Title: Quantum / optical mechanical sensors

Speakers: Markus Aspelmeyer

Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 21, 2022 - 4:30 PM

URL: https://pirsa.org/22090015

Table-Top Experiments for Fundamental Physics, PI, September 2022

Probing the quantum nature of gravity

- or: how to avoid the appearance of a classical world in gravity experiments?

Markus Aspelmeyer

Vienna Center for Quantum Science and Technology (VCQ)
Faculty of Physics , University of Vienna, Austria
IQOQI, Austrian Academy of Sciences

Summary

- There are **few table-top experiments to date** that probe the **interface between quantum physics and gravity**. All these experiments can be described by quantum theory on a (classical) curved spacetime. Loosely speaking, the quantum system is used as a **„test particle“** in an external gravitational field. **Thus far there is no experiment that answers the question whether gravity requires a quantum description.**

- On the other hand, the last decade has seen large progress in controlling the **quantum regime of massive solid-state objects**. These systems may lead the way to a **new class of gravitational quantum physics experiments**, in which the quantum system itself, e.g. the center of mass degree of freedom of a massive sphere, serves as a **gravitational source mass**. This may enable **experiments that cannot be described by the joint assumption of GR and quantum theory**.

- The **experimental challenge** lies in meeting the **extreme requirements of both large mass and long coherence times**; the **conceptual challenge** lies (among others) in finding less demanding and yet similarly meaningful tests to probe how gravity reacts to quantum source masses.

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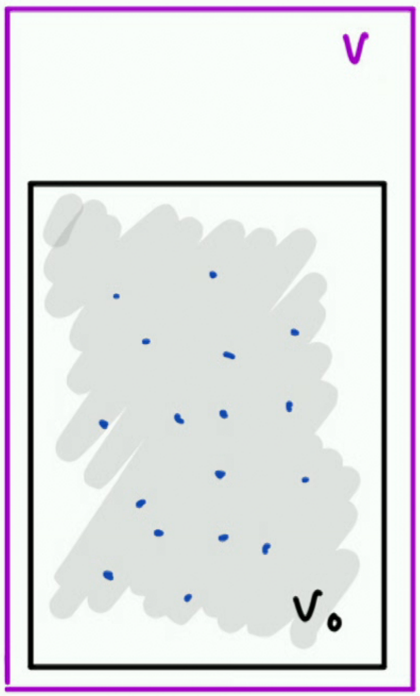
A. Einstein, Annalen der Physik 17, 132 (1905)

A brief history of quantum optics: does EM radiation require a quantum description?

6. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt;*
von A. Einstein.

Concerning a heuristic point of view about the creation and transformation of light



How does entropy change with volume?

Ideal gas: $S_1 - S_0 = k_B \cdot \ln\left(\frac{V}{V_0}\right)^{U/h\nu}$

blackbody radiation: $S_1 - S_0 = k_B \cdot \ln\left(\frac{V}{V_0}\right)^{N}$

→ ***"Monochromatic radiation of low density (…) behaves thermodynamically as if it consisted of mutually independent energy quanta of magnitude $R\beta\nu / N$"***

$E_{Photon} = h\nu$

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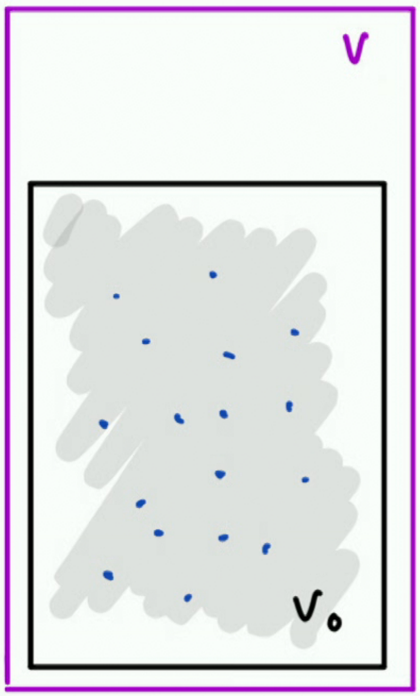

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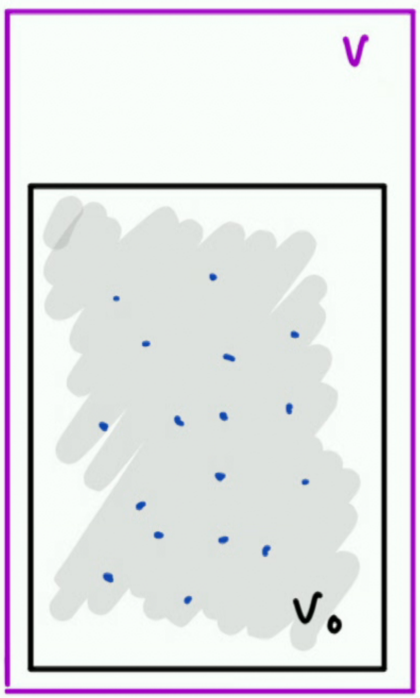
$$U = N \cdot h\nu$$



