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EINSTEIN-PODOLSKY-ROSEN-BOHM EXPERIMENT AND BELL INEQUALITY VIOLATION USING TYPE II PARAMETRIC DOWN CONVERSION

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Abstract

We report a new two-photon polarization correlation experiment for realizing the Einstein-Podolsky-Rosen-Bohm (EPRB) state and for testing Bell-type inequalities. We use the pair of orthogonally-polarized light quanta generated in Type II parametric down conversion. Using 1nm interference filters in front of our detectors, we observe from the output of a 0.5mm $\beta - BaB_2O_4$ (BBO) crystal the EPRB correlations in coincidence counts, and measure an associated Bell inequality violation of 22 standard deviations. The quantum state of the photon pair is a polarization analog of the spin-1/2 singlet state.

1 Introduction

The Einstein-Podolsky-Rosen-Bohm (EPRB) gedanken[1, 2] for two quantum particles has played an important conceptual role for viewing quantum-mechanical correlations that provide intrigue and challenge to classical intuition. In brief, the EPRB correlation considered here is contained in a two-particle, two detector setup in which a measurement is first made on one particle at one detector of a parameter that is indeterminate prior to the measurement. This outcome then implies with certainty the outcome of the measurement on the second particle. Demonstrations for spin-1/2 quanta[3], for photon polarization states [3, 4, 5, 6, 7, 8], and more recently for other variables [9, 10, 11, 12] have all shown these EPRB correlations in the coincidence registrations of two detectors.

The same quantum-mechanical state of two particles that generates an EPRB experiment also provides an enhancement of observed coincidence rates beyond a maximum bound set by Bell's two postulates[13, 3]. Violations of Bell-type inequalities are one application of EPRB states.

We have found a new and convenient way to generate quantum states that exhibit these EPRB correlations[1, 2], with an associated violation of two-particle Bell-type inequalities[13, 3]. Our source is the pair of light quanta generated in parametric down conversion with Type II phase matching. The pair is incident on one port of a nonpolarizing beamsplitter with output ports containing two linear analyzer-detector packages. The pair is orthogonally polarized, without the need for an interferometer or retardation plates. Our Bell Inequality violation in polarization variables is as large as 22 standard deviations.

2 Experimental Method

Our experimental configuration is shown in Fig. 1. A 351.1nm unfocussed Argon ion laser line is incident on a 0.5mm long BBO crystal oriented to achieve Type II phase matching in parametric down conversion, with the 702.2nm wavelength collinear with the pump. Pairs degenerate in propagation direction and frequency emerge from the BBO crystal and separate from the pump at a quartz prism. They are split at a nonpolarizing beamsplitter and sent to two Glan-Thompson analyzer-detector packages. Coincidence counts are collected in a 6nsec coincidence time window from two avalanche photodiode detectors operating in the Geiger mode.

Coincidence counts collected in a large time window are

$$N_{12} = N_o \left[cos^2\theta_1 sin^2\theta_2 + sin^2\theta_1 cos^2\theta_2 - \lambda sin\theta_1 cos\theta_1 sin\theta_2 cos\theta_2 \right], \tag{1}$$

for a constant N_o and parameter λ that is not a priori equal to two. Indeed, for filters of bandpass greater than 1nm, or for a BBO crystal of greater length (5.65mm), λ was found to be less than two. We discuss this bandwidth and crystal length dependence elsewhere in greater detail. For the present conditions (filters with FWHM of 1nm, crystal length 0.5mm), the large visibility (> 99%) in Figs. 2 and 3 is predicted from (1) only for λ nearly two. We obtained $\lambda = 1.98 \pm 0.04$.

This value of λ is within 1σ of 2, for which (1) reduces to $sin^2(\theta_1 - \theta_2)$, a function of only the difference angle, $\theta_1 - \theta_2$ This dependence on only one variable specifies an invariance with respect to the other, often referred to as a rotational invariance[3, 7].

