Quantum Superposition and Entanglement in Curved Spacetimes and the Branching Structure of the Many Worlds Interpretation

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the framework: particle-like quantum systems propagating in curved spacetime, sometimes treated as “test matter”, sometimes as sources of curvature

many deep foundational issues about superposition and entanglement for such systems, oddly untreated in the literature, relating both to MWI in particular and to QM more generally

I apologize for roughness of some slides—based on discussions I had recently with Harvey Brown, Simon and David, and on questions inspired by Alyssa’s talk, I decided to change the focus of the second half of the talk to something I hope will be more interesting and more directly relevant to the conference

Outline

Spacetime Curvature, Entanglement and Bell

Spacetime Geometry, Superposition and Many Worlds

Spacetime Curvature, Entanglement and Bell

Spacetime Geometry, Superposition and Many Worlds

to whet your appetite, the first set up (VERY rough and schematic):

1. spacetime $(\mathcal{M},\, g_{ab})$ with "mild curvature" (characteristic curvature scales everywhere $\gg$ de Broglie wavelength of electrons—electrons "see spacetime as essentially flat")
2. generate pair of electrons in a spin-singlet state at $a \in \mathcal{M}$, shooting off in different directions along timelike "paths" γ, η ("test matter")
3. Polly at p $(= \gamma(\tau))$ and Quincy at q $(= \eta(\tau))$, spacelike related to each other, are set to receive the electrons and measure their spin to begin to test EPR correlations
4. Polly measures electron in her fixed ζ^a direction, gets $\uparrow$

what direction ought Quincy measure in order to be guaranteed of getting $\downarrow$?

prima facie, there is no principled way to answer this question. . .

in curved spacetime, there is no principled way to compare directions at distant points—to say what direction at q is "the same" as ζ^a at p

("path-dependence of parallel transport")

what does—*can*—"singlet state" *mean* here?

what happens to Bell correlations
in curved spacetime?

possible way to answer: play Fermi transport ("gyroscopes") and parallel transport of vectors off each other...

I am not convinced it works, and it would take us too far afield, and involve too many technicalities of general relativity for a QM conference, to discuss in detail today anyway...

but it does raise interesting challenges for MWI, how to think about branching when one must take account of spacetime structure, which I will now turn to by tackling the issue more directly

Spacetime Curvature, Entanglement and Bell

Spacetime Geometry, Superposition and Many Worlds ambiguity in idea of "location" (*e.g.*, of a self) in branching structure, and in idea of branching itself, in many (most? almost all?) discussions of MWI:

1. does "spacetime itself branch" at a branching event, so there are "multiple copies of spacetime"? ("Bob doesn't split when Alice performs distant measurement; rather he is now co-located in both spacetimes")
2. or do only the matter fields "branch" while remaining in "one genidentical spacetime"? ("Bob splits when Alice performs distant measurement; there are two copies of him in same spacetime")

(Alyssa put her finger on this ambiguity in a particularly clear way in her talk, even though she did not explicitly discuss it; it is not clear to me that the two options map cleanly on to the difference between the "overlap" and "fission" views of MWI) but—what can either option mean?

- what parts or aspects of spacetime and its structure are or ought to be involved, and how?
- what can one reasonably mean by “spacetime” here, especially after branching?

Christodoulou and Rovelli (2019) argue, I think persuasively, that recently proposed "table-top QG" experiments (Bose et al. 2017; Marletto and Vedral 2017) suffice to take seriously the possibility of a superposition of macroscopically distinct spacetime geometries (including causal structure)

I will not discuss the details of the proposed experiments; I will only sketch the set up and assume Christodoulou and Rovelli's conclusion in order to investigate whether it may suggest a way to resolve the ambiguity and answer some of our questions first part of set up, currently technically feasible:

1. mesoscopic particle ($m \sim 10^{-11}\texttt{gm}$) with intrinsic spin, in definite spatial position eigenstate (source of spacetime curvature)
2. put into spatial superposition using, *e.g.*, Stern-Gerlach, with components spatially localized non-trivial distance apart
3. and then later "branches recombine", transforming spatial superposition back to spatial eigenstate

second part, possible in principle, perhaps in not too distant future:

