# The Measurement Problem of Quantum Mechanics

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# Outline

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- Stern-Gerlach experiment
- What is the measurement problem?
- Decoherence
- Potential solutions
  - Decoherence alone
  - Copenhagen interpretation
  - Spontaneous collapse
  - Many worlds
  - Bohmian mechanics
  - Consistent histories
- Quiz: what kind of quantum mechanic are you?

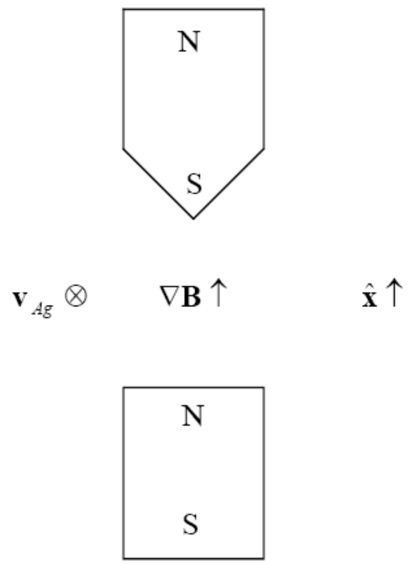
# Invitation

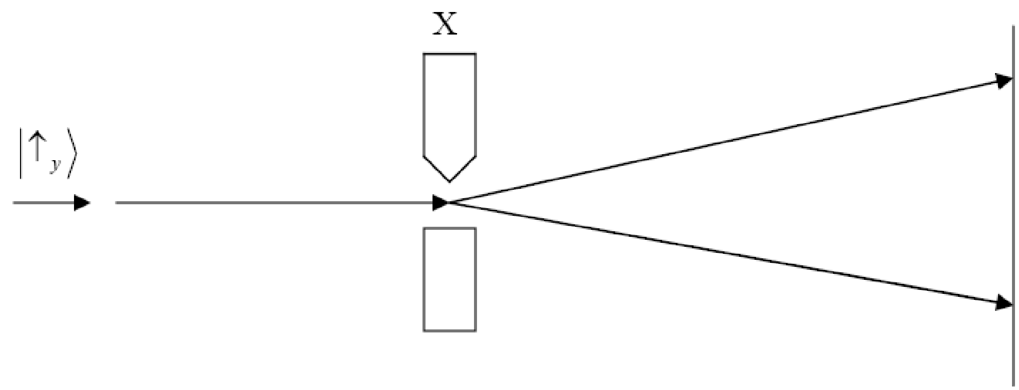
- "[The Copenhagen interpretation] has stood the test of time, and emerged unscathed from every experimental challenge. But I cannot believe this is the end of the story; at the very least, we have much to learn about the nature of measurement and the mechanism of collapse. And it is entirely possible that future generations will look back, from the vantage point of a more sophisticated theory, and wonder how we could have been so gullible." --David Griffiths, *Introduction to Quantum Mechanics*, p. 4
- "The difficulty is not that quantum mechanics is probabilistic—that is something we apparently just have to live with. The real difficulty is that it is also deterministic, or more precisely, that it combines a probabilistic interpretation with deterministic dynamics." --Steve Weinberg, *Physics Today,* Nov. 2005

# Invitation

- "One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small that *perhaps* in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the [Geiger] counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say hat the cat still lives *if* meanwhile no atom has decayed. The first atomic decay would have poisoned it. The ψ-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts." --Erwin Schrodinger, *Proc. Cambridge Phil. Soc.*, 31 (1935) 555-563.

