Bell was simply wrong

Bell oversimplified his model based on confusing a provisional precession eigen-value equation with Dirac's fundamental helicity eigenvalue equation. I derive a local classical model based on energy-exchange physics that Bell intentionally suppressed and I show that Bell's constraints determine whether the model is local or non-local. The physical theory upon which the model is based can be tested experimentally; if valid, Bell's claims of non-locality will be proved wrong.

H.L. Mencken said it well:

> *"Complex problems have simple, easy to understand, wrong answers."*

Bell demonstrated this by following his maxim [1]:

> *"Always test your general reasoning against simple models",*

while ignoring Einstein's maxim:

> *"... as simple as possible, but not simpler."*

This paper will demonstrate Bell's oversimplification of the complex physics underlying Bell's model, calling into question his conclusions about the non-local nature of reality. In "*50 years of Bell's theorem*", the editors remark [2] that "*...one may be surprised that 50 years later not all issues are settled...*" which I take as proof that the problem is complex. Because complex problems have many details, I have written longer treatments of the physics [3, 4]. This paper is a brief overview of critical errors in Bell's analysis, based on his

1. suppression of $\theta = (\vec{a}, \lambda)$ physics,
2. confusion over Dirac's spin eigenvalue equation,
3. constraints imposed on local models.

From *The Formalisms of Quantum Mechanics* [5]: the expectation value of an observable (the outcome of a measurement on the system in state ψ),

$$\langle A \rangle_\psi = \langle \psi \,|\, A \,|\, \psi \rangle = \langle \psi \,|\, A\psi \rangle , \qquad (1)$$

"*implies (or is equivalent to state) that the possible outcomes of the measurement of A must belong to the spectrum of A, i.e., can only be equal to eigenvalues of A.*"

This is what Bell believes he is assuring by constraining measurement values:

$$A(\vec{a}, \lambda) = \pm 1 \text{ and } B(\vec{b}, \lambda) = \pm 1 . \qquad (2)$$

If Bell had just claimed that his simple model does not work, there would be no serious problem. But that is not what Bell claimed. Instead, he concluded that the ultimate nature of reality is non-local. That's a lot of weight resting on a model that is based on suppressing the physics of the measurement.

Bell's key physical assumptions [6]:

1. Stern-Gerlach measures spin components.
2. The spin eigenvalue equation is $\sigma_z \,|\pm\rangle = \pm\,|\pm\rangle$.
3. The relevant physical force, $F\cos\theta \;\Rightarrow\; F\cos\theta / |\cos\theta\,|$.
4. The magnetic moment precesses as it traverses the magnetic field.

Based on these assumptions, Bell shows [7] that *a local model cannot produce* the correlation $-\vec{a}\cdot\vec{b}$, while analysis of Stern-Gerlach experiments [3,4] has led to construction of *a local model that does produce* the correlation $\langle AB\rangle = -\vec{a}\cdot\vec{b}$, based on physics that Bell suppressed. Subsequently, our local model has been challenged [8] as follows:

A. Electron spin has two eigenvalues, ± 1
B. Idealized experiments yield eigenvalue measurements.

Further, Dirac's equation shows spin $=\pm 1/2$*, so (A) implies (B).*

This, by definition, sounds logical, but an extensive treatment by Potel [9], in "*Quantum mechanical description of Stern-Gerlach experiments*", notes:

> *"Thus, we can conclude that the Stern-Gerlach experiment is not, even in principle, an ideal experiment, which would "project" the internal state into the eigenvalues of the measurement operator."*

Belief in *eigenvalue measurement,* as sufficient reason for constraints $A, B = \pm 1$, is challenged quantum-mechanically by Potel's paper.

