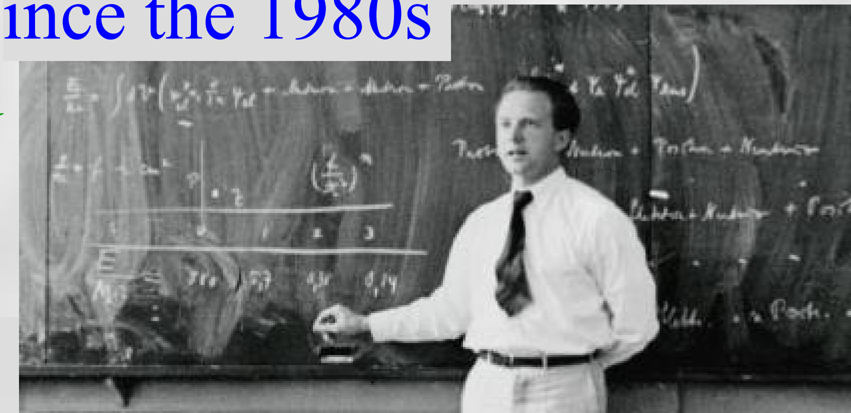
Decoherence and The Collapse of Quantum Mechanics

A "Modern" View

It's time to make decoherence mainstream

- QM is ~90 years old
  - But it is still taught like the 1930s
  - Modern textbooks still ignore measurement theory
  - Worse, they still teach hand-wavy "collapse" without precise definitions
- A surprising amount of current *scientific* literature is devoted to "interpretations" of QM
  - A surprising amount of decoherence literature is defending basic scientific principles, such as predictions and testability
- Decoherence has been around since the 1980s
  - It has been surprisingly neglected
  - It's not that hard



Heisenberg c. 1925

What is quantum mechanics?

- Is it mystic?
- Or is it science?

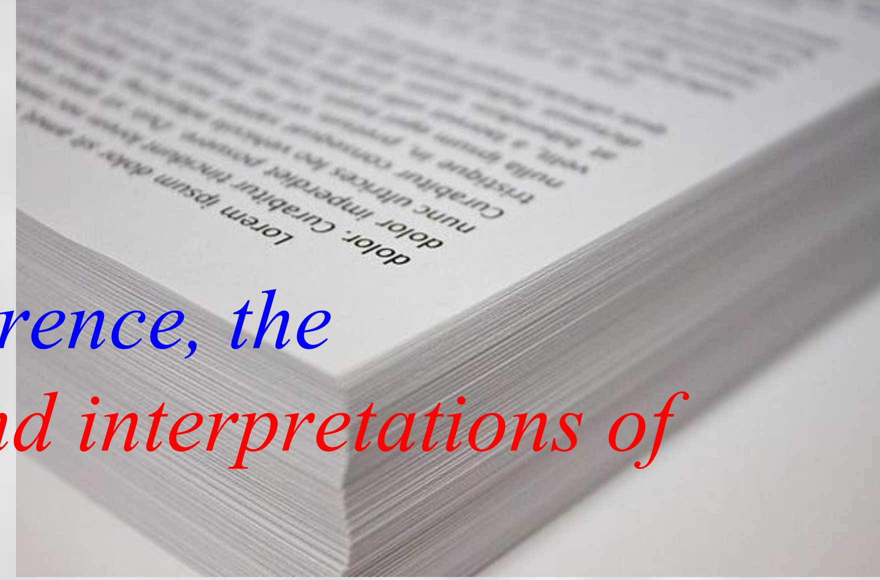
It's this one

Outline

- Motivation for decoherence
- First summary
- Probabilistic reality
- Interference
- The "measurement problem"
- Complementarity: 4 effects
- Second summary

Thanks to Eve Armstrong for very helpful comments and suggestions

Main paper



- M. Schlosshauer, *Decoherence, the measurement problem, and interpretations of quantum mechanics*
  - Reviews Of Modern Physics, Volume 76, 10/2004
  - 39 page review

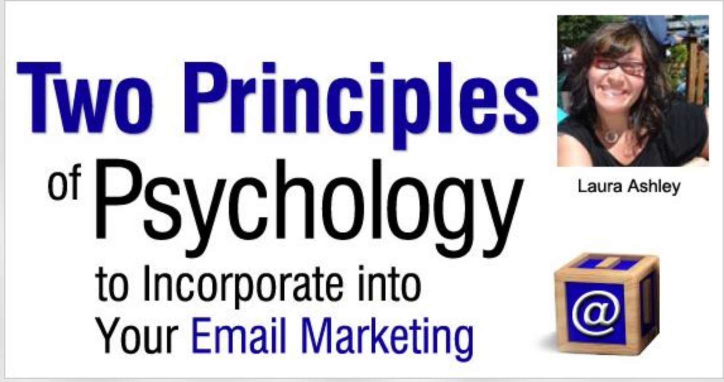
- Scully, Marlan O., Berthold-Georg Englert, Herbert Walther, *Quantum optical tests of complementarity*
  - Nature, 9 May 1991
- Decoherence
  - Maybe: Zurek, Wojciech H., *Decoherence and the Transition from Quantum to Classical - Revisited*, Los Alamos Science, number 27, 2002
    - I have mixed feelings about this

Motivation for decoherence

- The measurement problem
  - Where is the transition from quantum to classical?
    - No observed macroscopic superpositions
- What is a measurement?
  - I.e., when does the quantum state collapse?
    - Can a cat collapse it?