# Stern-Gerlach experiment



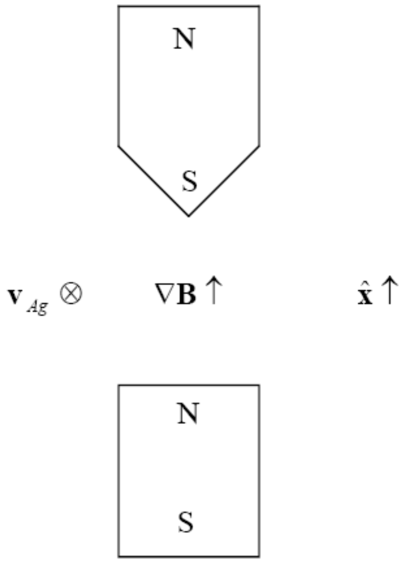



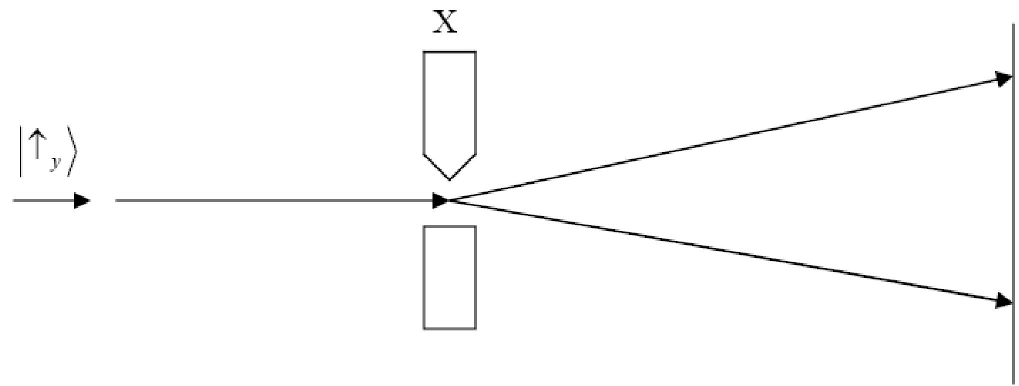

$$|\Psi_i\rangle = |\uparrow_y\rangle_{Ag}|ready\rangle_{SG} = \frac{1}{\sqrt{2}}\left(|\uparrow_x\rangle + |\downarrow_x\rangle\right)_{Ag}|ready\rangle_{SG}$$

$$\xrightarrow{\text{time}} \quad \cancel{|\Psi_f\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow_x\rangle_{Ag}|\text{"}\uparrow_x\text{"}\rangle_{SG} + |\downarrow_x\rangle_{Ag}|\text{"}\downarrow_x\text{"}\rangle_{SG}\right)}$$

$$|\Psi_f\rangle = |\uparrow_x\rangle_{Ag}|\text{"}\uparrow_x\text{"}\rangle_{SG} \qquad \text{OR} \qquad |\Psi_f\rangle = |\downarrow_x\rangle_{Ag}|\text{"}\downarrow_x\text{"}\rangle_{SG}$$

# Stern-Gerlach experiment




$$|\Psi_i\rangle = |\uparrow_y\rangle_{Ag} |ready\rangle_{SG} |ready\rangle_{obs} = \frac{1}{\sqrt{2}} \left( |\uparrow_x\rangle + |\downarrow_x\rangle \right)_{Ag} |ready\rangle_{SG} |ready\rangle_{obs}$$

$\xrightarrow{\text{time}}$

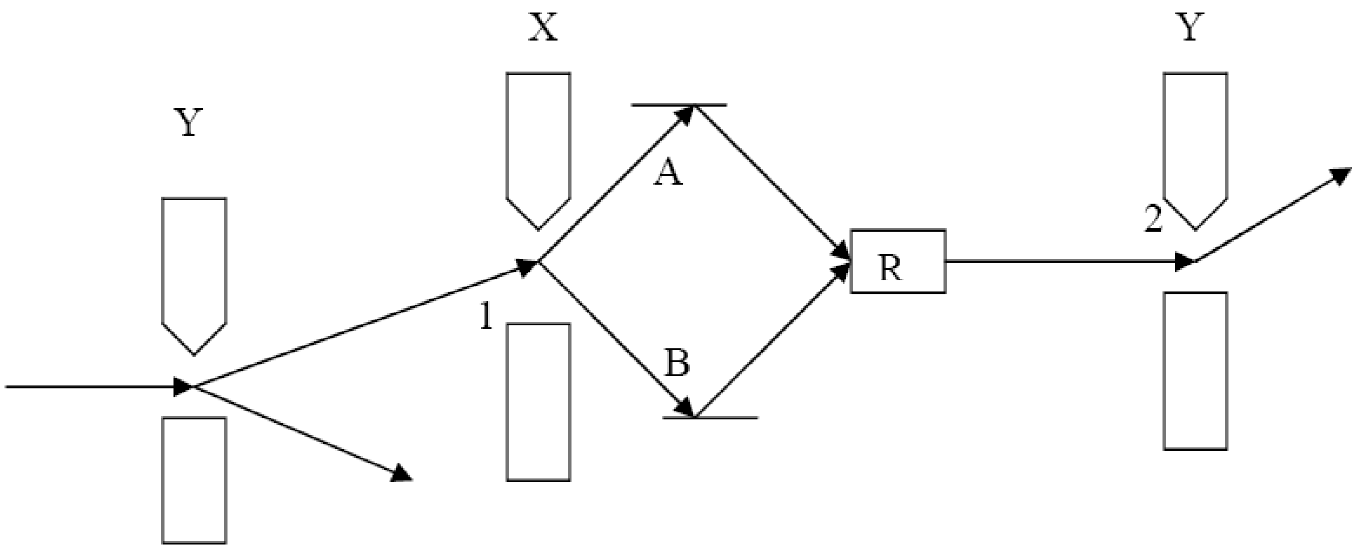
$$\cancel{|\Psi_f\rangle = \frac{1}{\sqrt{2}} \left( |\uparrow_x\rangle_{Ag} |"\uparrow_x"\rangle_{SG} |"\uparrow_x"\rangle_{obs} + |\downarrow_x\rangle_{Ag} |"\downarrow_x"\rangle_{SG} |"\downarrow_x"\rangle_{obs} \right)}$$

