Experiments to prove

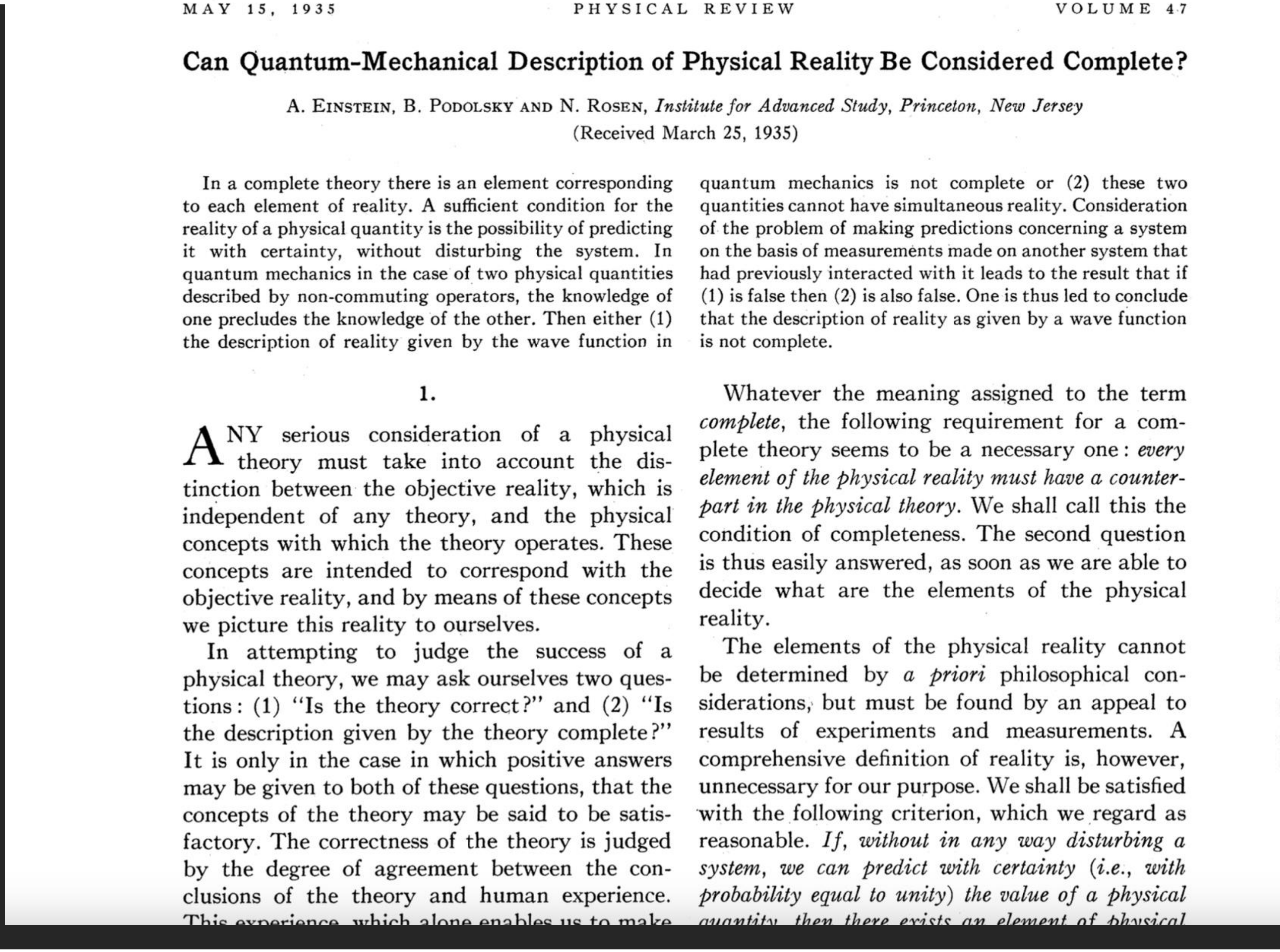
Quantum Entanglement

Prof. Mimoza Hafizi
University of Tirana

Science Week, Tirana, October 1, 2024

- **Quantum Entanglement: EPR paradox, QM-complete theory?**
- **Hidden variables**
- **Bell inequalities**
- **Experimental tests**

EPR paradox, QM-complete theory?



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

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

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.

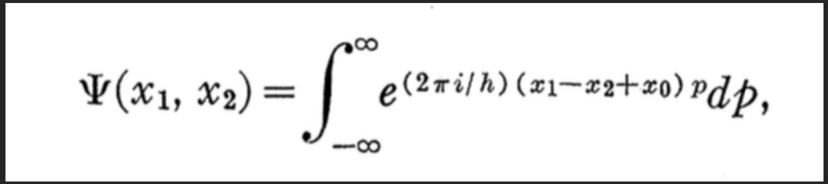
1.

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.

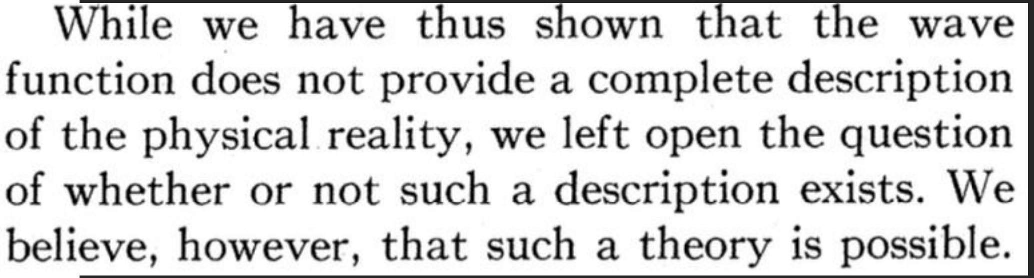
In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory 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

