Title: Interpretation of Quantum Theory: Lecture 18

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Abstract:

Summary of Previous Lecture

Consistent Histories:

1. Pure Hilbert space QM.
   - No classical world

2. Randomness intrinsic to nature
   - Not just measurements

3. Standard probability theory
   - Sample space $I = \sum_j P^j \quad P^j P^k = \delta_{jk} P^j$
     - Orthonormal basis is an example

4. Standard logic
   - Single framework rule: Cannot combine incompatible descriptions

5. Probabilities of dynamical processes
   - Use Schr Eqn to calculate probabilities
   - Born rule for two times

Histories

- Samples space $\mathcal{S}$ for classical stochastic process
  - Sequence of events
  - Example: coin tossed three times:

  HTH, HTT, HHT, ... are all different
  - *One and only one* sequence in given experiment
- Other stochastic processes:
  - Random walk
  - Brownian motion
  - Waterloo weather
- Quantum sequence of events for Hilbert space $\mathcal{H}$

$$Y = F_0 \odot F_1 \odot \cdots F_f$$

  - F_j projector on ray/subspace of $\mathcal{H}$
  - "F_0 at t_0, F_1 at t_1, ..."
  - Different F_j *not* (necessarily) related by Schr Eqn
  - Call such a sequence a *history*
- Technical comments:
  - $\odot$ is a modification of $\otimes$
  - History Y an element of $\mathcal{H} \odot \mathcal{H} \odot \cdots \mathcal{H}$.

Families of Histories

- Quantum sample space $\mathcal{S} = \{Y^\alpha\}$ consists of histories
- Simplest interesting situation:
  - Single initial state $[\psi_0] = |\psi_0\rangle\langle\psi_0|$ at t_0
  - $t_j > t_0: \; I = \sum_{\alpha_j} P_j^{\alpha_j}$
- Histories indexed by $\alpha = (\alpha_1, \alpha_2 \ldots)$
  $Y^\alpha = [\psi_0] \odot P_1^{\alpha_1} \odot P_2^{\alpha_2} \odot \cdots$
- *One and only one* history from $\mathcal{S} = \{Y^\alpha\}$ actually occurs in quantum system starting in $[\psi_0]$ at t_0.
  - Projectors $P_j^{\alpha_j}$ not related by Schr eqn
- QM does not say *which* history occurs
  - QM can assign probabilities

Probabilities for Histories

- Use isolated/closed system
  - Open systems more complicated
  - Any apparatus is *part* of quantum system
    – in contrast with textbook approach

- Born rule limited to 2-time histories, $t_0 < t_1$
  - New rule needed for 3 or more times
  - Quantum probabilities (usually) not Markovian

- Histories approach *only* assigns probabilities to *consistent* families
  - For consistent families these probabilities
    – make physical sense
    – agree with Born for two times

- Consistency conditions: Chs. 10, 11 of *Consistent Quantum Theory*

Consistency Conditions

- Simplest case: pure initial state $|\psi_0\rangle$, chain kets; see *Consistent Quantum Theory*, Sec. 11.6
- Recursively define

$$
\begin{aligned}
|\alpha_1\rangle &= P^{\alpha_1} T(t_1, t_0)|\psi_0\rangle, \\
|\alpha_1, \alpha_2\rangle &= P^{\alpha_2} T(t_2, t_1)|\alpha_1\rangle, \\
|\alpha_1, \alpha_2, \alpha_3\rangle &= P^{\alpha_3} T(t_3, t_2)|\alpha_1, \alpha_2\rangle
\end{aligned}
$$