$$|\Psi_f\rangle = |\uparrow_x\rangle_{Ag} |"\uparrow_x"\rangle_{SG} |"\uparrow_x"\rangle_{obs} \quad \text{OR} \quad |\Psi_f\rangle = |\downarrow_x\rangle_{Ag} |"\downarrow_x"\rangle_{SG} |"\downarrow_x"\rangle_{obs}$$

# What is the problem?

- The following claims of orthodox QM are mutually inconsistent (from T. Maudlin, *Topoi* 14 (1995) 7-15):
  A) The wave function of a system is *complete*, i.e., the wave function specifies (directly or indirectly) all the physical properties of a system.
  B) The wave function always evolves in accord with a linear dynamical equation (i.e., the Schrodinger equation).
  C) Measurements of, e.g., the spin of an atom, always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up).

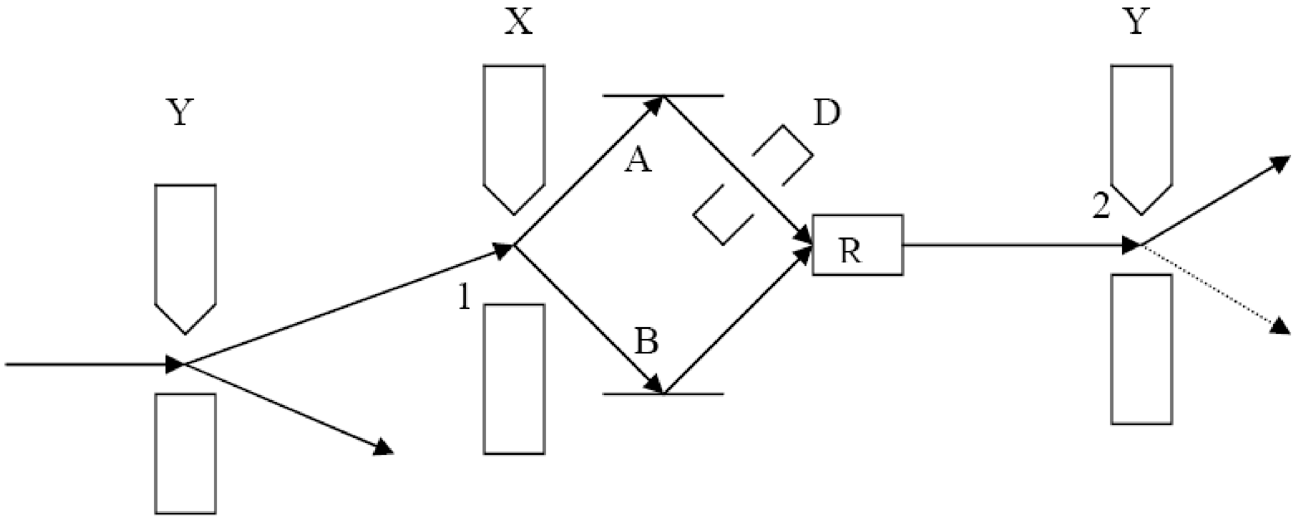
# Decoherence




$$\left|\uparrow_y\right\rangle_{Ag} \Rightarrow \frac{1}{\sqrt{2}}\left(\left|\uparrow_x, A\right\rangle + \left|\downarrow_x, B\right\rangle\right)_{Ag} \Rightarrow \left|\uparrow_y\right\rangle_{Ag}$$

