Dynamic Entanglement: A New Challenge to Peaceful Coexistence?

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The Problem of "Peaceful Coexistence"

- The problem: Bell's Theorem (1964) states that QM violates certain expectations of locality that seemed eminently reasonable.
- By early 1980s experimentation (Aspect *et al.*) made it clear that "the reasonable thing was wrong" (Bell's words).
- Bell: "The theorem says that maybe there must be something happening faster than light, *although it pains me even to say that much*" [emphasis added].
- Could nonlocality be *controlled* for faster-than-light communication or other science-fictional purposes?

How Far Could This Go??

Not To Worry...

- Numerous authors from late 1970s onward published "proofs" that nonlocality cannot be used for controllable superluminal signalling.
- Abner Shimony famously argued that nonlocality should be called not action at a distance but "passion at a distance," and stated that QM and relativity stand in a relationship of "peaceful coexistence," underpinned by the No-Controllable Signalling (NCS) proofs.
- Certain recent work on entanglement draws Shimony's own widely-cited NCS proof into question.

Trouble in Paradise. . . ?

- All NCS proofs (including Shimony's) depend upon *ad hoc* locality assumptions which could be the very points they should have established; hence they may be circular.
- This was argued by me, P. J. Bussey, J. B. Kennedy, P. Mittelstaedt, and Steve Weinstein, but this viewpoint has not been popular.
- The questions I raise today do not bear on all NCS proofs, just any argument like Shimony's that assumes dynamic localizability.

Alice and Bob and EPR

- Singlet state:

$$|\Psi_S\rangle = \frac{1}{\sqrt{2}}(|+-\rangle - |-+\rangle)$$

  with $|+-\rangle$ shorthand for $|+\rangle_A \otimes |-\rangle_B$
- Alice and Bob's results will look random locally, but will exhibit correlations of the form $-\cos\theta_{AB}$.
- Such sinusoidal correlations violate Boole-Bell Inequalities which follow from assumption that there is no "measurement bias" (Pitowsky, 1994); i.e., no influence of Alice's measurements on Bob's remote states.
- So why can't Alice manipulate the parameters of her apparatus so as to influence Bob's local statistics?
- Short answer:
  - Alice could indeed force her particle to go "up" or "down" but this collapses the wave function and destroys the nonlocal correlations between her results and Bob's.

Shimony's NCS Argument

- NCS: Alice's inability to control Bob's results is not due to mere technological limitations, but is a point of fundamental principle.
- Shimony's proof of this claim begins with the *assumption* that the system Hamiltonian has the general form

$$H_{AB} = H_A \otimes \mathbb{I}_B + \mathbb{I}_A \otimes H_B,$$

- Simplified form:

$$H_{AB} = H_A + H_B.$$

- This implies that the time evolution operator is separable:

$$U(t) = \exp[iH_{AB}(t - t_0)] = \exp[iH_A(t - t_0)] + \exp[iH_B(t - t_0)].$$

I.e., the two particles evolve independently *even though they are entangled*.

Parameter vs. Outcome Independence

- Suppose Bob measures some observable B on his particles; from Shimony's localizability assumptions, Shimony shows that $\langle G \rangle$ is independent of Alice's choice of measurement parameter—though (of course) not of her *results*!
  - Shimony concludes that entangled states exhibit Parameter Independence (NCS) but violate Outcome Independence, only the latter of which is needed to violate the BI.
  - Hence there is nonlocality but it is uncontrollable in principle.
- Questions about this proof:
  - Uncharitably, all it says is that if we assume Alice does not affect Bob's system, the QM formalism confirms this assumption.
  - Is this anything more than a trivial consistency check of the formalism?!?
  - I will review two recent results that draw Shimony's locality assumption into question.

Quantum Energy Teleportation

- Recent work by M. Hotta shows that quanta of energy can be teleported, using an application of the Ising spin chain.
- Hotta's Hamiltonian (in simplified form):

$$H_{AB} = \sigma_A^z + \sigma_B^z + \sigma_A^x \sigma_B^x$$

  where σ^z and σ^x are Pauli spin matrices.
- It is mathematically impossible to reduce this to a separable form (like Shimony's Hamiltonian).
  - Why? Because Pauli matrices are linearly independent, so the cross-term cannot be factorized without creating another cross-term.
- This does not mean that one *could* signal with Hotta's system, but *prima facie* it means that Shimony's proof is powerless to show that one cannot.

Entanglement in Photosynthetic "Light Harvesting Complexes"

- Recent work reported by M. Sarovar et al., in *Nature Physics*.

  Recent ultrafast spectroscopic studies have revealed the presence of quantum coherence at picosecond timescales in biological structures, especially in light-harvesting complexes. . . [Sarovar et al., Nature Physics, June 2010.]

  - The existence of QM entanglement at the biological scale could have many fascinating implications, which I will not explore here!

Sarovar's Hamiltonian

- Sarovar's Hamiltonian has the following structure:

$$H = \sum_{i=1}^{N} E_j |\, i \,\rangle\langle\, i \,| + \sum_{i=1}^{N} \sum_{j>i}^{N} J_{ij}(|\, i \,\rangle\langle\, j \,| + |\, j \,\rangle\langle\, i \,|).$$

  where the indices i and j run over the N chromophores of the system, E_j are energies, and the J_{ij} are coupling constants.
- The left-hand term is merely the sum of local energies of the chromophores (light-harvesting molecules).
- But as far as I can see the right side, representing coupling between sites, is non-factorizable; this Hamiltonian is therefore engangled and, again, violates Shimony's separability assumption.

Upshot...

- There are at least two recently studied examples of entangled states that violates Shimony's separability condition.
- Invites general question, are the Hamiltonians of *all* entangled states non-separable? Surprisingly, there is very little in the literature to help us with this question!
- Possible response by defender of peaceful coexistence:
  - These Hamiltonians with cross-terms are merely "effective Hamiltonians"—i.e., approximate in that they do not take into account the time delays required for the interactions between distinct sites; really, all such interactions are mediated by photons or other field quanta moving with velocity $\leq c$.

Counter-Conjectures

- My counter to this response:
  - The claim that all interactions in apparently entangled systems are local is a "reasonable" *conjecture* that has not been proven in general, even though it is one that many would prefer to accept.
  - I advance a counter-conjecture: at least one attempt to explain away cross-terms in some entangled Hamiltonian by means of local interactions will imply a Bell Inequality that is violated by some quantum-mechanical prediction.
- Stay tuned—and may the Force be with you!