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EXPERIMENT, ENTANGLEMENT AND THE FOUNDATIONS OF QUANTUM MECHANICS

I. INTRODUCTION

Albert Einstein[1] was the first who around 1910 realized that quantum physics contains elements which significantly go beyond any possible interpretive concepts in classical physics. Even before the invention of full quantum mechanics by Heisenberg and Schrödinger, he expressed discomfort about the new role played by randomness in quantum physics.

With the development of quantum physics, it became increasingly clear that a new interpretive foundation is needed and this foundation was most significantly laid by Bohr in close discussion with many other contributors[2]. From these discussions, the so-called Copenhagen interpretation emerged.

From the very beginning on, the discussion was signified by the use of *gedanken-experiments*, which is most clearly seen in the famous Bohr-Einstein dialogue. In these *gedanken-experiments*, it was the notion of complementarity, which was again and again put to demonstration and test. The paradigmatic experiment for the notion of complementarity is the famous double-slit interference, which, according to Feynman[3], "contains the heart of quantum mechanics".

The double-slit experiment is often discussed as a clear example of the complementarity between two mutually exclusive properties. Here, it is the puzzling question through which slit the particle goes when the interference pattern is observed. As has been pointed out by Bohr, this question is not a meaningful one. The reason is the observation that to observe the interference pattern, one needs an apparatus which by ist very construction does not permit to make any statement about the path the particle took. On the other hand, an apparatus determining through which slit the particle went precludes the possibility of observing the interference pattern. So, this complementarity feature arises for any type of radiation sent through a double-slit setup. The situation is intuitively more striking when massive particles are used. Figure shows the experimental results of the measurement of double-slit diffraction for neutrons. In the experiment, neutrons of a velocity $v = 200\text{m/s}$ (which corresponds to a deBroglie wavelength $\lambda = 2\text{nm}$) were incident on a massive double-slit assembly consisting of two slits, each about 23 microns wide, with a center-to-center distance of the order of 126 μm (for a precise definition of these quantities, see Zeilinger et al.[4]. We might note already here that the usual dictum is wrong, requiring the size of a diffracting object to be comparable to the wavelength in order to see diffraction effects. In our case, the small wavelength just required a large enough distance to absorb the diffraction pattern.

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Of the various features of the experimental data, it is worthwhile to mention two striking ones. Firstly, the intensity was such that we registered neutrons at the rate of one neutron every three seconds or less. This is to be compared with the flight-time of a neutron from the moment it is set free in the fission process to the moment of its registration in the detector. This flight-time is at most of the order of 10^{-1} sec. Thus, the diffraction pattern is clearly built up one by one by individual massive particles. The second interesting feature is that the solid line shows a first principles theoretical calculation using just the free-space solution of the Schrödinger equation including all experimental parameters. Clearly, no evidence for any deviation between experiment and theory is indicated by these data.

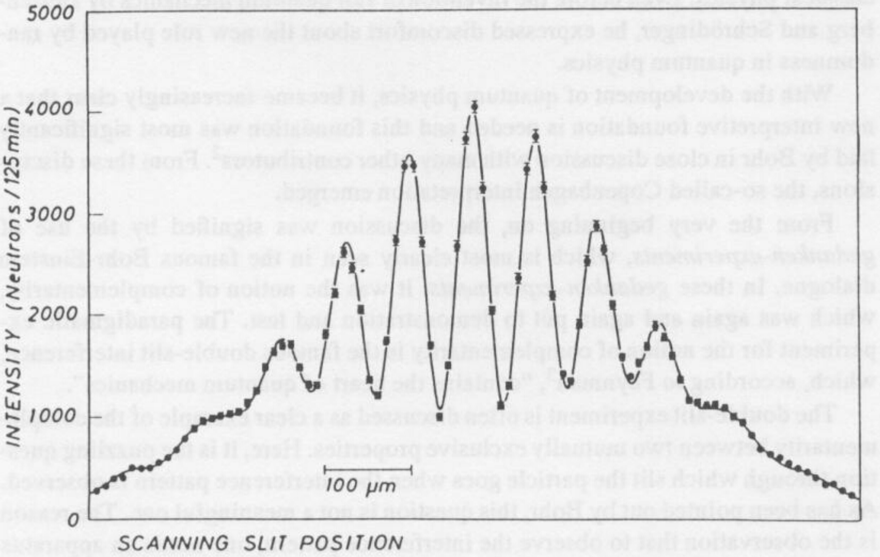

Figure 1: Double-slit diffraction of cold neutrons: the solid curve represents the first-principles theoretical prediction.