- We can see the effects of interference between the A and B trajectories

# Decoherence




$$\left|\uparrow_y\right\rangle_{Ag}\left|ready\right\rangle_D \Rightarrow \frac{1}{\sqrt{2}}\Big(\left|\uparrow_x, A\right\rangle\left|yes\right\rangle_D + \left|\downarrow_x, B\right\rangle\left|no\right\rangle_D\Big)_{Ag}$$

$$\Rightarrow \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}\Big(\left|\uparrow_y\right\rangle + \left|\downarrow_y\right\rangle\Big)\left|yes\right\rangle_D + \frac{1}{\sqrt{2}}\Big(\left|\uparrow_y\right\rangle - \left|\downarrow_y\right\rangle\Big)\left|no\right\rangle_D\right)_{Ag}$$

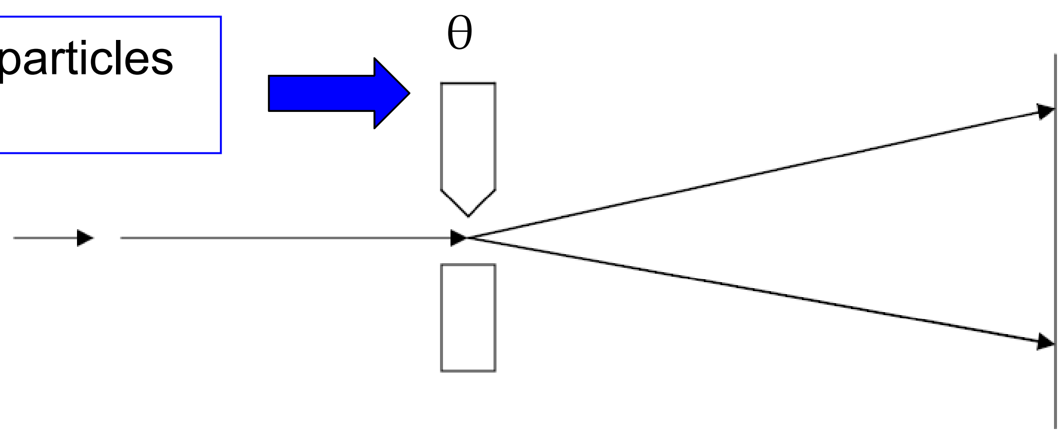
- Decoherence: the loss of interference effects, due to interaction with environment
  - Explains why we never observe anything corresponding to the interference between dead and alive cats.
  - Can it do more?

# Mixtures vs. superpositions

- Mixture: collection of particles in definite but unknown states
  - classical, not quantum uncertainty
- A Stern-Gerlach device can differentiate between:
  - A mixture of x-up particles and x-down particles
  - Many particles, each with spin aligned in some direction in the xy plane:

$$\psi = N\left(\left|\uparrow_z\right\rangle + e^{i\phi}\left|\downarrow_z\right\rangle\right)$$

Rotate until all particles go up




- If the angle ϕ is varied at random, no orientation will yield "all-up"
  - A superposition with randomly fluctuating coefficients is experimentally equivalent to a mixture.

# Superpositions posing as mixtures

- Interaction with the environment can cause the coefficients of a superposition to fluctuate rapidly

$$\psi(t) = \psi(0)e^{-iEt/\hbar}$$

$$V_{environment} = \gamma B_z S_z$$

$$\psi(0) = \frac{1}{\sqrt{2}}\left(\left|\uparrow_z\right\rangle + \left|\downarrow_z\right\rangle\right)$$

