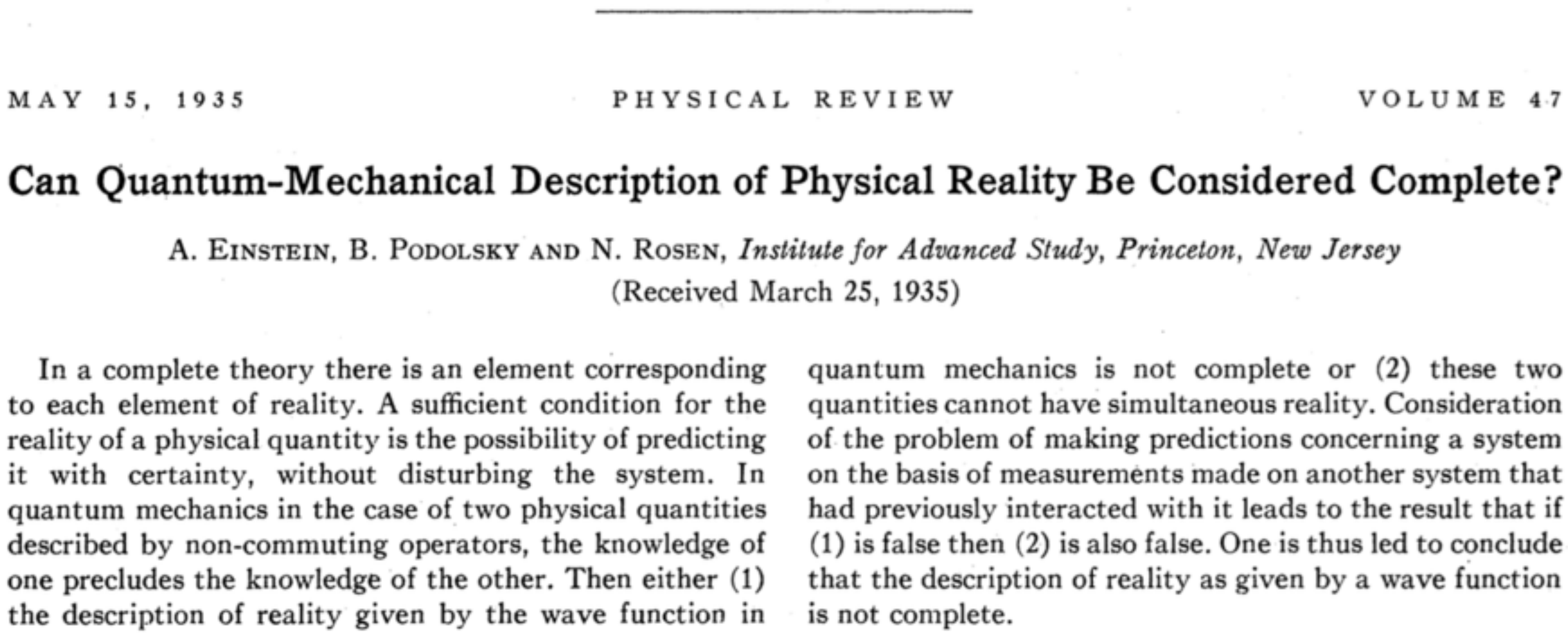
Experimental tests of Bell Inequalities

Resolution of E.P.R. Paradox

Physics 491 Friday feature

Fall 2016, M. Gold



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

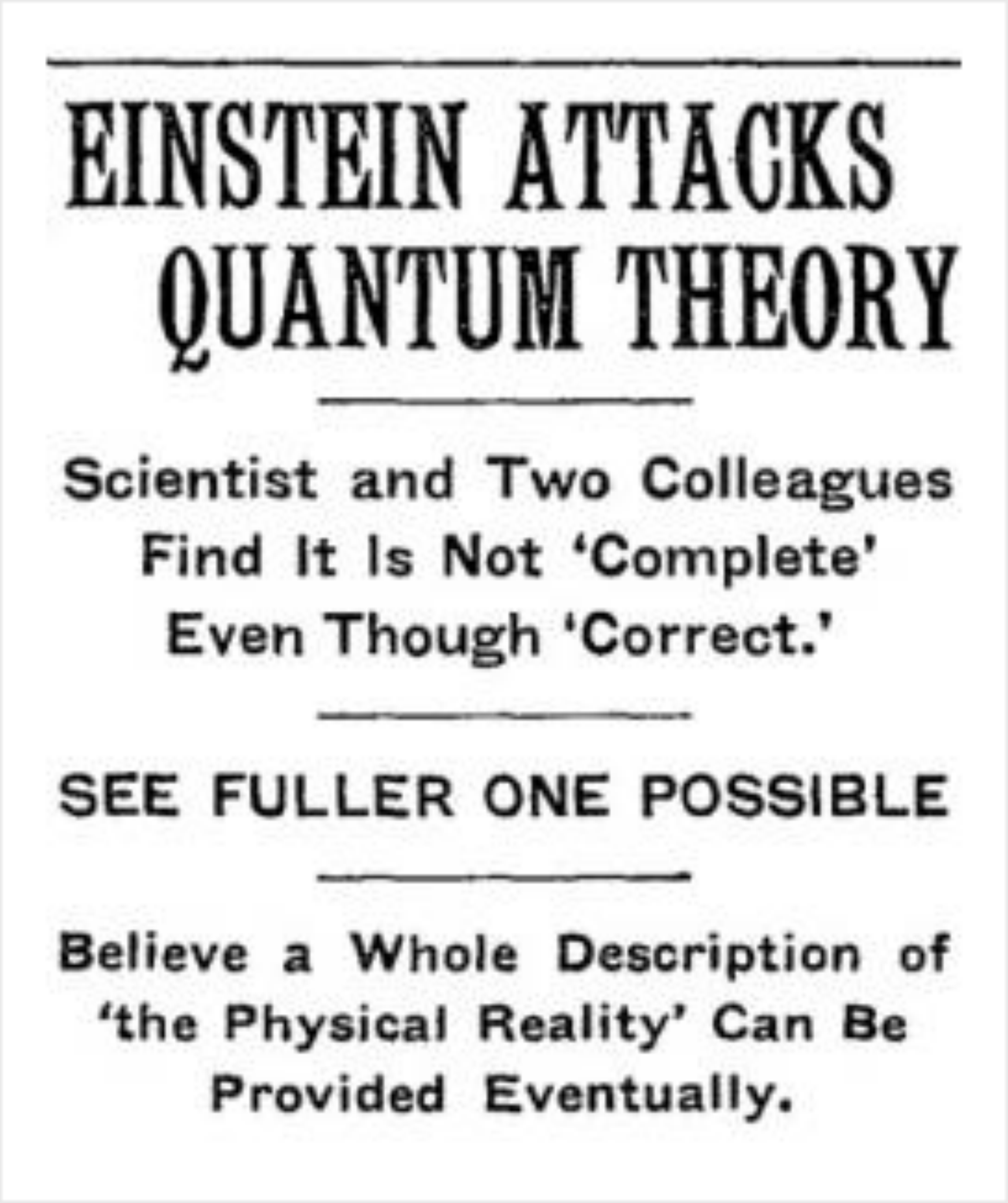
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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.

New York Times, May 4, 1935.

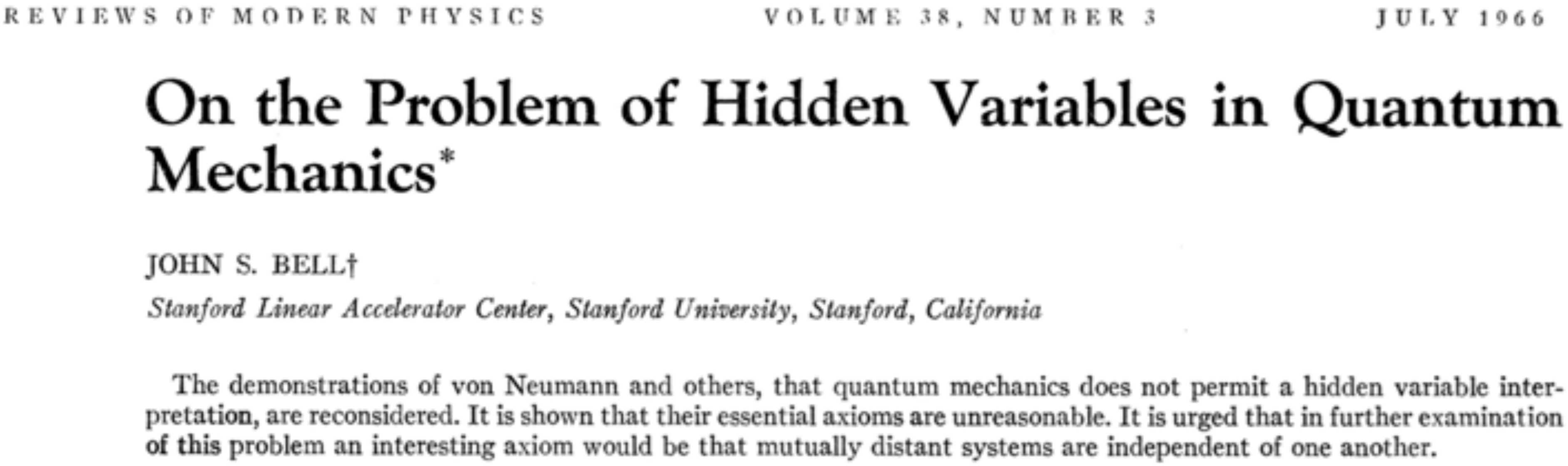


EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.