II. ENTANGLEMENT

The dialogue between Einstein and Bohr reached its culmination in 1935 with the publication of the famous Einstein-Podolsky-Rosen paper, where the question whether quantum mechanics provides a complete description of physical reality was raised in a most succinct way.[5] The novel states were called by Schrödinger "Entangled States" ("Verschränkte Zustände")[6] in the same year, and it was also Schrödinger who pointed out that entangled states contain the essence of quantum mechanics. The most simple entangled state is

$$|\psi\rangle = \frac{1}{\sqrt{2}}\{|a\rangle_1|b\rangle_2 + |c\rangle_1|d\rangle_2\} \tag{1}$$

where, as a product of kets, we always imply the tensor product, and where the first ket always refers to particle 1, the second ket to particle 2 etc. The quantum state of Figure 1 describes a superposition of product states of two particles where particle 1 can be found either in state $|a\rangle$ or $|c\rangle$ and particle 2 can be found either in state $|b\rangle$ or $|d\rangle$. The interesting feature of state 1 is that neither particle has a state independent of the other. In other words, whenever particle 1 is found in state $|a\rangle$ ($|c\rangle$) then particle 2 is found in $|b\rangle$ ($|d\rangle$).

The essential point of the EPR argument is to start from the observation that the state of equation 1 does not ascribe to either particle properties independent of the other one. Furthermore, particle 1 and particle 2 could be separated over arbitrarily large distances, thus implying that their real properties should be independent of each other[7]. But, since the state of equation 1 does not permit such independent properties, the description of quantum mechanics must be incomplete.

Niels Bohr in his reply[8] did point out that one cannot separate a quantum system from the apparatus with which it is measured, and, in the case of an entangled state, one has to consider the totality of the experimental setup, including all apparata for the individual particles entangled with each other, no matter how widely they are separated. They altogether constitute the condition under which experimental predictions can reasonably be made. Thus, a significant limitation arises in our possibilities of assigning properties to quantum systems.

John Bell[9] was able to show that any assignment of local properties, as envisaged by EPR, would lead to a contradiction with quantum mechanics. It is interesting to know that at a time when Bell proposed his theorem no experimental evidence did exist which would have been able to decide between quantum mechanics and alternative local theories. Since then, a convincing body of experiments has been produced, which overwhelmingly support quantum mechanics, beginning with the experiment of Freedman and Clauser.[10]

More recently, the discussion has again gained momentum through the demonstration[11] that entanglement in systems with more than 2 particles creates even more striking contradictions between quantum mechanics and local realism, which arise already on the level of individual events! The most simple state where such events may occur is

$$|\psi\rangle = \frac{1}{\sqrt{2}}\{|a\rangle_1|b\rangle_2|c\rangle_3 + |d\rangle_1|e\rangle_2|f\rangle_3\} \tag{2}$$

which describes three particles, each one defined in the two-dimensional Hilbert space whose properties are maximally entangled. For a detailed presentation and discussion of the argument, see the second item in note 11 and the didactic presentations given by Mermin[12].

III. EINSTEIN-PODOLSKY-ROSEN INTERFEROMETRY

The last ten years saw the vigorous development of a new field of experimentation which might aptly be called Einstein-Podolsky-Rosen interferometry or just simply multi-particle interferometry[13]. In the generic case[14,15,16], one assumes a source which produces momentum- correlated particle pairs (Figure). Each of the particles can be emitted into two modes, which can then be superposed at a beam-splitter. A significant feature of the experimental setup is that interference fringes as a function of the freely variable phases only arise in the correlations between the detectors for the two particles. It can easily be seen that such an interferometer is another manifestation of a situation where the Einstein-Podolsky-Rosen criteria are applicable, and, since the outputs for each particle are dichotomic, Bell's theorem directly applies. While the initial proposal[17] discussed the rather academic possibility of using positronium annihilation photons for such an experiment, it was soon realized that parametric down-conversion is an ideal actual source for exactly these experiments[18]. Subsequent experimental realization by Rarity and Tapster[19] very clearly confirmed the expected entangled nature of the two-photon state.

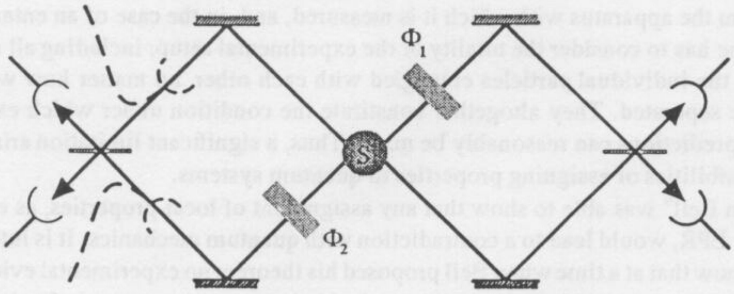

Figure 2: A two-photon interferometer utilizing a momentum correlated source. Detectors for one photon at the dashed positions could provide path information for both photons. Interference fringes can therefore be observed only if both photons are detected after recombination at their respective beam splitters.