Yet the appeal to Dirac's authority is interesting; Stern-Gerlach experiments are nonrelativistic, so the Dirac equation is normally not part of Bell's analysis. Nevertheless, this argument seems reasonable, so we review Dirac's solution, [10], a 4-component vector:

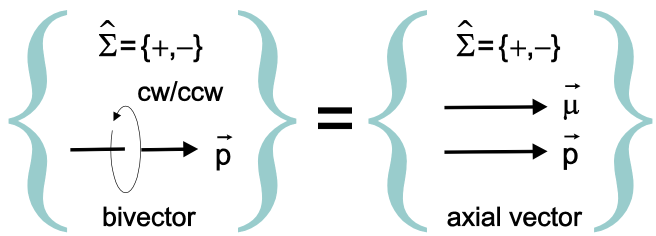
Energy	Spin
+	+
	-
-	+
	-

$$\Rightarrow \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

Since the energy terms can mix, there is no simple spin eigenvalue equation of the sort assumed by Bell. This motivates the Foldy-Wouthuysen transformation [11,12] which eliminates the negative energy components to any desired order in v/c while transforming from Dirac's point-based formalism to one averaged over a Compton wavelength around the particle, producing a 'mean' spin, Σ. *Projecting* this spin on particle momentum, $\vec{p}$, yields the following equation:

$$\hat{\Sigma}\cdot\hat{p}\,|\pm\vec{p}\rangle = \pm\,|\pm\vec{p}\rangle\,, \qquad (3)$$

where $\hat{p}=\vec{p}/|\vec{p}|$ and $|\pm\vec{p}\rangle = |\pm\rangle \otimes |\vec{p}\rangle$ with $|\pm\rangle =$ intrinsic angular momentum eigenvector and $|\vec{p}\rangle =$ linear momentum eigenvector. This equation, which is based on the 2-component FW-Dirac solution, has the same *form* as the spin equation used by Bell, but it does *not* represent the same physics. For example, Griffiths [13] notes there is no 'spin-up' or 'spin-down' associated with Dirac's equation, unless the spin is pointed in the $\vec{p}$ direction. Equation (3) describes helicity, or 'handedness' of the spin, as seen from the perspective of momentum $\vec{p}$, with eigenvalues representing CW and CCW. This is perhaps best understood in terms of a geometric algebra *bivector representation* of spin rather than the usual *axial vector representation*:



The 2-dimensional bivector is characterized by *area* and *direction,* with the two directions labeled CW and CCW. The area is unity, appropriately normalized. 'Projecting' unit magnitude spin on momentum, $0 \le |\vec{p}| < \infty$, makes no physical sense; rather it is the *direction of rotation* with respect to $\vec{p}$ that is described by the *fundamentally dichotomous FW-Dirac helicity eigenvalue equation.*

Another of Bell's key assumptions is that of no θ-dependence, since Bell [6] replaces the classical $F\cos\theta$ with $F\cos\theta/|\cos\theta|$. But an *Energy-Exchange theorem* [3,4] proves that if two energy modes depend on a common variable, the modes will exchange energy. For Stern-Gerlach the precession energy is $f(\theta) = -\vec{\mu}\cdot\vec{B}$, where $\vec{\mu}$ is the magnetic dipole of the particle and $\vec{B}$ is the external magnetic field with angle $\theta = \cos^{-1}\left(\vec{\mu}\cdot\vec{B}/|\mu||B|\right)$. If the field has a non-zero gradient, then a force, $\vec{\nabla}(\vec{\mu}\cdot\vec{B})$, is exerted on the dipole, resulting in deflection energy $g(\theta) = \vec{\nabla}(\vec{\mu}\cdot\vec{B})\cdot d\vec{x}$ in the $\hat{x}$ direction. The energy equation is