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*

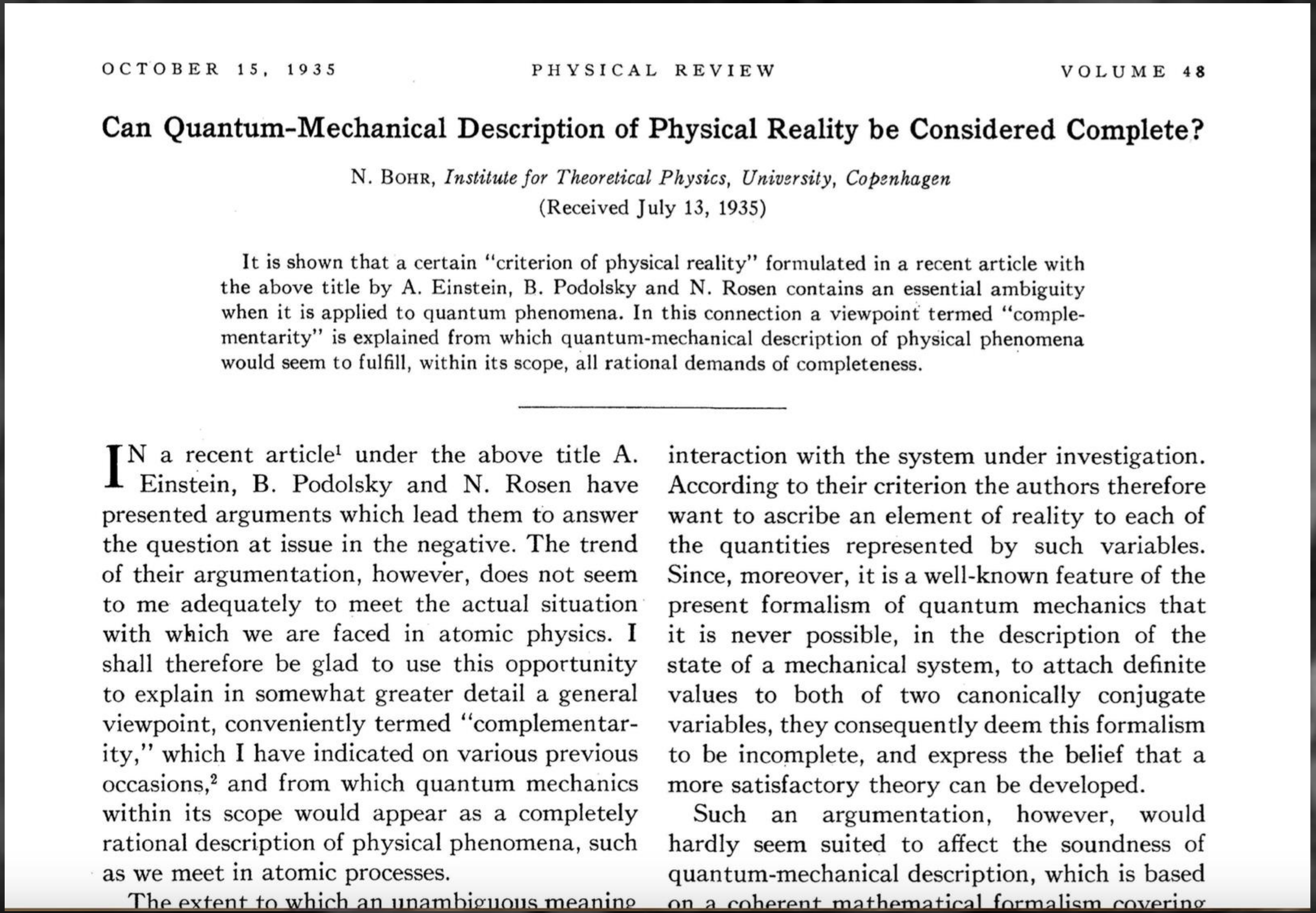


$$\Psi(x_1, x_2) = \int_{-\infty}^{\infty} e^{(2\pi i/h)(x_1 - x_2 + x_0)p}dp,$$



While we have thus shown that the wave function does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe, however, that such a theory is possible.

EPR paradox, QM-complete theory?



OCTOBER 15, 1935 PHYSICAL REVIEW VOLUME 48

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

N. Bohr, *Institute for Theoretical Physics, University, Copenhagen*
(Received July 13, 1935)

It is shown that a certain "criterion of physical reality" formulated in a recent article with the above title by A. Einstein, B. Podolsky and N. Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed "complementarity" is explained from which quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness.

IN a recent article[1] under the above title A. Einstein, B. Podolsky and N. Rosen have presented arguments which lead them to answer the question at issue in the negative. The trend of their argumentation, however, does not seem to me adequately to meet the actual situation with which we are faced in atomic physics. I shall therefore be glad to use this opportunity to explain in somewhat greater detail a general viewpoint, conveniently termed "complementarity," which I have indicated on various previous occasions,[2] and from which quantum mechanics within its scope would appear as a completely rational description of physical phenomena, such as we meet in atomic processes.

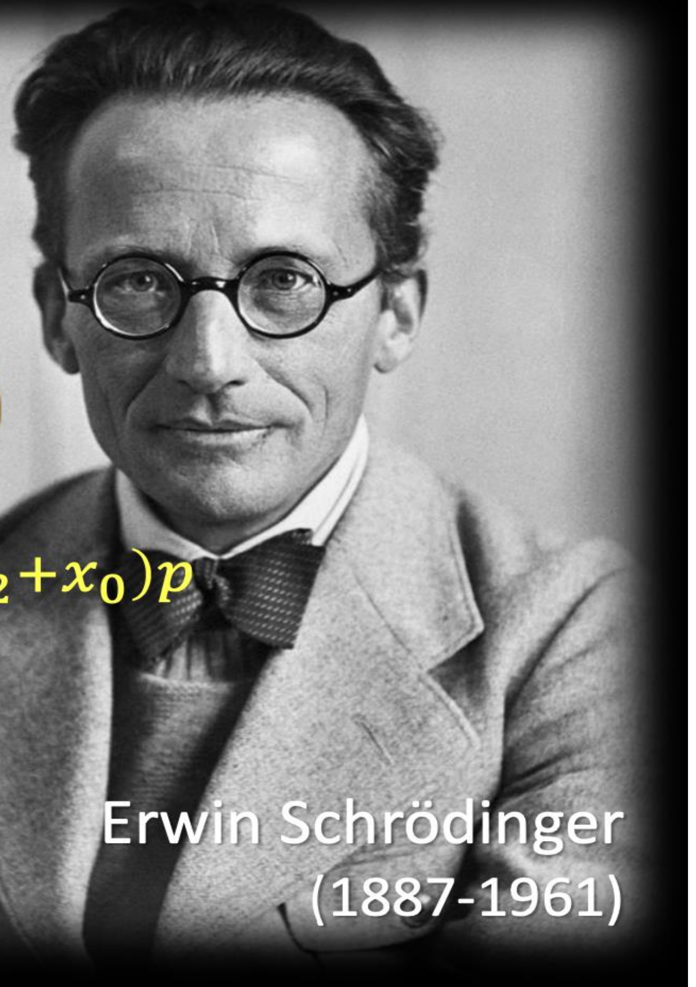
The extent to which an unambiguous meaning

interaction with the system under investigation. According to their criterion the authors therefore want to ascribe an element of reality to each of the quantities represented by such variables. Since, moreover, it is a well-known feature of the present formalism of quantum mechanics that it is never possible, in the description of the state of a mechanical system, to attach definite values to both of two canonically conjugate variables, they consequently deem this formalism to be incomplete, and express the belief that a more satisfactory theory can be developed.

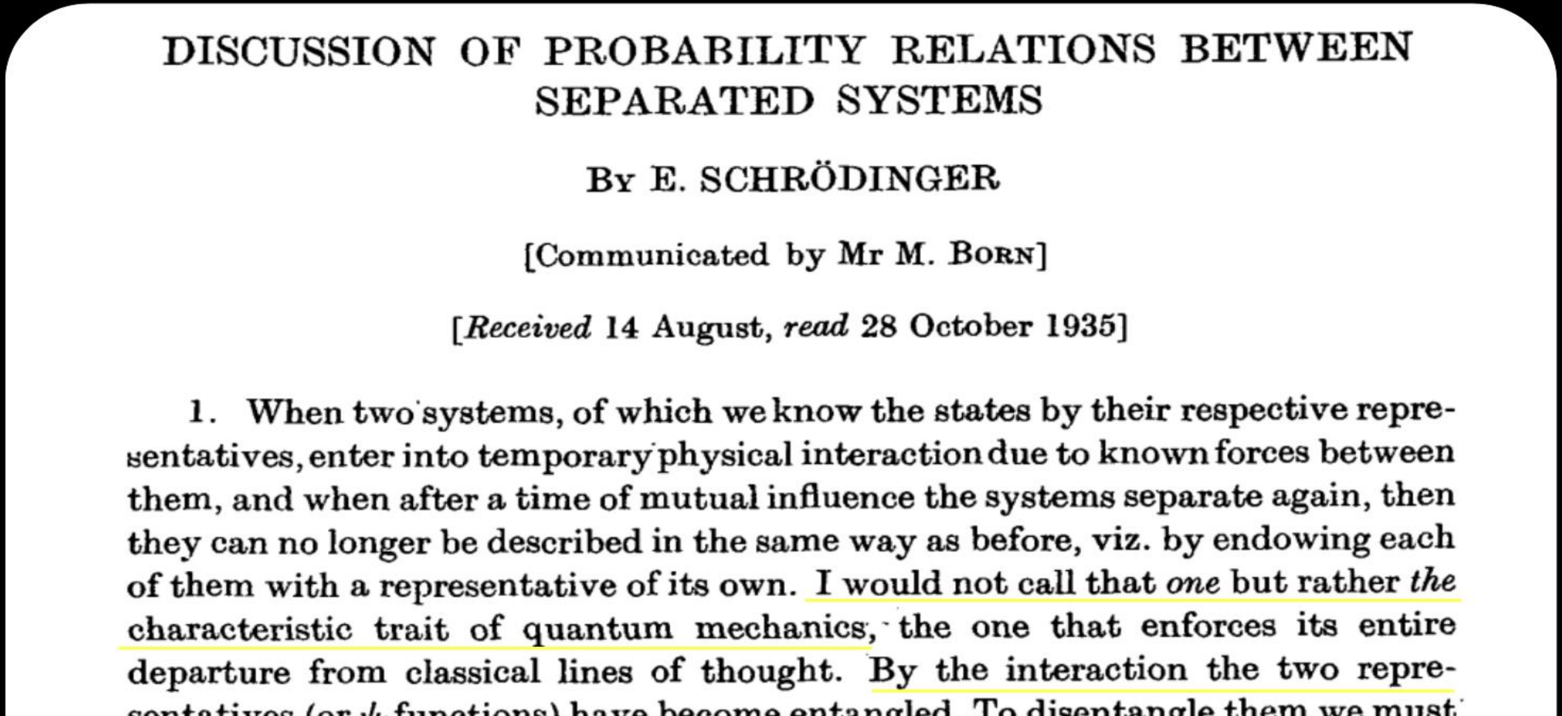
Such an argumentation, however, would hardly seem suited to affect the soundness of quantum-mechanical description, which is based on a coherent mathematical formalism covering

