16. Bell-like experiments and non-locality.

The Bell experiment and Bell inequalities.

One type of experiment that is relevant to building a conceptual picture of what matter is really like was proposed by Bell in 1964 [1]. (See A16.1 for details.) He showed that if one assumes matter is particle-like in the sense that its influence is limited to a single **localized** region, then there is a conflict with quantum mechanics. In particular, he considered the case where there were two particles, electrons or photons, which were initially in a spin 0 state that split into two single-particle states that moved away some distance from each other, as in Fig. 16-1.

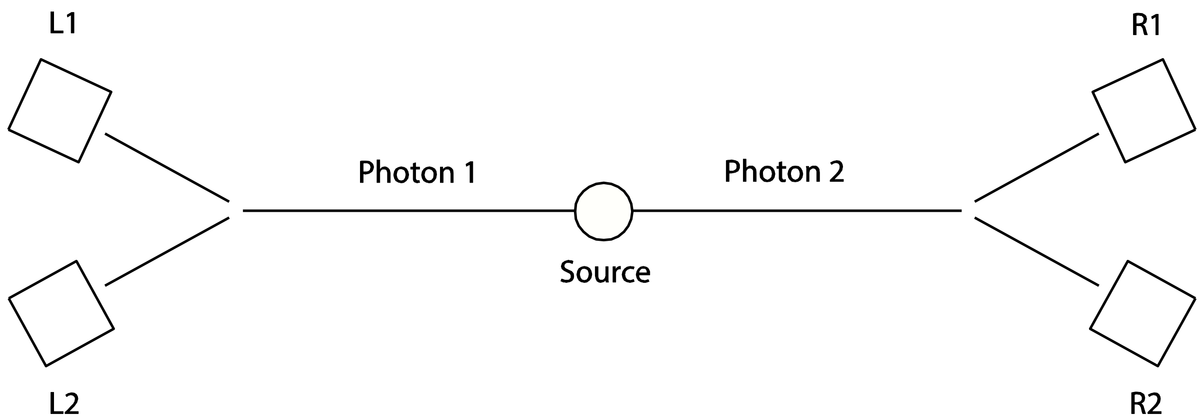

Fig. 16-1

Figure 16-1 Diagram of the Bell experiment. Photons in a total spin 0 state are emitted to the left and to the right. L1, L2, R1, and R2 are detectors which measure the polarization states, at different angles on the Left and Right.

If he assumed these distant particles could not influence each other's states—that is, a measurement on one 'particle' could not change the state of the other particle—he found limitations—Bell inequalities—on the correlations of their properties. These limitations led to a disagreement with the predictions of quantum mechanics.

The Aspect experiment: quantum mechanics wins, localization loses.

The experiment was beautifully carried out by Aspect et al [2], and it was found that the quantum mechanical laws were obeyed, while the Bell inequalities were violated. This constitutes a proof that there can be no *localized* particles—no particles that have their influence and properties confined to within some volume.

No particles or long-range interactions needed.

In interpreting the results of this experiment and others like it, it is often assumed there really are particles. Under that assumption, one needs instantaneous long-range interactions between the particles—not present in basic quantum mechanics—to account for the non-local correlations observed in the Aspect experiment.

On the other hand, quantum mechanics by itself—with the reasoning in Chs. 10-15, and with no particles and no macroscopically long-range interactions—agrees perfectly with the Aspect results (A16.1). The wave function for two distant, entangled particles, with no long-range interactions, has built into it an inherently non-local **correlation** (but not interaction) between the properties of distant particle-like wave functions whose states started off entangled.

This provides an indirect argument in favor of no particles: If there are particles, one has a good deal of trouble understanding the results of the Bell-Aspect experiment. But if there are no particles, the difficulty simply goes away; quantum mechanics describes the results perfectly well.

Related experiments.

There are related experiments that seem to show peculiar properties for matter if one assumes there are particles. The most interesting of these, given in A16.2, [3] is the quantum eraser. If one assumes there are particulate photons in addition to the photon wave function, it appears one can change the outcome for one photon by a measurement on a second photon.

There is also the Ionicioiu-Terno [4] variation of the Wheeler delayed choice experiment which probes wave-particle duality. The conclusion from this gedanken experiment is that if one assumes a photon is an actual classical wave on some runs while it is an actual classical particle on the remaining runs, then the results conflict with quantum mechanics (which is presumed correct). Thus this particular understanding of wave-particle duality—that each particular photon acts *either* like a classical particle *or* like a classical wave—is ruled out.

Evaluation.

All physicists familiar with the field would agree that the mathematics of basic quantum mechanics, with no introduction of any additional mathematics corresponding to action at a distance, correctly describes the results of all entangled-state Bell-like experiments.

References.

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[3] S. P. Walborn, M. O. Terra Cunha, S. Paua, and C. H. Monken, "Double Slit Quantum Eraser," *Phys. Rev. A*, 65 033818, (2002).

[4] R. Ionicioiu and D. R. Terno, Proposal for a quantum delayed-choice experiment. *Phys. Rev. Lett*., **107**, 230406 (2011).