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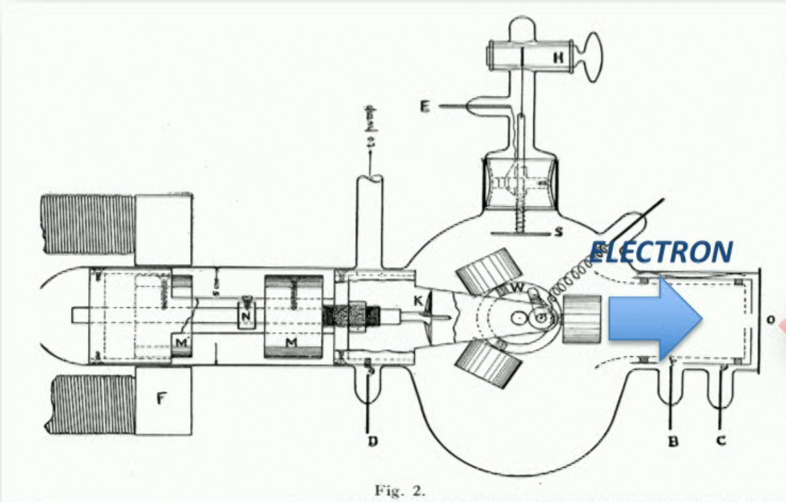
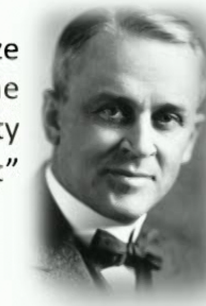
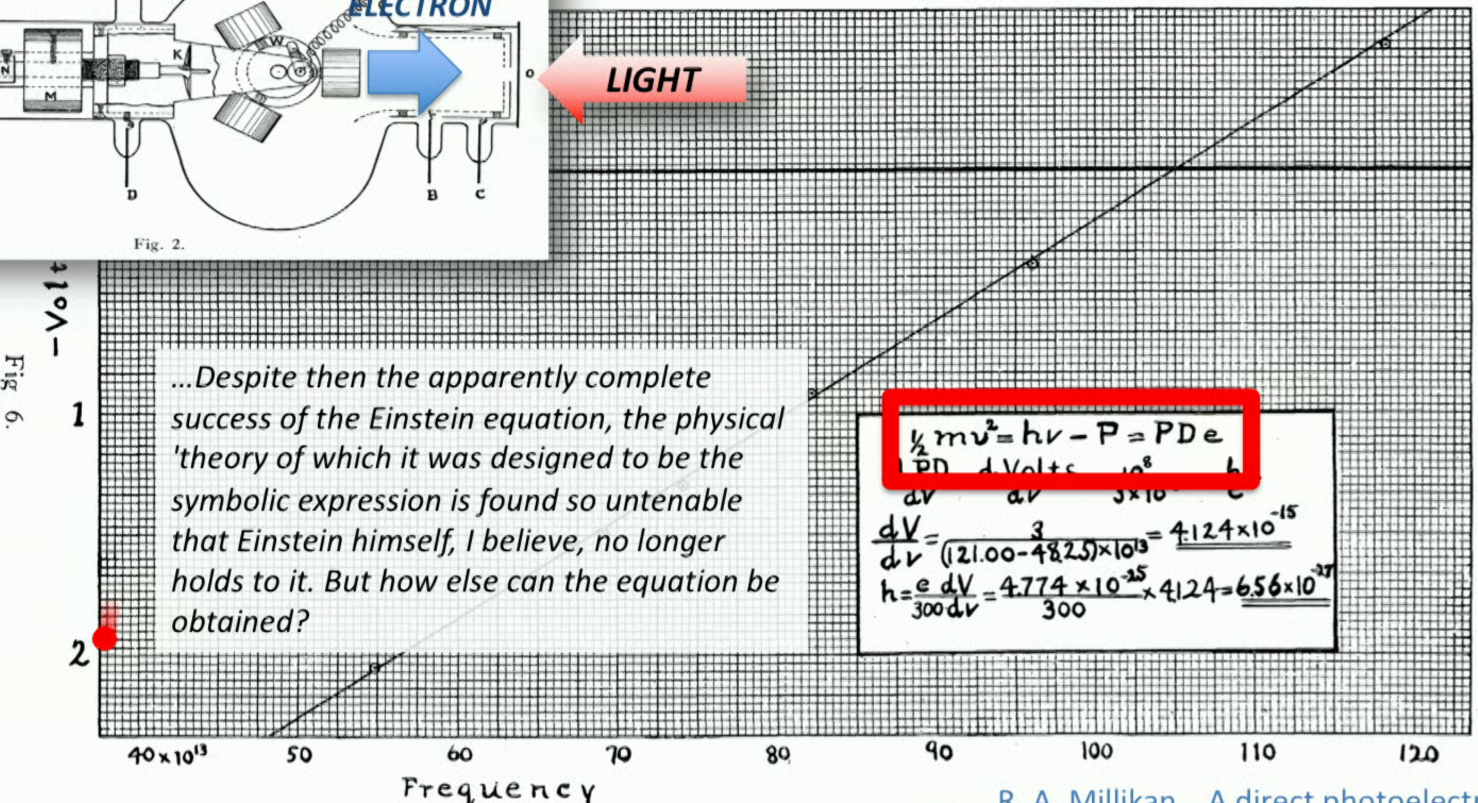


Fig. 2.