Quantum Entanglement

$$\Psi(x_1, x_2) = \int_{-\infty}^{+\infty} dp\, e^{i\frac{2\pi}{\hbar}(x_1 - x_2 + x_0)p}$$



Erwin Schrödinger
(1887-1961)



DISCUSSION OF PROBABILITY RELATIONS BETWEEN SEPARATED SYSTEMS

By E. SCHRÖDINGER

[Communicated by Mr M. BORN]

[*Received* 14 August, *read* 28 October 1935]

1. When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ functions) have become entangled. To disentangle them we must

Have become entangled

Remain entangled

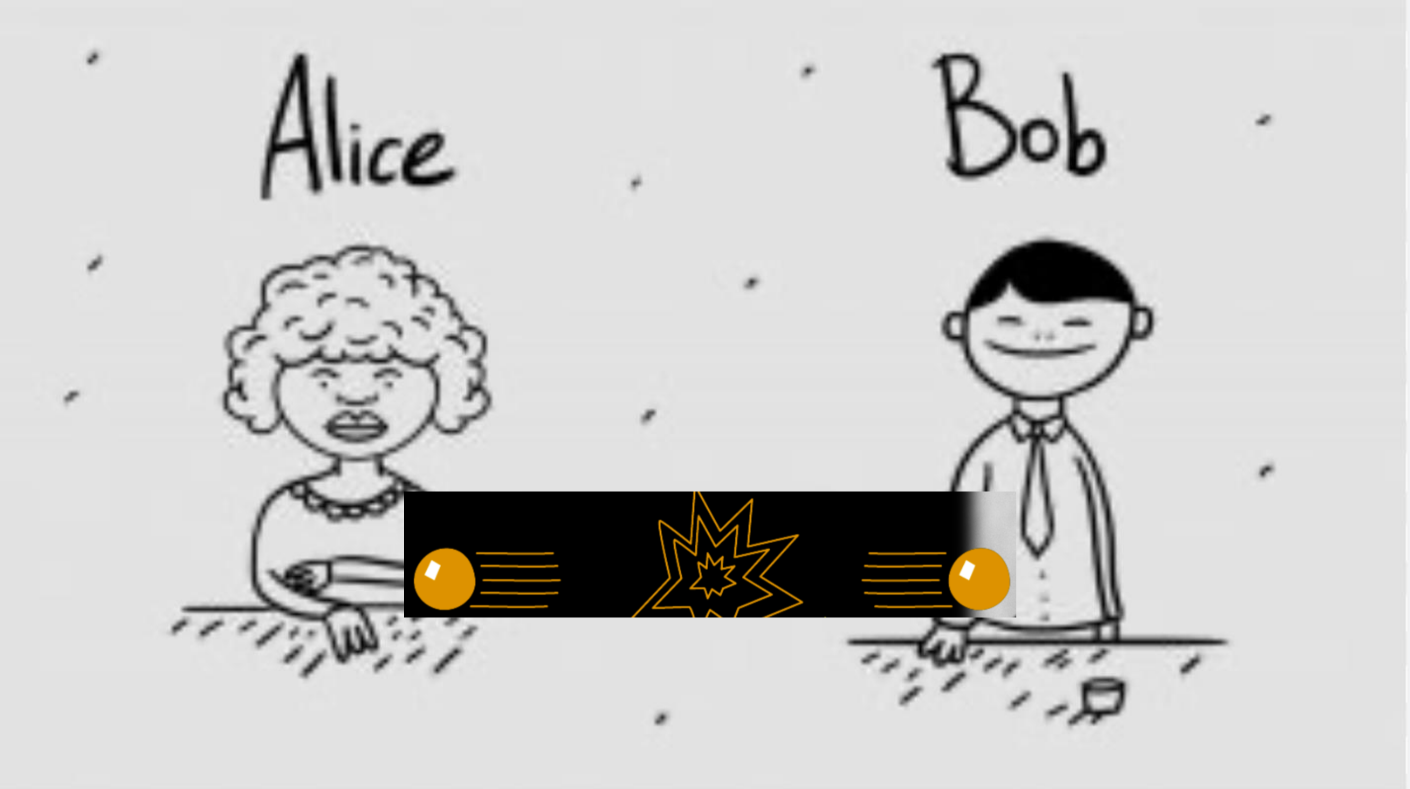
Wave function is not a product

Spooky action!

The entanglement is maintained despite the separation of two particles by vast distances.

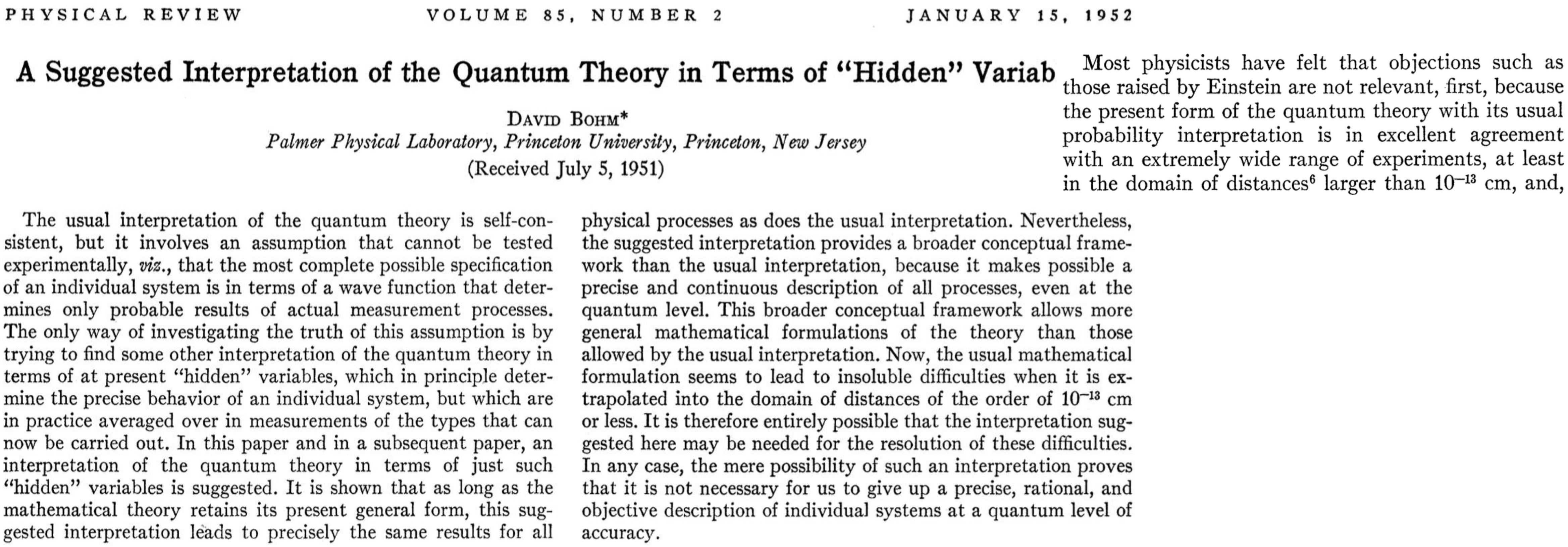
The particles disentangle only upon the interaction of one of them with the medium (during an experiment, f.ex.)

