Can a falling tree make a noise in two forests at the same time?

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Abstract
It is a commonplace to claim that quantum mechanics supports the old idea that a tree falling in a forest makes no sound unless there is a listener present. In fact, this conclusion is far from obvious. Furthermore, if a tunnelling particle is observed in the barrier region, it collapses to a state in which it is no longer tunnelling. Does this imply that while tunnelling, the particle can not have any physical effects? I argue that this is not the case, and moreover, speculate that it may be possible for a particle to have effects on two spacelike separate apparati simultaneously. I discuss the measurable consequences of such a feat, and speculate about possible statistical tests which could distinguish this view of quantum mechanics from a “corpuscular” one. Brief remarks are made about an experiment underway at Toronto to investigate these issues.

Jean-Pierre Vigier has long been at the center of some of the deepest controversies in quantum mechanics, his work bearing on questions of determinism, locality, and the very nature of light. At this meeting in his honour, we have seen that these disputes rage on, and have heard analyses of experiments as old as the Michelson-Morley and as recent as the latest work on correlated photon pairs. I hope it is fitting to extend this range yet further into the future, and attempt to draw conclusions from an experiment so new that we have only begun to build it at the University of Toronto.

It is of course well-known that many aspects of quantum mechanics, most notably the EPR experiments and the Aharonov-Bohm effect, are nonlocal; but also that causality is always enforced, \textit{i.e.}, that no information is ever conveyed faster than light. The tension between these concepts points to a gap between our theory and our understanding of this theory. It seems worthwhile to study the varieties of nonlocality predicted by quantum mechanics, so as to begin improving this state of affairs. In this paper, I make some brief remarks about some “local” intuitions I believe have survived quantum theory in the minds of many practicing physicists, and speculate about whether or not they are in fact consistent with our theory. I will describe a set of experiments we are currently preparing at Toronto for the purpose of investigating these issues in the laboratory.

What do we mean when we say that quantum mechanical nonlocality does not violate causality? In the most well-known example, the case of EPR correlations, what occurs at one point may depend nonlocally on what occurs at some far-separated point. However, neither occurrence depends on
anything we control at a far-separated point. In the language of Shimony, quantum mechanics may violate “outcome independence,” but it preserves “parameter independence”[1, 2]. No information about our own decisions gets transmitted faster than light; only random information about which of several possible outcomes was realised is “propagated” (one might better say created) in a nonlocal fashion.

The other best-known example of nonlocality in quantum mechanics, the Aharonov-Bohm effect, shows that the phase of a particle may be affected by a magnetic field the particle never actually enters. However, this absolute phase is unmeasurable. Only by having a portion of the particle’s wave function go around the other side of the confined field can we measure a relative phase and thus acquire information about the quantity of enclosed flux. This requires us to spatially close the loop, removing any possibility of acquiring the desired information in a superluminal fashion.

Published discussions of “nonlocality of a single particle”[3, 4, 5] have so far relied on examples where there are in fact at least two particles at play (one typically masquerading as a “local oscil-lator”). The fact that one cannot tell which of the two one observes is used as an indication that one’s interpretation ought not ascribe a local existence to either one of the particles.

Finally, it has been observed that in the presence of gain, loss, or tunnelling, the peak of a transmitted wave function may appear to traverse a region faster than the vacuum speed of light c. However, it has also been shown that no information is conveyed by this superluminal propagation, and that the obstacle merely serves as a sort of analog computer, predicting within a certain level of approximation what the future of the wave function ought to look like[6, 7].

It has been shown in the context of relativistic quantum field theory[8] that information transfer faster than light is in general impossible. More precisely formulated, the statement is as follows: no action performed at a spacetime point \((r_0, t_0)\) has any effect on the expectation value for any measurement performed at a point \((r_1, t_1)\) s.t. \(|c(t_1 - t_0)| < |r_1 - r_0|\).