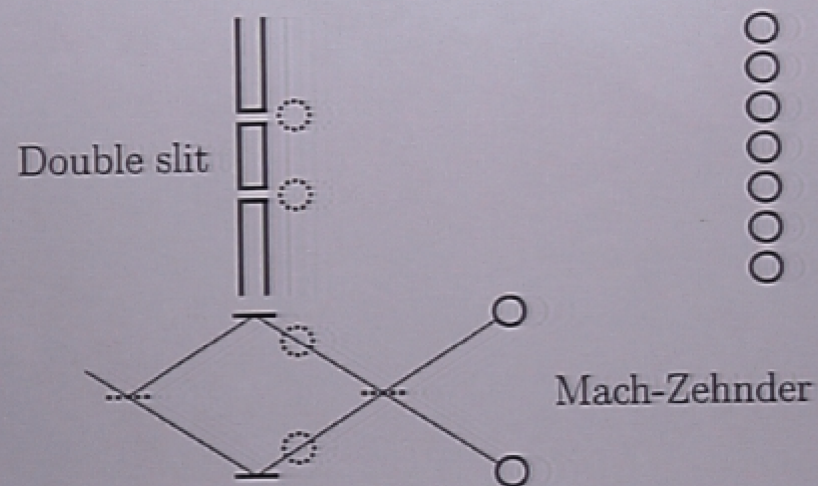
and so forth

- Require orthogonality at each stage:

$$
\begin{gathered}
\alpha_1 \neq \alpha_1' \Rightarrow \langle \alpha_1 | \alpha_1' \rangle = 0, \\
\alpha_1 \neq \alpha_1' \text{ OR } \alpha_2 \neq \alpha_2' \Rightarrow \langle \alpha_1, \alpha_2 | \alpha_1', \alpha_2' \rangle = 0, \\
\text{Etc.}
\end{gathered}
$$

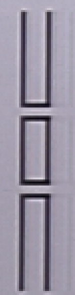
- $\Pr\left(Y^{(\alpha_1, \alpha_2, \ldots)}\right) = \langle \alpha_1, \ldots \alpha_f | \alpha_1, \ldots \alpha_f \rangle$.
- $\{P_1^{\alpha_1}\}$ orthogonal *implies*: $\alpha_1 \neq \alpha_1' \Rightarrow \langle \alpha_1 | \alpha_1' \rangle = 0$
  - Two-time $t_0 < t_1$ histories automatically consistent
  - Born rule always works
- Consistency not trivial for 3 or more times.

Double Slit + Mach-Zehnder



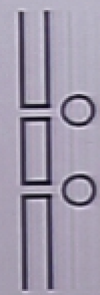
- Correspondences:
  - Which slit? ↔ Which arm?
  - Detectors behind slits ↔ inside interferometer
  - In interference zone ↔ following 2d beam splitter
- For precise description, use Mach-Zehnder
  - Basic idea applies to double slit

No detectors



- Family "Super" (superposition)
  - Initial wave $|\psi_0\rangle$ arrives at slits
  - – Ignore reflection (Mach-Zehnder better for this)
  - Passes through slits in *coherent superposition*
- Family "Which" (which slit?)
  - Same $|\psi_0\rangle$
  - Particle passes through definite slit
- Either family gives *valid quantum description*
  - Physicist can choose either. Liberté !
  - Spin 1/2 analogy: Use *either* S_z *or* S_x basis
- Both families equally "fundamental" QM: Egalité !
- Cannot combine Super with Which: Incompatibilité !

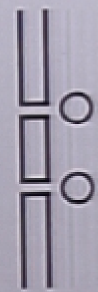
Detectors Behind Slits I



- Detectors are quantum objects!
  - Hilbert space includes detectors
  - Histories include projectors on detector states
  - "Pointer basis": Macroscopically distinct detector states for decomposition of identity

- Histories: $[\Psi_0] \odot$ Particle $\odot$ Detector
  - Initial $|\Psi_0\rangle = |\psi\rangle \otimes |\text{Detectors Ready}\rangle$
  - Particle: Super(position) OR Which (slit) basis
  - Detector: Point(er) basis OR Scat (Schr. cat) basis

Detectors Behind Slits II



Family:	Particle:	Detector:	Consistent?
1. Unitary	Super	Scat	Yes
2. Textbook	Super	Point	Yes
3. Exptlist	Which	Point	Yes
4. Nonsense	~~Super~~ Which	~~Point~~ Scat	No

- Families 1, 2, 3 equally good quantum descriptions!