$$E = f(\theta) + g(\theta)\,. \qquad (4)$$

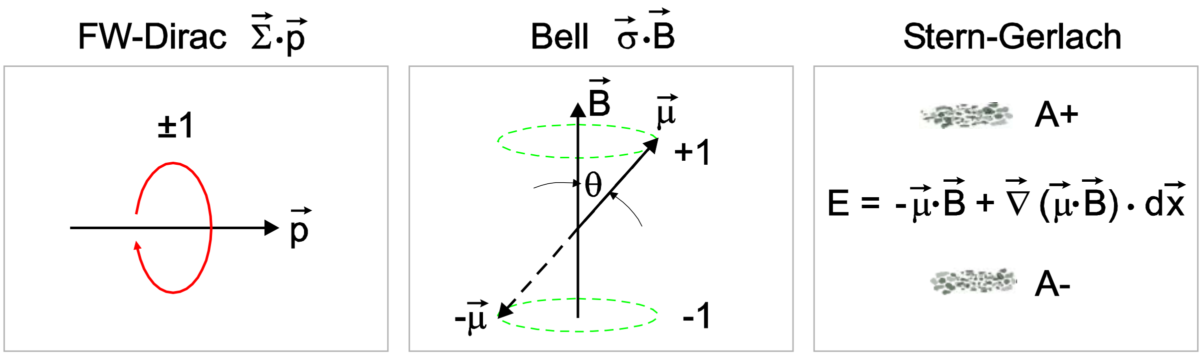
As a result the precessing moment will dissipate energy into deflection mode, and will align with the local field. Bell's suppression of θ-dependent energy exchange, and assumption that the magnetic moment simply precesses as it traverses the Stern-Gerlach apparatus, meant that only the simple term $\hat{\sigma}\cdot\vec{B}$ appears in Schrödinger's equation [14], leading to the eigenvalue equation

$$\hat{\sigma}\cdot\hat{B}\,|\pm\vec{p}\rangle = \pm\,|\pm\vec{p}\rangle\,. \tag{5}$$

Thus Bell relied upon a precession eigenvalue equation that superficially resembles the Dirac helicity eigenvalue equation [15]:

$$\hat{\Sigma}\cdot\hat{p}\,|\pm\vec{p}\rangle = \pm\,|\pm\vec{p}\rangle \quad\approx\quad \hat{\sigma}\cdot\hat{B}\,|\pm\vec{p}\rangle = \pm\,|\pm\vec{p}\rangle\,. \tag{6}$$

These equations appear formally equivalent, but they are essentially different in nature: Dirac's helicity eigenvalue equation is *fundamental* for any particle with spin-$1/2$, but Bell's precession eigenvalue equation is *provisional*, provided that the external field is constant. *This leads to a contradiction*: Stern-Gerlach produces a null result if the field is constant [16], while, on the other hand, the provisional precession eigenvalue equation does *not* produce discrete eigen-values, but a continuous spectrum, if the gradient force term is included in the Schrödinger equation: $A(\vec{a},\lambda)\neq\pm1$ and $B(\vec{b},\lambda)\neq\pm1$, as shown in the diagram…



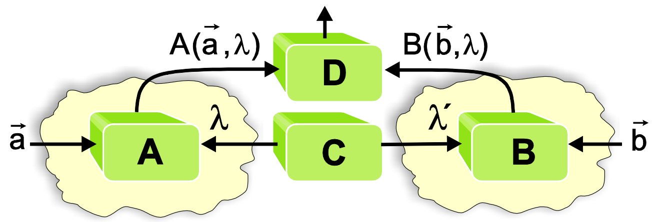
$\hat{\sigma}\cdot\hat{p}\,|\,\hat{p}\lambda\rangle = \lambda\,|\,\hat{p}\lambda\rangle$	$\hat{\sigma}\cdot\hat{B}\,|\pm\rangle = \pm\,|\pm\rangle$	no discrete eigenvalues
Fundamental particle: Helicity eigenvalues	Quasi-particle: Precession eigenvalues	helicity not relevant and precession varies

By suppressing the θ-dependence of the physics, and by confusing the eigen-value equations, the assumptions upon which Bell bases his constraints, eqn (2), are simply wrong. Bell oversimplified the problem.

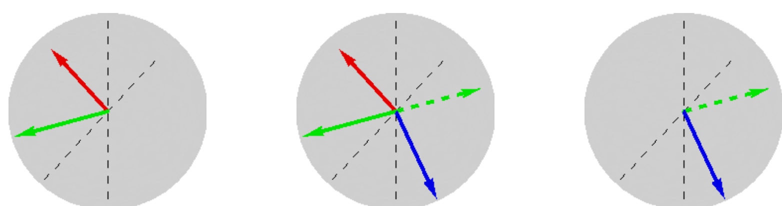
How can we test this? Based on the energy-exchange theorem, [3][4] the classical model will exchange θ-dependent precession energy with deflection mode energy leading to variable deflection with the contribution

$$x = \left(\frac{|\vec{\mu}|\,|\vec{B}|}{|\nabla(\vec{\mu}\cdot\vec{B})|}\right)(1-\cos\theta)\,. \tag{7}$$