Utilizing the recent discovery[20] that any unitary linear operator can be built in the laboratory just out of beam splitters and phase shifters, one can now indeed realize correlations between two or possibly more particles in higher dimensional Hilbert spaces[21]. A typical experiment in that direction was to use a so-called quarter, i.e. a beam splitter assembly with four input ports and four output ports, and investigate its two-photon statistics properties[22]. Recently, using exactly this device, it could be demonstrated[23] that there, too, nonclassical correlations[24] arise.

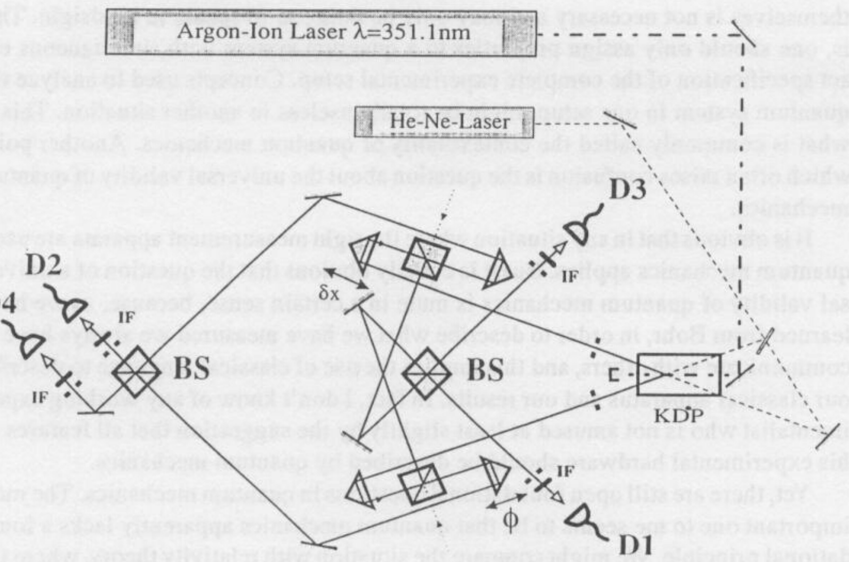

Figure 3: Experimental set-up of the measurement of nonclassical two photon distributions for a symmetric quarter. The correlated photon pair is produced by parametric downconversion in a nonlinear KD$*$P crystal pump by an Ar$^+$-Laser ($\lambda = 351.1$ nm). Optical trombones allow path length adjustment and phase setting, Si-avalanche photodiodes are used for single photon counting. The He-Ne laser is needed for the alignment.

IV. INTERPRETIVE ISSUES, OUTLOOK

In the present brief overview, it was not possible to discuss in detail all the various fundamental experiments which have recently been done, essentially using two-photon states. Two directions of research which should be mentioned here are on the one hand so-called *Welcher-Weg* detector schemes[25,26,27] where one tries to study in detail the complementarity between path and interference pattern in a interferometry situation and on the other hand the recent development of interaction-free measurement[28,29,30].

With all these experiments demonstrating or even exploiting fundamental features of quantum mechanics, the question arises as to what their implication is for fundamental interpretive issues. It is the conviction of the present author not only that there is no reason whatsoever to doubt the Copenhagen interpretation, it actually appears that the Copenhagen interpretation is an excellent pragmatic tool in the hands of the experimentalist[31]. If we, for example, raise questions like "What is the nature of ψ?" it is obvious that the wave-function ψ just represents that part of our knowledge of the experimental setup which permits us to make the maximal set of probabilistic predictions of future possible properties of the setup, i.e. of the possible experimental outcomes. Assignment of properties to quantum objects themselves is not necessary and may only be done, so to speak, in hindsight. That is, one should only assign properties to a quantum system with simultaneous exact specification of the complete experimental setup. Concepts used to analyze the quantum system in one setup might be totally useless in another situation. This is what is commonly called the contextuality of quantum mechanics. Another point which often raises confusion is the question about the universal validity of quantum mechanics.

It is obvious that in any situation where the right measurement apparata are used, quantum mechanics applies. But it is equally obvious that the question of a universal validity of quantum mechanics is mute in a certain sense, because, as we have learned from Bohr, in order to describe what we have measured we always have to communicate with others, and this implies the use of classical language to describe our classical apparatus and our results. In fact, I don't know of any working experimentalist who is not amused at least slightly by the suggestion that all features of his experimental hardware should be described by quantum mechanics.

Yet, there are still open foundational questions in quantum mechanics. The most important one to me seems to be that quantum mechanics apparently lacks a foundational principle. We might compare the situation with relativity theory, where the foundational principle is the principle of equivalence which simply says that all laws of nature should be the same in all inertial reference frames. This principle is intuitively reasonable, maybe even obvious. It might very well be that such a principle also exists for quantum mechanics, and it is my hope that the enormous increase of experiments on the foundations of quantum mechanics will help to lead our intuition in the right direction.