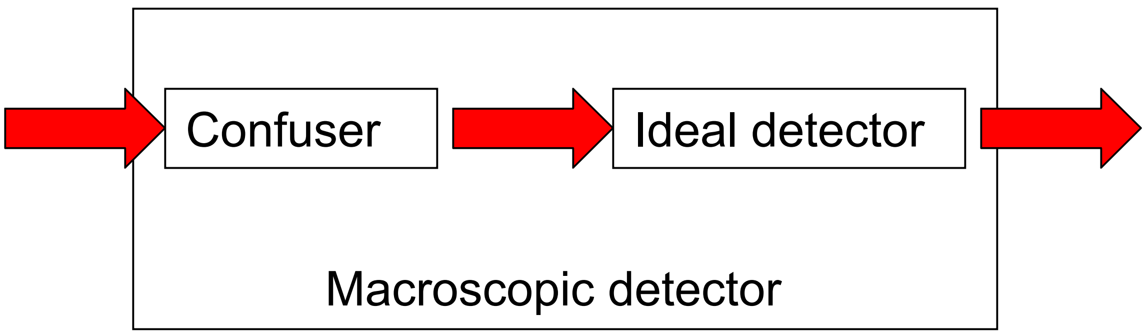
$$\psi(t) = \frac{1}{\sqrt{2}}e^{-i\gamma B_z t/2}\left(\left|\uparrow_z\right\rangle + e^{i\gamma B_z t}\left|\downarrow_z\right\rangle\right)$$

- Only a small difference in energy is needed: for a mass of 1 g, the difference in gravitational potential energy from a height change of $10^{-10}$ m will alter the phase factor within $\sim 10^{-22}$ s

# Solutions to the Measurement Problem

# Decoherence

- Some argue that decoherece by itself solves the measurement problem
  - The environment is constantly fluctuating.
  - Different terms of a superposition have different interaction energies with the environment.
  - The time evolution of different terms will constantly and irregularly fluctuate.
  - This is indistinguishable from a mixture.




- Objection: A superposition with fluctuating coefficients is not in principle the same as a mixture.
- Objection: The quantum eraser experiment shows that quantum behavior is not destroyed by decoherence.

# The Copenhagen interpretation

- Every measurement induces a collapse of the state vector of the system onto one of the eigenstates of the measurement device.
- Objection: The mechanism of the collapse or the point at which it occurs (somewhere between decoherence and consciousness) is not specified.
- Objection: The definition of a measurement is unclear.

# Spontaneous collapse

- One formulation proposed by Ghirardi, Rimini, and Weber, *Phys Rev. D* 34 (1986) 470.
- Every particle has a probability t/T for a given time t to collapse onto the position basis. No measurement required.
- GRW suggest $T = \sim 10^8$ years, so a macroscopic system with $N = 10^{23}$ particles undergoes localization on average every $10^{-7}$ seconds, long enough to allow for interference effects, but far shorter than conscious observers can perceive.
- Another approach is to add "white noise" terms to the Schrodinger equation.
- Objection: why is position the preferred basis?
- Objection: collapsing onto a definite position violates the uncertainty principle; collapsing onto a Gaussian distribution of position allows small interference terms to persist from the tails.

# Many worlds

- Proposed by H. Everett, *Rev. Mod. Phys.* 29 (1957) 454.
- No collapses occur. Each possible outcome is realized, but an observer sees only a single outcome. Other terms of a superposition become inaccessible due to decoherence.

$$\left|\Psi_f\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow_x\right\rangle_{Ag}\left|"\uparrow_x"\right\rangle_{SG}\left|"\uparrow_x"\right\rangle_{obs} + \left|\downarrow_x\right\rangle_{Ag}\left|"\downarrow_x"\right\rangle_{SG}\left|"\downarrow_x"\right\rangle_{obs}\right)$$

- Objection: how to reproduce expected statistical outcomes.

$$\psi = \sqrt{0.9}\left|\uparrow_z\right\rangle + \sqrt{0.1}\left|\downarrow_z\right\rangle$$

- Objection: the claim that unobservable branches of superpositions continue to evolve is untestable.