This rotational invariance is a key property of our quantum state. Either the o-ray or the e-ray could trigger either detector, making detection of single counts ideally independent of analyzer angle. Once one detector has fired, the conditional probability of registering an event in the second detector is given by the coincidence probability, which for $\lambda = 2$ can be rewritten as $\propto cos^2(\theta_1 - \theta_2 + 90\,\mathrm{deg})$. This is Malus' law for detection of a linear polarization at angle $\theta_1 - \theta_2 + 90\,\mathrm{deg}$. The polarization at the second detector is known with certainty to be linear at this angle after the first detector has fired. This is a correlation of the EPRB type.

The $\lambda-$dependent mixing term in (1) foils any interpretation specifying the o-ray to be localized at detector 1 and the e-ray at detector 2, or vice-versa. Both of these quantum-mechanical amplitudes are present, and their interference generates the $\lambda-$ dependent term of (1) that represents an overlap of "o-ray resolved at D1, e-ray resolved at D2" ($\sim cos\theta_1 sin\theta_2$) with "e-ray at D1, o-ray at D2" ($\sim sin\theta_1 cos\theta_2$).

3 Results

We use the coincidence count expression (1) to exhibit Bell inequality violations. This application of (1) proceeds without any necessary regard to the underlying mechanism producing the $\lambda-$dependent interference term.

For the $\lambda = 2$ singlet state analog, we measured the Bell inequality expression as derived by Freedman[14, 3]

$$\left| \frac{N_{12}(\phi) - N_{12}(3\phi)}{N_{12}(-,-)} \right| \leq 0.25, \tag{2}$$

for $\phi \equiv \theta_1 - \theta_2 = 22.5\,\text{deg}$ (see Table I).

It is possible to avoid exhibiting the aforementioned symmetry properties used to derive (2) by testing a more general Bell inequality form. We proceed from the inequality[15, 3, 8]

$$[-N_{12}(\theta_1', \theta_2') + N_{12}(\theta_1', \theta_2) + N_{12}(\theta_1, \theta_2') + N_{12}(\theta_1, \theta_2)] - (N_{12}(\theta_1, -) + N_{12}(-, \theta_2)) \leq 0, \tag{3}$$

in which the Clauser-Horne no-enhancement assumption[15] has already been imposed, and in which probabilities have been converted to coincidence counts N_{12} accumulated in some time interval.

Although we have generated violations of (3), we advocate a stronger version in which the transmission losses of the analyzers are recognized and removed. The basis for this is a generalized version of the no-enhancement hypothesis, in which the passive, polarization-independent analyzer losses are assumed not to affect the behavior of the source whose coincidence properties are under study. We note that these analyzer losses must be controlled[15, 3, 16] in a rigorous Bell inequality test. For our purpose here of exhibiting the coincidence behavior of the source, we use this generalization to alter (3) to the form

$$[-N_{12}(\theta_1', \theta_2') + N_{12}(\theta_1', \theta_2) + N_{12}(\theta_1, \theta_2') + N_{12}(\theta_1, \theta_2)] - (\eta_2 N_{12}(\theta_1, -) + \eta_1 N_{12}(-, \theta_2)) \leq 0. \tag{4}$$

We deduced a choice of four angles ($\theta_1 = 22.5\,\text{deg}, \theta_2 = 135\,\text{deg}, \theta_1' = 67.5\,\text{deg}, \theta_2' = 90\,\text{deg}$) that would violate (3) or (4) maximally. Coincidence counts (Table II) in eight minutes are collected for these angles. Table III shows the deduced violation in these counts of both (3) and (4).

As has been noted[8], violations of (4) occur for any greater-than-zero value of the left hand side. For a relevant figure of merit in judging Bell inequality violations, we advocate the quantity Q-1, for Q the ratio of the term of (4) in square brackets to the term in parentheses. For Q-1>0, the form (4) is violated. We compare in Table III the measured Q-1 to the prediction generated from λ. As another consistency check, we list the ratio $\eta_2 N_{12}(\theta_1, -) : \eta_1 N_{12}(-, \theta_2)$, which should be 1:1, within experimental error.