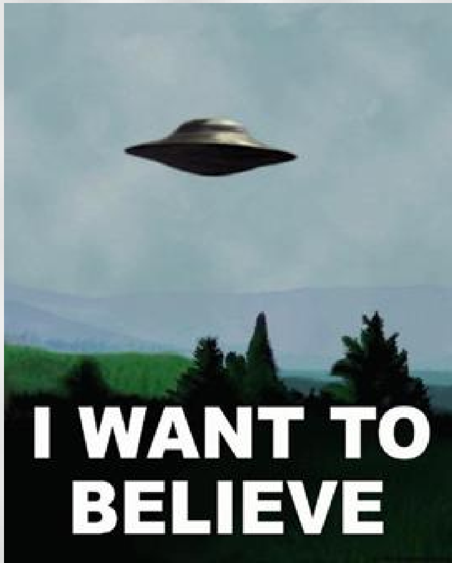
- For me, the transition from quantum to classical is “easier”
  - The transition from quantum field theory to quantum mechanics is “harder”

First summary



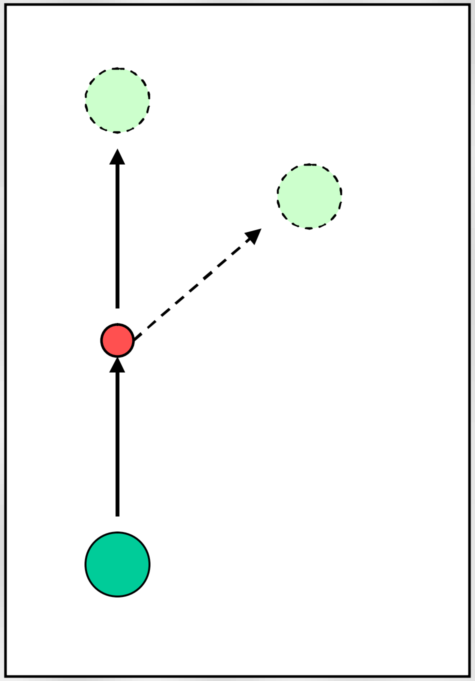
- The decoherence model explains everything from two principles:
  - Time evolution, according to Schrödinger Equation
  - "Mini-collapse" when a result is observed (by me!)

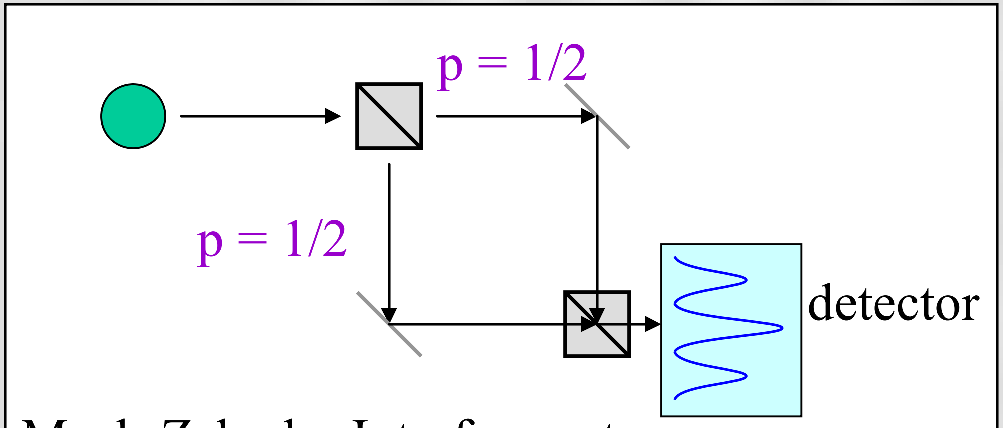
    ↖ My words
- IMHO
  - Decoherence is the simplest, most intuitive QM model
    - Most consistent with other laws of physics
    - It predicts the outcomes of experiments
  - Much of the literature discussion around decoherence is meaningless
    - "Decoherence is wrong because it contradicts my preconceived notions of what reality should be like."