  1. Individual detectors cannot be discussed.
     Misleading concept of “dead and live” cat
  2. “Which slit?” is meaningless question for this family
  3. Experimentalist description: Particle came through slit preceding triggered detector

- Family 4 unacceptable: violates consistency conditions

Detectors in Interference Region

Family:	Particle:	Detector:	Consistent?
1. Unitary	Super	Scat	Yes
2. Textbook	Super	Point	Yes
3. DefinSlit	Which	Scat*	Yes
4. Nonsense	Which	Point	No

- Families 1, 2, 3 equally good quantum descriptions!
  1. Individual detectors cannot be discussed
  2. "Which slit?" is meaningless question
  3. Scat* differs from Scat, but equally odd
- Family 4 unacceptable: violates consistency conditions

Delayed Choice

- Detectors behind slits removed at last moment
  - Does the future influence the past?
- Consistent families in the two cases:

Family:	Particle:	Near Detectors:	Far Detectors:
1. Unitary	Super	Scat	
2. Textbook	Super	Point	
3. Exptlist	Which	Point	
4. Unitary	Super		Scat
5. Textbook	Super		Point
6. DefinSlit	Which		Scat*

- Future influences past = misunderstanding
  - Many *equally valid* quantum descriptions
  - Chosing one does not influence reality; it determines which questions have answers

Delayed Choice

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Family:	Particle:	Near Detectors:	Far Detectors:
1. Unitary	Super	Scat	
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3. Exptlist	Which	Point	
4. Unitary	Super		Scat
5. Textbook	Super		Point
6. DefinSlit	Which		Scat*

- Future influences past = misunderstanding
  - Many *equally valid* quantum descriptions
  - Chosing one does not influence reality; it determines which questions have answers

Einstein Podolsky Rosen

- Phys. Rev. 1935 "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"
  - Their answer: No
- Bohm 1952. Particles a and b far apart in spin singlet
  - $|\psi_0\rangle = \left(|z_a^+ z_b^-\rangle - |z_a^- z_b^+\rangle\right) / \sqrt{2}$
  - A measures S_{az}, gets result $+1/2$ or $-1/2$
    Conclusion $S_{bz} = -S_{az}$
  - A could measure S_{ax}, get result $+1/2$ or $-1/2$
    Conclusion $S_{bx} = -S_{ax}$
- EPR objection, stated in Bohm language
  - Measurement of a cannot affect b, so
  - S_{bz} values same *before and after* A measurement
  - A could just as well measure S_{ax}
  - Both S_{bz}, S_{bx} have definite values regardless of what is measured
  - QM is incomplete: Hilbert space is too small!

Nonlocality

- Claim: EPR $\Rightarrow$ QM nonlocal!
  - A's measurement of particle a has an Instantaneous Nonlocal Superluminal (INS) influence on particle b
  - Idea supposedly supported by Bell inequalities

- Laborious analysis proves that
  - INS influences carry no information!

- Histories response:
  - INS influences carry no information — because they do not exist!
  - Bell ineq. violations $\Rightarrow$ hidden variables don't work
  - Hilbert space QM, properly understood, is *local*

Classical Analogy

- Two colored slips of paper: R(ed), G(reen)
- Pete in Pittsburgh
  - Seals them in opague envelopes
  - Shuffles envelopes
  - Addresses one to Alice in Atlanta
  - The other to Bob and Boston
- Alice opens her envelope, sees G
  - Conclusion: Bob's envelope contains R
- Does this indicate INS influence of Alice's action on Bob's envelope?
  - Perhaps there is some simpler explanation