In conclusion, we have identified a new source useful in realizing the EPRB gedanken and in testing Bell Inequalities. We achieve the EPRB correlations by virtue of a coincidence probability $\propto sin^2\phi$ for $\phi = \theta_1 - \theta_2$. We obtain a violation of the form (2) for polarization variables that is 22 standard deviations and limited here only by accumulation time. The quantum state is entangled[17] in polarization variables, leading to an interference term in coincidence counts that, because of EPRB correlations and Bell-type inequality violations, is manifestly quantum in nature.

4 Acknowledgements

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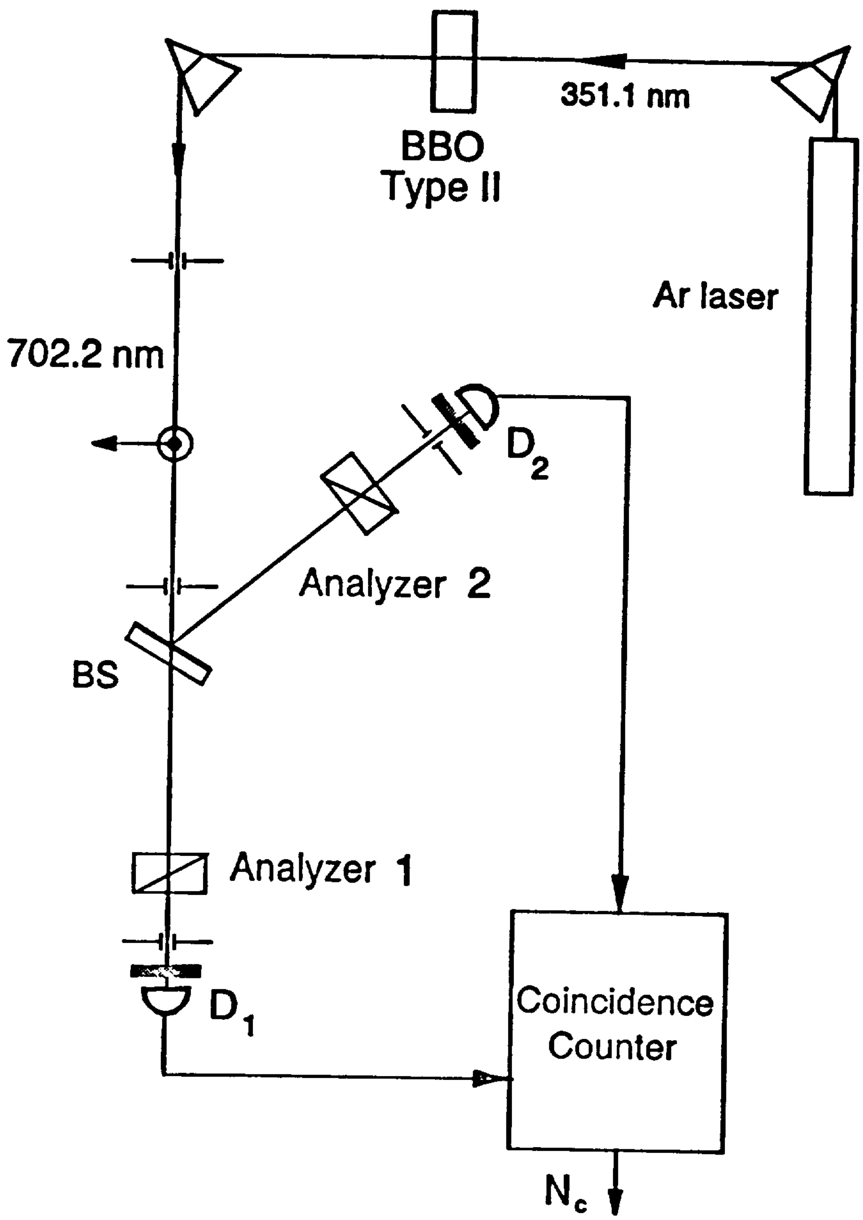

FIG. 1. Experimental Setup. Pairs from collinear Type II down conversion in a BBO crystal are separated from the pump at a prism and directed to a 50:50 beam-splitter. The coincidence registrations in detectors 1 and 2 are recorded as a function of the angles θ_1 and θ_2 of the Glan Thompson analyzers, for each bandwidth filter installed in front of the detectors.