When Alice conducts a measurement on the first particle, the behaviour of the second particle becomes determined, **regardless of the significant distance separating them!**



Einstein wrote to Max Born, 1947: “I cannot seriously believe (in quantum mechanics) because the theory is incompatible with the requirement that physics should represent reality in space and time without **spooky action** at distance …”

Hidden variables



PHYSICAL REVIEW VOLUME 85, NUMBER 2 JANUARY 15, 1952

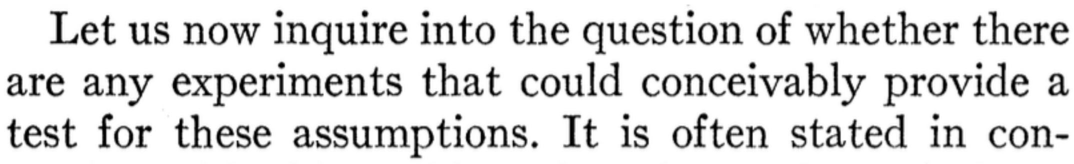
A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variab

DAVID BOHM*
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received July 5, 1951)

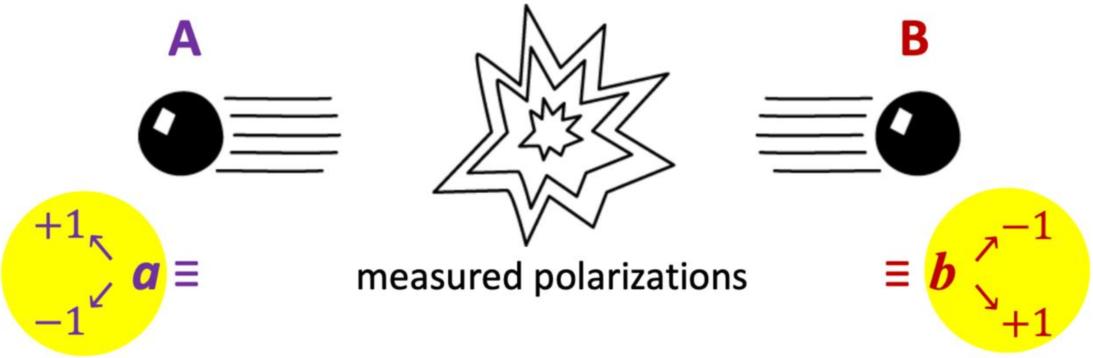
The usual interpretation of the quantum theory is self-consistent, but it involves an assumption that cannot be tested experimentally, *viz.*, that the most complete possible specification of an individual system is in terms of a wave function that determines only probable results of actual measurement processes. The only way of investigating the truth of this assumption is by trying to find some other interpretation of the quantum theory in terms of at present "hidden" variables, which in principle determine the precise behavior of an individual system, but which are in practice averaged over in measurements of the types that can now be carried out. In this paper and in a subsequent paper, an interpretation of the quantum theory in terms of just such "hidden" variables is suggested. It is shown that as long as the mathematical theory retains its present general form, this suggested interpretation leads to precisely the same results for all physical processes as does the usual interpretation. Nevertheless, the suggested interpretation provides a broader conceptual framework than the usual interpretation, because it makes possible a precise and continuous description of all processes, even at the quantum level. This broader conceptual framework allows more general mathematical formulations of the theory than those allowed by the usual interpretation. Now, the usual mathematical formulation seems to lead to insoluble difficulties when it is extrapolated into the domain of distances of the order of 10^{-13} cm or less. It is therefore entirely possible that the interpretation suggested here may be needed for the resolution of these difficulties. In any case, the mere possibility of such an interpretation proves that it is not necessary for us to give up a precise, rational, and objective description of individual systems at a quantum level of accuracy.

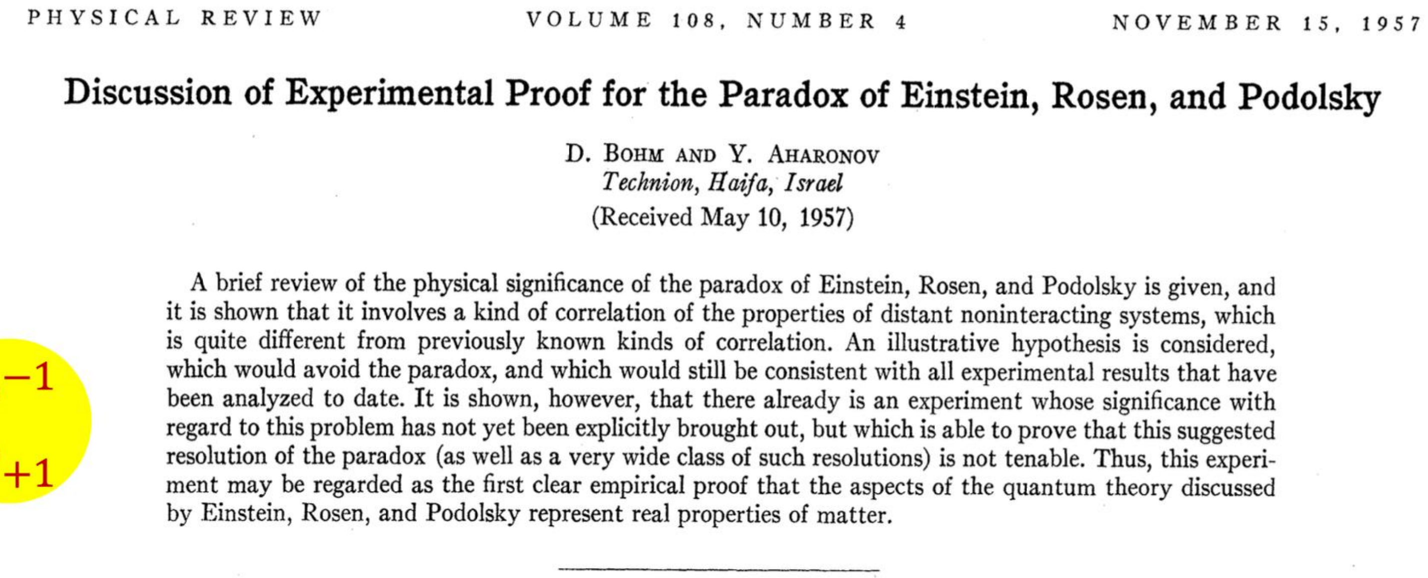
Most physicists have felt that objections such as those raised by Einstein are not relevant, first, because the present form of the quantum theory with its usual probability interpretation is in excellent agreement with an extremely wide range of experiments, at least in the domain of distances[6] larger than 10^{-13} cm, and,



Let us now inquire into the question of whether there are any experiments that could conceivably provide a test for these assumptions. It is often stated in con-

Towards the experiment. Spin and polarization



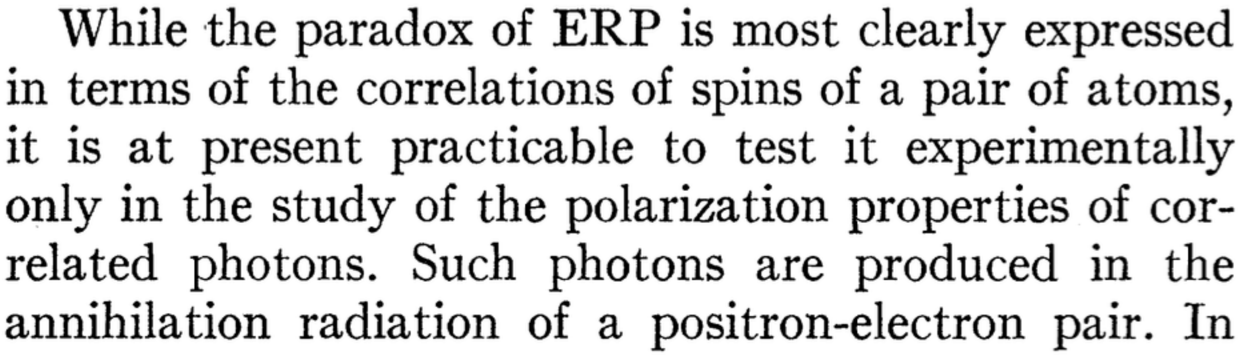

PHYSICAL REVIEW VOLUME 108, NUMBER 4 NOVEMBER 15, 1957

Discussion of Experimental Proof for the Paradox of Einstein, Rosen, and Podolsky