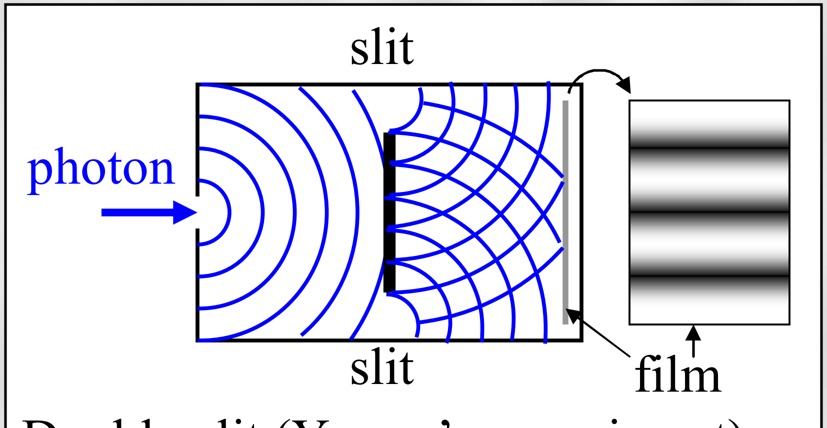
Reality is probabilistic

- The *exact* same setup, measured multiple times, produces different results
- If two possible outcomes never cross paths, they are indistinguishable from a coin toss
  - A particle scatters, or it doesn't
  - Classical probability (nothing weird)
- If two possible outcomes are recombined, we get **interference**, even from one particle at a time





Mach-Zehnder Interferometer



Double-slit (Young's experiment)

Interference is the hallmark of quantum mechanics

- If it interferes, it's quantum
  - If it doesn't, it's classical

- Quantum interference requires two things:
  - Recombining two components of the quantum state
  - Many "trials," each of a single particle

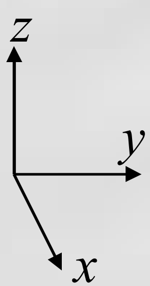
But it's not just interference

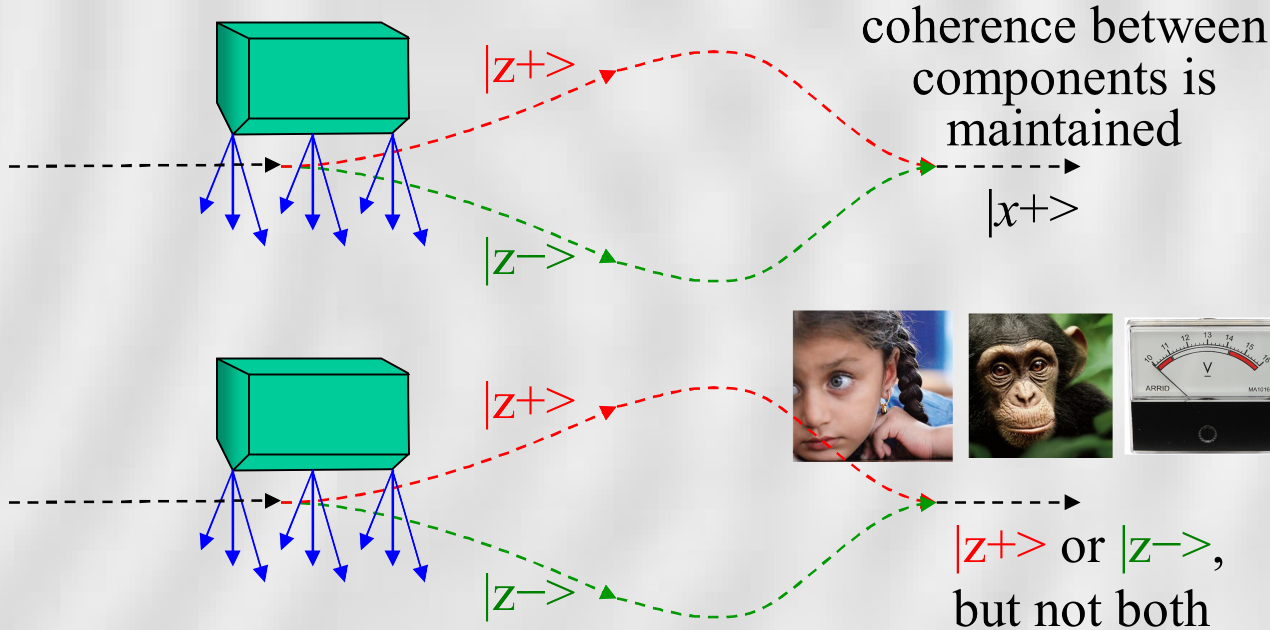
- It's phase coherence between components of a superposition
- E.g., Stern-Gerlach is *not* a measurement
- Unless we look at the result
  - Or any other macroscopic device gets entangled with the result

$$\left|x+\right\rangle = \frac{\left|z+\right\rangle + \left|z-\right\rangle}{\sqrt{2}}$$