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NOTES

1. Pais, Rev.Mod.Phys. **51** (1979) 861.
2. Bohr, in *A. Einstein, Philosopher-Scientist*, P.A. Schilpp, ed., The Library of Living Philosophers, Evanston, (1949).
3. Feynman, R.B. Leighton and M.L. Sands, *The Feynman Lectures on Physics*, Addison-Wesley Publishing Co., Inc., Reading (1989).
4. Zeilinger, R. Gähler, C.G. Shull, W. Treimer and W. Mampe, Rev.Mod.Phys. **60** (1988) 1067.

5. Einstein, B. Podolsky, and N. Rosen. Phys. Rev. **47**, (1935) 777.
6. Schrödinger, Naturwissenschaften, Vol. 23 (1935) 807, 823, 844.
7. Einstein, in *A. Einstein, Philosopher-Scientist*, P.A. Schilpp, ed., The Library of Living Philosophers, Evanston, (1949).
8. Bohr, Phys.Rev. **48** (1935) 696.
9. Bell, Physics **1** (1964) 195, reprinted in J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge U.P., Cambridge, 1987).
10. Freedman and J.S. Clauser, Phys.Rev.Lett **28**, (1972) 938, A. Aspect, J. Dalibard and G. Roger, Phys.Rev.Lett. **47**, (1982) 1804.
11. Greenberger, M. Horne and A. Zeilinger, in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe*, M. Kafatos, ed., Kluwer Academic, Dordrecht (1989) 73.
12. Greenberger, M. Horne, A. Shimony and A. Zeilinger, Am.J.Phys. **58** (1990) 1131.
13. Mermin, Am.J.Phys. **58** (1990) 731; Phys.Today **43** (1990) 9.
14. Greenberger, M.A. Horne and A. Zeilinger, Phys.Today (August 1993) 22.
15. Horne and A. Zeilinger, in *Proc. Symp. Foundations of Modern Physics*, P. Lahti, P. Mittelstaedt, eds., Word Scientific, Singapore (1985) 435.
16. Horne, A.Zeilinger: A Possible Spin-Less Experimental Test of Bell's Inequality, in *Microphysical Reality and Quantum Formalism*, A. van der Merwe, F.Selleri, G.Tarozzi, eds., Kluwer Academic, Dordrecht (1988) 401.
17. Horne and A.Zeilinger: Einstein-Podolsky-Rosen Interferometry, in: *New Techniques and Ideas in Quantum Measurement Theory,* D.Greenberger, ed., Annals of the New York Academy of Sciences, 480 (1986) 469.
18. Horne, A. Shimony and A. Zeilinger, Phys.Rev.Lett. **62** (1989) 2209.
19. Rarity, P.R. Tapster, Phys.Rev.Lett. **64** (1989) 2209.
20. Reck, A. Zeilinger and H.J. Bernstein, Experimental Realization of Any Discrete Unitary Operator, Phys. Rev. Lett. **73** (1994) 589.
21. Zeilinger, H.J. Bernstein, D.M. Greenberger, M.A. Horne and M. Zukowski: Controlling Entanglement in Quantum Optics, in "Quantum Control and Measurement", H. Ezawa, Y. Murayama (Eds.), Elsevier Science Publishers (1993) p. 9.
22. M. Michler, H. Weinfurter, A. Zeilinger and M. Zukowski, Appl.Phys. B 60 (1995).
23. Michler, diploma thesis, University of Innsbruck (1994) unpublished.
24. Reid and D.F. Walls, Phys.Rev.A 34 (1986) 1260.
25. Scully, B.G. Englert and H. Walther, Nature 351 (1991) 111.
26. Herzog, J. Rarity, H. Weinfurter and A. Zeilinger, Phys.Rev.Lett. 72 (1994) 629.
27. Weinfurter, T. Herzog, P.G. Kwiat, J.G. Rarity, A. Zeilinger and M. Zukowski, in Fundamental Problems in Quantum Theory: A Conference Held in Honor of Prof. John A. Wheeler, Annals of the New York Academy of Sciences, Vol. 755 (1995) 61.
28. Elitzur and L. Vaidman, Found.Phys. 23 (1993) 987.
29. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger and M.A. Kasevich, in Fundamental Problems in Quantum Theory: A Conference Held in Honor of Prof. John A. Wheeler, Annals of the New York Academy of Sciences, Vol. 755 (1995) 383.
30. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger and M. Kasevich, Phys.Rev.Lett (1995), in press.
31. Experiment and Quantum Measurement Theory, in Quantum Theory Without Reduction, M.Cini and J.-M.Levy-Leblond, eds., Hilger, Bristol (1990) 9.