D. Bohm and Y. Aharonov
Technion, Haifa, Israel

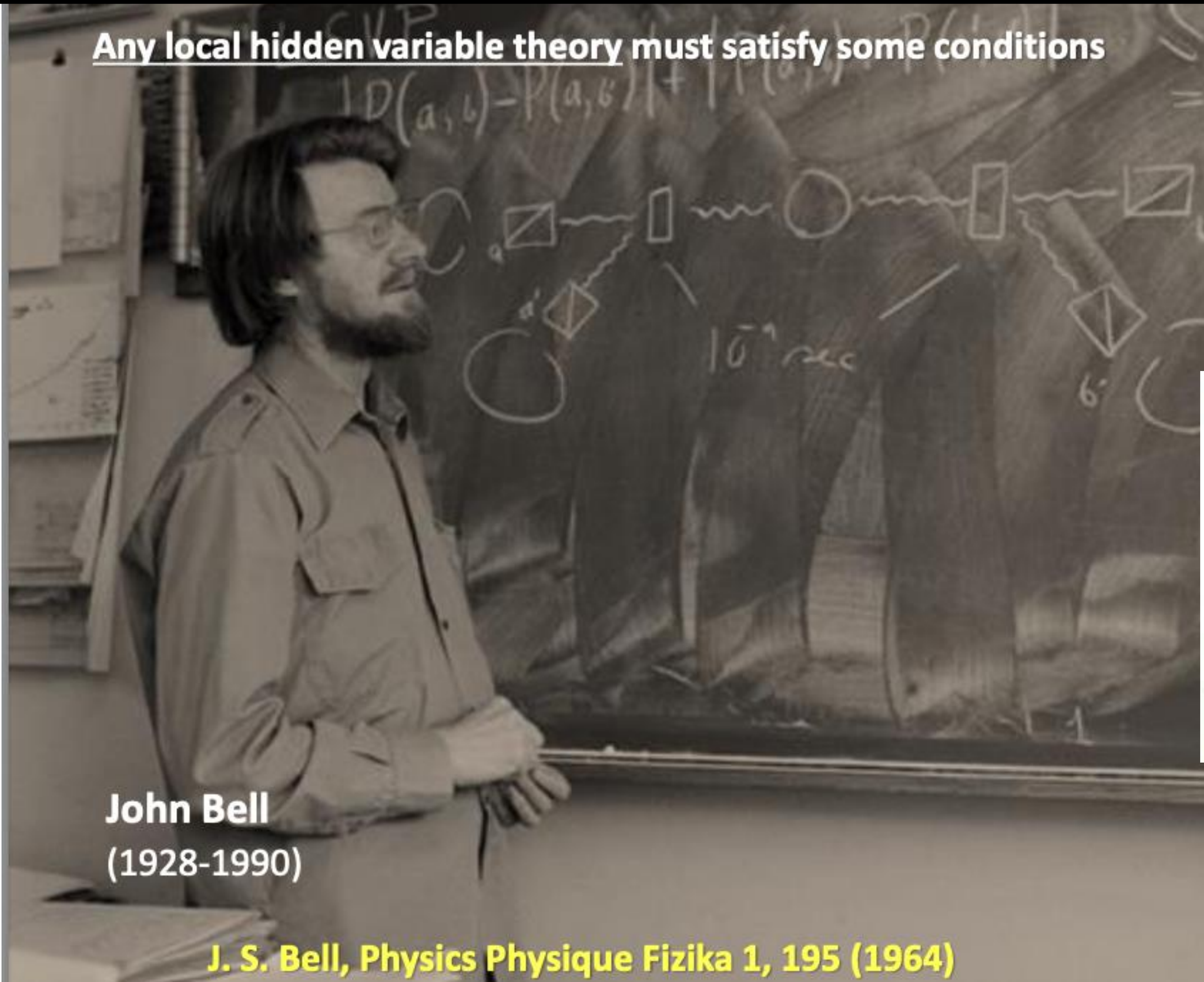
(Received May 10, 1957)

A brief review of the physical significance of the paradox of Einstein, Rosen, and Podolsky is given, and it is shown that it involves a kind of correlation of the properties of distant noninteracting systems, which is quite different from previously known kinds of correlation. An illustrative hypothesis is considered, which would avoid the paradox, and which would still be consistent with all experimental results that have been analyzed to date. It is shown, however, that there already is an experiment whose significance with regard to this problem has not yet been explicitly brought out, but which is able to prove that this suggested resolution of the paradox (as well as a very wide class of such resolutions) is not tenable. Thus, this experiment may be regarded as the first clear empirical proof that the aspects of the quantum theory discussed by Einstein, Rosen, and Podolsky represent real properties of matter.


While the paradox of ERP is most clearly expressed in terms of the correlations of spins of a pair of atoms, it is at present practicable to test it experimentally only in the study of the polarization properties of correlated photons. Such photons are produced in the annihilation radiation of a positron-electron pair. In

Bell inequality

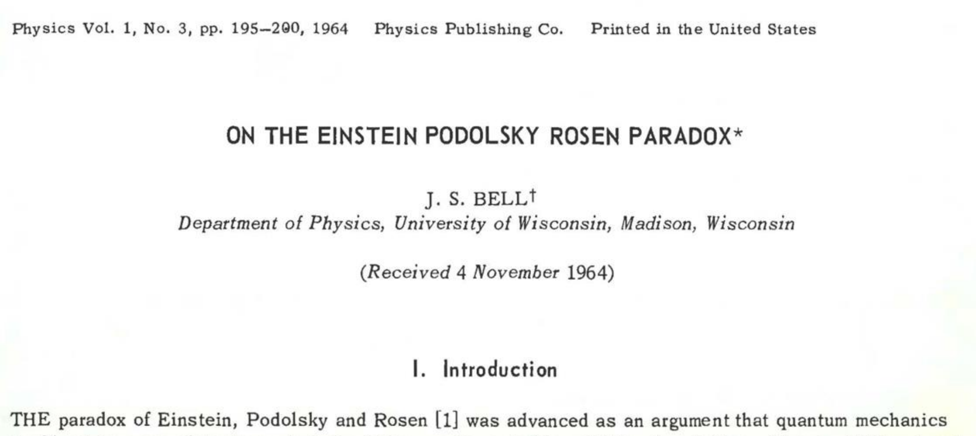
Any local hidden variable theory must satisfy some conditions



John Bell

(1928-1990)

J. S. Bell, Physics Physique Fizika 1, 195 (1964)


Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

(*Received* 4 *November* 1964)

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

Bell’s Theorem (CHSH version 1969)

For realistic models (hidden variable models, hidden variable λ), the outcomes of experiment are described by random variables.

Correlation

$$C'(\alpha-\beta)=\int s_{\alpha 1}(\lambda)s_{\beta 2}(\lambda)p(\lambda)d\lambda$$

1. Measurement outcomes can be described by two families of random variables: Realism.

2. Measurement outcomes are independent of the remote setting: Locality

3. Measurement outcomes are $+\hbar/2$ or -$\hbar/2$ in case of particle’s spin (+1 or -1 in case of photon polarisation)

$$\boldsymbol{S}=\frac{\mathbf{4}}{\hbar^{2}}[\boldsymbol{C}'(\boldsymbol{\alpha}-\boldsymbol{\beta})+\boldsymbol{C}'(\boldsymbol{\alpha}-\boldsymbol{\beta}')+\boldsymbol{C}'(\boldsymbol{\alpha}'-\boldsymbol{\beta}')-\boldsymbol{C}'(\boldsymbol{\alpha}'-\boldsymbol{\beta})].$$

$$|\boldsymbol{S}|\leq \mathbf{2}$$

CHSH (Clauser, Horn, Shimony, Holt) 1969.

Bell inequallity is violated by quantum-mechanical predictions.

Early experiments: Reliability
Freedman, Clauser Experiment

The first experiments (70') have not yielded consistent results regarding the violation of the Bell Inequality.

Kasday et al.; Faraci et al., Gutkowski et al., Wilson et al., Bruno et al.

Photons comming from positronium annihilation.

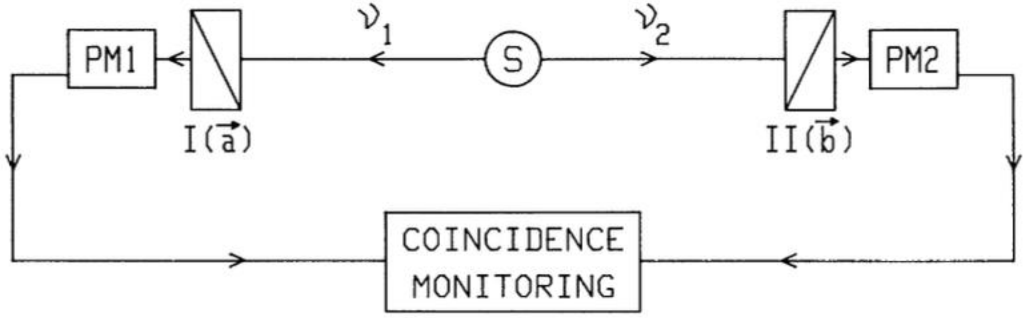


FIG. 1. Optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*. The pair of photons ν_1 and ν_2 is analyzed by linear polarizers I and II (in orientations $\vec{a}$ and $\vec{b}$) and photomultipliers. The coincidence rate is monitored.