Thus, in a classical model, the initial spin λ (hidden from quantum mechanics) will make angle $\theta = (\vec{a}, \lambda)$ when Alice chooses $\vec{a}$ as the direction of her Stern-Gerlach magnetic field; she will calculate a scattering angle with a component given by equation (7). Bob will see an initial spin $\lambda' = -\lambda$ with angle $\theta' = (\vec{b}, \lambda')$ and calculate the local deflection predicted for his SG apparatus. Two values of deflection representing measured outputs can, post-experiment, be processed by a decision module (D) to generate the correlations. The system based on a local classical model is shown below



The model is run by generating random local spins $\lambda + \lambda' = 0$ and sending λ to Alice's A-module and λ' to Bob's B-module. Alice chooses a random direction $\vec{a}$ and calculates the θ-dependent contribution to deflection from eqn (7). An example of the randomly generated values for each experiment is shown below, with spin λ (green), λ' (dashed green), and vectors $\vec{a}$ (red) and $\vec{b}$ (blue).



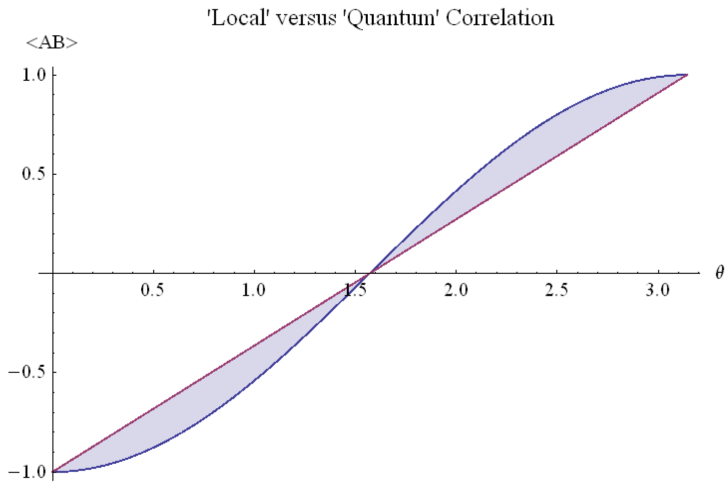
Recall that actual experiments show that the correlated measurements agree with the quantum mechanical prediction, and the consensus of physicists is:

"No local model can reproduce QM prediction"

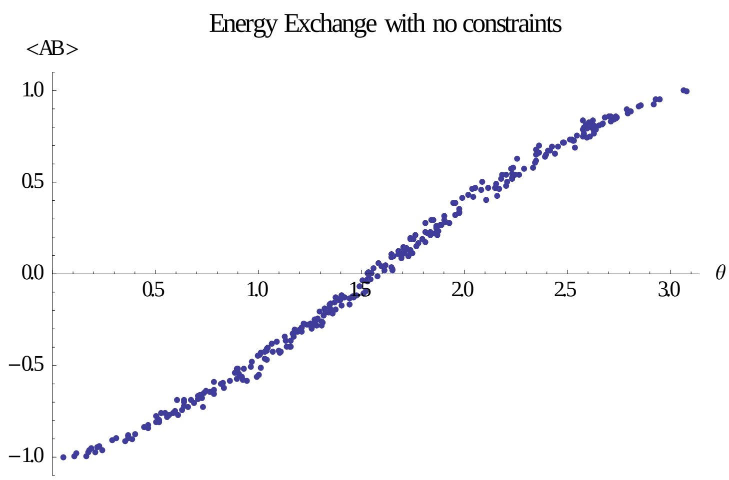
Quantum mechanics predicts the correlation

$$\langle AB \rangle \quad = \quad \langle singlet \,|\, \hat{\sigma}_A \cdot \vec{a} \; \hat{\sigma}_B \cdot \vec{b} \,|\, singlet \rangle \quad = \quad -\vec{a} \cdot \vec{b} \qquad (8)$$