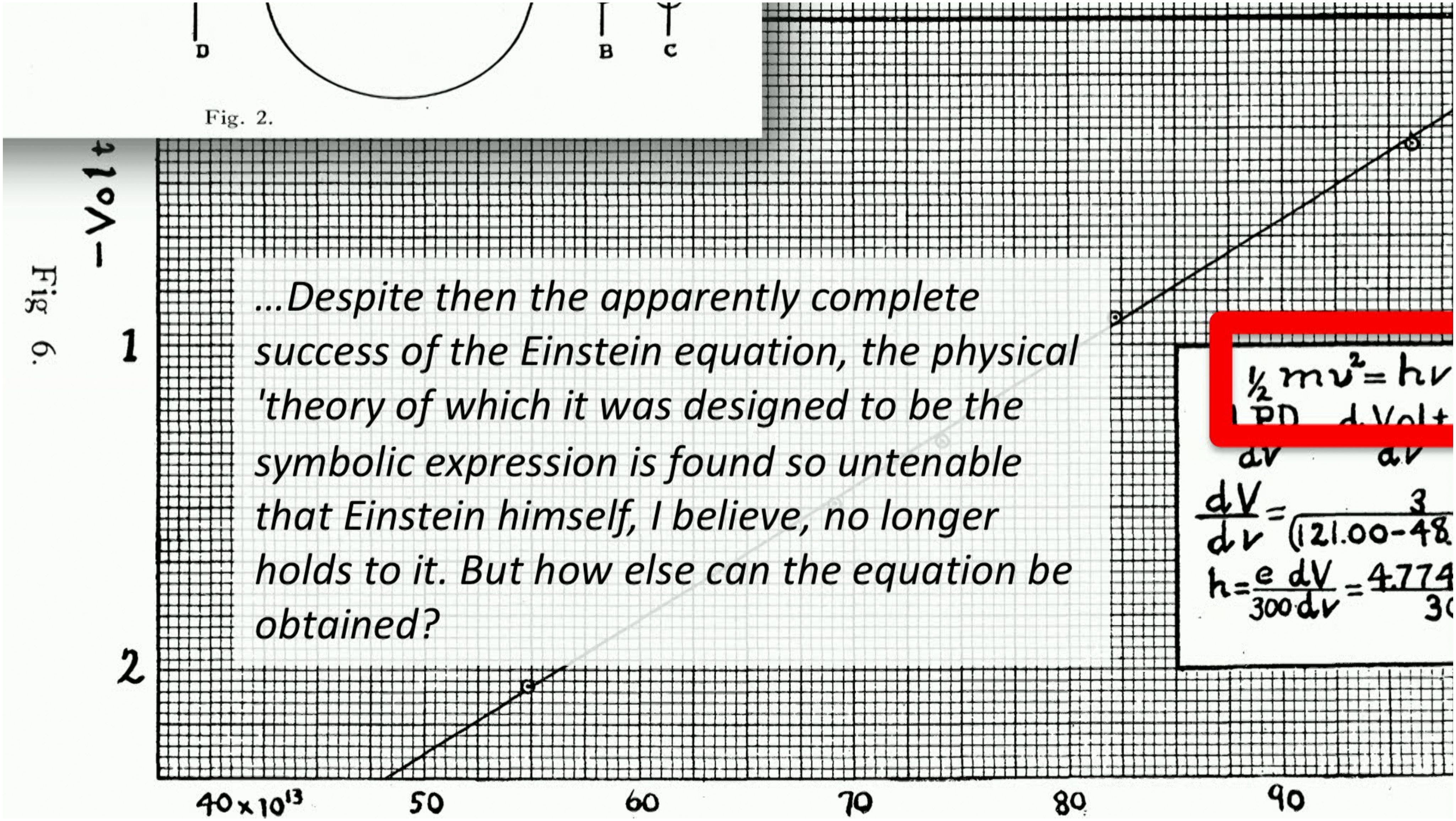
Robert Millikan, Nobel Prize 1923 "for his work on the elementary charge of electricity and on the photoelectric effect"





…Despite then the apparently complete success of the Einstein equation, the physical 'theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it. But how else can the equation be obtained?

R. A. Millikan, „A direct photoelectric determination of Planck's h", Phys. Rev. 7, 355 (1916)



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›ptics:

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Planck (1909): *"[The rejection of Maxwell's electromagnetic waves] seems to me to be a step which in my opinion is not yet necessary."*

fact that he has now and then overshot in his light quantum hypothesis, should not be held too amount of risk there cannot be any real innovation ces"

Millikan (1916): *"Einstein's bold, not to say reckless light-quantum hypothesis flies in the face of the thoroughly established facts of interference"*

A brief history of quantum optics:
does EM radiation require a quantum description?

Can we have an experiment whose outcome canot be described by a semiclassical theory?

Can we have an experiment whose outcome canno
by a semiclassical theory?

$$g^{(2)}(\tau) = \frac{\langle I(t)\, I(t+\tau) \rangle}{\langle I(t) \rangle \langle I(t+\tau) \rangle}$$

$$\downarrow$$

$$\frac{\langle I(t)\, I(t+\tau) \rangle}{\langle I \rangle^2}$$

Can we have an experiment whose outcome canot be desc by a semiclassical theory?

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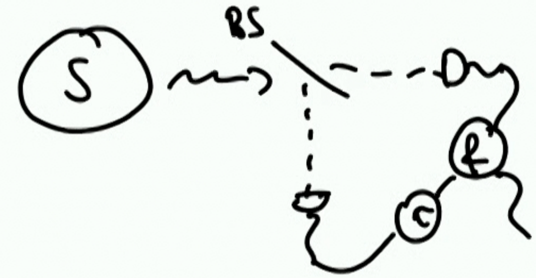

$\tau = 0$: $g^{(2)}($

Can we have an experiment whose outcome canot be desc by a semiclassical theory?

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$$\downarrow$$

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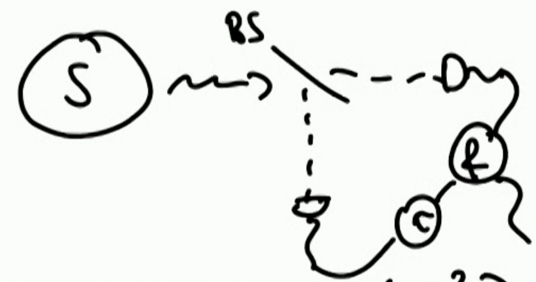


$\underline{\tau=0}$: $g^{(2)}(0) = \frac{\langle I^2\rangle}{\langle I\rangle^2} \geq 1$

$\uparrow$ CAUCHY SCHWARZ

does EM radiation require a quantum description?

PHYSICAL REVIEW D VOLUME 9, NUMBER 4 15 FEBRUARY 1974

Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect*

John F. Clauser

Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 30 October 1973)

We have measured various coincidence rates between four photomultiplier tubes viewing cascade photons on opposite sides of dielectric beam splitters. This experimental configuration, we show, is sensitive to differences between the classical and quantum field-theoretic predictions for the photoelectric effect. The results, to a high degree of statistical accuracy, contradict the predictions by any classical or semiclassical theory in which the probability of photoemission is proportional to the classical intensity.