# Bohmian Mechanics

- No-collapse hidden-variables theory developed by David Bohm in 1952.
- 4 postulates, as described in Durr, et al., *J. Stat. Phys.* 67 (1992) 843:
  - The complete description of a system of N particles is provided by its wave function, $\Psi(q,t)$ where q = $(\mathbf{q}_1,\ldots,\mathbf{q}_N) \in \mathbf{R}^{3N}$ and by its configuration, Q = $(\mathbf{Q}_1,\ldots,\mathbf{Q}_N) \in \mathbf{R}^{3N}$ . Particles have definite positions at all times.
  - The wave function evolves according to Schrodinger's equation: $i\hbar\dfrac{\partial\Psi}{\partial t} = \mathrm{H}\Psi$
  - The position vector **Q**k representing particle k evolves according to Bohm's Guiding Equation: $\dfrac{\partial \mathbf{Q}_k}{\partial t} = \dfrac{\hbar}{m_k}\mathrm{Im}\left(\dfrac{\nabla_k \Psi}{\Psi}\right)$, where $\nabla_k = \dfrac{\partial}{\partial \mathbf{q}_k}$
  - The Quantum Equilibrium Postulate: a system with wave function ψ will have a distribution ϱ of coordinates given by: ϱ = |ψ|2.

# Bohmian Mechanics

- Though particles have definite positions, we can never uncover them.
- Objection: Bohm's interpretation is untestable, since there is no way to measure the true position of the particle.
- Objection: Wave functions never collapse; parts of them just become inaccessible due to decoherence. Isn't this just as "messy" as many-worlds?

# Consistent histories

- Developed in the 1980's by R. Griffiths, R. Omnes, and others.
- Eliminate the fundamental role of measurements and instead study quantum histories—sequences of events—and assign probabilities to such histories.
- No external observer is invoked.
- The consistency criterion requires that any possible history yield a classical outcome.
- Objection: It's not clear what kind of criterion is necessary to explain the emergence of classicality; maybe decoherence alone will ensure it.
- Objection: Do we have to abandon our understanding of what it means to make a measurement?

**Which quantum mechanic are you?**

# Which quantum mechanic are you?

**The Tool User.** All I care is that I can get the calculations right. As to what constitutes a measurement, I'm not worried—I know a measurement when I see one.

Copenhagen interpretation

# Which quantum mechanic are you?

**The Minimalist.** I don't need to believe that wave functions exist in nature. I want to be able to describe the likelihood of something to happen.

$\boxed{\text{Consistent histories / decoherence}}$

# Which quantum mechanic are you?

**Determinist.** It doesn't make sense to me that nature is fundamentally probabilistic. Some process must be responsible for the outcome of an experiment, even if that mechanism is fundamentally inaccessible to us.

Bohmian mechanics

# Which quantum mechanic are you?

**Faith in large numbers.** All I care about is that superpositions collapse before they get to me—a conscious being made up of lots of particles.

Spontaneous collapse

# Which quantum mechanic are you?

**The Agnostic.** None of these solutions make sense to me. There must be some missing piece that we don't understand. Quantum mechanics as presently formulated is incomplete.

Get to work! What else could be more important?

# Sources

- For non-physicists
  - D. Lindley, *Where does the weirdness go?*, 1996.
  - D. Albert, *Quantum Mechanics and Experience*, 1992.
- For physicists
  - J. Bell, *Speakable and Unspeakable in Quantum Mechanics*, 1987.
  - G. Greenstein and A. Zajonc, *The Quantum Challenge,* 1997.
  - M. Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics." *Rev. Mod. Phys.* 76 (2004) 1267-1305.

# Conclusion

- The measurement problem is a gap in the formulation of quantum mechanics that deserves serious treatment.
- Decoherence explains why interference effects are not observed in macroscopic systems
- But still we must answer: how and when do wavefunctions collapse—or if they don't collapse, how do we get definite outcomes?
- Several approaches attempt to solve the measurement problem
  - Decoherence alone
  - Copenhagen interpretation
  - Many worlds
  - Bohmian mechanics
  - Spontaneous collapse
  - Consistent histories
- No single interpretation is universally accepted among physicists—the choice is often, as M. Tegmark puts it, "a matter of taste."
- An experimental or theoretical breakthrough could bring consensus.

**Someone could solve this problem. Why not you?!**

# Backup

- "Nobody understands quantum mechanics." -- Richard Feynman
- J.S. Bell: *But to admit things not visible to the gross creatures that we are is, in my opinion, to show a decent humility, and not just a lamentable addiction to metaphysics.*
- E. Schrodinger: *If we have to go on with these damned quantum jumps, then I'm sorry that I ever got involved.*