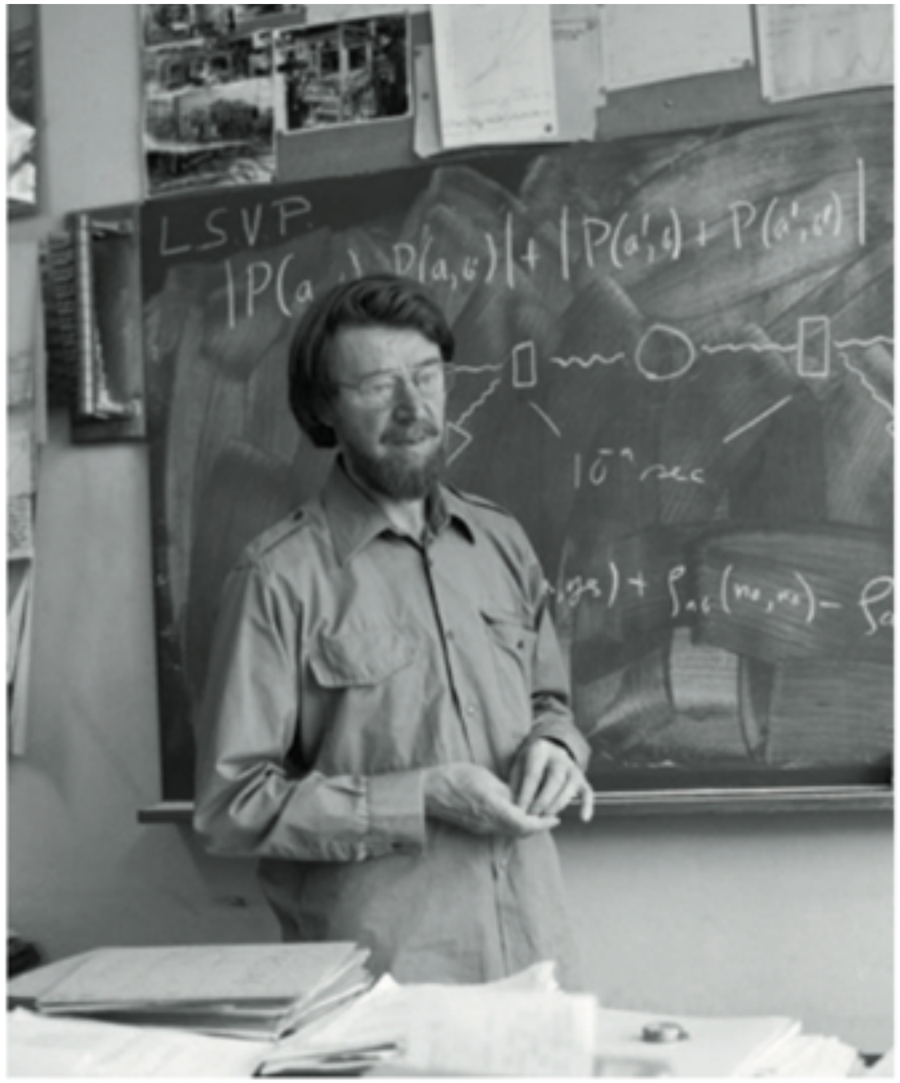
REVIEWS OF MODERN PHYSICS VOLUME 38, NUMBER 3 JULY 1966

On the Problem of Hidden Variables in Quantum Mechanics*

JOHN S. BELL†

Stanford Linear Accelerator Center, Stanford University, Stanford, California

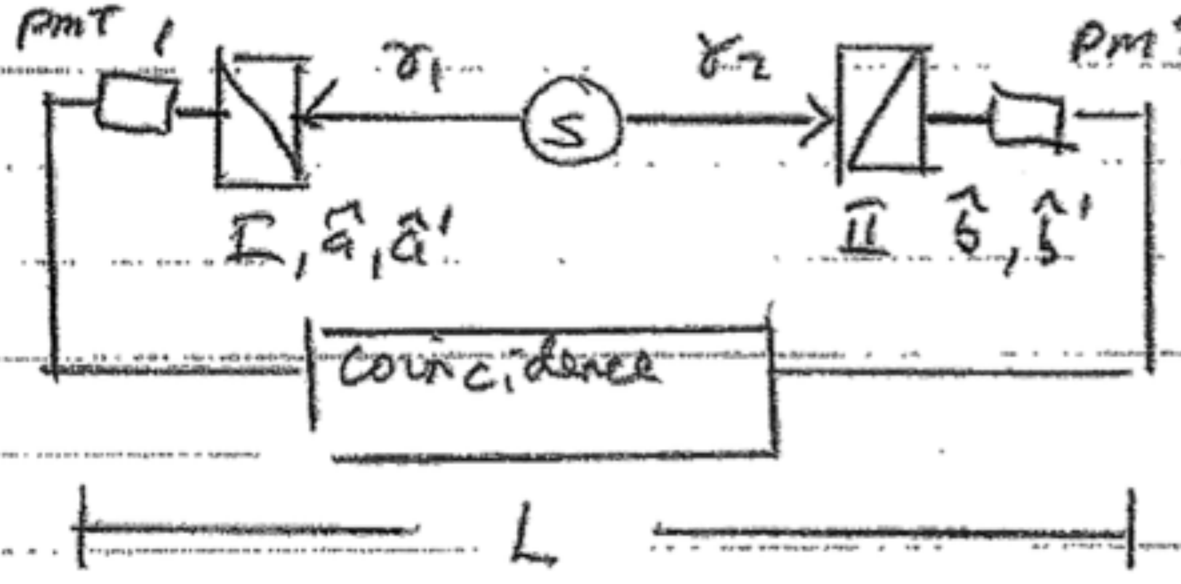
The demonstrations of von Neumann and others, that quantum mechanics does not permit a hidden variable interpretation, are reconsidered. It is shown that their essential axioms are unreasonable. It is urged that in further examination of this problem an interesting axiom would be that mutually distant systems are independent of one another.



John Bell devised a test to show that nature does not 'hide variables' as Einstein had proposed.

Aspect *et al.* PRL 49 (1804) 1982

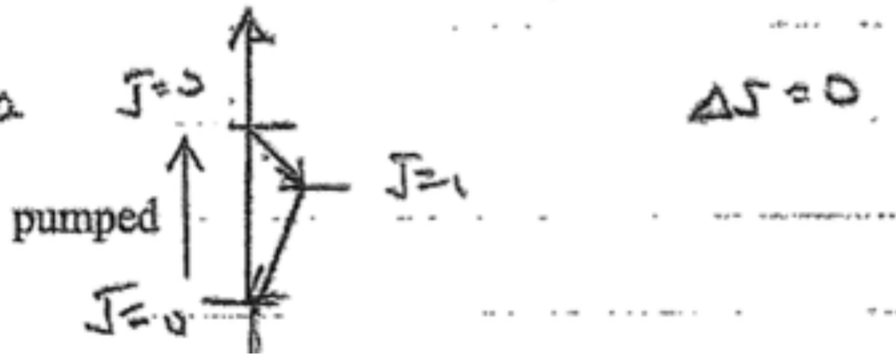
schematic – linear polarizers I, II



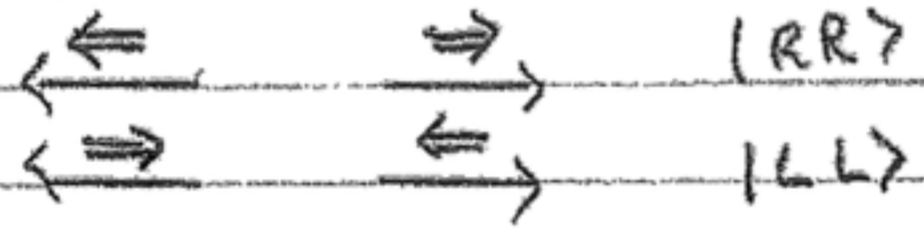
switch $\hat{a} \leftrightarrow \hat{a}'$, $\hat{b} \leftrightarrow \hat{b}'$ $\delta t = 10\,\text{ns} \ll \frac{L}{c} = 40\,\text{ns}$ synchronously