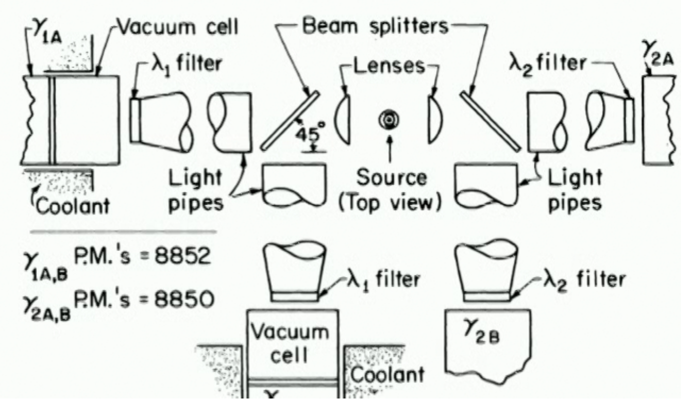
Experimental Evidence for a Beam Splitter: A New Lig

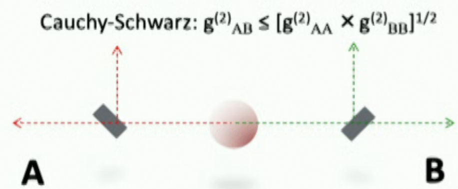
P. GRANGIER, G. ROGER and A.

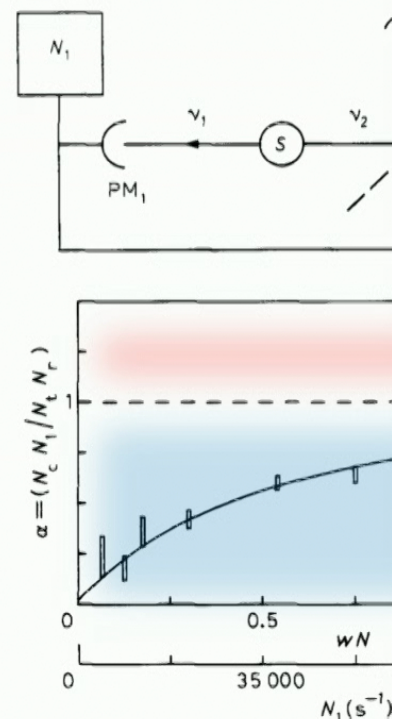
Institut d'Optique Théorique et A

(received 11 November 1985; acce

PACS. 42.10. – Propagation and tran
PACS. 42.50. – Quantum optics.







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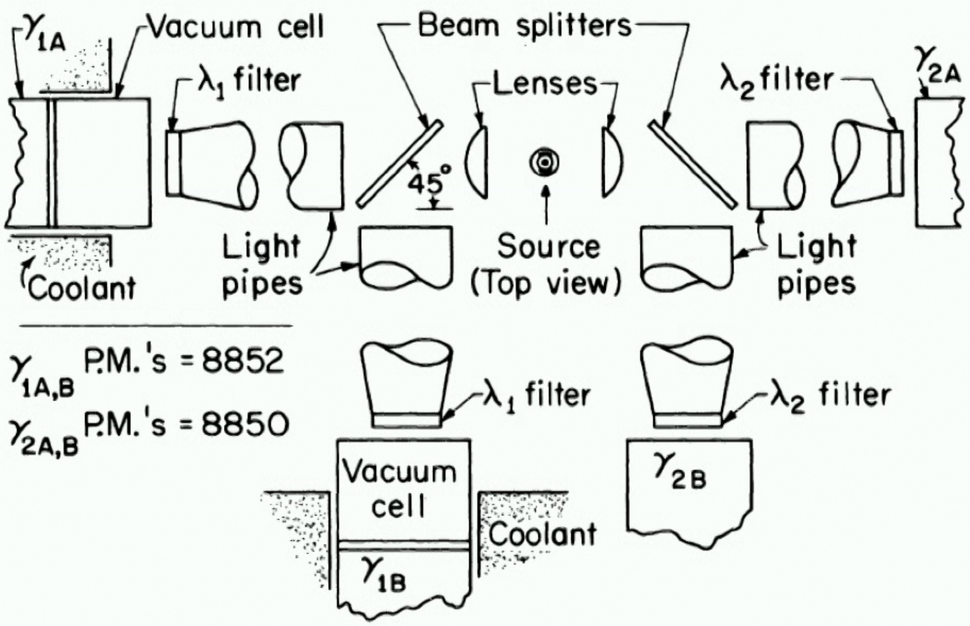

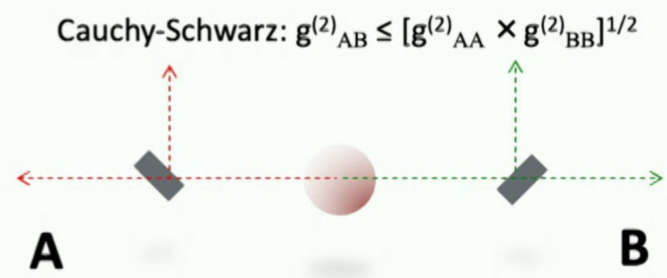

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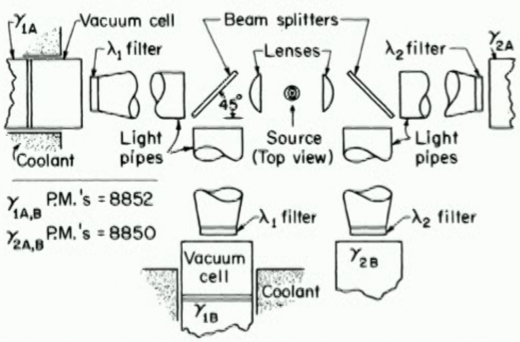
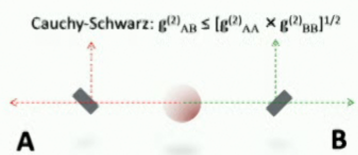


FIG. 2. Schematic diagram of our apparatus.