Let us then consider a slightly different question. Granted, a cause can have no spacelike-separated effect. But can a cause have two different effects which are spacelike-separated from each other (not, of course, from the cause itself)? A simple example is a radio broadcast, where two receivers on opposite sides of the transmitter may simultaneously receive a message; there is clearly no problem with causality here. There is also no problem with locality: the antenna sends out many photons, some going one way and some going the other. Were it only to send out a single photon, no more than one of the receivers could detect it.

Or is this so? Can a single particle/wave influence “detectors” at two spacelike-separated positions? I believe most practicing physicists share with the layman the classical intuition I shall call “corpuscular,” which says that such a thing is impossible. Even if a particle’s behaviour is described by a wave equation, in the end all of the acceptable alternate outcomes we expect quantum mechanics to offer us generally involve a particle being in one place or another. This is enforced by collapse: if I detect a particle at receiver 1, the state of the system collapses to one in which the wave function of the particle no longer extends out to receiver 2. The implication here is that the wave function is “epistemological,” rather than “ontological,” to follow the usage of Aharonov et al., who have recently argued that we should recognise the physical reality of a wave function itself[9, 10, 11].

The question becomes significantly less clear if we remove the collapse event from the equation. A particle has an extended wave function. Even if its interactions are purely local, it may therefore influence two separated measuring devices simultaneously. This is not to say that two separated detectors will at the same instant fire at the instigation of a single particle, but only that the wave functions of both detectors may be modified by the particle’s passage. If the interaction
between the particle and either device is extremely strong, then the two possible final states of the device corresponding to presence or absence of a passing particle will be nearly orthogonal. This orthogonality will lead to decoherence, or an effective “collapse,” such that one detector’s firing will completely inhibit any effect of the particle on a spacelike separated detector[12, 13, 14].

Following the ideas of Aharonov et al. on “weak measurement, let us consider instead the limit where this interaction between the particle and the detectors is exceedingly weak[15, 16, 17]. The predictions of quantum mechanics are clear: both detectors’ wave functions are modified by the passing particle, but neither is modified very much. By “not very much,” we mean that the inner product of the initial and final states is close to unity. Since no measurement can distinguish perfectly between nonorthogonal states, we can never be certain whether either detector was influenced by the particle. Therefore on no occasion will we find ourselves in the uncomfortable position of having to say that an individual particle definitely interacted with both spacelike separated detectors.

But what can we say after many particles have passed the detectors, each one having a wave function split evenly between the two (see Fig. 1)? Eventually, each detector will have accumulated a measurable shift. We may attribute this shift to the detector having been shifted slightly by that half of the particles which interacted with it – or alternatively, to its having been shifted by half of each particle, since half of each particle’s wave function interacted with it. Is it possible to distinguish these pictures? Can we conclude (not on a case-by-case basis, but for an ensemble of passing particles) that both detectors must sometimes have been influenced by the same particle?

It seems likely that a statistical procedure will in fact make such an investigation possible. Let \( N \) particles each be split into a two-part wavefunction, interacting with \( 2N \) detectors \( A_i \) and \( B_i \) (\( i \) running from 1 to \( N \)). Let the initial state of the detectors be described by gaussians centered at 0:

\[
\Psi(x) = \exp\left(-\frac{x^2}{4\sigma^2}\right) \equiv G_A(0, \sigma).
\]

Further let the action of a single passing particle be to shift the wave function of the relevant detector by an amount \( \Delta \ll \sigma \) to \( G_A(\Delta, \sigma) \) or \( G_B(\Delta, \sigma) \), the inequality enforcing the “weakness” of the measurement, \( i.e., \) the non-orthogonality of initial and final detector states.