Levels of calcium

Source: Ca



$$|0,0\rangle = \frac{1}{\sqrt{2}}\left(|RR\rangle + |LL\rangle\right)$$



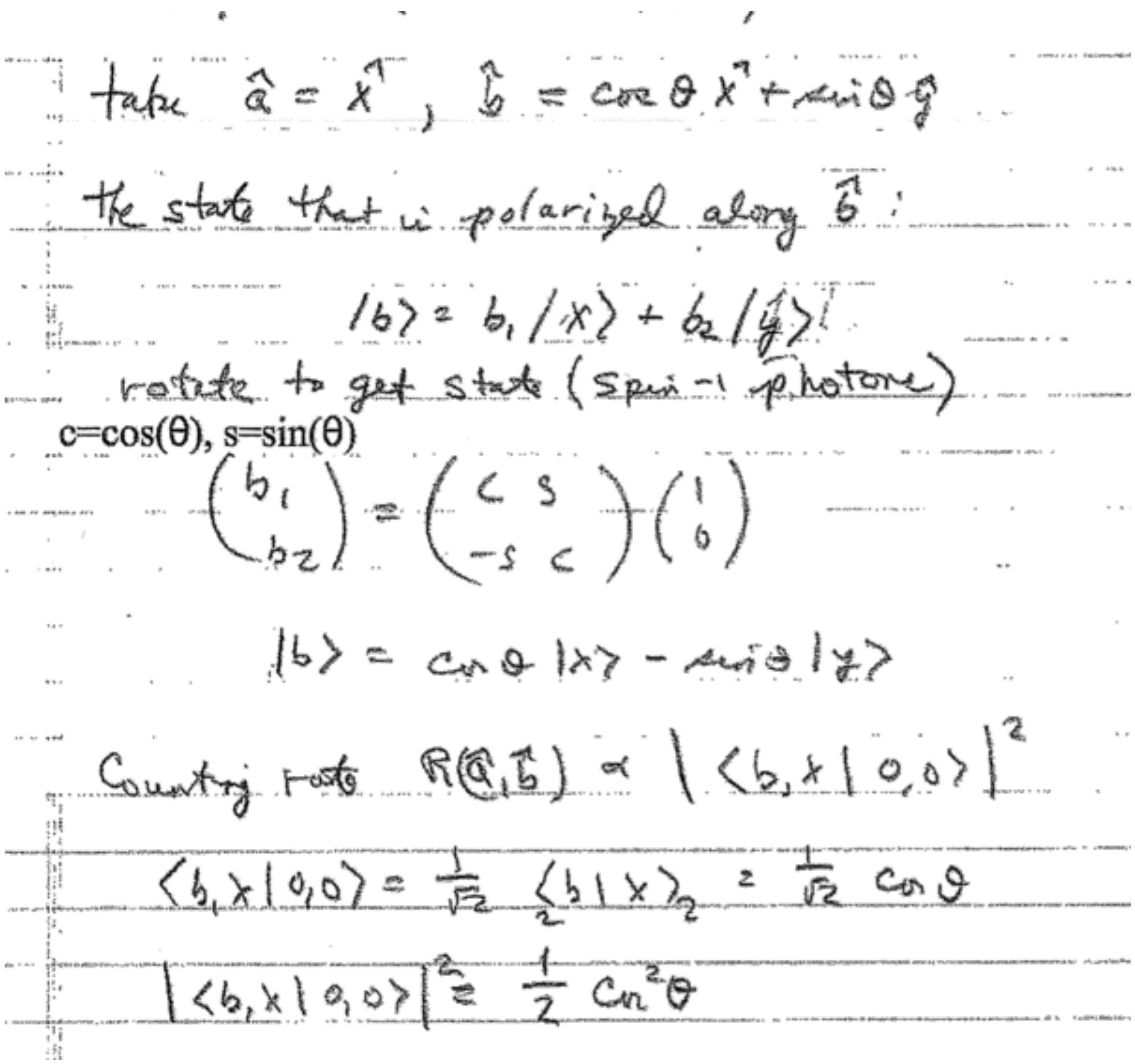
The spin components along the direction of motion add to zero, so m=0.
The fact that this combination is spin-0, |0,0>, is not obvious. The state |1,0> has the minus sign.

Being careful about direction of rotation of classical E vector
for particle 1 moves in +x direction and particle 2 moves in -x direction (see hw 5.13)

use $|R\rangle_1 = (|x\rangle + i|y\rangle)/\sqrt{2} = |L\rangle_2$

$|L\rangle_1 = (|x\rangle - i|y\rangle)/\sqrt{2} = |R\rangle_2$

$$|0,0\rangle = \frac{1}{\sqrt{2}}\left(|xx\rangle + |yy\rangle\right)$$ see problem 5.23



take $\hat{a} = \hat{x}$, $\hat{b} = \cos\theta\,\hat{x} + \sin\theta\,\hat{y}$

the state that is polarized along $\vec{b}$:

$$|b\rangle = b_1|x\rangle + b_2|y\rangle$$

rotate to get state (spin-1 photons)

c=cos(θ), s=sin(θ)

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$|b\rangle = \cos\theta\,|x\rangle - \sin\theta\,|y\rangle$$

Counting rate $R(\vec{a},\vec{b}) \propto \left|\langle b,x|0,0\rangle\right|^2$

$$\langle b,x|0,0\rangle = \frac{1}{\sqrt{2}}\,{}_2\langle b|x\rangle_2 = \frac{1}{\sqrt{2}}\cos\theta$$

$$\left|\langle b,x|0,0\rangle\right|^2 = \frac{1}{2}\cos^2\theta$$

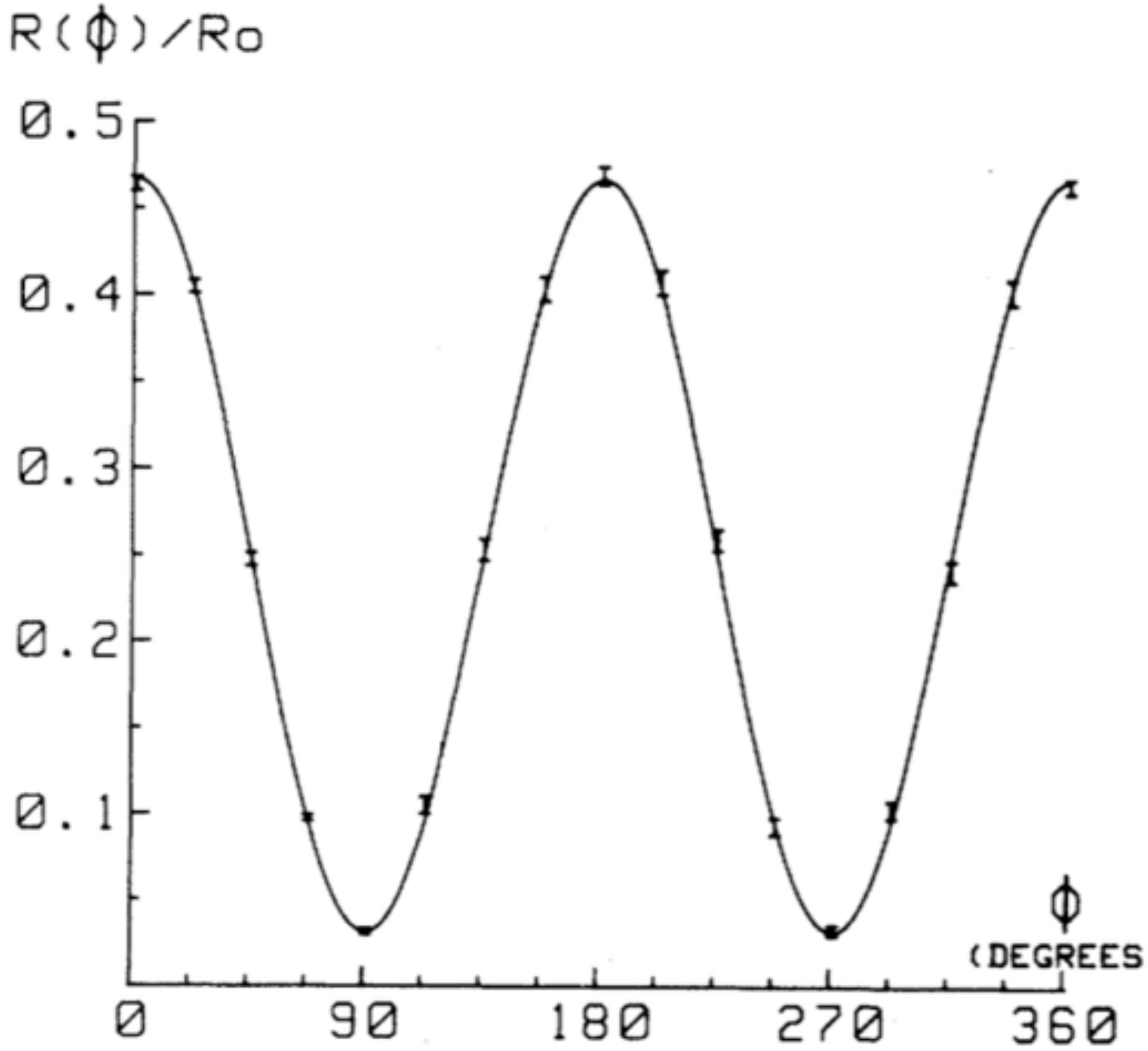


FIG. 4. Normalized coincidence rate as a function of the relative polarizer orientation. Indicated errors are ± 1 standard deviation. The solid curve is not a fit to the data but the prediction of quantum mechanics.