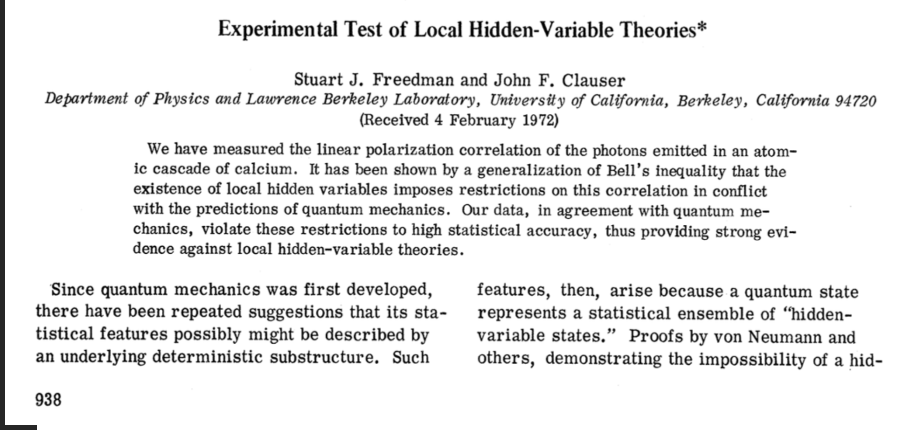

John Clauser
(*1942)

Freedman, Clauser (Berkeley Lab), 1972

The first reliable test using Ca cascade confirmed CHSH inequality violation on the level of 6.5σ

Detectors separated about 3m.

Suffered from communication loophole.


Experimental Test of Local Hidden-Variable Theories*

Stuart J. Freedman and John F. Clauser
Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 4 February 1972)

We have measured the linear polarization correlation of the photons emitted in an atomic cascade of calcium. It has been shown by a generalization of Bell's inequality that the existence of local hidden variables imposes restrictions on this correlation in conflict with the predictions of quantum mechanics. Our data, in agreement with quantum mechanics, violate these restrictions to high statistical accuracy, thus providing strong evidence against local hidden-variable theories.

Since quantum mechanics was first developed, there have been repeated suggestions that its statistical features possibly might be described by an underlying deterministic substructure. Such features, then, arise because a quantum state represents a statistical ensemble of "hidden-variable states." Proofs by von Neumann and others, demonstrating the impossibility of a hid-

938

Loopholes

It is necessary to freely choose a direction for analysis, to set the analyser and to register the particle such that it is impossible for any information about these processes to travel via any (possibly unknown) channel to the other observer before he finishes his measurement.

Several tests performed in the 1970's had some "loopholes"

Loopholes

Locality: ambiguity when the *communication* between the parts of the experiment is possible.
In the case of static polarizers locality could be questioned: they allow them to reach some mutual rapport by exchanging signals with velocities les than or equal with the velocity of light.
It is crucial that the settings be changed during the flight of the particles (fast switching), to prevent the communication.

Detection: The experiments detect a small subset of all pair created.

Predictability during a sequence of settings is problematic. The memory must be avoided.

Freedom of choice of the settings. "The hidden variable" has not to influence to the setting.

Aspect Experiment

Aspect, Dalibard, Roger, 1982 (Institut d’Optique, Orsay, France)

Each polarizer is replaced by a setup involving a switching device followed by two polarizers in two different directions.

Timing experiment, where the locality condition becomes a consequence of Eistein’s causality, preventing any faster than light influence.
Photons coming from a cascade in Ca.

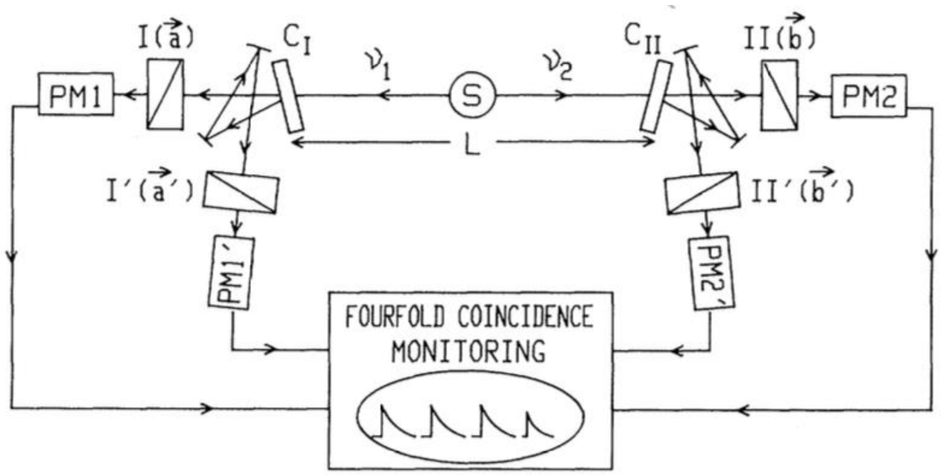
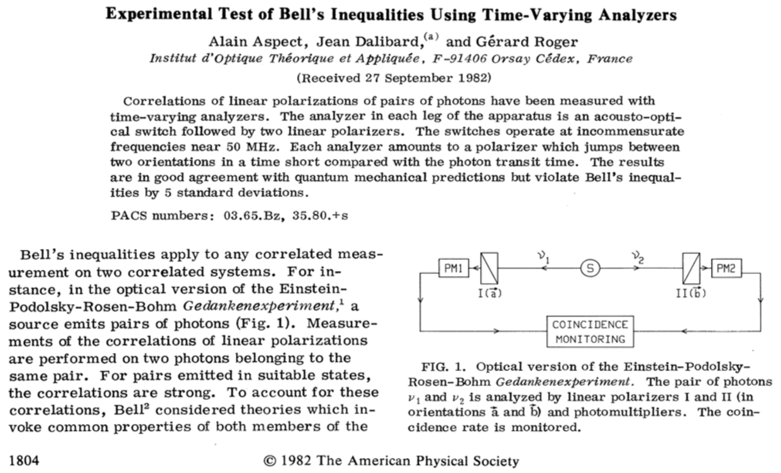


FIG. 2. Timing experiment with optical switches. Each switching device (C_I, C_{II}) is followed by two polarizers in two different orientations. Each combination is equivalent to a polarizer switched fast between two orientations.

- Switching between two channels occurs about each 10 ns, whereas L/t is 40 ns and the lifetime of the cascade is 5 ns.
- Particles separated at about 12 m.
- Obtained a violation of Bell’s Inequallity.
- But their switching was periodic and predictable in the future.



Experimental Test of Bell’s Inequalities Using Time-Varying Analyzers

Alain Aspect, Jean Dalibard,[a] and Gérard Roger
Institut d’Optique Théorique et Appliquée, F-91406 Orsay Cédex, France

(Received 27 September 1982)

Correlations of linear polarizations of pairs of photons have been measured with time-varying analyzers. The analyzer in each leg of the apparatus is an acousto-optical switch followed by two linear polarizers. The switches operate at incommensurate frequencies near 50 MHz. Each analyzer amounts to a polarizer which jumps between two orientations in a time short compared with the photon transit time. The results are in good agreement with quantum mechanical predictions but violate Bell’s inequalities by 5 standard deviations.

PACS numbers: 03.65.Bz, 35.80.+s

Bell’s inequalities apply to any correlated measurement on two correlated systems. For instance, in the optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*,[1] a source emits pairs of photons (Fig. 1). Measurements of the correlations of linear polarizations are performed on two photons belonging to the same pair. For pairs emitted in suitable states, the correlations are strong. To account for these correlations, Bell[2] considered theories which invoke common properties of both members of the

FIG. 1. Optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*. The pair of photons ν_1 and ν_2 is analyzed by linear polarizers I and II (in orientations $\vec{a}$ and $\vec{b}$) and photomultipliers. The coincidence rate is monitored.

… Zeilinger experiment

Since late 1980, all experiments performed with entangled photons produced by a process of the splitting of an incident photon in a crystal into two photons with orthogonal polarizations.