time evolution →

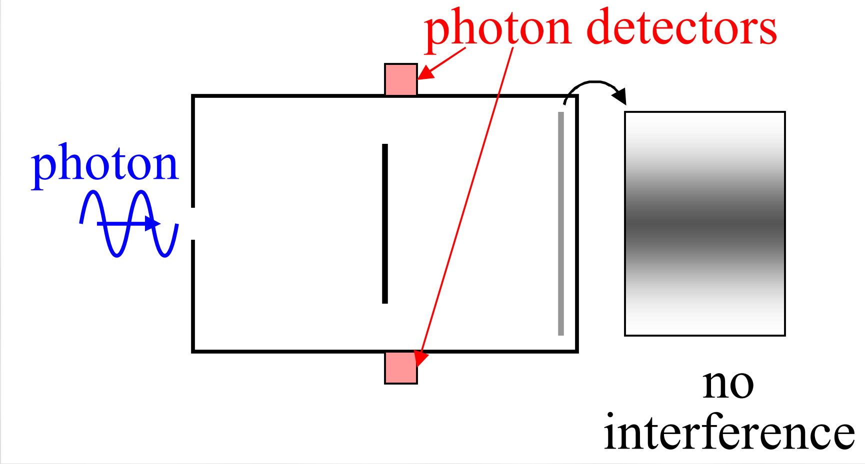
$$\left|x+\right\rangle = \frac{\left|z+\right\rangle + \left|z-\right\rangle}{\sqrt{2}}$$





Prevention of interference

- If we try to see "which way" (welcher Weg) the photon went, we prevent interference
  - Only one photon detector triggers at a time
  - Suggests "complementarity": it's either a wave, or a particle, but not both at the same time
    - But how does it know which to be?



Complementarity

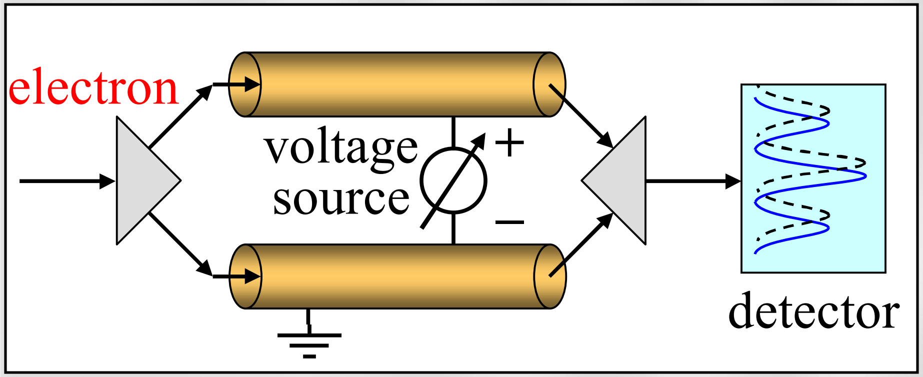
- Prevention of interference led to "Wave-particle duality," aka "complementarity"
  - Particles behave like either a wave or a particle, but not both
  - Which one depends on the experiment
- There are 4 completely different phenomena that have all been called examples of "complementarity"
  - Bohr microscope
  - "Fake" decoherence
  - Measurement entanglement
  - "Real" decoherence

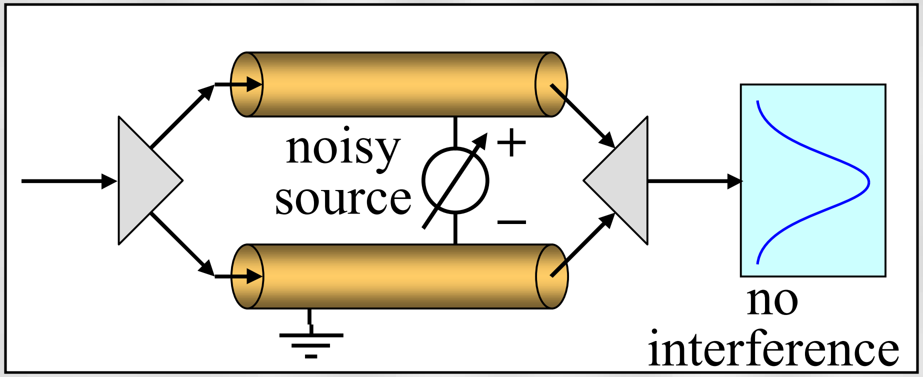
(1) Bohr microscope

- Position-momentum uncertainty is from measurement clumsiness
  - Measurement "bumps" the particle out of a consistent state
  - Prevents an interference pattern
- I never liked this
  - Belies the nature of wave-functions
    - It's not: a particle has a well-defined momentum and position, but nature is mean, and won't let you know them both
    - It is: A particle cannot *have* a well-defined position and momentum
  - Motivates a search for a "kinder, gentler" measuring device
    - Such a device exists, and disproves "clumsy measurement"! (More soon.)