Typical coincidence rates without polarizers are 240 coincidences per second in the null delay

The generalized Bell theorem[2,3] yields the following inequalities:

$$-1 \leqslant S = [R(\vec{a},\vec{b}) - R(\vec{a},\vec{b}') + R(\vec{a}',\vec{b}) + R(\vec{a}',\vec{b}') - R_1(\vec{a}') - R_2(\vec{b})]/R_0 \leqslant 0, \qquad (1)$$

where $R(\vec{a},\vec{b})$ is the rate of coincidences with polarizer I in orientation $\vec{a}$ and polarizer II in orientation $\vec{b}$, $R_1(\vec{a}')$ is the coincidence rate with polarizer II removed and polarizer I in orientation $\vec{a}'$ [and similarly for $R_2(\vec{b})$], and R_0 is the coincidence rate with the two polarizers removed. On the other hand,

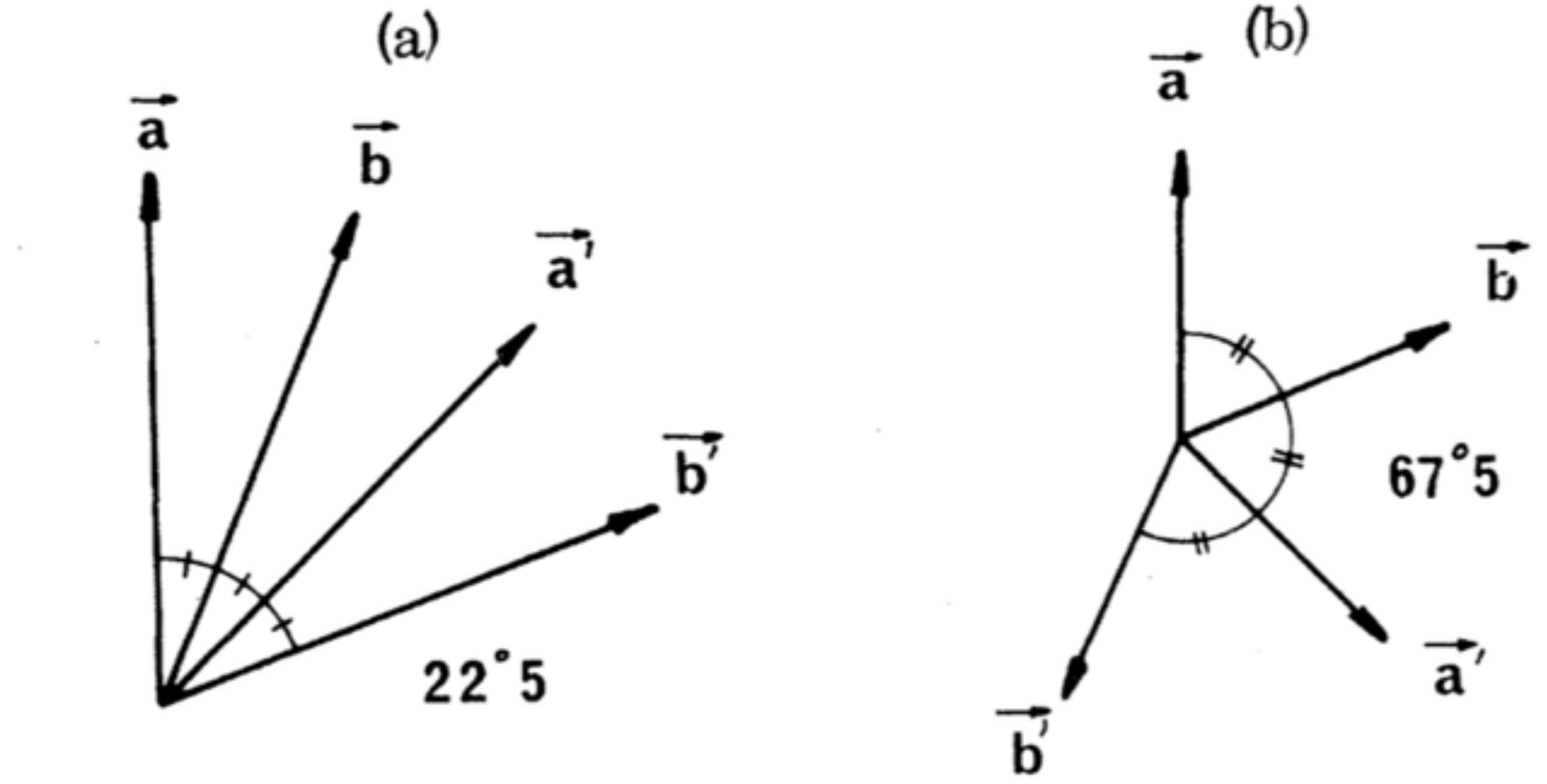
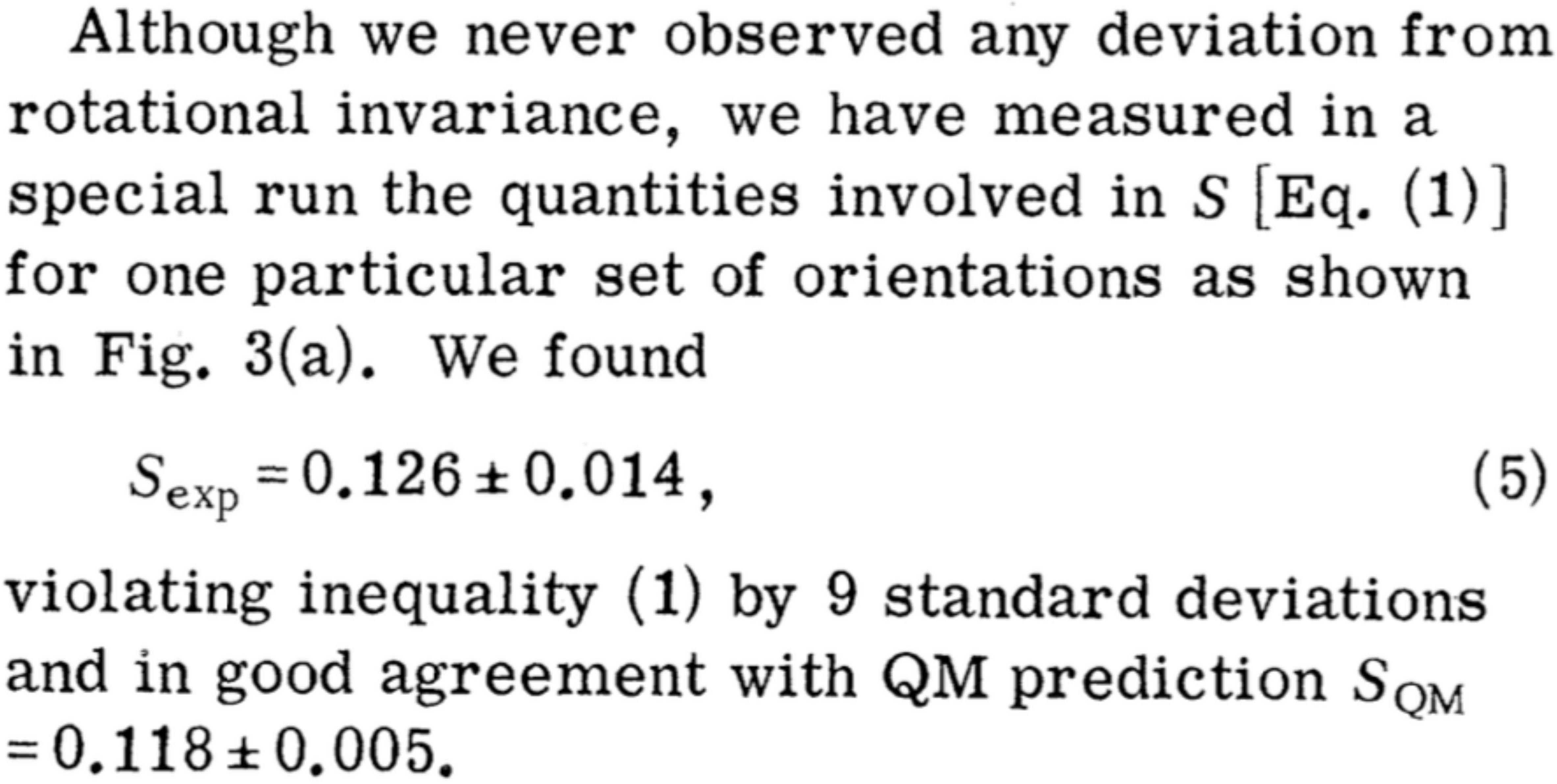


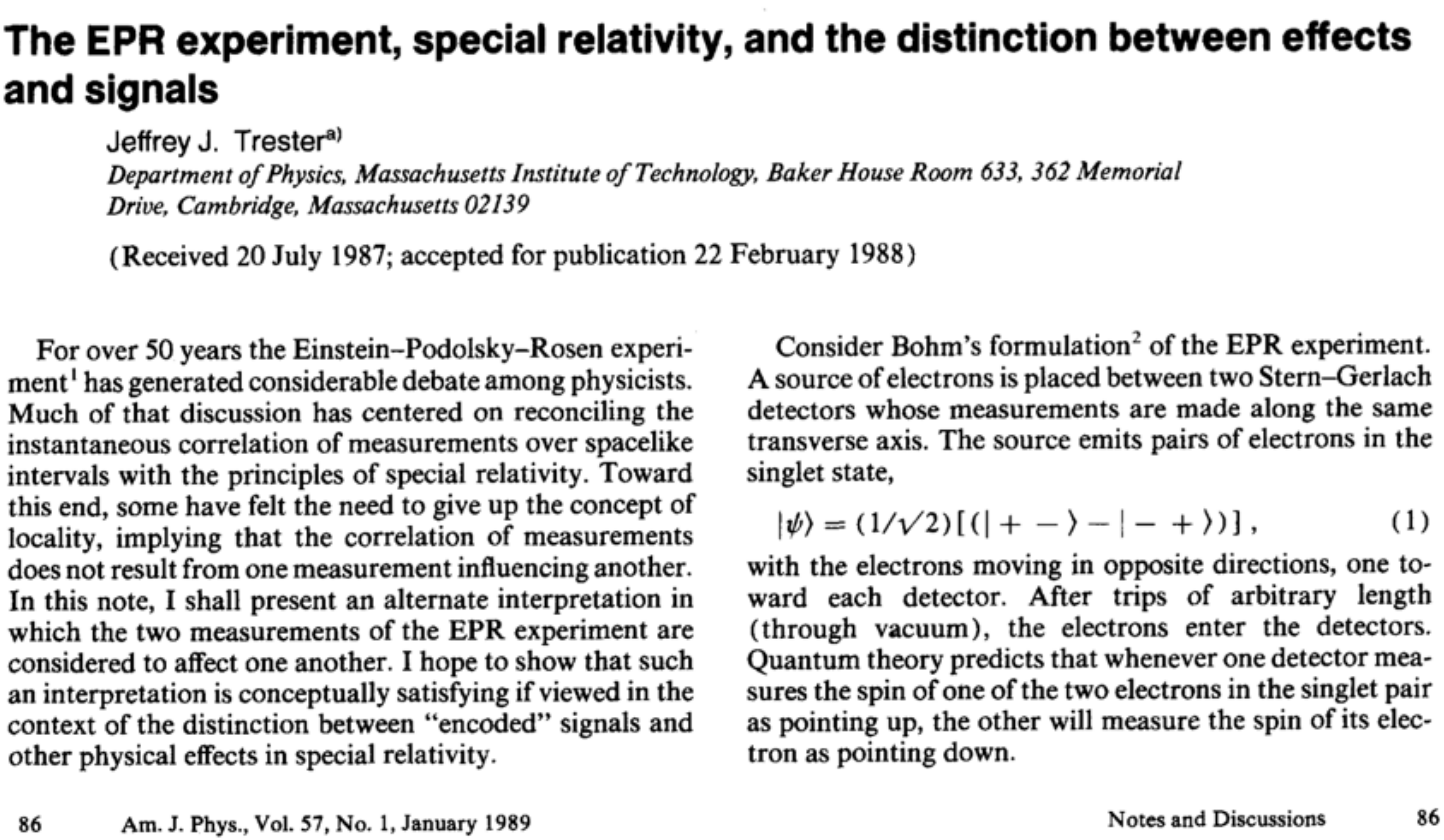
FIG. 3. Orientations leading to the maximum violations of generalized Bell inequalities.