Table I. Bell Inequality Measurements for $\phi = 22.5$ deg.

θ_1	$N(\phi)$	$N(3\phi)$	$N(-,-)$	Eq.(8)	
0 deg	1052	6054	16048	0.3117	±0.0058
0 deg	1033	5931	15482	0.3164	±0.0059
45 deg	902	5718	14915	0.3229	±0.0061
45 deg	877	5424	14468	0.3143	±0.0061

Table II. Bell Inequality Measurements.

$N(\theta_1', \theta_2')$	$N(\theta_1', \theta_2)$	$N(\theta_1, \theta_2)$	$N(\theta_1, \theta_2')$	$N(\theta_1, -)$	$N(-, \theta_2)$
951	4060	3701	4054	4534	5060

Table III: Bell Inequality Violations Using Counts of Table II.

Eq.(9)	Eq.(10)	$\eta_2 \cdot N(\theta_1, -)$	$\eta_1 \cdot N(-, \theta_2)$	$Q-1$	$Q_{pred}-1$
1188	1778	4425	4579	0.198	0.207
±143	±178	±97	±98	±0.022	±0.010
(8σ)	(10σ)				

BANQUET TALK

THE RELATION BETWEEN PHYSICS AND PHILOSOPHY

A. Shimony

The Relation Between Physics and Philosophy

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It is an honor to be invited to give the banquet talk at this Workshop. The invitation by Profs. Shih and Rubin provides an opportunity to present to a new audience some theses to which I am devoted. I hope that you will hear some things that you have more or less believed for a long time but have never heard articulated explicitly.

Working physicists, I believe, almost inevitably have strong philosophical interests, regardless of whether they have taken courses labeled "Philosophy" and whether they have liked what they have sampled. Their interest is implicit in the discipline of physics itself. Peter Bergmann, in the introduction to his *Basic Theories of Physics I* attributed to Einstein the view that "a theoretical physicist is ... a philosopher in workingman's clothes." I would omit the adjective "theoretical" and apply the characterization to experimentalists as well. This claim depends, of course, on a conception of what philosophy is. I propose the following: philosophy is the systematic search for perspective, for connections among aspects of the world, and for depth of explanation. Some physicists are drawn into their profession from the beginning because they have been convinced by a few revealing examples that the procedures of physical investigation help to achieve perspective, connections, and depth of explanation. These are philosophers from the start. Others are drawn in because of their fascination with specific phenomena. In my case, the onset of curiosity about the physical world, so far as I can recall, came at the age of four, when I saw my father siphoning wine out of a barrel, and I was amazed that the wine went up in the siphon before it descended. But even if the route to professional physics is via wonder at specific phenomena, an approach to philosophy, in the sense mentioned, is unavoidable, because the physicist's understanding of phenomena goes beyond the phenomena themselves to underlying causes and to connections.

There are various ways to subdivide the discipline of philosophy, but the following will be convenient for our purposes:

1. epistemology, which assesses claims to knowledge;
2. metaphysics, which considers what kinds of things exist and what are the basic principles governing them;
3. theory of value.

I'll put greatest stress upon the relations between physics and metaphysics, because they are richer and more surprising than its relations to epistemology and value theory.

Epistemology:

Among the many problems of epistemology I shall focus on these: (i) what is the proper formulation of scientific method, and to what extent is that method rationally justified? (ii) To what extent can we disentangle subjective from objective contributions in our experience of the world? There were serious and highly intelligent figures in the history of thought, like Descartes, who maintained that these and related questions in epistemology had to be answered before the substantive work of the sciences could begin, because a foundation is necessary before constructing the edifice of science. We can confidently say, I believe, that this architectural metaphor was mistaken, because all attempts to establish the foundations of knowledge without any substantive assertions about the world seem to have failed. Instead, work on the theory of knowledge and work on substantive science had to proceed in tandem, and – judging by the spectacular successes of the natural sciences – we can say that somehow human beings are capable of this remarkable and somewhat paradoxical intertwining of investigations.