(2) “Fake” Decoherence

- Consider a 2-slit experiment where the energy of one path is controllable
  - Position of interference pattern is then controllable
- What if energy is uncontrollable and unrepeatable, i.e. **noise**?
  - Interference pattern moves randomly, washes out
- Uncontrolled and unrepeatable energy transfer leads to classical probabilities
  - Loss of coherence ~10^{-12} s



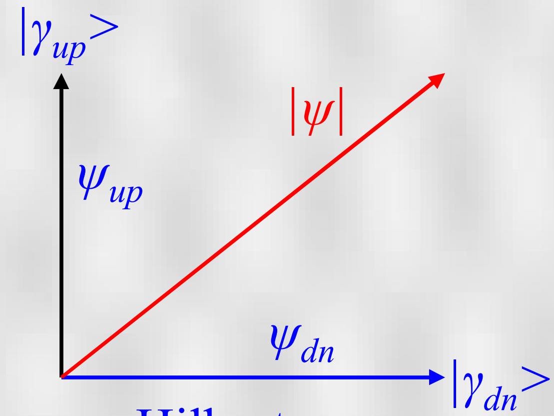


(3) Measurement device entanglement

- Excited atom radiates a photon into the cavities

$$|a_{up}\rangle + |a_{dn}\rangle \rightarrow |a_{up}\rangle|\gamma_{up}\rangle + |a_{dn}\rangle|\gamma_{dn}\rangle$$

  - Is it a measurement?
  - Does it cause collapse?



Hilbert space

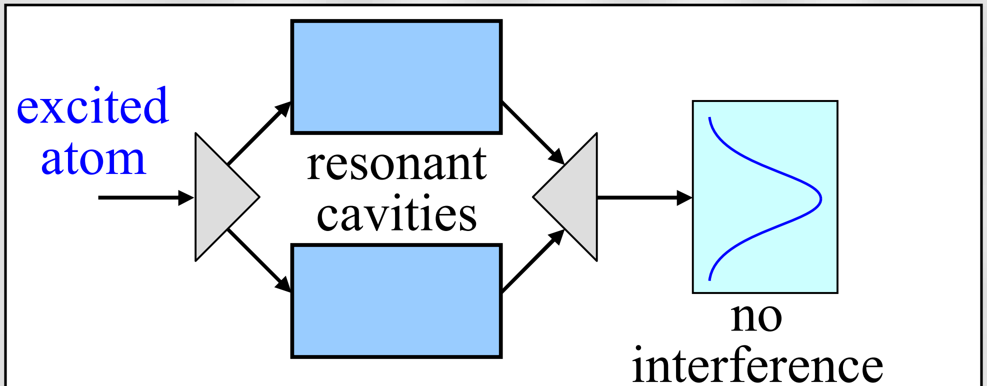
$$\Pr(x) = \left| \psi_{up}(x)|\gamma_{up}\rangle + \psi_{dn}(x)|\gamma_{dn}\rangle \right|^2$$

$$= \psi^*_{up}\psi_{up} + \boxed{\cancel{\psi^*_{up}\psi_{dn}\langle\gamma_{up}|\gamma_{dn}\rangle} + \cancel{\psi^*_{dn}\psi_{up}\langle\gamma_{dn}|\gamma_{up}\rangle}} + \psi^*_{dn}\psi_{dn}$$

$\rightarrow$ no interference because $\langle\gamma_{up}|\gamma_{dn}\rangle = \langle\gamma_{dn}|\gamma_{up}\rangle = 0$

1. The presence or absence of an observer is irrelevant.

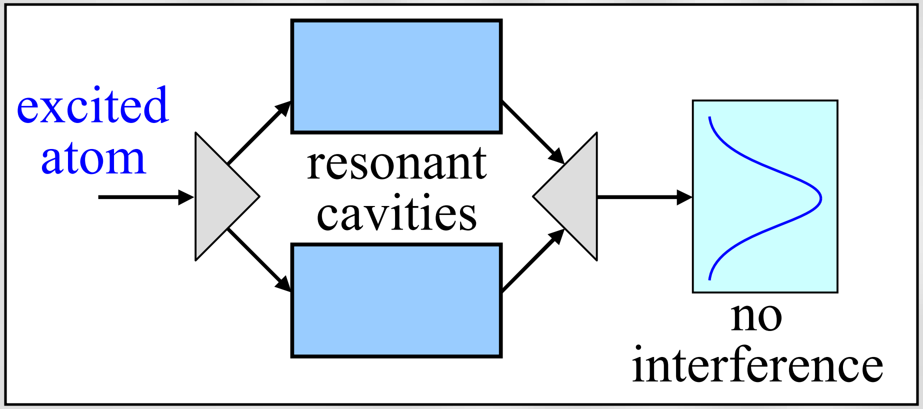
2. The orthogonality of the photon states is important.



Scully, et. al., Nature, 351, 9-May-91, p111.

Measurement device entanglement (cont.)

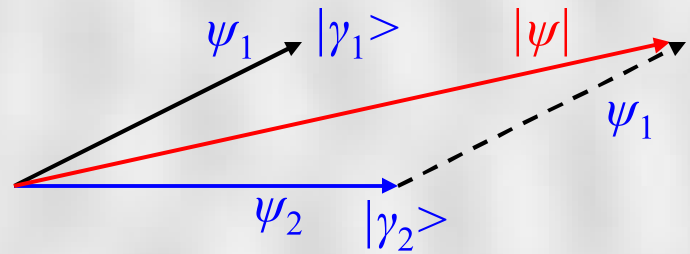
- This *is* a kinder, gentler measurement
  - The radiated photon has insignificant effect on the atom's center-of-mass wave-function
  - Disproves the Bohr microscope "clumsy measurement" idea



QNDM: quantum non-demolition measurement

What if the entangled states overlap (i.e., are *not* orthogonal)?