Although we never observed any deviation from rotational invariance, we have measured in a special run the quantities involved in S [Eq. (1)] for one particular set of orientations as shown in Fig. 3(a). We found

$$S_{\mathrm{exp}} = 0.126 \pm 0.014 , \qquad (5)$$

violating inequality (1) by 9 standard deviations and in good agreement with QM prediction $S_{\mathrm{QM}} = 0.118 \pm 0.005$.



The EPR experiment, special relativity, and the distinction between effects and signals

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(Received 20 July 1987; accepted for publication 22 February 1988)

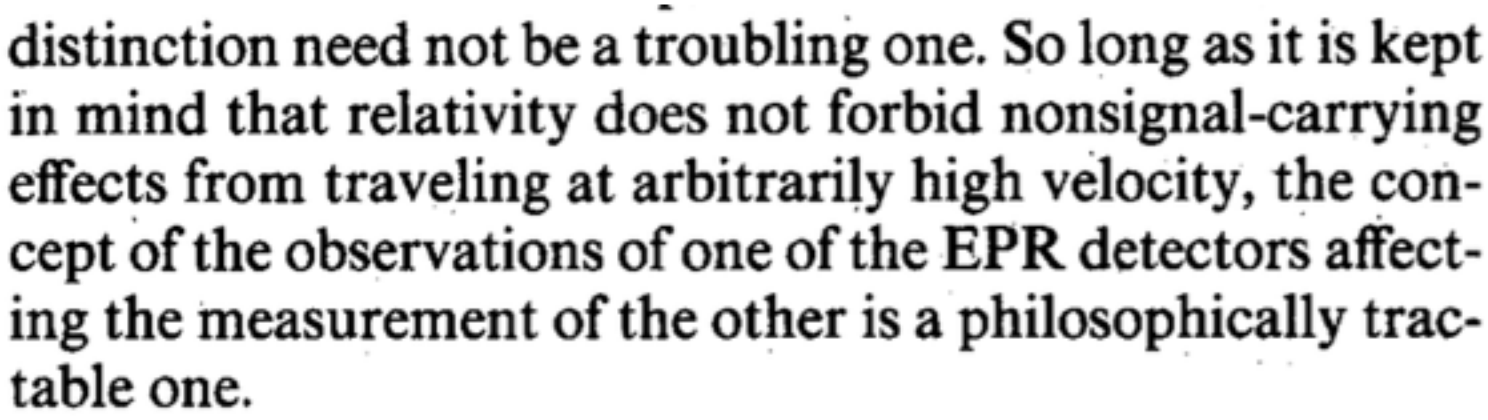
For over 50 years the Einstein–Podolsky–Rosen experiment[1] has generated considerable debate among physicists. Much of that discussion has centered on reconciling the instantaneous correlation of measurements over spacelike intervals with the principles of special relativity. Toward this end, some have felt the need to give up the concept of locality, implying that the correlation of measurements does not result from one measurement influencing another. In this note, I shall present an alternate interpretation in which the two measurements of the EPR experiment are considered to affect one another. I hope to show that such an interpretation is conceptually satisfying if viewed in the context of the distinction between "encoded" signals and other physical effects in special relativity.

Consider Bohm's formulation[2] of the EPR experiment. A source of electrons is placed between two Stern–Gerlach detectors whose measurements are made along the same transverse axis. The source emits pairs of electrons in the singlet state,

$$|\psi\rangle = (1/\sqrt{2})[(|+\,-\rangle - |-\,+\rangle)]\,, \tag{1}$$

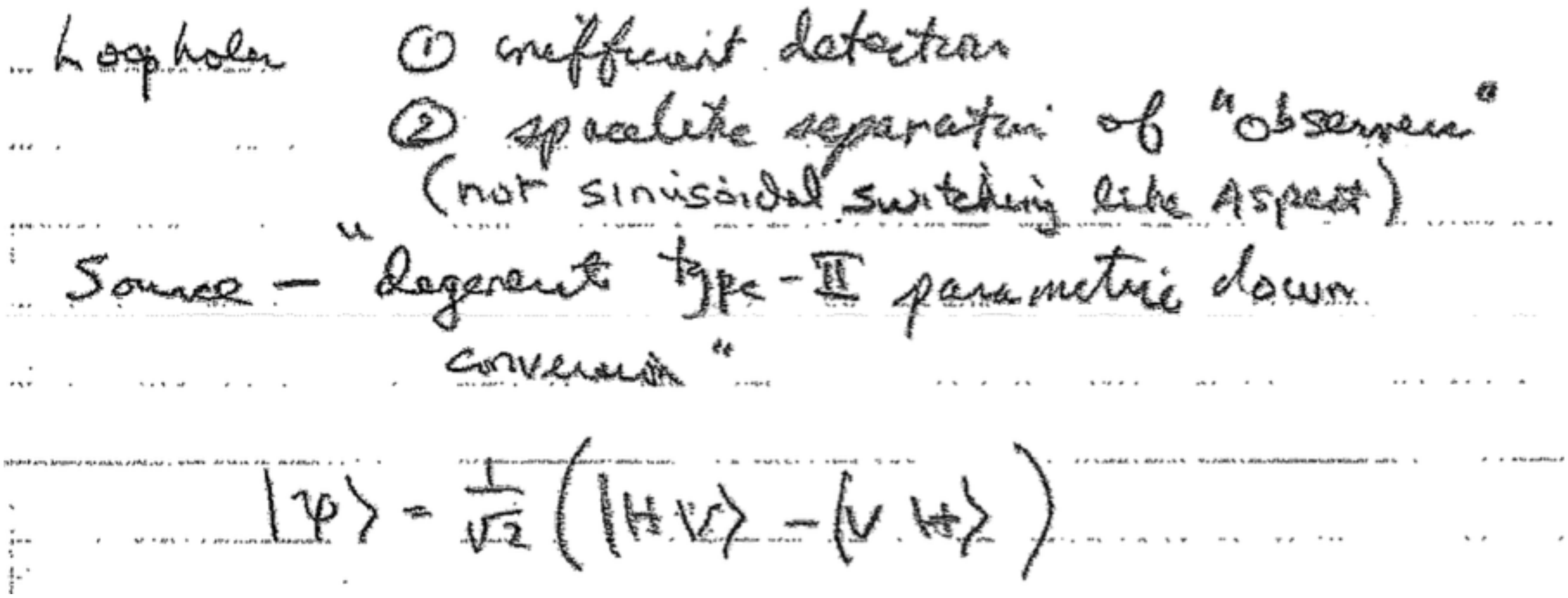
with the electrons moving in opposite directions, one toward each detector. After trips of arbitrary length (through vacuum), the electrons enter the detectors. Quantum theory predicts that whenever one detector measures the spin of one of the two electrons in the singlet pair as pointing up, the other will measure the spin of its electron as pointing down.

86 Am. J. Phys., Vol. 57, No. 1, January 1989 Notes and Discussions 86



distinction need not be a troubling one. So long as it is kept in mind that relativity does not forbid nonsignal-carrying effects from traveling at arbitrarily high velocity, the concept of the observations of one of the EPR detectors affecting the measurement of the other is a philosophically tractable one.