The expectation values of both \( x_A \) and \( x_B \) have shifted by \( \Delta/2 \) due to the passage of the particle, and of course, the expectation value of \( x_A - x_B \) remains unchanged at 0. This does not yet resolve the question. What must be examined is the distribution of \( x_A - x_B \). Its initial width of \( \sqrt{2}\sigma \) will be found to have grown slightly (to \( \sqrt{2}\sigma^2 + \Delta^2 \)) in the final state

\[
\frac{G_A(\Delta, \sigma)G_B(0, \sigma)|a\rangle + G_A(0, \sigma)G_B(\Delta, \sigma)|b\rangle}{\sqrt{2}}.
\]

This is because the orthogonality of the free-particle states \( |a\rangle \) and \( |b\rangle \) make the effective density matrix describing the detectors an incoherent mixture of \( A \) having shifted and \( B \) having shifted. That is, the information contained in the particle makes it always possible in principle to go back and ascertain which detector has shifted (albeit by a nearly immeasurable amount).

The situation becomes significantly more subtle if this information is erased[18, 19, 20, 21]. That is, suppose the particle’s two paths are recombined and the particle is postselected to be in the initial superposition

\[
\frac{|a\rangle + |b\rangle}{\sqrt{2}}
\]
(this is what I mean by a “conditional measurement”). This then leaves the detectors in the combined state

\[ K \{ G_A(\Delta, \sigma)G_B(0, \sigma) + G_A(0, \sigma)G_B(\Delta, \sigma) \} , \]  

where the normalisation constant \( K \equiv [2 (1 + |\langle G_A(0, \sigma)|G_A(\Delta, \sigma)\rangle|^2)]^{-1/2} \). We see, however, that even this entangled state implies an anticorrelation between the two detectors, and therefore expect that the uncertainty in \( x_A - x_B \) will still have grown. (Finding \( A \) at \( x = 0 \), for example, would leave \( B \) centered somewhat to the right of \( \Delta/2 \), while finding \( A \) at \( x = \Delta \) would leave \( B \) further to the left.)

It is not yet clear whether such an anticorrelation must always persist, but there is at least one situation which seems worthy of further investigation. Consider a particle tunnelling from left to right across a rectangular barrier. At early times, prepare it in a wavepacket incident from the left. At late times, it will be in a superposition of a reflected and a transmitted wavepacket; in certain regimes, the peak of the latter will have appeared superluminally with respect to the peak of the incident packet \([22, 23, 24, 25, 26, 27]\) (these effects, and their lack of implications for causality, are discussed in \([6]\)). Now suppose that we observe the particle on the right—in effect, this constitutes a projection onto the superluminally transmitted portion of the wave packet. Following the weak measurement formalism alluded to earlier, Fig. 2 shows the “conditional probability distribution” for the particle’s position as a function of time (see \([28, 29]\)). Note that this distribution is normalized, and reproduces exactly the state preparation and post-selection; at intermediate times, it is composed of a diminishing series of peaks near the entrance of the barrier, and a growing series of peaks near the exit. Physically, this distribution represents the magnitude of the effect which standard quantum mechanics predicts the particle would have on a detector at the position and time in question. A striking feature of the group delay time for quantum tunnelling is that it saturates as a finite value even as the barrier thickness grows \([30, 31, 26, 23]\). For extremely thick barriers, the shrinking peaks on the left and the growing peaks on the right will be almost entirely spacelike-separated, and yet each, when integrated over time, will contain nearly 100% of the particle density (contingent, of course, on the post-selection, whose success rate falls exponentially with barrier thickness).

