Nonlocality in MWI, from the 'everything' list 2016

Some of the comments from Bruce Kellett at that time.

Let me reduce this to simple steps:

1. MWI is an interpretation of QM only, *I.e.*, it reproduces all the results of QM without adding any additional structure or dynamics.
2. The QM state describing an entangled singlet pair does not refer to, or depend on, the separation between the particles.
3. The quantum calculation of the joint probabilities depends on the relative orientation between the separate measurements on the separated particles.
4. This quantum calculation is the same for any physical separation, since the singlet state itself does not depend on the separation.
5. The quantum calculation is, therefore, intrinsically non-local because it does not depend on the separation, which can be arbitrarily large, and space-like.
6. Since MWI does not add anything to standard QM, and standard QM gives a non-local account of the probabilities we are considering, any MWI account must also be intrinsically non-local.

The mathematical rule that gives the differing probabilities for each outcome depending on the relative angle of the magnets is just quantum mechanics. But that is intrinsically non-local — QM treats the separated component of the entangled pair as a single system, and the description of that entangled state does not depend on the physical separation of the components — the components are treated as a single unit at all separations. Quantum mechanics is thus mute about any local physical mechanism whereby the information about the orientation of A's magnet is conveyed to B (or *vice versa*) — quantum mechanics, unlike laboratory experiments, does not recognize the existence of any separation.

Note added: *The singlet state is local in configurations space, even though non-local in ordinary 3-space.*

The $\cos^2(\theta/2)$ comes from applying the standard quantum rules to the singlet state

$$|\psi\rangle = (|+\rangle|-\rangle - |-\rangle|+\rangle)/\sqrt{2}$$

I think it would be instructive to actually go through the usual quantum derivation of the correlations, because what you call "reducing the wave after the measurement" is actually the result of applying the standard quantum rules. It has nothing to do with so-called 'collapse' interpretations: it is simply in the theory.

Quantum rules for measurement say that the initial state can be expanded in the basis corresponding to the particular measurement in question (contextuality). That is what the state $|\psi\rangle$ above is — the quantum expansion of the singlet state in the basis in which say Alice is doing her measurement. Quantum rules then say that the result of the measurment (after decoherence has fully operated) is one of the eigenstates in the expansion, and the measured result is the corresponding eigenvalue. In our case, there are two possibilities for Alice after her measurement is complete: result '+', with corresponding eigenstate $|+\rangle|-\rangle$, or '−', with corresponding eigenstate $|-\rangle|+\rangle$. There are no other possibilities, and Alice has a 50% chance of obtaining either result, or of being in the corresponding branch of the evolved wave function.

The question now arises as to how the formalism describes Bob's measurement, assuming that it follows that of Alice (there will always be a Lorentz frame in which that is true for space-like separation. For time-like separations, it is either true, or we reverse the A/B labels so that it is true.) Since the description of the state does not depend on the separation between A and B, after A gets '+' and her eigenstate is $|+\rangle|-\rangle$, Bob must measure the state $|-\rangle$ in the direction of his magnet. To get the relative probabilities for his results, we must rotate the eigenfunction from Alice's basis to the basis appropriate for Bob's measurement. This is the standard rotation of a spinor, given by

$$|-\rangle = -\ \sin(\theta/2)|+'\rangle + \cos(\theta/2)|-'\rangle.$$

Applying the standard quantum rules to this state, Bob has a probability of $\sin^2(\theta/2)$ of obtaining a '+' result, and a probability of $\cos^2(\theta/2)$ of obtaining a '$-$' result.

Using test values for the relative orientation, θ, we get the usual results. For $\theta = 0°$ orientation, Bob has probability 0 of obtaining '+', and probability 1 of obtaining '$-$'. For 90° orientation, the probabilities for '+' and '$-$' are both 0.5. For a relative orientation of 120°, Bob's probability of getting '+' is 0.75 and the probability of his getting '$-$' is 0.25.

This is not controversial, and the result depends only on the standard rules of quantum mechanics. The problem of interpretation, of course, is that since Alice and Bob are at different locations, and the state they are measuring is independent of separation, there is an intrinsic non-locality implied by the standard calculation. If you take out the quantum rule that the result of a measurement is, after decoherence, reduction to an eigenstate with the corresponding eigenvalue, you take away an essential ingredient of the quantum derivation, and leave Bob's measurement as being completely independent of that of Alice, so the only possible results for Bob ar '+' and '$-$' with equal probability, whatever the orientation of his magnet.

Any account that deviates from this is no longer a standard quantum account because it would not conform to the above rules. And these rules are among the best-tested rules in all of physics. They are the basis for the whole of the phenomenal success of this theory over nearly a hundred years and in every field in which it has been applied. You abandon these principles only at extreme peril.

There is a widely cited paper by Tipler (arxiv:quant-ph/0003146v1) that claims to show that the MWI does away with non-locality. It is instructive to go through his argument, and to see how he has managed to deceive himself. We start with the singlet state:

$$|\psi\rangle = (|+\rangle|-\rangle - |-\rangle|+\rangle)/\sqrt{2},$$

and then expand the state for the second particle in a different basis (at relative angle θ):

$$\begin{aligned} |+\rangle_2 &= \quad \cos(\theta/2) * |+'\rangle + \sin(\theta/2) * |-'\rangle, \\ |-\rangle_2 &= -\ \sin(\theta/2) * |+'\rangle + \cos(\theta/2) * |-'\rangle. \end{aligned}$$

Substituting this in to the singlet state above, we get

$$|\psi\rangle = -\Big[\sin(\theta/2) * |+\rangle|+'\rangle - \cos(\theta/2) * |+\rangle|-'\rangle + \cos(\theta/2) * |-\rangle|+'\rangle + \sin(\theta/2) * |-\rangle|+'\rangle\Big]/\sqrt{2},$$

which exactly represents the requisite four worlds, corresponding to the (+,+′), (+,−′), (−,+′), and (−,−′) possibilities for joint results, each world weighted by the required probability. Tipler claims that this shows how the standard statistics come about by local measurements splitting the universe into distinct worlds.

Tipler is, of course, deluding himself, because the above calculation is not local. It is, in fact, nothing more than the stadard quantum calculations (with the projection postulate evident) that I gave above for the possible '+' and '−' results for Alice, combined in the one equation. It still uses the fact that Alice's measurement of particle 1 affects the quantum state for particle 2 (which is, by then, a large space-like distance away). Tipler utilizes the non-local natuure of this change to extract θ, the relative orientation of magnets — a relative orientation that can only be known by comparing orientations at A and B directly. So Tipler's derivation is every bit as much local or non-local as the conventional calculation — he has not eliminated non-locality by his trivial re-working of the derivation.

Note added: The expectation value for the product of the spins is just the sum of each outcome, multiplied by the probability of that outcome

$$(+1)(+1)P_{++} + (+1)(-1)P_{+-} + (-1)(+1)P_{-+} + (-1)(-1)P_{--},$$

where P_{+-} is the probability that the first spin measured spin up, and the second spin is measured spin down, and similarly for the other Ps. Inserting these probabilities — the squares of the coefficients in the above equation — into the equation for the expectation value, gives

$$\begin{aligned}\langle \hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2 \rangle &= \frac{1}{2}\big[\sin^2(\theta/2) - \cos^2(\theta/2) - \cos^2(\theta/2) + \sin^2(\theta/2)\big] \\ &= -\cos(\theta)\end{aligned}$$

which is the quantum expectation value for the correlation of the two spin measurements.