Weihs *et al.* PRL 81 (5039) 1998



Loopholes ① inefficient detectors

② spacelike separation of "observers"

(not sinusoidal switching like Aspect)

Source — "degenerate type-II parametric down conversion"

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|HV\rangle - |VH\rangle\right)$$

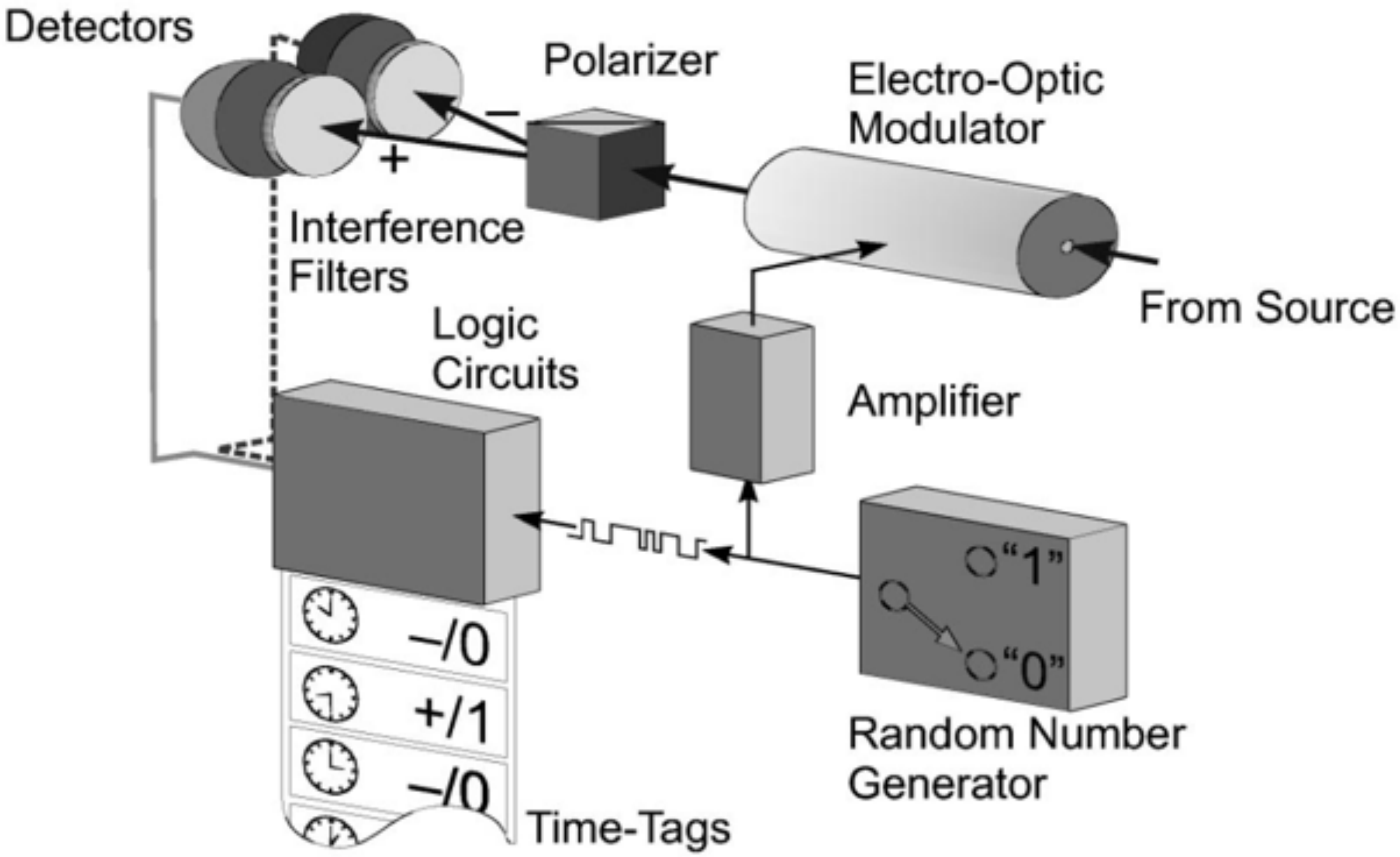
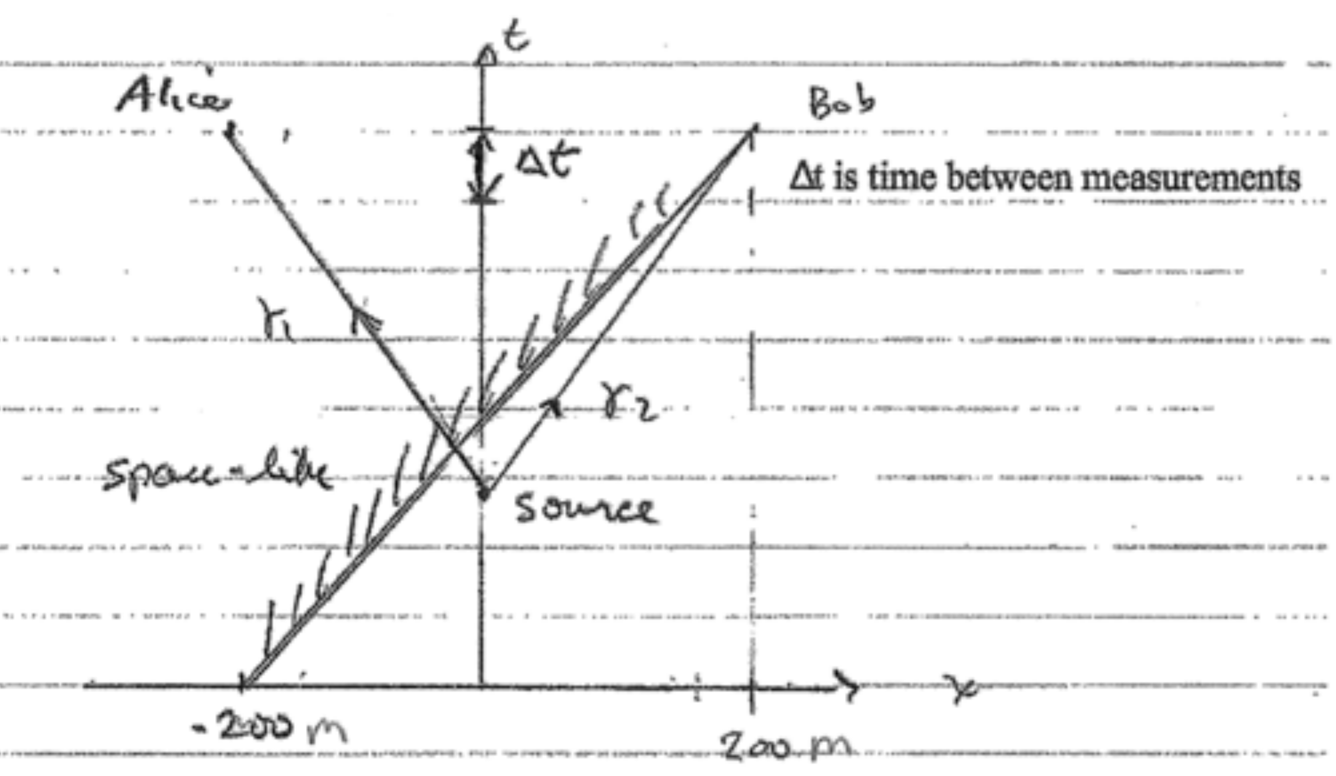


FIG. 2. One of the two observer stations. A random number generator is driving the electro-optic modulator. Silicon avalanche photodiodes are used as detectors. A "time tag" is stored for each detected photon together with the corresponding random number "0" or "1" and the code for the detector "+" or "−" corresponding to the two outputs of the polarizer.



light fiber 250m length

Generalised Bell inequality –

$$S(\alpha,\alpha',\beta\beta') = \left|E(\alpha,\beta) - E(\alpha',\beta)\right| + \left|E(\alpha,\beta') + E(\alpha',\beta')\right| \le 2$$

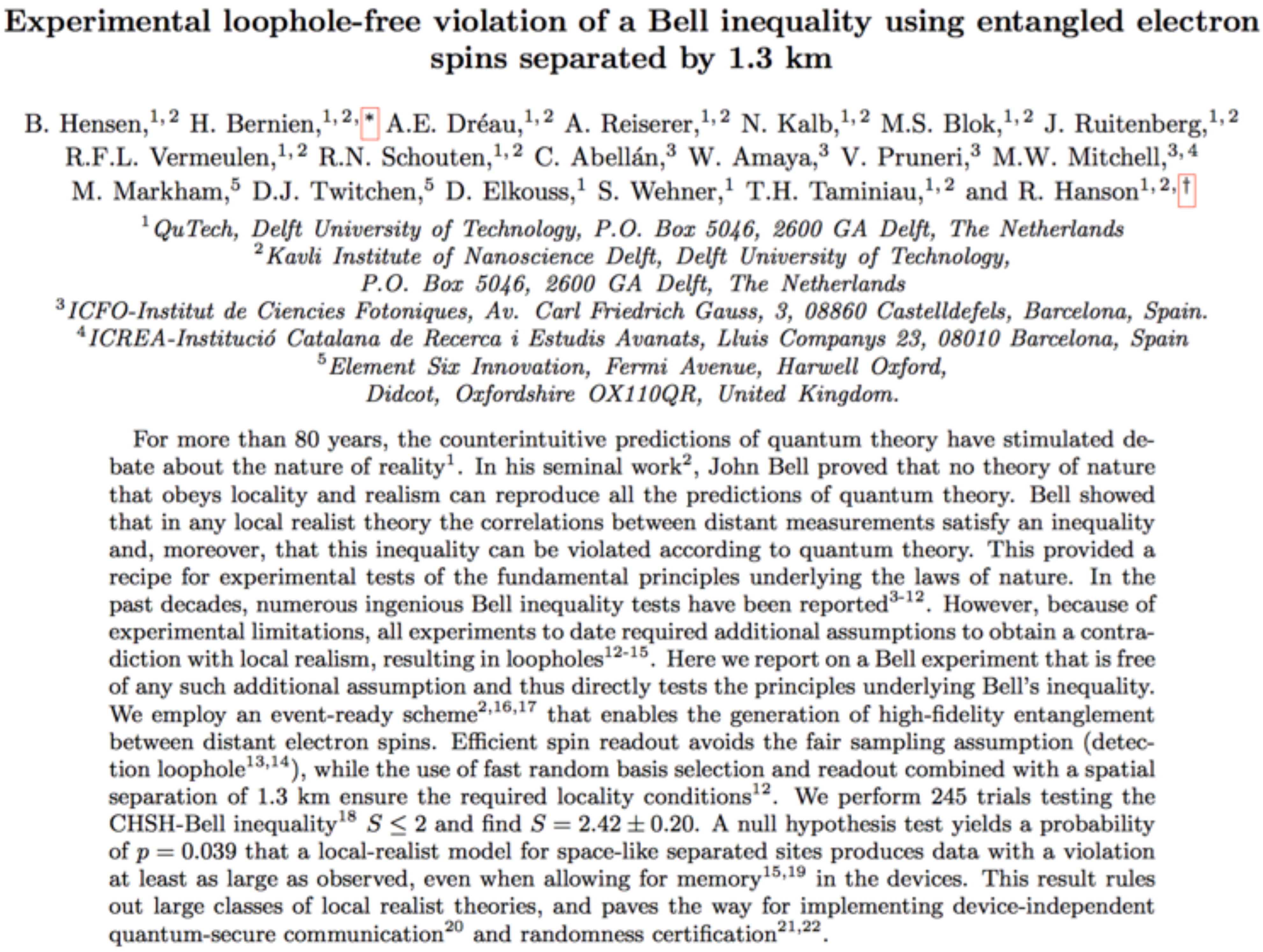
$$S^{QM}_{max}(0, 45^\circ, 22.5^\circ, 67.5^\circ) = 2\sqrt{2} = 2.82$$