- Then interference is possible
  - With reduced visibility



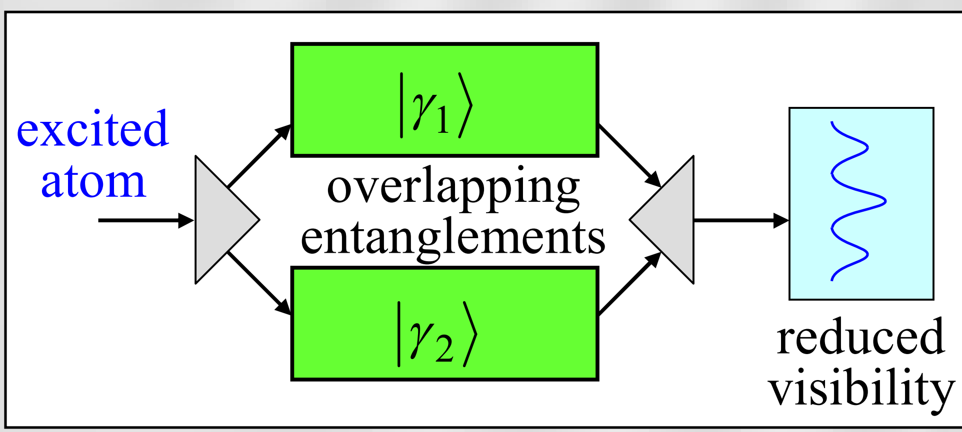
reinforcement (interference maximum)

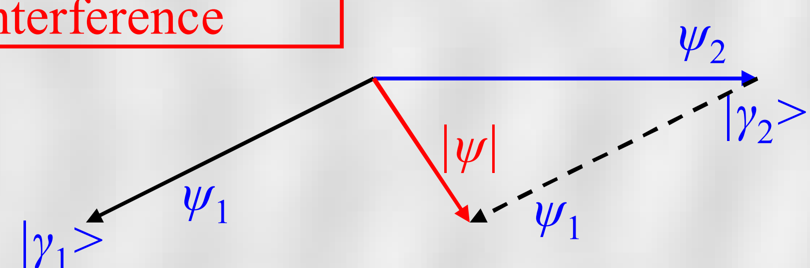
$$\Pr(x) = |sys(x)|^2 = \left|\psi_{up}(x)|\gamma_1\rangle + \psi_{dn}(x)|\gamma_2\rangle\right|^2$$

$$= \psi_{up}^*\psi_{up} + \psi_{up}^*\psi_{dn}\langle\gamma_1|\gamma_2\rangle + \psi_{dn}^*\psi_{up}\langle\gamma_2|\gamma_1\rangle + \psi_{dn}^*\psi_{dn}$$

$\rightarrow$ interference because $\langle\gamma_1|\gamma_2\rangle = \langle\gamma_2|\gamma_1\rangle \neq 0$

The overlap of the entangled states sets the *visibility* of any interference





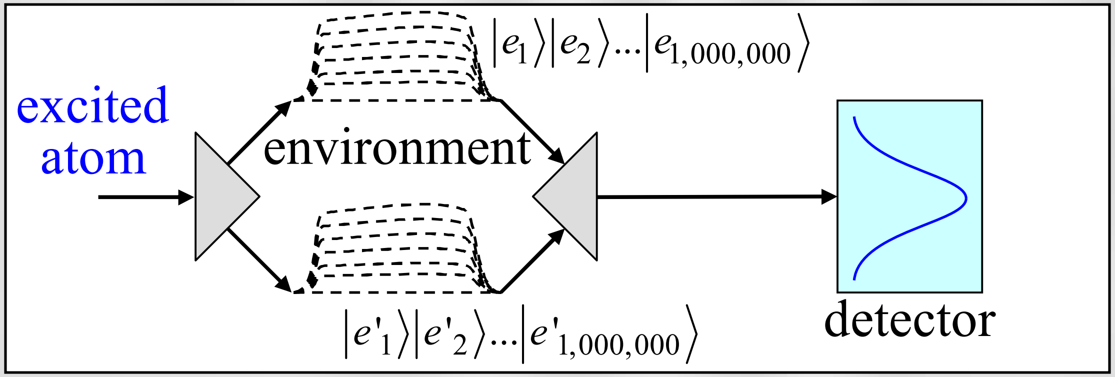
cancellation (interference minimum)

(4) "Real" decoherence

- The two components of the split particle interact with their macroscopic environment
  - Evolving through as cascade of progressively more entanglement with time
  - Even though the environmental states have significant overlap
    - The product of millions of numbers $< 1 \approx 0$