EUROPHYSICS LETTERS 15 February 1986

Europhys. Lett., 1 (4), pp. 173-179 (1986)

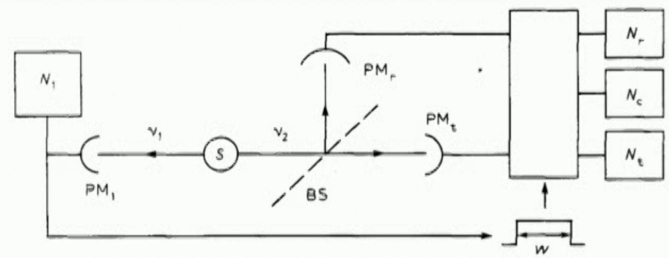
Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences.

P. Grangier, G. Roger and A. Aspect (*)

Institut d'Optique Théorique et Appliquée, B.P. 43 - F 91406 Orsay, France

(received 11 November 1985; accepted in final form 20 December 1985)

PACS. 42.10. – Propagation and transmission in homogeneous media.
PACS. 42.50. – Quantum optics.



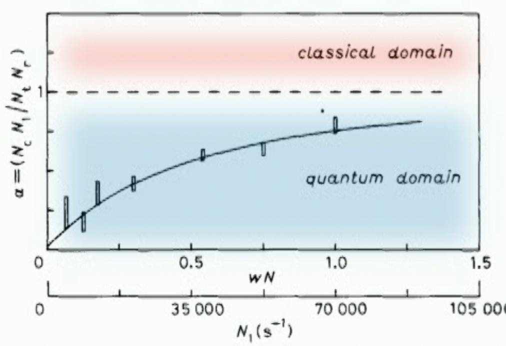


Fig. 2. – Anticorrelation parameter α as a function of wN (number of cascades emitted during the gate) and of N_1 (trigger rate). The indicated error bars are ± one standard deviation. The full-line curve is the theoretical prediction from eq. (8). The inequality $\alpha \geq 1$ characterizes the classical domain.

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does EM radiation require a quantum description?

Can we have an experiment whose outcome canot be described by a semiclassical theory?

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$B_{1,2} = \pm 1$

$A_{1,2} = \pm 1$

Can we have an experiment whose outcome canot be described by a semiclassical theory?

$$\langle |(A_1 + A_2) B_1 + (A_1 - A_2) B_2| \rangle = 2 \geq |\langle \qquad \rangle|$$

$$\to \langle A_1 B_1 \rangle + \langle A_2 B_1 \rangle + \langle A_1 B_2 \rangle - \langle A_2 B_2 \rangle \leq 2$$

A brief history of quantum optics:
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$B_{1,2} = \pm 1$ $\longleftarrow$ (S) $\longrightarrow$ $A_{1,2} = \pm 1$

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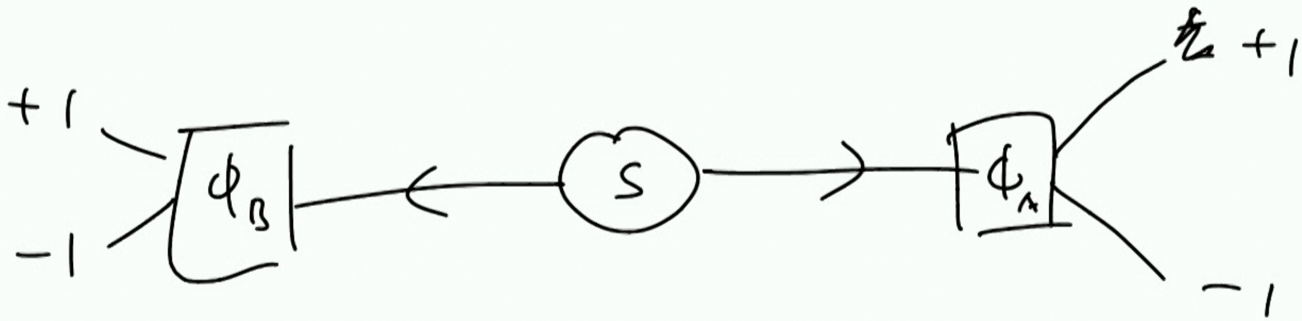
BELL INEQUALITY

1) LOCALITY HOLDS

2) PHYSICAL REALISM HOLDS

3) QT is Correct

BELL THEOREM



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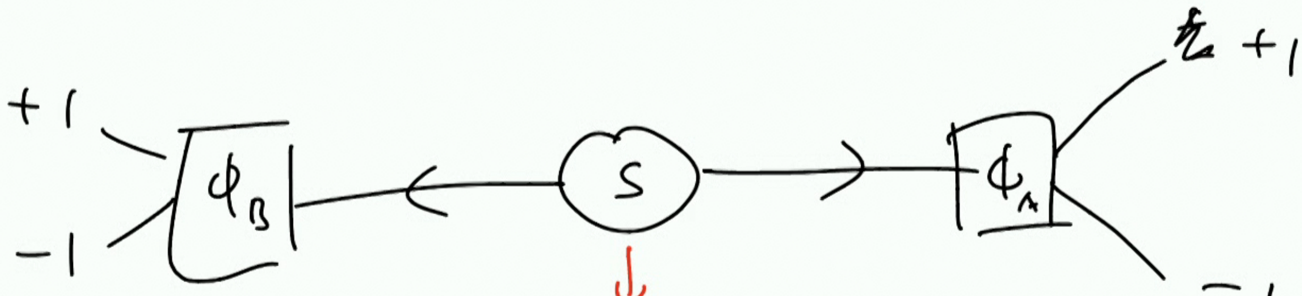

ENTANGLED

$$|\psi\rangle_1 = \frac{1}{\sqrt{2}}\left(|H\rangle|V\rangle + |V\rangle|H\rangle\right)$$

