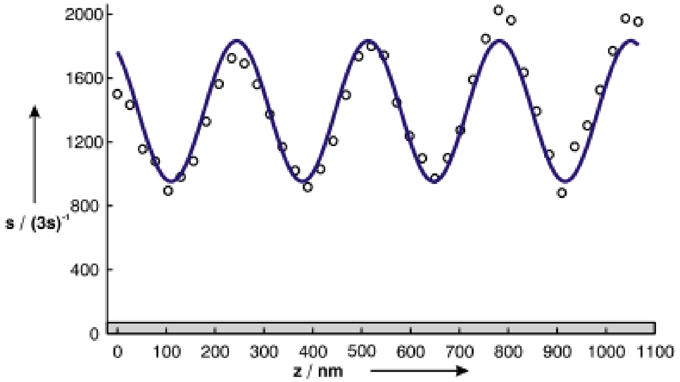
Ref: M. Arndt, et al. (1999)
S. Eibenberger, et al. (2013)
K. Hornberger, et al. (2003)
M. Schlosshauer (2019)

Decoherence in Matter-Wave Interferometry

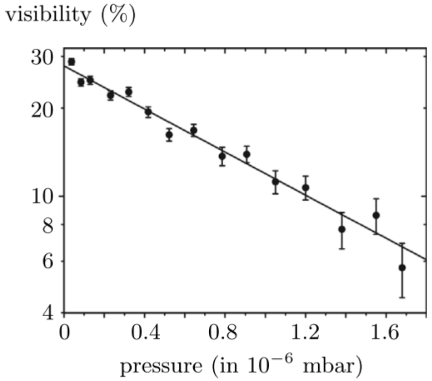
- Matter-wave interference measured from diffraction of fullerenes
- Very small de Broglie wavelength due to large mass
  - Cannot use simple double-slit, but detectable interference possible with Talbot effect
- Probes important class of “collisional” decoherence



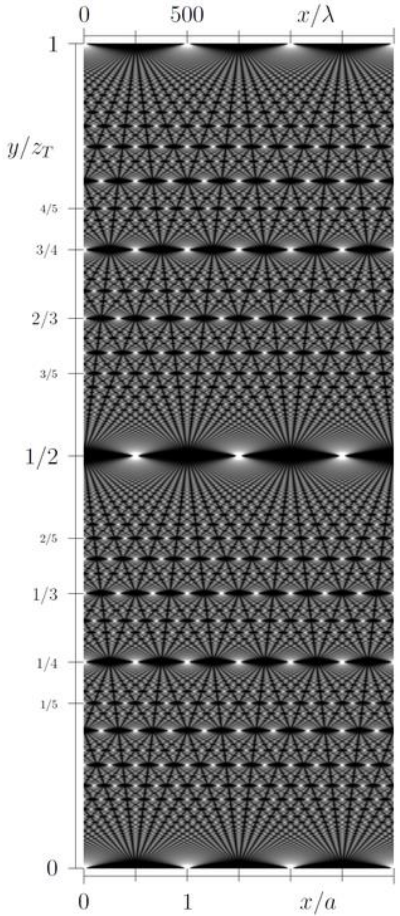
Fullerene molecule with 60 carbon atoms



Intensity (molecular density) reconstructions at Talbot lengths



Pressure-dependent interaction strength

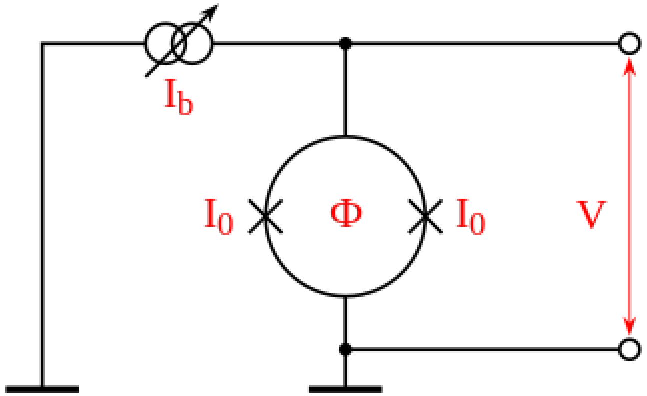


Optical Talbot Carpet

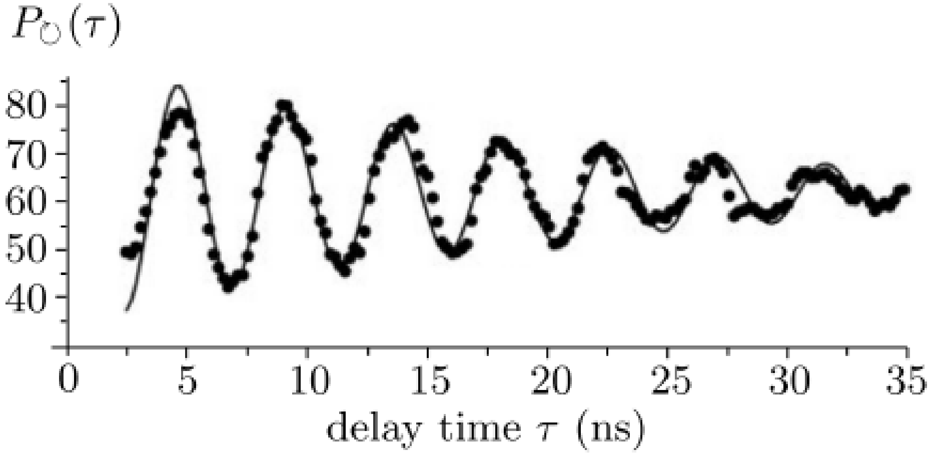
Ref: I. Chiorescu, et al. (2003)
M. Schlosshauer (2019)

Decoherence in SQUIDs

- **S**uperconducting **QU**antum **I**nterference **D**evices
- Very popular hardware implementation for quantum computing



Electrical schematic of SQUID



Decoherence of SQUID measured with Ramsey interferometry

Quantum Decoherence…

- Is an irreversible “seep” of information into environment
  - “Arrow of Time”
- Plays an important role in quantum/classical boundary
- Informs understanding of measurement and interpretations
- Can be measurably separated from dissipation and other effects
- Impacts *many* applications utilizing highly non-classical states
  - Quantum computing, quantum communication, precision measurement, etc.

References

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