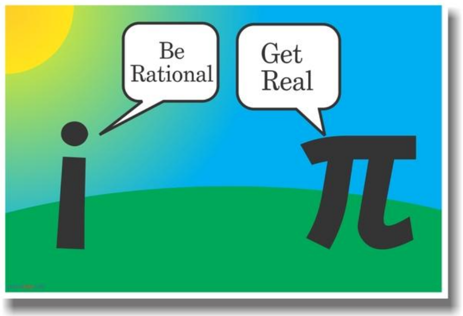
$$\psi = \psi_{up} + \psi_{dn} \rightarrow \psi_{up} \left|e_1\right\rangle \left|e_2\right\rangle \ldots \left|e_{1,000,000}\right\rangle + \psi_{dn} \left|e'_1\right\rangle \left|e'_2\right\rangle \ldots \left|e'_{1,000,000}\right\rangle$$

$$\text{interference terms} \propto \left\langle e_1 \middle| e'_1 \right\rangle \left\langle e_2 \middle| e'_2 \right\rangle \ldots \left\langle e_{1,000,000} \middle| e'_{1,000,000} \right\rangle \approx 0$$

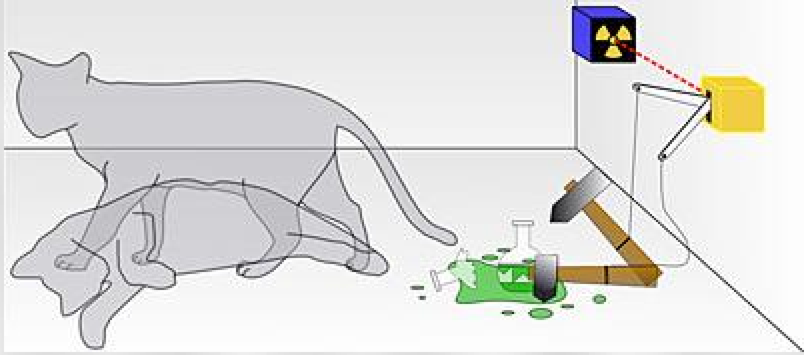


"Real" decoherence (cont.)

- Real experiments are inevitably connected to their surrounding environment
- Macroscopic ones are connected to billions of particles ("subsystems") in the environment
  - This means they decohere on extremely short timescales, $\sim 10^{-18}$ s??
- The decoherence model still requires a collapse:
  - After I see a measurement, all other components of the superposition disappear (the wave function collapses)
  - In the decoherence model, this is the only "weird" phenomenon of quantum mechanics
    - The rest is just a deterministic time evolution of the quantum state according to the Schrödinger equation



Total loss of coherence is equivalent to collapse



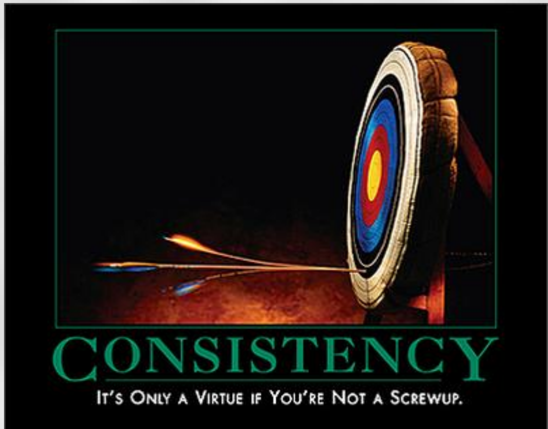
- Doesn't matter what causes loss of coherence (fake or real decoherence)
- Both total loss of coherence *and* collapse lead to classical probabilities
  - Equivalent to: the particle is in *one* definite state, we just don't know which state it is
- But the collapse model has problems:
  - Cannot explain partial coherence
    - Collapse is binary: it happens or it doesn't
    - Decoherence is continuous: relative phase of components becomes smoothly more statistically diverse

Consistency and collapse

- The "consistency postulate" requires a collapse somewhere along the line (even in the decoherence model)
  - Once I observe a result, all other possible outcomes disappear: nonunitary collapse
- To allow for partial coherence, a physical model must defer the collapse to the last possible moment
  - All other time evolution simply follows the Schrodinger equation

Observers are macroscopic

- When I look at a measurement device, my macroscopic body totally decoheres the possible measurement outcomes long before my brain can interpret the results
- Therefore, the decoherence model implies that "mini-collapse" can only occur *after* total decoherence
  - This is more complete than old-fashioned collapse, because it connects the measurement all the way to the observer with just entanglement and the Schrödinger Equation



Second summary

- A **measurement** is *defined* to be irreversible (for all practical purposes)
- The decoherence model is (IMHO) the simplest, most intuitive quantum model
  - Is just the Schrödinger Equation + mini-collapse
  - Eliminates any confusion about when is a measurement, when is collapse, etc.
- I don’t think “interpretations” of QM have any scientific basis (angels on the head of a pin)

Gravity Induced Neutron Interference (GINI)

- Phys. Rev. A 21, 1419–1438 (1980), *Gravity and inertia in quantum mechanics*
  - J. -L. Staudenmann and S. A. Werner