EPR Correlations

- Histories with initial $|\psi_0\rangle = \left(|z_a^+ z_b^-\rangle - |z_a^- z_b^+\rangle\right)/\sqrt{2}$
  - No measurements (until later)
- Unitary family $[\psi_0] \odot [\psi_0] \odot [\psi_0] \odot \cdots$
  - Consistent, probability 1
  - Incompatible with individual properties of a, b
  - Must consider $|\psi\rangle$ pre-probability in order to use reduced density operators ρ_a, ρ_b
- Family using S_z bases: $[\psi_0] \odot \begin{cases} z_a^+ z_b^- \\ z_a^- z_b^+ \end{cases}$
  - Perfect correlations with no measurements
  - Like R, G slips of paper inside envelopes
  - Good measurements will show what is there
- Family using S_x bases: $[\psi_0] \odot \begin{cases} x_a^+ x_b^- \\ x_a^- x_b^+ \end{cases}$
  - Incompatible with previous family
- No magical INS influences thus far!
  - Will measurements bring them to light?

EPR Measurement Correlations

- Measuring apparatus Z_a for S_{az}
  - Initial state $|\Psi_0\rangle = |\psi_0\rangle \otimes |Z_a^0\rangle$
  - Pointer basis projectors Z_a^+, Z_a^-

- Unitary history → apparatus Schrödinger cat state
  - Good QM, but does not address our questions

- Family 1. $[\Psi_0] \odot \begin{cases} z_a^+ z_b^- \odot Z_a^+ \\ z_a^- z_b^+ \odot Z_a^- \end{cases}$
  - Apparatus $Z_a^{\pm}$ correlated with prior states of both particles
  - Good measurements show what is there

- Extensions of this family show that:
  - Z_a^+ outcome implies $S_{bz} = -1/2$ for particle b *before*, *during* and *after* measurement
  - No sign of INS influence!

EPR Delayed Choice

- Measure S_{ax} instead of S_{az}
  - Use $|\Psi_0\rangle = |\psi_0\rangle \otimes |X_a^0\rangle$
  - Or use quantum coin to replace Z_a with X_a
  - – Possibly at the last moment
- Family 2. $[\Psi_0] \odot \begin{cases} x_a^+ x_b^- \odot X_a^+ \odot x_b^- \\ x_a^- x_b^+ \odot X_a^- \odot x_b^+ \end{cases}$
  - Outcome X_a^+ correlated with x_b^- — both before and after measurement
- Family 3. $[\Psi_0] \odot \begin{cases} z_b^+ \odot \{X_a^+, X_a^-\} \odot z_b^+ \\ z_b^- \odot \{X_a^+, X_a^-\} \odot z_b^- \end{cases}$
  - Can discuss S_{bz} when S_{ax} measured, why not?
  - S_{bz} for particle b *exactly the same* before and after measurement on particle a
  - Demonstration of *absence* of INS influences!

Is QM Complete?

- Quantum description of physical reality *available in 1935* was *incomplete* because it:
  - Lacked consistent probabilities
  - Limited set of stochastic descriptions
  - Misleading reliance on "measurement"
  - Lacked good description of measurement apparatus
  - Wavefunction "collapse" not well formulated
- Einstein, Podolsky, Rosen correct in raising objections
- Quantum description *available in 2005* has
  - Consistent system of probabilities for microsystems
  - Broad class of stochastic descriptions
  - Formulation does not rely on measurement
  - Same principles for measurements, other processes
  - Conditional probabilities replace "collapse"
- Is it now complete?

Discussion Topics

- Liberty in choosing alternative descriptions / consistent families
  - Analog of ordinary historian
  - Approach is consistent; does not lead to contradictions

- Measurements
  - Reveal pre-existing properties *if* the latter are included in the description
  - Von Neumann type
    - Very special
    - Usual interpretation not wrong, but misleading

- Approximate consistency   Dowker & Kent

- CH vs. Everett. $|\Psi_t\rangle$ a pre-probability of limited utility

- CH vs. Bohm   Particle that triggers detector by not passing through it