As to problem (i), concerning scientific method, the great breakthrough occurred in the sixteenth and seventeenth centuries, and was inseparable from the development of the new physics and astronomy of Copernicus, Kepler, Galileo, Huygens, and Newton. It had been known from the time of the great Greek philosophers, and probably in a vague way many millennia earlier, that somehow human beings can learn by sense experience and also by reasoning. The division between Plato and his followers, on the one hand, and Aristotle and his followers on the other, concerned the primacy of sense experience or reason. In the work of the new physicists, culminating in Newton's *Principia*, the interplay of the contributions of experience and reason was clarified. These physicists recognized that human beings are not so constituted that they can have direct sensory experience of the fundamental structure of matter or of the fundamental forces among material things. However, if tentative propositions about fundamental physics are formulated in mathematical terms, then logical and mathematical reasoning leads to conclusions that can be checked by sense experience, notably the trajectories of terrestrial bodies and the apparent positions of planets in the celestial sphere. Newton's successful prediction that the orbit of Saturn would be distorted when that planet is close to Jupiter, and Halley's successful prediction of the recurrence of a comet, and other spectacular verifications of predictions, indirectly confirmed the tentative propositions about fundamental physics which were incapable of direct check. Thus, in tandem with the substantive advance in physics and astronomy was the demonstration of the power of the scientific method summarized above, called the "hypothetico-deductive method." This method was not discredited by the significant refinements of scientific methodology in the centuries that followed, notably enrichment with probability theory. Reflection upon scientific practice was largely responsible for these refinements, since it was noticed by Gauss, Bessel, and others that experimental data are subject to random errors, and they realized that in addition to the dominant causes of a natural phenomenon there are always innumerable small perturbations that cannot be completely catalogued and yet can be treated rationally in terms of probability distributions. Further refinements of scientific method have been made in the twentieth century, and there are still controversial questions concerning inductive inference. Nevertheless, I would maintain that the great revolutions of physics of the twentieth century were accomplished essentially with a classical methodology. The propositions of relativity theory, quantum mechanics, elementary particle theory, etc. were established by applications of the hypothetico-deductive method, refined somewhat by probability theory, without a methodological revolution.

As to problem (ii), concerning the disentanglement of subjective from objective factors in experience, there was not – so far as I can see – a single critical breakthrough, but rather a long, intricate, progressive, and still incomplete development. As the human observer was recognized to be a natural system, the experiences of that observer could be studied as the termini of causal chains, some of which are initiated within the observer, while others are initiated externally. Of course, all external stimuli eventually impinge upon the neural and psychic machinery of the observer. The naturalistic point of view regarding the human observer has made it possible for psychologists and neurophysiologists to understand such matters as optical illusions, the limited range of the visual and auditory spectra, and the distortion of perceptual judgments by emotional and conceptual bias. In turn, such understanding of the subjective element in experience permits scientists to take counter-measures, by instruments and procedures of observation, in order to enhance the revelation of objective factors in experience. Of course, the ultimate subjective elements of experience, such as sensory qualities, are entirely beyond present science, and will continue to be mysterious until we have a scientific world view that can accommodate consciousness. There has been, however, a capital negative achievement concerning the subjectivity of experience: namely, an accumulation of evidence that the structure of space and time are not imposed upon experience by the operation of the human mind, as Kant maintained in his doctrine of transcendental idealism. Kant's primary argument proceeds from the apparent necessity and universality of geometrical propositions, understood not as mere statements of a formal calculus but as assertions about physical space. The invention of non-Euclidean geometry by Lobatchevsky and Bolyai, the demonstration of its consistency relative to Euclidean geometry by Klein, and the success of its incorporation in general relativity theory are devastating to Kant's argument. Furthermore, when his exemplary geometric instances of synthetic a priori judgments are undercut, then his further claim, that the principles of causality, substance, etc. are necessary because they are imposed by the mind, is seriously weakened; and it is weakened even further by the triumph of a non-deterministic physics. In other words, the epistemological explanation of the basis of science – which was a major part of Kant's program –is undermined, and we are driven to recognize that in so far as science is valid, even as an approximation, it is so because it is a quite good description of the world as it is. The foregoing anti-Kantian argument is regrettably condensed, but it suffices to point to my next thesis: that there are important connections between physics and metaphysics.