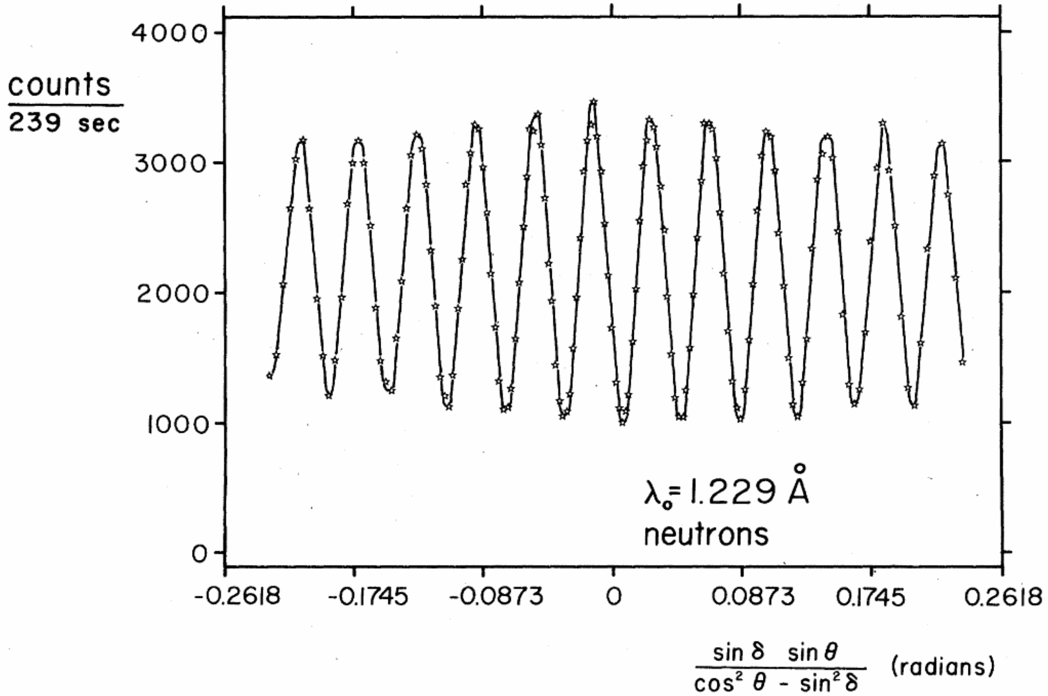
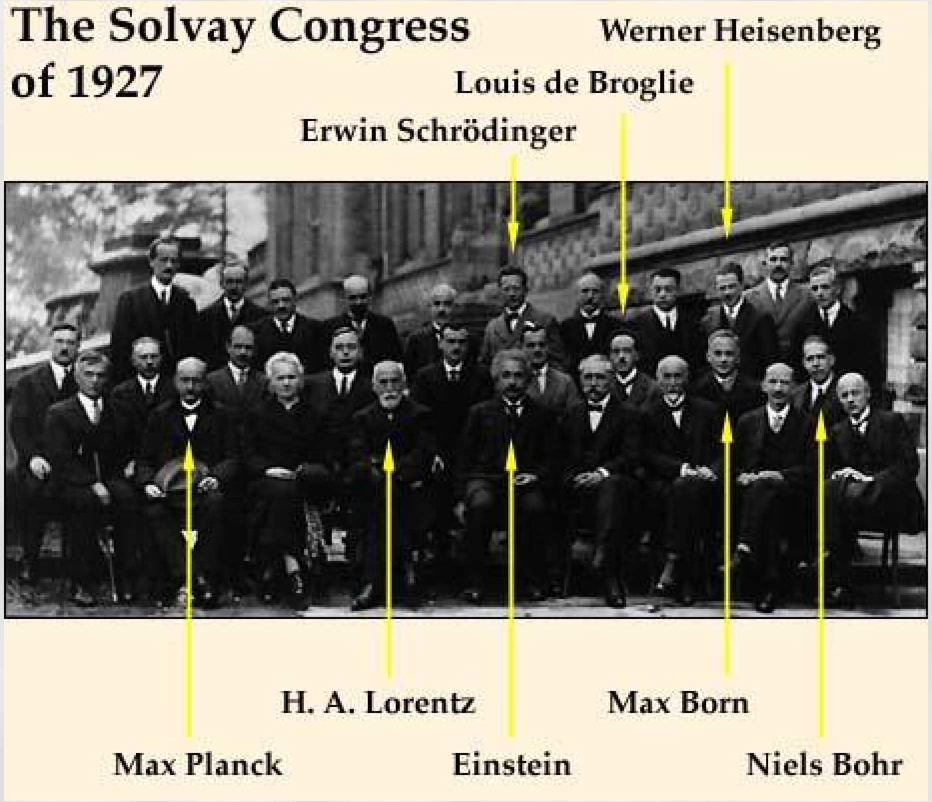


FIG. 7. Example of data obtained by rotating an Si slab in the interferometer (Fig. 6). The counts in detector C_3 are shown.


The Solvay Congress of 1927
Werner Heisenberg
Louis de Broglie
Erwin Schrödinger
H. A. Lorentz
Max Born
Max Planck
Einstein
Niels Bohr