due to imperfect correlation "visibility" of source (97%) expect $S \simeq 2.74$

$$S^{exp.} = 2.73 \pm 0.02$$

$$N = 14700$$

Nature V526, October 29, 2015



Experimental loophole-free violation of a Bell inequality using entangled electron spins separated by 1.3 km

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For more than 80 years, the counterintuitive predictions of quantum theory have stimulated debate about the nature of reality[1]. In his seminal work[2], John Bell proved that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. Bell showed that in any local realist theory the correlations between distant measurements satisfy an inequality and, moreover, that this inequality can be violated according to quantum theory. This provided a recipe for experimental tests of the fundamental principles underlying the laws of nature. In the past decades, numerous ingenious Bell inequality tests have been reported[3-12]. However, because of experimental limitations, all experiments to date required additional assumptions to obtain a contradiction with local realism, resulting in loopholes[12-15]. Here we report on a Bell experiment that is free of any such additional assumption and thus directly tests the principles underlying Bell's inequality. We employ an event-ready scheme[2,16,17] that enables the generation of high-fidelity entanglement between distant electron spins. Efficient spin readout avoids the fair sampling assumption (detection loophole[13,14]), while the use of fast random basis selection and readout combined with a spatial separation of 1.3 km ensure the required locality conditions[12]. We perform 245 trials testing the CHSH-Bell inequality[18] $S \leq 2$ and find $S = 2.42 \pm 0.20$. A null hypothesis test yields a probability of $p = 0.039$ that a local-realist model for space-like separated sites produces data with a violation at least as large as observed, even when allowing for memory[15,19] in the devices. This result rules out large classes of local realist theories, and paves the way for implementing device-independent quantum-secure communication[20] and randomness certification[21,22].

Entangled State of B mesons

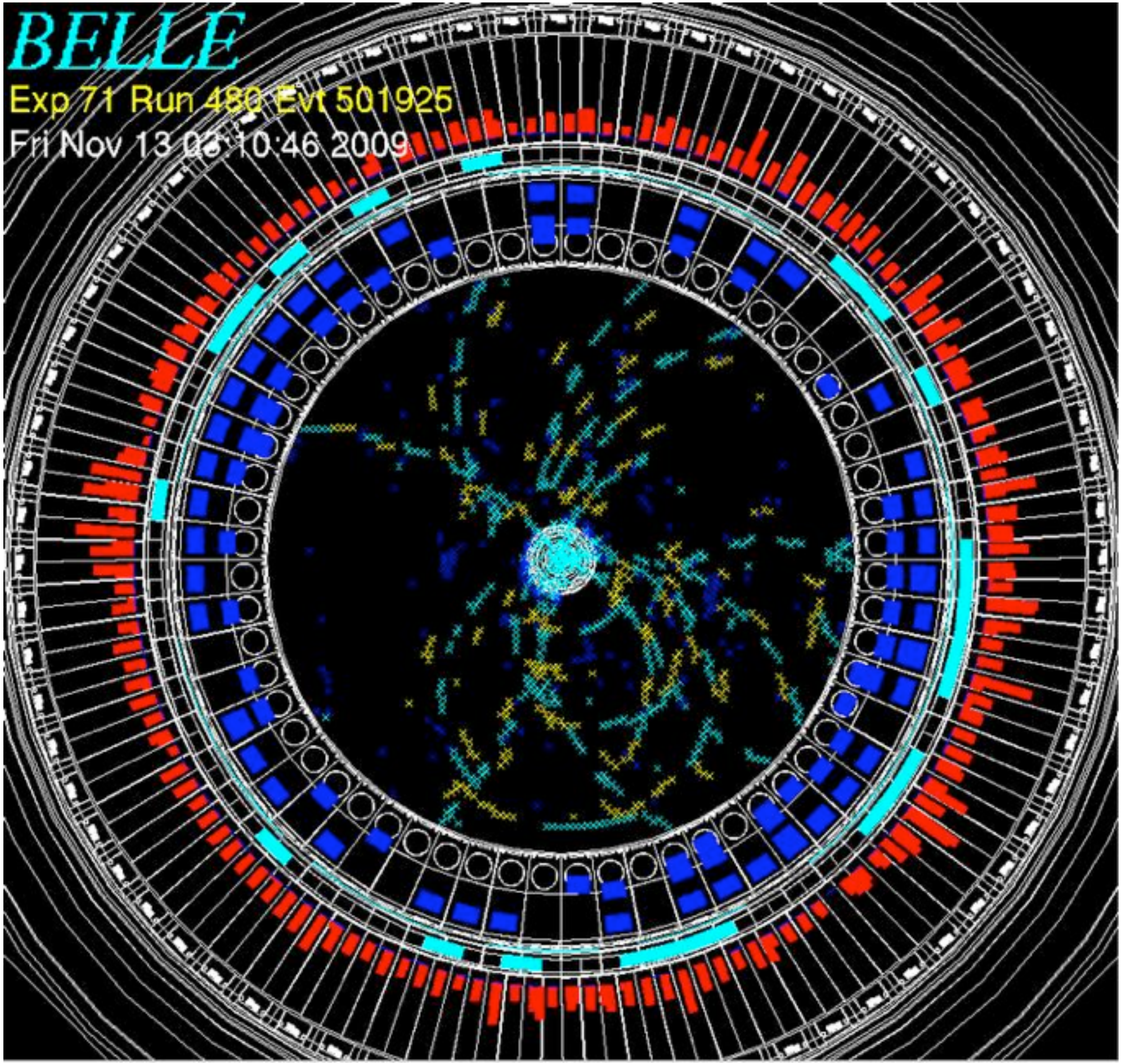
$e^+e^- \rightarrow \Upsilon \rightarrow bb$ produces $B_0\ \overline{B}0$ entangled state.

$$\Upsilon \rightarrow \frac{1}{\sqrt{2}}\left[|B_0\rangle_1|\bar{B_0}\rangle_2 - |\bar{B_0}\rangle_1|B_0\rangle_2\right]$$

$$B_0(\bar{B_0}) \rightarrow e^{\pm}X^{\mp}$$

$B_0\ \overline{B}_0$ are completely anti-correlated. A decay of one is a measurement of the state and collapses the wave function.

example BELLE event



BaBar mixing measurement

Fig.6 shows two distributions, one for the interval Δt between the times of decays $B_d \rightarrow l^+X$ and $\bar{B}_d \rightarrow \psi K_S$ and the other one for the CP conjugate process $\bar{B}_d \rightarrow l^-X$ and $B_d \rightarrow \psi K_S$. They are clearly different proving that CP is broken.