Metaphysics:

This thesis may be disconcerting to many people, because the word "metaphysics" is commonly used as a pejorative by physicists, even by those who are sympathetic to epistemology. Until the beginning of the eighteenth century there were great scientists who were also metaphysicians, like Aristotle and Leibniz, and a case can be made for adding Newton to the list. The historical consequence of Kant's work at the end of the eighteenth century and Hegel's at the beginning of the nineteenth was a rift between science and philosophy, regardless of their intentions; and Hegel's grandiose and obscurely reasoned attempt at a "System" of thought engendered a negative reaction among many careful and critical scientists. The positivism of Mach and the Vienna Circle was a consequence of the quest for clarity of expression and rigor of demonstration, and to some extent it was a reaction against the excesses of Hegel. The enterprise of systematic philosophy – aiming at perspective, connections, and depth, as I proposed at the beginning of my talk – became generically suspect, because of the weaknesses of exposition, the excessive claims, and the remoteness from scientific practice of the most influential systematic philosopher of the nineteenth century. The Vienna Circle, which originally called itself the "Mach verein," was nearly unanimous in its condemnation of metaphysics as nonsense and its desire to purge scientific discourse of any residue of metaphysics. At the time of the great scientific revolutions of the early twentieth century, positivism was a pervasive influence among scientifically oriented philosophers and philosophically oriented scientists. It is not surprising, then, that many of the revolutionaries gave an anti-metaphysical interpretation to their discoveries. Einstein for a long time expressed great sympathy with Mach's ideas, and some of his expositions of special relativity centered around the operationalist analysis of space-time concepts like "simultaneity." Heisenberg's initial formulation of quantum mechanics dispensed with position and momentum, which he regarded as unobservable on a microscopic scale, and tried to express his theory in terms of observables like frequency and intensity. Both Einstein and Heisenberg eventually deviated from positivism and both espoused some form of physical realism – Einstein in his argument for "elements of physical reality" and Heisenberg in a statement that the wave function of an atom can be regarded as a description of the atom as a "thing-in-itself." But Bohr to the end of his life gave interpretations of quantum mechanics with a positivistic flavor, e.g., saying of the wave function that "we are dealing here with a purely symbolic procedure, the unambiguous physical interpretation of which in the last resort requires a reference to a complete experimental arrangement." Bohr believed that the philosophical implications of quantum mechanics are epistemological, concerning limitations of human knowledge and renunciations of unitary pictures of the kind offered by classical physics. His consistent playing down of metaphysical interpretations of quantum mechanics reflect a pervasive suspicion of metaphysical speculation in the scientific community, and it is therefore not surprising that he maintained a strong grip upon the attitude of physicists towards quantum mechanics until fairly recently. I have to confess that in spite of my thesis about the relation of physics to metaphysics, I have respect and sympathy for the positivists' pursuit of clarity of concepts and rigor of demonstrations. I am skeptical, however, that criteria for the meaningfulness of sentences, such as "verifiability," "confirmability," or "falsifiability." can be formulated a priori without drastically damaging scientific investigation. Mach was right that there was an obscurity in Newton's concept of "absolute motion," but the reason is Galilean invariance, which precludes an absolute distinction between rest and uniform rectilinear motion; however, Galilean Invariance is entirely consistent with a clear concept of absolute acceleration. In sum, the clarification of scientific language must proceed in tandem with the progress of scientific knowledge, analogously to the linkage of scientific methodology and substantive science. If physics has progressed to the point where some of the traditional metaphysical problems can be formulated with precision, and even subjected to experimental treatment, then we are presented with a wonderful opportunity, that ought not be neglected because of a suspicion of the sterility of metaphysics. And I contend that modern physics has reached such a stage of development. We are fortunate enough to be invited to a great feast of ideas, and it would be a self-defeating austerity to decline the invitation.