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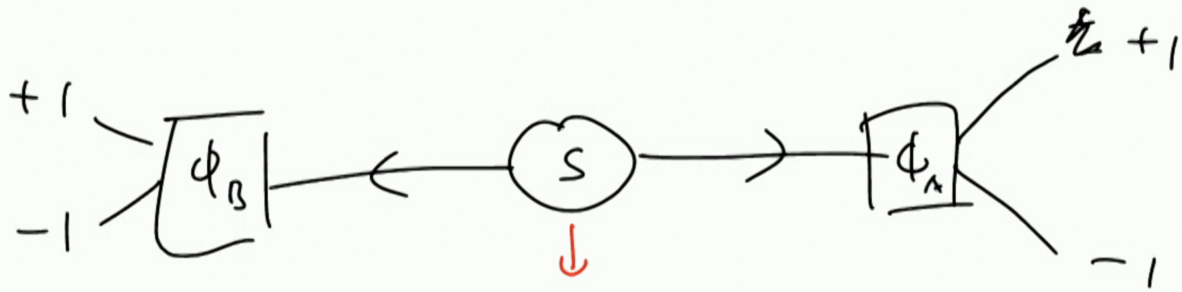


ENTANGLED

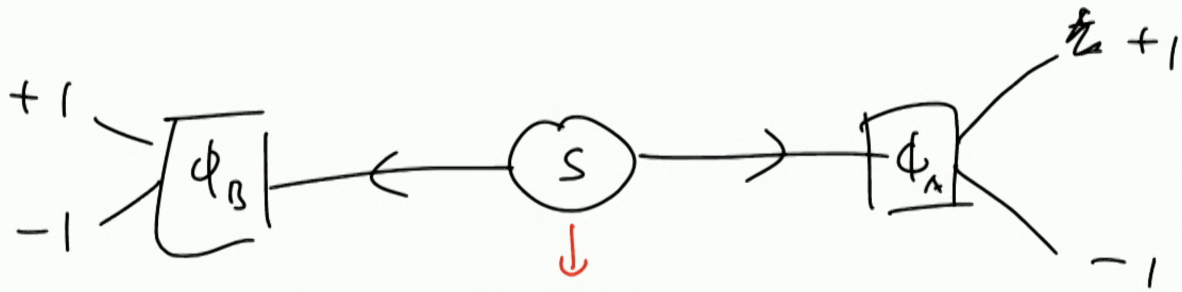
$$|\psi\rangle_s = \frac{1}{\sqrt{2}}\left(|H\rangle|V\rangle + |V\rangle|H\rangle\right) \rightarrow \langle AB\rangle = \cos\Delta\phi$$

1) LOCALITY HOLDS

2) PHYSICAL REALISM HOLDS

3) QT is Correct

BELL THEOREM → 1) or 2) or 1)+2) are WRONG



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Bell Tests

PRL 14, 938 (1972)
PRL 49, 1804 (1982)
PRL 81, 5039 (1998)

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.

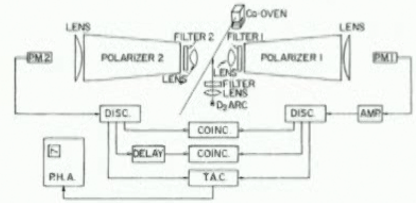


FIG. 1. Schematic diagram of apparatus and associated electronics. Scalers (not shown) monitored the outputs of the discriminators and coincidence circuits during each 100-sec count period. The contents of the scalers and the experimental configuration were recorded on paper tape and analyzed on an IBM 1620-II computer.

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.

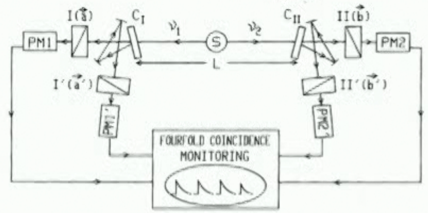


FIG. 2. Timing experiment with optical switches. Each switching device (C_I, C_{II}) is followed by two polarizers in two different orientations. Each combination is equivalent to a polarizer switched fast between two orientations.

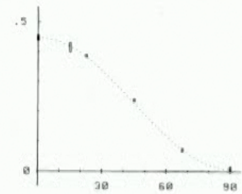


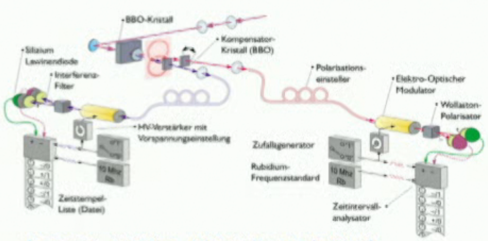
FIG. 4. Average normalized coincidence rate as a function of the relative orientation of the polarizers. Indicated errors are ±1 standard deviation. The dashed curve is not a fit to the data but the predictions by quantum mechanics for the actual experiment.

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]

Abbildung 0.1.: *Long-distance test of Bell's inequalities at the Innsbruck university science campus. The source was located at the center, whereas the observers Alice and Bob had their stations at the western and eastern rims of the site respectively.*



from: G. Weihs, PhD Thesis (1998)

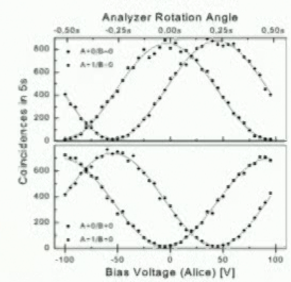


FIG. 3. Four out of sixteen coincidence rates between various detection channels as functions of bias voltage (analyzer rotation angle) on Alice's modulator. A + 1/B − 0, for example, are the coincidences between Alice's "+" detector with switch having been in position "1" and Bob's "−" detector with switch position "0". The difference in height is explained by different efficiencies of the detectors.