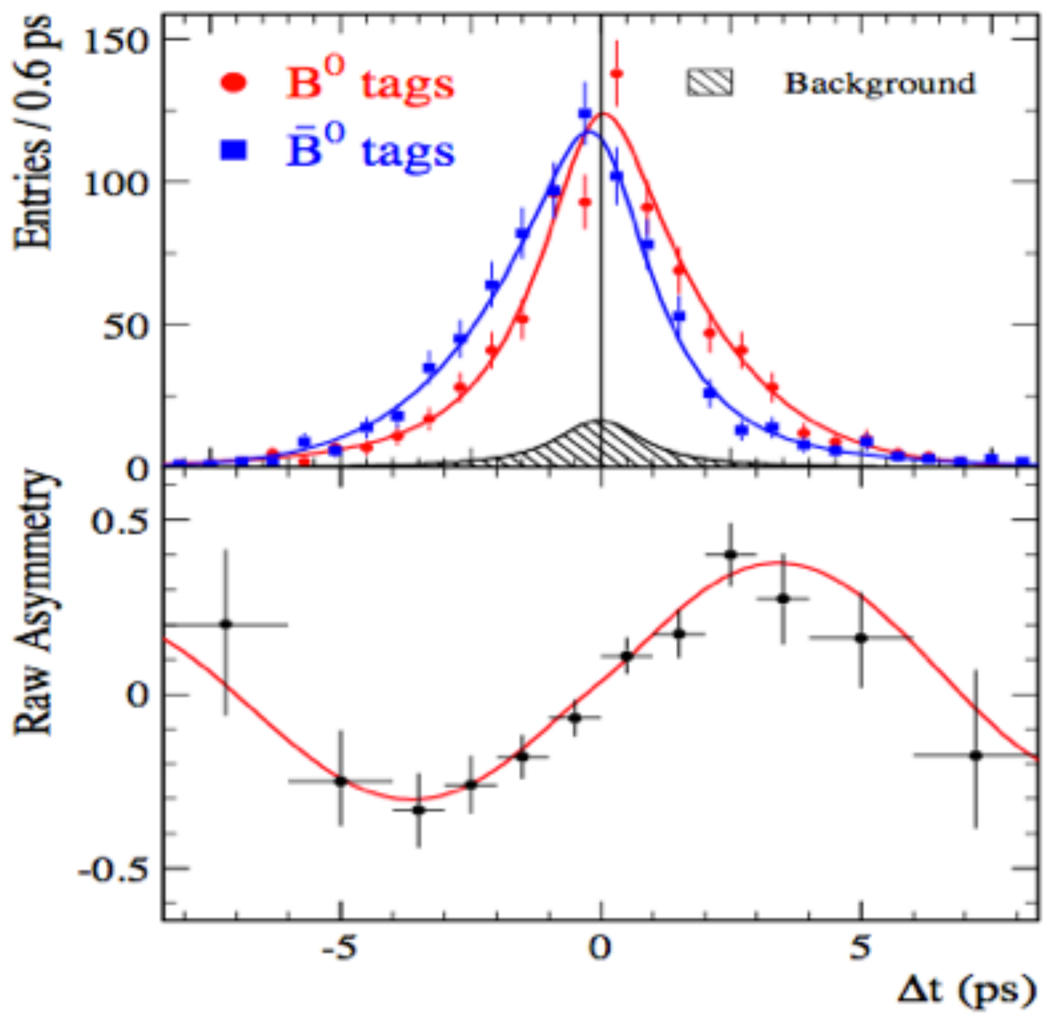


Figure 6: The observed decay time distributions for B^0 (red) and $\bar{B}^0$ (blue) decays.

time asymmetry!

difference vs. Δt

time difference between decays measured as length between decay vertices. to be continued…

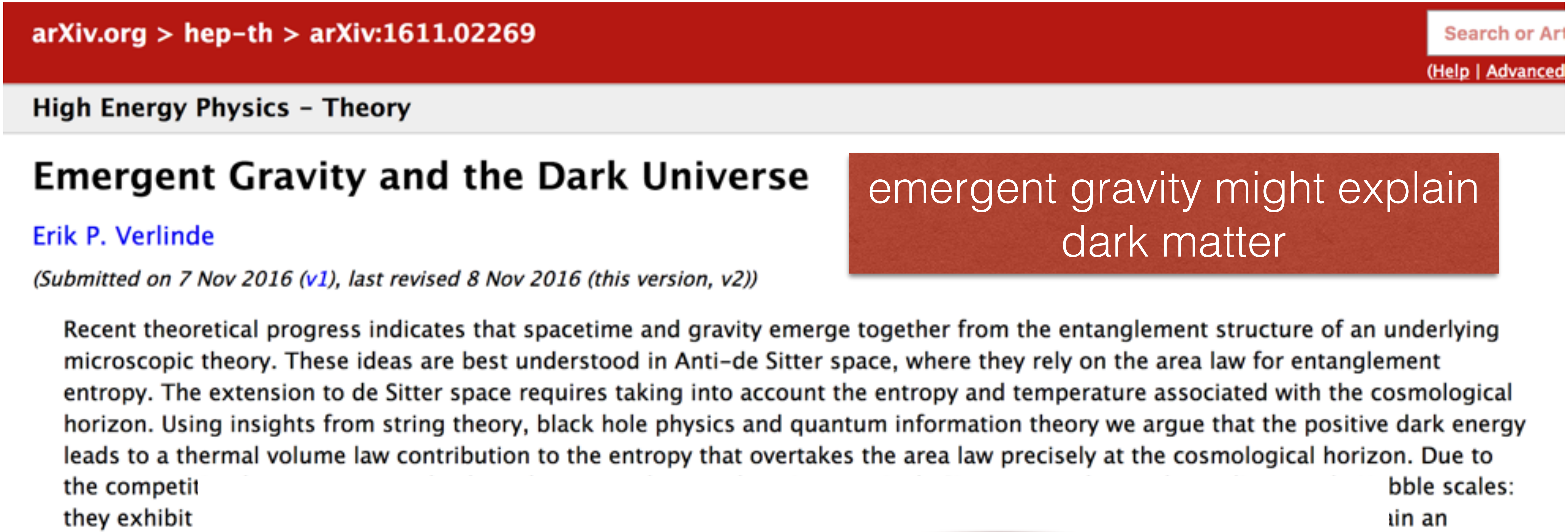
CP Violation in the SM, Quantum Subtleties and the Insights of Yogi Berra,

I.I. Bigi hep-ph/0703132 "Praise the Gods Twice for EPR Correlations"

"Yet the main point to be noted is that EPR correlations, which represent some of quantum mechanics most puzzling features, serve as an essential precision tool, which is routinely used in these measurements. I feel it is thus inappropriate to refer to EPR correlations as a paradox." *I.I. Bigi*

"When you come to a fork in the road, take it." *Yogi Berra*

"I know of no more concise formulation of one of quantum mechanics most counter-intuitive features that underlies the interference pattern observed in a double-slit experiment with particle beams: even a single electron can pass through both slits." I.I. Bigi



arXiv.org > hep-th > arXiv:1611.02269

High Energy Physics – Theory

Emergent Gravity and the Dark Universe

Erik P. Verlinde

(Submitted on 7 Nov 2016 (v1), last revised 8 Nov 2016 (this version, v2))

emergent gravity might explain dark matter

Recent theoretical progress indicates that spacetime and gravity emerge together from the entanglement structure of an underlying microscopic theory. These ideas are best understood in Anti-de Sitter space, where they rely on the area law for entanglement entropy. The extension to de Sitter space requires taking into account the entropy and temperature associated with the cosmological horizon. Using insights from string theory, black hole physics and quantum information theory we argue that the positive dark energy leads to a thermal volume law contribution to the entropy that overtakes the area law precisely at the cosmological horizon. Due to

the competit bble scales:
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additional `(nate of the
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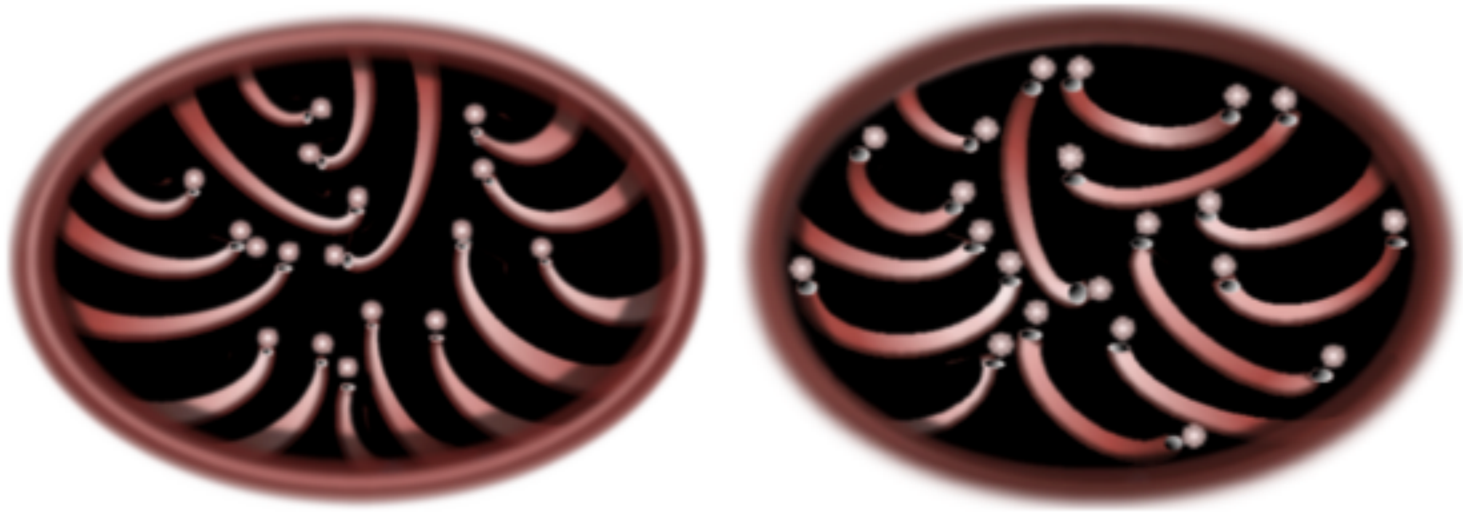

Figure 1: *Two possible quantum entanglement patterns of de Sitter space with a one-sided horizon. The entanglement between EPR pairs is represented pictorially by tiny ER-bridges. The entanglement is long range and connects bulk excitations that carry the positive dark energy either with the states on the horizon (left) or primarily with each other (right). Both situations leads to a thermal volume law contribution to the entanglement entropy.*