Here is a partial list of results of modern physics having metaphysical implications. Of course, all of these results are subject to modification as science progresses, but it is most unlikely that any of them will cease to be good approximations (in the sense of the correspondence principle) to their successors. For this reasons, the implications that we can draw from them are likely to have a quasi-permanent status.

1. Modern physics (broadly understood to include chemistry) has established the granular character of matter, the present candidates for elementarity being quarks, leptons,. and various bosons. That the immense variety of kinds in the natural world can be understood in terms of combinations of these elementary units is a great vindication of the atomic vision of Democritus.

But the modern qualifications of the Democritean vision are as important metaphysically as the vindication, especially that none of the elementary units is immortal, but all are subject to creation and annihilation in allowable processes; and that certain quantities, notably energy and momentum, are conserved in all of these transformation processes, and others are approximately conserved.

2. The overwhelming evidence that the quantum state of a physical system is a complete description of it, without any need or place for supplementary "hidden variables," implies that various features of the quantum formalism must be attributed to individual physical systems and not just to ensembles. There is objective indefiniteness, because in any quantum state some physical variables have no definite value; there is objective chance, because the different behaviors of various systems with the same quantum state cannot be attributed to differences among hypothetical hidden variables; there is objective probability, because the chance behavior of an ensemble of systems in the same quantum state conforms to definite probability distributions. These three properties conjoined are called"potentiality," in Heisenberg's terminology. That the state of a physical system involves potentialities and cannot be fully understood in terms of actualities is one of the profound metaphysical implications of quantum mechanics. This interpretation of the quantum formalism, it may be noted, is entirely different from Bohr's, which is epistemological in character. For instance, the unceertainty principle is not interpreted in Bohr's fashion as a limitation upon human ability to measure both position and momentum, but rather as an acknowledgment of the objective fact that position and momentum cannot both be actual.

3. Quantum mechanics also has a remarkable implication for the relation between parts and wholes. There are states of composite systems, called "entangled" by Schroedinger, that cannot be expressed as the product of states of the individual components. Entanglement is manifested by the occurrence of correlations that cannot be accounted for by product states. By contrast, classical physics is pervasively analytic and characterizes the state of composite systems in terms of the states of components. Thus quantum mechanics has brought an unprecedented kind of holism into our view of the natural world.

4. When the parts of a composite system are spatially separated, the entanglement of its state implies a kind of non-locality: there is correlated behavior that cannot be explained by any propagation of causal influences that is not superluminal. Nevertheless, the probabilistic nature of quantum mechanics ensures that this kind of non-locality cannot be used to send a signal faster than light. For this reason, quantum non-locality can be characterized facetiously as "passion at a distance" rather than "action at a distance." In ways that are not fully understood, however, we can tentatively say that quantum non-locality requires some modification of classical ideas of causality.

5. The combination of quantum mechanics with the intrinsic indistinguishability of elementary particles of a given type leads to the conclusion that that a system of n identical integral spin particles are in an entangled fully symmetric state (except in the special case that all are in the same one-particle state), whereas n identical half-integral spin particles are in an entangled anti-symmetric state. There are important differences between these two types of entanglement, especially that the Pauli exclusion principle holds in the latter case and not in the former. In either case, however, the status of the individual particle is problematic. The individuality or thisness (Latin "haecceitas") does not seem to be manifested except in interactions with macroscopic

systems, as emphasized in Frisch's famous article, "Take a photon." (I suspect, incidentally, that the word "haecceitas" has seldom if ever occurred at a physics conference since the seventeenth century, but I use it to emphasize again the thesis that modern physics throws some light upon traditional metaphysical problems.)

5. Gauge field theories provide strong constraints upon the interactions permitted among elementary particles. This is an advance of great importance, since a perennial obscurity of the Democritean point of view has been the nature of interactions.