It is not pointless to stress the procedure of a conditional measurement and the meaning of the quantities graphed in the figure. These measurements, while described by the standard apparatus of quantum theory, are not the type of measurement we are accustomed to dealing with, and the expectations we have of quantum measurements are not always fulfilled by them. Consider an ensemble of particles prepared in some state \( |i\rangle \). Let each particle interact with a detector via the familiar von Neumann interaction \( H_{\text{int}}(t) = g(t)x_p \cdot p_D \) such that subsequent to the interaction, the mean detector position \( \langle x_D \rangle \) will have shifted by an amount equal (for an appropriately normalised \( g(t) \)) to the particle position \( \langle x_p \rangle \). (The uncertainty in the detector position may be small or large, corresponding, respectively, to ideal quantum measurements or to Aharonov’s “weak” measurements. In the former case, an effective collapse occurs, but in the latter case, the back-action on the particle may be arbitrarily small.) But before recording the detector position, we may study the particle further. We may, for example, test whether or not it is in the final state \( |f\rangle \). If this test fails, we discard the detector reading, and only when the desired final state is reached do we record the position of the detector; this additional projection, or post-selection, constitutes the heart of a conditional measurement. We are now free to ask what the mean position of the detector is. The insight of Aharonov and his coworkers was that due to the time-reversibility of quantum evolution (in the absence of collapse), this quantity ought to depend as much on the post-selected state \( |f\rangle \) as on the preselected state \( |i\rangle \). In the limit of a sufficiently weak measurement, they found that
The inferred value of a measured operator $A$ is

$$\langle A \rangle_{wk} = \frac{\langle f | A | i \rangle}{\langle f | i \rangle}.$$  \hspace{1cm} (5)

It is easy to see that in the “standard” case $f = i$, this reduces to the usual expectation value. Now, for a weak measurement, any individual observation will have such a large uncertainty that very little information will be obtained; but by repeating many such observations, all the necessary statistics can nevertheless be built up. One has thus sacrificed case-by-case precision in the name of “gentleness,” of avoiding uncontrollable quantum back-action\[15, 16, 17\].

These conditional weak measurements have many interesting linearity-related properties. For example, if $\text{either}$ the initial or the final state is an eigenstate of the operator to be measured, the result is simply the corresponding eigenvalue. This leads to counter-intuitive results when combined with linearity. For example, if one prepares a particle in an eigenstate $S_z = +1/2$ and post-selects it in an eigenstate $S_x = +1/2$, consider a measurement of the spin-projection operator $[S_z + S_x]/\sqrt{2}$. It will yield a value of $1/\sqrt{2}$, which is outside the eigenvalue spectrum of the measured operator. Of course, no individual event will give definite evidence of such a value, because of the large uncertainty of the measurement; it is only when the average of many events is taken that this anomalously large shift will be observed\[15, 32\].

We are investigating the possibility that a similar anomaly will occur in connection with tunnelling\[28, 29, 6\]. Namely, a wave packet prepared to the left of a barrier will be certain to affect a detector at the entrance face of the barrier, as long as the detector is left open for a time longer than the wave-packet width. At the same time, a wave packet detected (post-selected) on the right of the barrier will be certain to have affected a detector at the exit face of the barrier. Due to the superluminality of the transmission indicated in Fig. 2, the time windows for these two detectors may be spacelike-separated for a thick enough barrier. Both detectors have then acquired a certain shift due to the nonlocal passage of the tunnelling particle, to be contrasted with the possible (and anticorrelated) shifts of Eq. (4). It seems possible that both detectors will therefore shift, without any increase in the uncertainty of their difference. A corpuscular model, on the other hand, would necessarily cause that uncertainty to grow, since only one detector would be affected by each particle. We are looking into the possibility of deriving rigorous inequalities to describe the predictions of such corpuscular models. We will also investigate the generalisation of Eq. (5) to higher moments, in order to compare the quantum-mechanical predictions for such conditional distributions with the requirements of corpuscularity. Iannaccone has already begun studying such quantities\[33\].

