Appendix C: Quantum Revolution of Your Generation: Entangled States

We encountered two-entity states of the form

$$\left.\begin{array}{ll}\text{2-spin: } \psi(1,2) \propto |\uparrow\rangle_1 |\downarrow\rangle_2 \pm |\downarrow\rangle_1 |\uparrow\rangle_2 & \text{OR } \alpha(1)\beta(2) \pm \beta(1)\alpha(2) \\ \text{2-particle: } \phi_a(\vec{r}_1)\phi_b(\vec{r}_2) \pm \phi_b(\vec{r}_1)\phi_a(\vec{r}_2) & \end{array}\right\} \quad (C1)$$

These are entangled states, first introduced by Schrödinger in 1935 (his cat!)

- According to QM, the 2-entity wavefunction contains all the information of the 2-entity system. Even so, it does not carry definite property for individual entity.

- The two entities (1 & 2) are strongly correlated

Forget about atoms for the moment

Some source

↓

two entities (spins) in

$$\psi(1,2) \sim \left(|\uparrow\rangle_1 |\downarrow\rangle_2 \pm |\downarrow\rangle_1 |\uparrow\rangle_2 \right) \text{ state}$$

and they fly apart

entity 1 ←   → entity 2

Entity 1 does <u>not</u> have a definite spin m_s (before measurement) [in contrast to classical thinking]

Entity 2 does <u>not</u> have a definite spin (before measurement)

This quantum effect is there even the entities are <u>far far apart</u>

- Only when a measurement is done (say on entity 1), entity 1's spin <u>becomes a reality</u> (has a value), if it is $|\uparrow\rangle_1$ (up), then entity 2's spin must be $|\downarrow\rangle_2$; and vice versa.

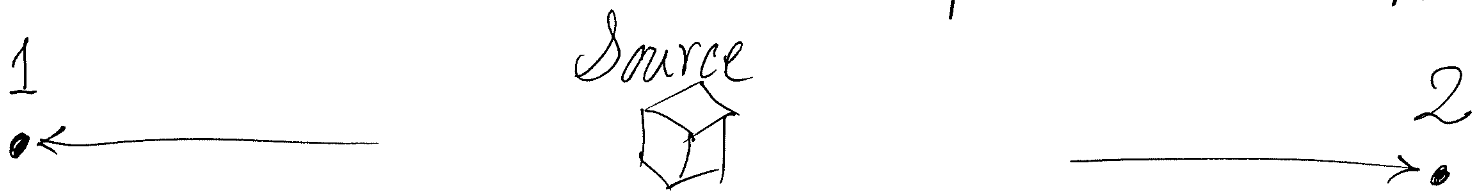
[i.e. one's reality affects the other, even they are far apart]

[measurement results are correlated in a way that classical physics can't explain!]

[states (C1) have stronger-than-classical correlation]

Pictorially $\psi(1,2) \sim |\uparrow\rangle_1 |\downarrow\rangle_2 \pm |\downarrow\rangle_1 |\uparrow\rangle_2$

[A measurement either picks up $|\uparrow\rangle_1 |\downarrow\rangle_2$ OR $|\downarrow\rangle_1 |\uparrow\rangle_2$]



if $|\uparrow\rangle_1$ must be $|\downarrow\rangle_2$ (instantaneously)

if $|\downarrow\rangle_1$ must be $|\uparrow\rangle_2$

[no matter how far 1 & 2 are]

Einstein, Podolsky, Rosen ("EPR") didn't like it!

"Spooky action at a distance"

How could measuring 1 affect state of 2 at no time? Is QM a complete theory?

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Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

1.

ANY serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves.

In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory may be said to be satisfactory. The correctness of the theory is judged by the degree of agreement between the conclusions of the theory and human experience. This experience, which alone enables us to make inferences about reality, in physics takes the form of experiment and measurement. It is the second question that we wish to consider here, as applied to quantum mechanics.

Whatever the meaning assigned to the term *complete*, the following requirement for a complete theory seems to be a necessary one: *every element of the physical reality must have a counterpart in the physical theory.* We shall call this the condition of completeness. The second question is thus easily answered, as soon as we are able to decide what are the elements of the physical reality.

The elements of the physical reality cannot be determined by *a priori* philosophical considerations, but must be found by an appeal to results of experiments and measurements. A comprehensive definition of reality is, however, unnecessary for our purpose. We shall be satisfied with the following criterion, which we regard as reasonable. *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.* It seems to us that this criterion, while far from exhausting all possible ways of recognizing a physical reality, at least provides us with one

AP-AppC-(6)

1935-1964 philosophical discussions

Bell (1964): Proposed a way to test if QM really works in the way we know

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ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

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I. Introduction

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty. There have been attempts [3] to show that even without such a separability or locality requirement no "hidden variable" interpretation of quantum mechanics is possible. These attempts have been examined elsewhere [4] and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory [5] has been explicitly constructed. That particular interpretation has indeed a grossly non-local structure. This is characteristic, according to the result to be proved here, of any such theory which reproduces exactly the quantum mechanical predictions.

"Bell's inequality"

Experiments since 1980's showed that entangled states behave in the way QM predicts. Entangled states are beyond the scope of Classical Physics. [See exp'ts by Alain Aspect]

<u>Two properties for Second Quantum Revolution</u>

$$\psi(1,2) \sim |\uparrow\rangle_1 |\downarrow\rangle_2 \pm |\downarrow\rangle_1 |\uparrow\rangle_2$$ (maximally entangled (Bell) states^{+})

- Superposition
- Entanglement (concerns two or more objects)

  objects: spins, electrons, ions, etc.

$^{+}$ $(|\uparrow\rangle_1 |\uparrow\rangle_2 \pm |\downarrow\rangle_1 |\downarrow\rangle_2)$ are also maximally entangled (Bell) states

These two properties are essential for...

- Quantum computing
- Quantum information
- Quantum teleportation

⋮

- Experimental challenges: How to form $\psi(1,2)$ for two objects?
  How to keep $\psi(1,2)$ for sufficient time to do manipulations?

[Other QM-related courses and research work in Department]

Places to read... (non-technical but needs QM background)

- A. I. M. Rae, Quantum Physics: illusion or reality?
- Chad Orzel, How to teach quantum physics to your dog
- M. G. Raymer, Quantum Physics: What everyone needs to know