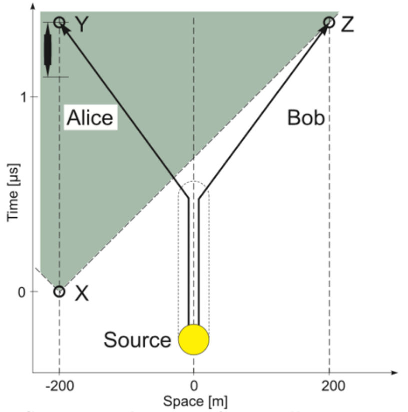
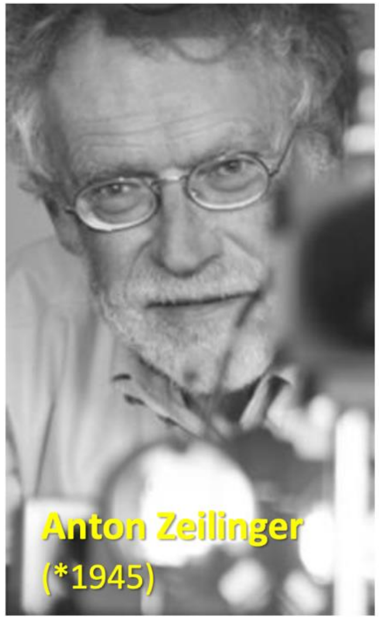
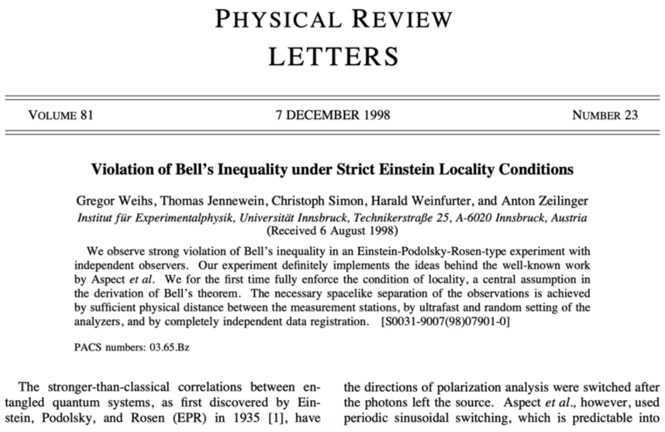


FIG. 1. Spacetime diagram of our Bell experiment. Selecting a random analyzer direction, setting the analyzer and finally detecting a photon constitute the measurement process. This process on Alice's side must fully lie inside the shaded region which is, during Bob's own measurement, invisible to him as a matter of principle. For our setup this means that the decision about the setting has to be made after point "X" if the corresponding photons are detected at spacetime points "Y" and "Z" respectively. In our experiment the measurement process (indicated by a short black bar) including the choice of a random number only took less than a tenth of the maximum allowed time. The vertical parts of the kinked photon world lines emerging from the source represent the fiber coils at the source location.

Weihs, Jennewein, Simon, Weinfurter, Zeilinger, 1998 (Universitat Innsbruck)

- Alice and Bob were spatially separated by a distance of 400m (1 μ s) across the Innsbruk University campus.
- High speed (far below 1μs) physical random number's generators to set the analyser's direction.
- Indipendent data registration associated with atomic clocks.
- Closing the communication loophole
- Obtained a violation of Bell's Inequallity.





PHYSICAL REVIEW LETTERS

VOLUME 81 7 DECEMBER 1998 NUMBER 23

Violation of Bell's Inequality under Strict Einstein Locality Conditions

Gregor Weihs, Thomas Jennewein, Christoph Simon, Harald Weinfurter, and Anton Zeilinger
Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, A-6020 Innsbruck, Austria
(Received 6 August 1998)

We observe strong violation of Bell's inequality in an Einstein-Podolsky-Rosen-type experiment with independent observers. Our experiment definitely implements the ideas behind the well-known work by Aspect *et al*. We for the first time fully enforce the condition of locality, a central assumption in the derivation of Bell's theorem. The necessary spacelike separation of the observations is achieved by sufficient physical distance between the measurement stations, by ultrafast and random setting of the analyzers, and by completely independent data registration. [S0031-9007(98)07901-0]

PACS numbers: 03.65.Bz

The stronger-than-classical correlations between entangled quantum systems, as first discovered by Einstein, Podolsky, and Rosen (EPR) in 1935 [1], have the directions of polarization analysis were switched after the photons left the source. Aspect *et al.*, however, used periodic sinusoidal switching, which is predictable into

Following Experiments

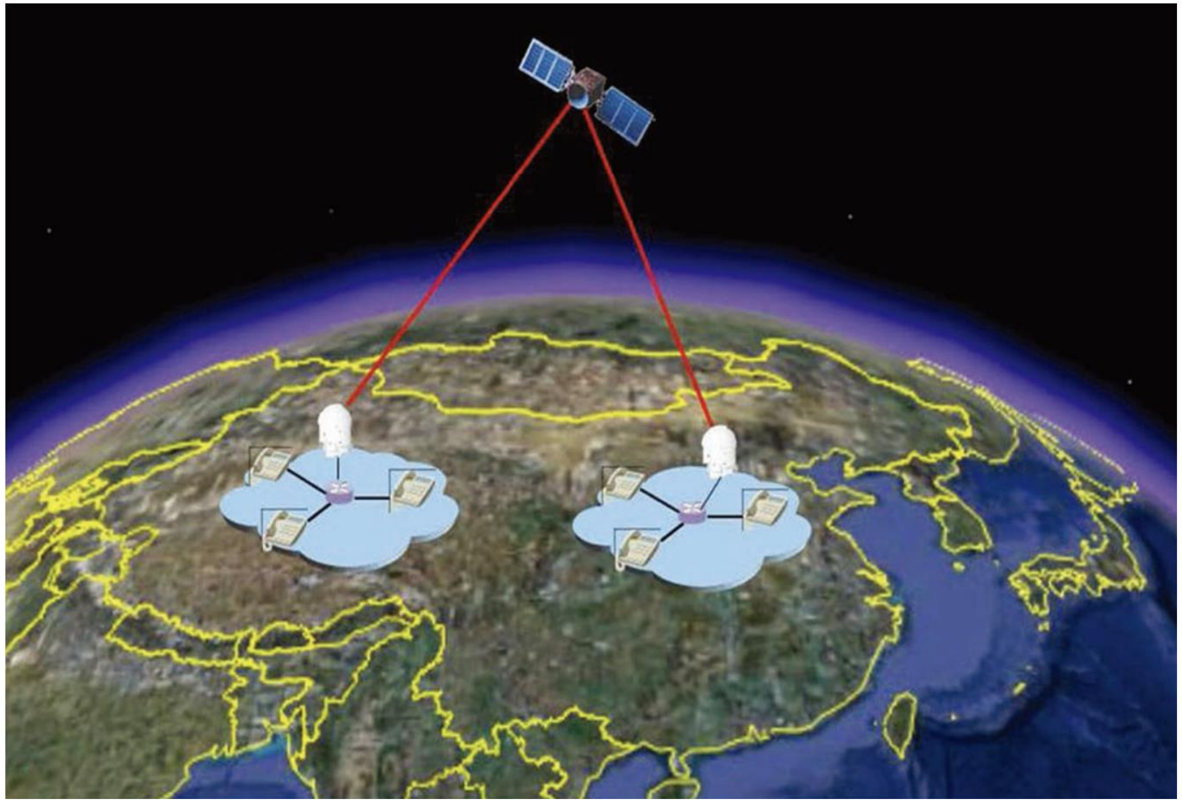
Tittel, Brende, Gisin, Herzog, Zbinden, 1998 (University of Geneva), entangled photons sent 10.9 km appart to two villages of Geneva.

Rowe, Kielpinski, Meyer, Sacket, Itano, Monroe,Wineland 2001 (University of Boulder, Colorado), efficiency of photons detection over 90%. Massive particles (9Be).

Three announced fully loop-free tests
Hensen et al. 2015 (Delft University), Electron spins (spatial separation 1.3km)
Giustina et al. 2015 (University of Vienna)
Shalm et al. 2015 (Boulder Colorado).

Hendsteiner, … Zeilinger 2017 (Vienna), settings of both detectors by photons coming from two different Milky Way sources (any casual connection strictly excluded).

Quantum Space satellite Mozi (2018), the first and the only satellite in space to prove quantum entanglement by testing the Bell's inequallity in a distance about 1200 km, between two astronomical observatories in China.