At the same time, we are building an atom-optics experiment which will let us directly test these questions, along with related issues to do with decoherence, dissipation, quantum-mechanical motion in time-dependent potentials, et cetera. We will start with a sample of laser-cooled Rubidium atoms in a magnetic trap, and use a tightly focussed beam of intense light detuned far to the blue of the D2 line to create a dipole-force potential for the atoms\[34, 35, 36\]. Using a 5W laser at 532 nm, we will be able to make repulsive potentials with maxima on the order of the Doppler temperature of the Rubidium vapour. Acousto-optical modulation of the beam will let us shape these potentials with nearly total freedom, such that we can have the atoms impinge on a thin plane of repulsive light, whose width would be on the order of the cold atoms’ de Broglie wavelength. This is because the beam may be focussed down to a spot several microns across (somewhat larger than the wavelength of atoms in a MOT, but of the order of that of atoms just below the recoil temperature, and hence accessible by a combination of cooling and selection techniques). This focus may be rapidly displaced \[37, 38\] by using acousto-optic modulators. As the atomic motion is in
the mm/sec range, the atoms respond only to the time-averaged intensity, which can be arranged to have a nearly arbitrary profile.

While eventually we plan to study ultracold (ideally, Bose-condensed) atoms in free fall, initial experiments will operate in the presence of the magnetic trap, relying on the dipole force both to perform additional velocity selection and to split the trap potential into an asymmetric double-well (cf. [39]). A “classical” barrier much wider than the wavelength will be used to adiabatically sweep all atoms with energies below the barrier height off to one side; atoms with higher energies will return to the center of the trap. We will thus have a secondary trap with velocity-selected atoms dominating the local density (see Fig. 3). By subsequently reducing the barrier width to a minimum (and simultaneously increasing the barrier height), we will be able to move into the quantum-mechanical regime. The tunnelling rate through this thin barrier will be monitored by imaging the trap and measuring the leakage from one well into the other. (For feasible parameters, predicted tunnelling rates are of the order of 1% per secular period, and the secular period will be on the order of tens of milliseconds, far shorter than the lifetime of the trap.) In the longer term, further cooling techniques will be used and the atoms will be allowed to fall freely, impinging on a barrier in otherwise free space. Multiple barriers, and combinations of magnetic and RF fields, will be used to form more complicated structures, such as Fabry-Perot cavities for the atoms.

The advantage of observing atoms tunnelling through these micron-scale barriers is that the atoms’ internal degrees of freedom offer an ideal way to perform the types of conditional measurements implicit in Figure 2. (Not only will this allow us to investigate the questions of locality I have raised here, but also simpler issues such as the prediction that the particle will almost never be seen in the center of the tunnel barrier, even when it is found to be transmitted.) In analogy with the Larmor clock championed by Büttiker[40], we will use the Zeeman and/or hyperfine levels of the Rubidium ground state to keep track of where the atoms have been. A focussed probe beam can be used to optically pump the atoms between different long-lived ground states. It is straightforward to calculate, and to measure in free space, the time rate of change of the polarisation under the influence of this beam. The transmitted and reflected atoms will be spatially separated, and their polarisations can therefore be measured independently by standard optical techniques. In this way, we will be able to measure how long each subensemble spent in the region illuminated by the probe beam. If the probe beam is pulsed, we can investigate a specific area of time as well as space. The analogy to a spin tunnelling through a magnetic-field region which causes Larmor precession is clear, although the use of optical beams makes it much easier to create a confined interaction region (with both spatial and temporal variability). The existence of multiple hyperfine and Zeeman levels only enriches the problem, and as discussed in [28], there are aspects of weak measurements which only become clear for the Larmor clock when dealing with spin > 1/2.

For the idealized tests we are aiming at, we will eschew optical pumping due to the dissipation inherent in its spontaneous emission phase. At the start, we plan to use the entirely coherent process of stimulated Raman scattering as a probe. More elaborate investigations of dissipation-induced decoherence will follow at a later date. Not only is the connection between decoherence and the measurement of a particle in a forbidden region interesting (any measurement which in fact collapses the atom into the barrier region necessarily imparts enough energy to the atom that it is now classically allowed, and evolves freely at subsequent times), but tunnelling itself in the presence of dissipation has long been an important problem[41, 42]. As for the size of the probe beam, it too will be diffraction-limited at at least several microns, so in order to study scales smaller than that of the barrier, we will produce small displacements, carrying out a differential measurement.