1. second mesoscopic particle identical to first
2. put into equivalent superposition at same time (in lab frame) as first, so all 4 spatially localized components lie in a straight line
3. such that the closest spatially localized components are mesoscopic distance apart $d \sim 10^{-4}\texttt{cm}$
4. and remain so for a time $t \sim 1\texttt{s}$ before spatial superpositions of both particles transformed back to respective original position eigenstates

(see Aspelmeyer 2022)

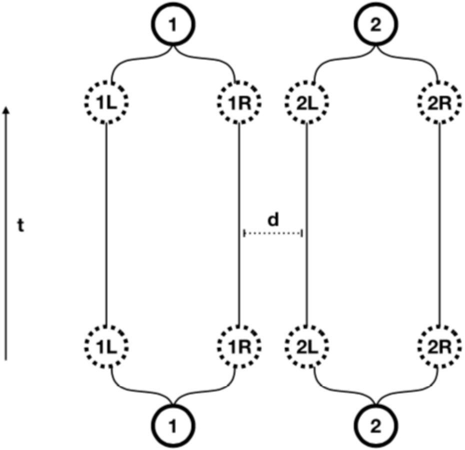

Fig. 1. The BMV setting.

(taken from Christodoulou and Rovelli 2019)

- one expects entanglement to develop between the two particles due to the “rotation” of the quantum state phases induced by the shift in energy of each particle from their non-negligible mutual gravitational attraction in branch $1\textsc{r}\text{-}2\textsc{l}$

- Bose et al. (2017) and Marletto and Vedral (2017) develop information-theoretic arguments that such entanglement can be mediated by a physical entity (in this case, “the gravitational field”) only if that entity is itself a quantum system

- Christodoulou and Rovelli denominate this “the BMV effect”

Christodoulou and Rovelli further argue to explicitly conclude (p. 64, their emphasis):

> [T]he BMV effect counts as evidence that *quantum superposition of different [classical] spacetime geometries is possible, can be achieved in the lab, and has observable effects*.

- during the period when there are 4 branches (1R-2L, 1L-2L, 1L-2R, 1R-2R), there is a quantum superposition of 2 classical spacetime geometries

- when the particles' superpositions ("branches") recombine, returning to position eigenstates, the spacetime geometry does so as well

option 1 "spacetime itself branches"

1. there are "two copies of the entirety of spacetime" during superposition
2. they recombine back into one when superposition is re-combined

I have no idea how to understand this

option 2 "only matter fields branch"

1. there are "two copies of (parts of) spacetime geometry" during superposition
2. they recombine back into one when superposition is re-combined

I think I may have a way to begin to try to understand this

- on the decoherence branching picture, the splitting spacetime geometries are (presumably) effective descriptions, (presumably) emergent from some (presumed) underlying structures of a quantum gravity world
- only those “parts” of the total classical spacetime geometry non-negligibly affected by the changes in the matter distribution (causal or null cone structure, affine structure, metric structure, but not differential structure or topology?) are in an effective superposition *locally* (the spacetime region affected by the superposition of the matter distribution)
- these “localized superposed parts” spread out from branching event with speed determined by the decoherence process—in this case, presumably c, since the decoherence process will be mediated by gravitational interaction

still leaves us (me?) with several questions; here are a few:

1. after recombination of superpositions, do the previously localized superposed parts of spacetime geometry continue to "propagate outward"?
2. if "parts" of local geometries can branch without the entirety of spacetime structure replicating itself in new branches, how do the branched and unbranched parts relate to each other?
3. does, *e.g.*, only the "Ricci part" of ${R^a}_{bcd}$ branch while the "Weyl part" doesn't? how then can causal structure branch?
4. but the Weyl tensor is sensitive to the 4-gradient of T_{ab}, and spatially localized matter has non-trivial momentum spread: is the (presumably) induced quantum fuzziness of the conformal structure in each branch in some sense consistent with the splitting of the causal structure?
5. there are delicate but rigid relations of inter-dependence between levels of spacetime structure in classical GR, *e.g.*, between curvature and topology—how is one supposed to make sense of these relations during the branching if only one level of structure branches but not the other?
6. it does not seem that the usual position basis can serve as the privileged decoherence basis when spacetime structure branches—can one make sense of a decoherence basis in this process at all? if so, what is it? how about when "recombining branches"?

and on that unresolved dissonance,
I end

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