PRL 14, 938 (1972)
PRL 49, 1804 (1982)
PRL 81, 5039 (1998)

Theories*

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fornia, Berkeley, California 94720

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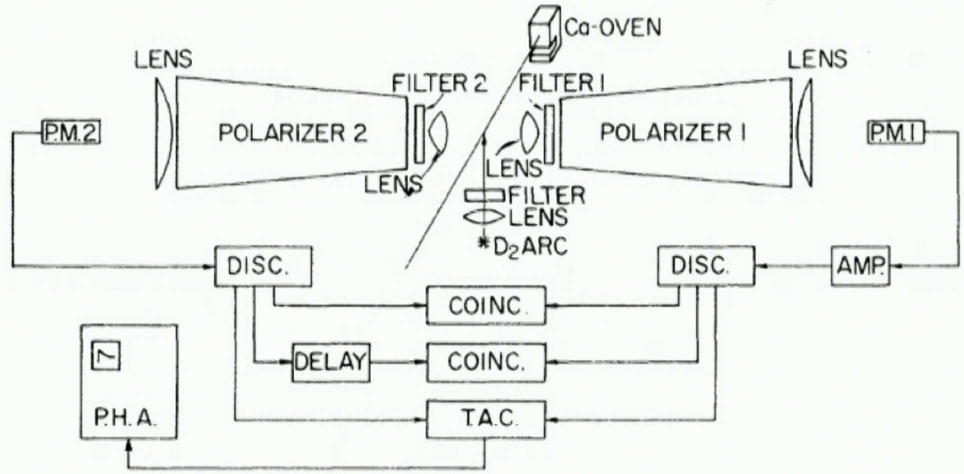

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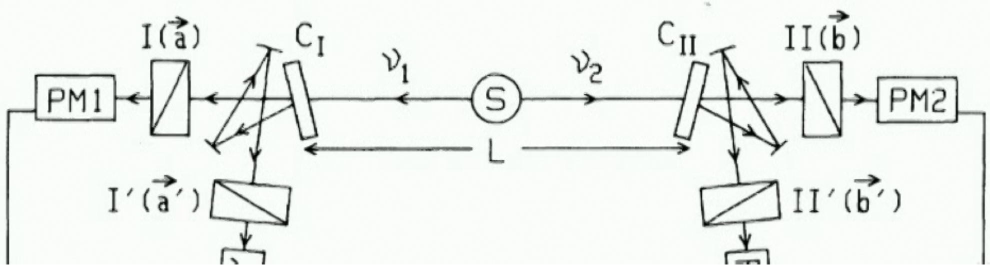

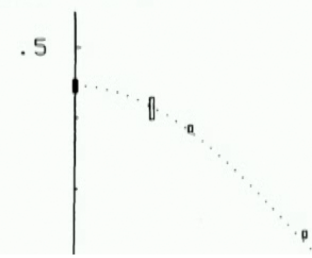

Does gravity require a quantum description?

Can we have an experiment whose outcome canot be described by a semiclassical theory?

Prelude: The 1957 Chapel Hill Conference

The absence of any paradox or discrepancy in gravitation theory at the human and astronomical levels creates an obligation to apply Einstein's ideas down to smaller and smaller distances. One must check as one goes, until one has either a successful extension to the very smallest distances, or a definite contradiction or paradox that will demand revision. ... The challenge cannot be evaded. Exactly how to proceed is a matter of wisdom, skill, judgement, and a good idea. Nobody guarantees to have a good idea, but the DeWitts, fortunately, have a very sound plan of what to do while searching for a good idea.

John A. Wheeler (letter to Bahnson, November 25, 1955)

→ 1957 Chapel Hill Conference: The Role of Gravitation in Physics

Do gravitational waves exist?

Do we require a quantum description of gravity?

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C. M. DeWitt, D. Rickles, Eds., The Role of Gravitation in Physics. Report from the 1957 Chapel Hill Conference (Max Planck Research Library for the History and Development of Knowledge, 2011).

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Two approaches to probe if the laws of quantum mechanics apply to gravity…

I) **Assume that there exists a quantum theory of gravity** and probe its (low-energy) consequences (does not necessarily require gravity measurements)

e.g. Lämmerzahl Appl. Phys. B 84, 563 (2006);

or specifically for mechanical quantum systems:
Nature Physics 8, 393 (2012); Nature Comm. 6, 7503 (2015); PRL 116, 161303 (2016); Nature Comm. 11, 3900 (2020)

II) **Assume nothing about the interplay between quantum physics and gravity** and directly probe the consequences of quantum configurations of gravitational source masses (requires gravity measurements)

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PHYSICAL REVIEW LETTERS 9 JUNE 1975

...f Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
...Physics, Purdue University, West Lafayette, Indiana 47907

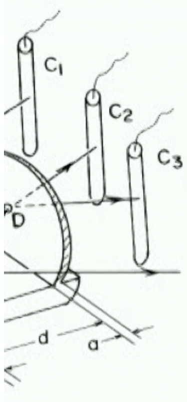
and

S. A. Werner
...rch Staff, Ford Motor Company, Dearborn, Michigan 48121

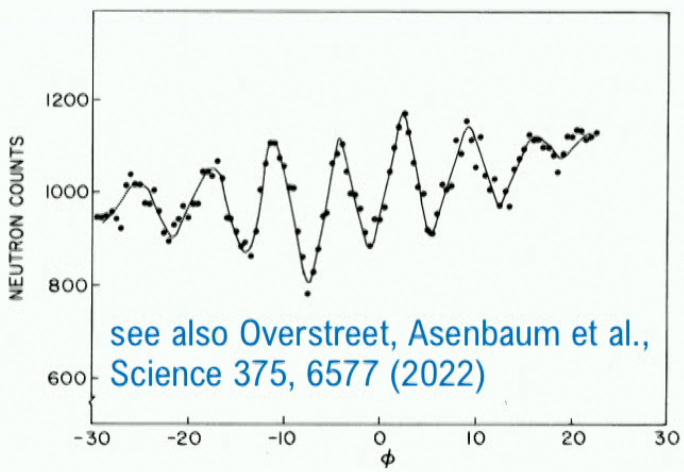
(Received 14 April 1975)

$\Delta\Psi = \frac{1}{\hbar}\int m\,\Delta\phi\,dt$ — $\Delta\phi$: gravitational potential (on Earth: $\phi = g \cdot h$)

...ron interferometer to observe the quantum-mechanical phase shift ... their interaction with Earth's gravitational field.