In order to address the question from the title, we will apply two simultaneous probe beams,
and study their joint action of the atoms’ internal states. For example, if one beam is adjusted to pump into higher Zeeman levels and the other to lower Zeeman levels, we can study whether half the atoms move in each direction or whether the two effects cancel out, leaving the atoms in their initial states. Such a cancellation would imply that an atom can be simultaneously influenced by two separate beams while it is tunnelling. (In practice, we will be dealing with length scales on the order of microns, and will of course not be able to check locality directly. We will have probe pulses separated sufficiently so that to cross both of them would require velocities larger than any characteristic speeds of the atoms in the experiment, and test whether the atoms nevertheless interact simultaneously with both beams; this is analogous to performing a test of Bell’s Inequalities without having fast enough timing to close the loophole.) We expect to see that this is in fact the case: that while both probes get shifted by the particles, the difference of the two shifts does not become any more uncertain. Coupled with appropriate inequalities, such an observation would serve as an experimental demonstration that in quantum mechanics, not only can an atom falling through a forbidden barrier make a sound, but it can make sounds in two places at the same time—but only if no one is there to listen too closely.

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Figure Captions

• Two spacelike-separated receivers may be simultaneously affected by a classical radio broadcast. What if the receivers are instead looking at different arms of an interferometer, both of which are simultaneously traversed by each particle which enters the device? As discussed in the text, an ideal detection event will lead to collapse (inhibiting interference, of course), but “weak” measurements will create a situation in which both detectors \( D_1 \) and \( D_2 \) pick up small shifts, only measurable after many many trials. The question of corpuscularity can be addressed by asking whether the difference \( D_1 - D_2 \) increases in uncertainty during this process or whether the two detectors shift in parallel with no extra dispersion. We are looking for quantitative inequalities for testing the hypothesis of corpuscularity. While the experiment drawn in this figure is not expected to disprove the hypothesis, we speculate in the text that a modified version involving tunnelling particles may well offer certain surprises.

• For a tunnel barrier extending from \( x = -5 \) to \( x = +5 \) (not shown), this sequence of snapshots shows the evolution of a tunnelling probability distribution. At early times, this is equivalent to \( |\Psi(x)|^2 \) for a wave packet incident from the left, while at late times it mimics a wave packet exiting (superluminally, for appropriate parameters) on the right. The formalism for calculating these conditional probability distributions is explained in [28, 29]. Note that at no time is there significant probability for the tunnelling particle to “be” near the center of the barrier, and that (to within the packet width) the distribution “jumps” instantaneously from the entrance to the exit of the barrier. This behavior persists for arbitrarily wide barriers.

• This is a schematic of our proposed experimental setup. Atoms initially cooled to sub-Doppler temperatures and trapped in a quadrupole magnetic trap will be subjected to the dipole force of an intense, focussed blue-detuned laser. If the beam waist is far greater than the atoms’ de Broglie wavelengths, the motion is essentially classical: all atoms with high enough energies surmount the barrier, and all others are reflected. As we slide the barrier through the atom cloud at velocities small with respect to the atomic motion, the lowest-energy atoms are adiabatically carried away from the trap center. By abruptly decreasing the beam waist and increasing the intensity, we will now be able to study the tunnelling of this velocity-selected sample through a quantum-mechanical barrier. (In experimental practice, the beam waist will be as small as possible from the start, but rapid dithering of the beam position will be used to create a time-averaged potential with an effective waist several times larger.)
receiver 1

receiver 2

radio broadcast

mirror 1

mirror 2

"click!"

det. 1

det. 2

beam splitter

$D_1 - D_2$

$D_1$

$D_2$

$D_1 - D_2$