6. Both the special and the general theories of relativity transform our conception of space and time. The special theory asserts an inseparability of space and time in a much stronger sense than in classical kinematics. Classically, space-time is a four-dimensional affine space, with metric properties restricted to space separately and time separately, whereas the space-time of special relativity is a four-dimensional metric space (with a three-one metric). General relativity envisages a dynamical interaction of space-time with matter, instead of regarding the former as a fixed arena in which material dynamics occurs.

7. The interface of physics and biology has a metaphysical implication of great significance: that all biological processes not involving mentality can in principle be understood in terms of physical interactions. Even the program of pre-biotic evolution – of understanding the emergence of mutually catalytic molecules and eventually explaining the evolution of the genetic code in terms of ordinary physical processes – is very promising. I should note that the qualification "not involving mentality" was not inserted for the purpose of hedging but for the positive reason that, in my opinion, a further scientific revolution is needed in order to understand the place of mentality in the natural world.

8. Elementary particle theory and cosmology already have, or are on the verge of having, profound metaphysical implications. But since the assessment of these implications is beyond my expertise, I encourage others to make them explicit.

Finally, I wish to warn against construing this list of metaphysical implications as indicating that all is settled or nearly settled in fundamental physics, and that we need only read off the corollaries in order to do philosophy properly. Rather, there seem to me to be dark clouds showing the need for radical changes in physical theory. One dark cloud is the problem of the reduction of the wave packet, which I prefer to call the problem of the actualization of potentialities. Of course, the advocates of many-worlds and decoherence theories say that there is no such problem, but I am skeptical of their solution (which obliterates the distinction between potentiality and actuality), not for reasons of sophisticated physics, but because of a straightforward philosophical analysis of the relevant concepts. The outcome of this philosophical analysis is to provide a motivation for a modification of quantum dynamics, such as the stochastic modification advocated by Pearle, Ghirardi-Rimini-Weber, Piron, Karolyhazy-Frenkel, Gisin, Percival, Diosi, Penrose, and Bell. They all hope to provide a physical, rather than an epistemological, explanation of the actualization of potentialities. Here is an instance in which philosophical considerations may turn out to provide valuable heuristics for physical investigations. Another dark cloud is the problem of mentality. Before one takes too literally the phrase "theory of everything," applied to the hoped-for theory that explains all forces of nature, the spectrum of elementary particles, the values of all parameters, and the structure of space-time, one should inquire whether such a theory could even in principle account for the immediacy of consciousness.

Theory of value:

I shall say little about the relation between physics and theory of value, partly because of my lack of expertise. However, I do have a few strong opinions. There is, I believe, a real danger that our emotional and moral senses will be dulled by the advance of technology. The case is not hopeless, and the humanities and social sciences have serious suggestions for confronting this danger. But I think that the natural sciences can also make a contribution. A sense of wonder is one of the great motivations of the investigations of science, and the discoveries of science should provide much new nourishment of the sense of wonder. If physics is to offer an antidote against emotional flattening, however, it is essential that its discoveries be understood as revelations of the real structure of the world, to a good approximation, and not just as recipes for making laboratory predictions. My personal experience is that penetrating even a little into the secrets of the universe provides an emotional satisfaction that is like the satisfaction traditionally provided by religion. I suspect that others share this experience.

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The Third International Workshop on Squeezed States and Uncertainty Relations was held at the University of Maryland Baltimore County on August 10 - 13, 1993. This workshop was jointly organized by the University of Maryland and the Lebedev Physical Institute of the Russian Republic. These workshops were initiated by Y. S. Kim, of the University of Maryland, College Park. The first of these workshops was held in 1991 at the University of Maryland, College Park, and the second, in Moscow in 1992.

The purpose of these workshops is to bring together an international selection of scientists to discuss the latest developments in Squeezed States in various branches of physics, and in the understanding of the foundations of quantum mechanics. At the third workshop, special attention was given to the influence that quantum optics is having on our understanding of quantum measurement theory.

The fourth meeting in this series will be held in the People's Republic of China. The principal organizer will be Q. C. Peng, of the Shanxi University at Taiyun, P. R. C.

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