Experiments with other particles

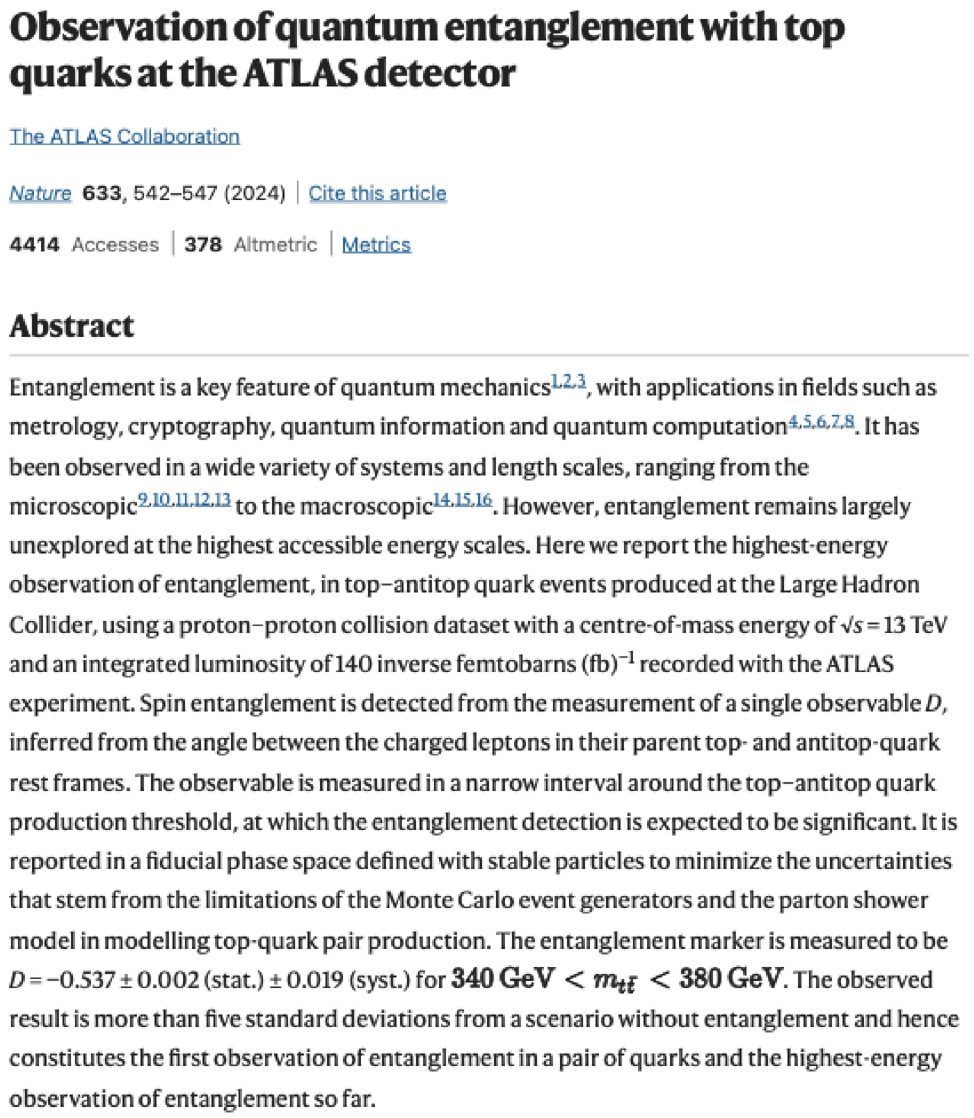
Schmied et al., (Basel) 2016, detection of Bell's correlations between particle spins in the Bose-Einstein condensate of Rb atoms.

Rosenfeld et al., (Munich) 2017, detection of correlations between two distant atoms (entanglement achieved via a photon exchange).

Holland et al. Princeton, 2022, entanglement of individually prepared molecules (CaF).

Lee et al. (University of Oxford, UK) 2011, motional vibrational entanglement between vibrational states of two spatially separated, millimeter-sized diamonds.

ATLAS, (CERN), 2024, entanglement between quarks. Pairs of top quarks were analysed (about one million). An entanglement between particle spins. First prove of entanglement in high energies.



Observation of quantum entanglement with top quarks at the ATLAS detector

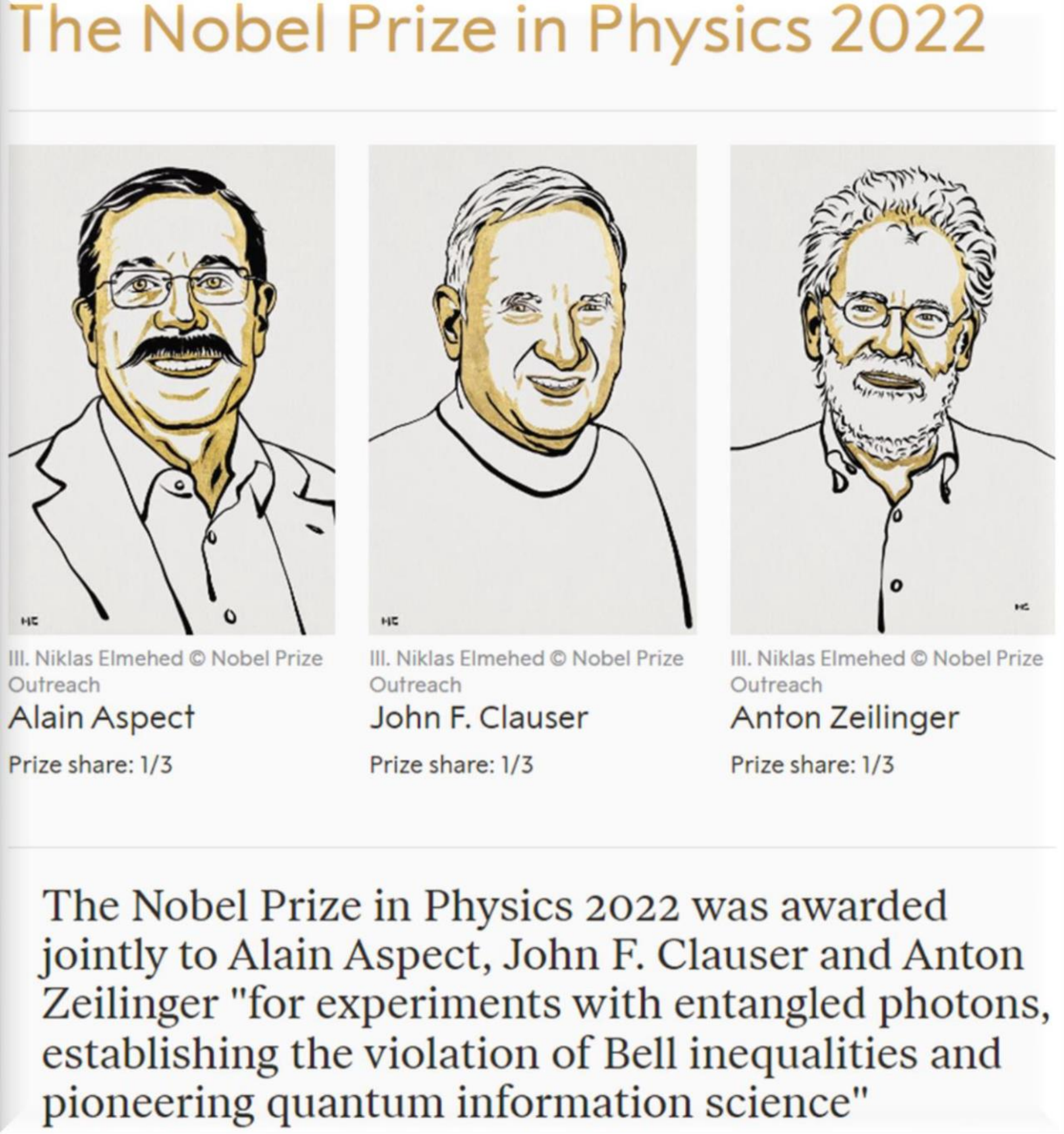
The ATLAS Collaboration

Nature **633**, 542–547 (2024) | Cite this article

4414 Accesses | **378** Altmetric | Metrics

Abstract

Entanglement is a key feature of quantum mechanics[1,2,3], with applications in fields such as metrology, cryptography, quantum information and quantum computation[4,5,6,7,8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic[9,10,11,12,13] to the macroscopic[14,15,16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision dataset with a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 inverse femtobarns $(\text{fb})^{-1}$ recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, at which the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from the limitations of the Monte Carlo event generators and the parton shower model in modelling top-quark pair production. The entanglement marker is measured to be $D = -0.537 \pm 0.002$ (stat.) ± 0.019 (syst.) for $340\ \text{GeV} < m_{t\bar{t}} < 380\ \text{GeV}$. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.



The Nobel Prize in Physics 2022

III. Niklas Elmehed © Nobel Prize Outreach

Alain Aspect

Prize share: 1/3

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John F. Clauser

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Anton Zeilinger

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The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

- **Quantum Computer**
- **Quantum Cryptography**
- **Quantum teleportation**
- **Entanglement-enhanced microscope**