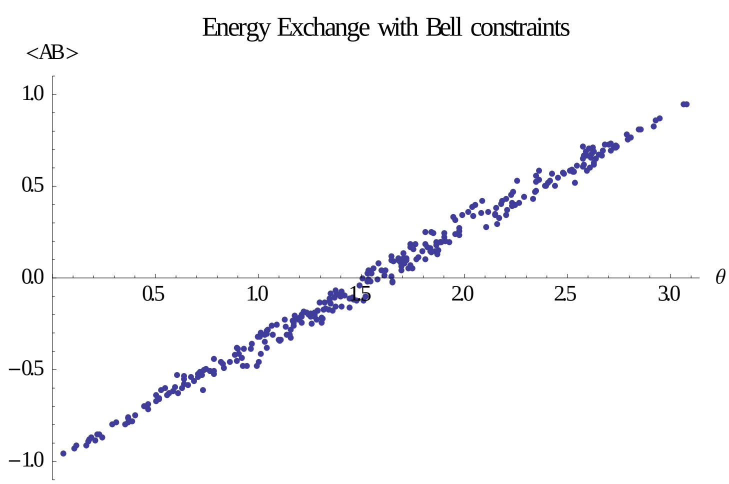
and this value agrees with experiment. Bell proved to everyone's satisfaction that, subject to his constraints, the correlation cannot exceed the straight line characterized by $-1 + 2\theta/\pi$. Peres [17] overlays these two correlations:



Our local classical model with 10,000 random particles spins λ for each of the 300 random pairs of control settings, $\vec{a}$ and $\vec{b}$, is shown below:



This result exactly agrees with the quantum prediction that Bell claimed to be impossible for local models. How can this be? Compare to results obtained from the same local model with Bell's constraints applied:



Not surprisingly, my constrained local model matches Bell's theorem, while our unconstrained model violates Bell's theorem, and matches QM predictions and reality. Our analysis and local model are based on Energy-Exchange physics (QSLR and SPIN) since two energy modes – precession and deflection – appear in the Stern-Gerlach system. To apply Bell's constraints to our model we truncate both calculations to ± 1 rather than use the value of $A(\vec{a},\lambda)$ calculated by Alice and $B(\vec{b},\lambda)$ calculated by Bob. With Bell's constraints applied to our model, the model fails to predict $-\vec{a}\cdot\vec{b}$, but without his constraints, our local model does what Bell claims to be impossible. Bell's overly simple assumptions led to his imposition of constraints, which in turn led to his incorrect predictions.

Conclusion:

Thus our analysis shows Bell's theorem to be oversimplified and wrong. His assumptions led to his claim that it is impossible for <u>any</u> local deterministic model to reproduce the quantum prediction, $-\vec{a}\cdot\vec{b}$. Analysis of the eigenvalue basis of his hidden constraints (*hidden*, because they are not recognized as constraints by physicists) shows that Bell confused a *provisional precession eigenvalue equation* with Dirac's *fundamental helicity eigenvalue equation* . The FW-Dirac equation is assumed always true, but the provisional equation is true only provided that the local magnetic field is constant, and this leads to a contradiction, thus bringing Bell's claim of non-locality into question.

In our energy-exchange model of local classical physics the unconstrained results agree perfectly with the experimentally verified quantum predictions. However, the same model with Bell's constraints applied obtains the results claimed by Bell. Thus [18] Bell's 50 year old 'proof' of the non-local nature of the Universe is based on an oversimplified solution to a somewhat complex problem, and, as this is generally considered the basis of "entanglement" it suggests that a reappraisal of much of current physics is in order. Susskind claims that entanglement is 'weird' in that it describes the system, even when nothing is known about either particle. Pre-Bell this was simply understood as conservation of energy and momentum; nothing weird about it.

Fortunately, this θ-dependent scattering should be testable experimentally. If the experimental test of θ-dependence agrees with our energy-exchange theory, the fifty-year old belief in non-intuitive non-locality will be seen as consequence of overly simple assumptions leading to the imposition of hidden constraints.

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