...tron interferom-
...riment.



see also Overstreet, Asenbaum et al., Science 375, 6577 (2022)

...ty impacts the wavefunction of a quantum particle

see also Bothwell et al. (Ye group), Nature 602, 420 (2022)

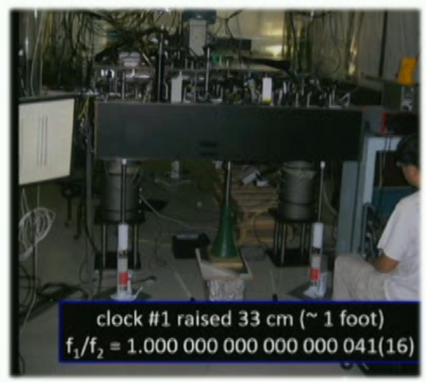
Science AAAS

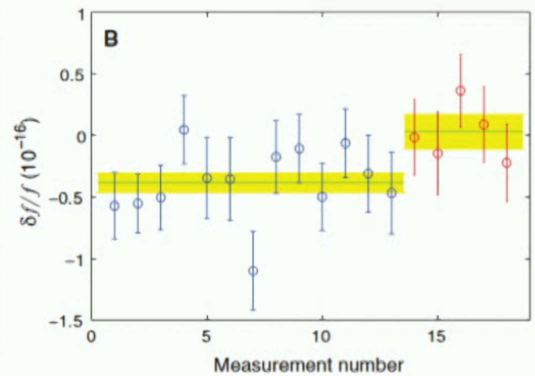
Optical Clocks and Relativity
C. W. Chou, *et al.*
Science **329**, 1630 (2010);
DOI: 10.1126/science.1192720

Optical Clocks and Relativity

C. W. Chou,* D. B. Hume, T. Rosenband, D. J. Wineland

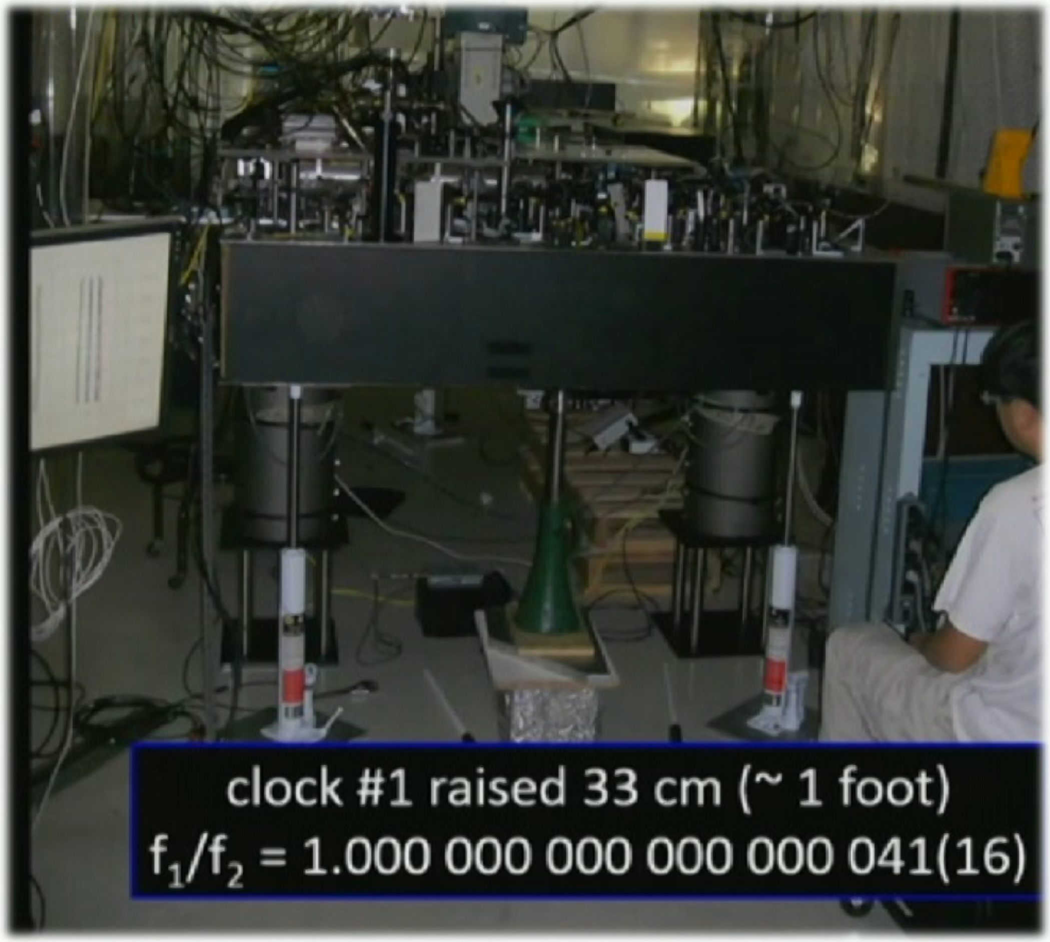
Observers in relative motion or at different gravitational potentials measure disparate clock rates. These predictions of relativity have previously been observed with atomic clocks at high velocities and with large changes in elevation. We observed time dilation from relative speeds of less than 10 meters per second by comparing two optical atomic clocks connected by a 75-meter length of optical fiber. We can now also detect time dilation due to a change in height near Earth's surface of less than 1 meter. This technique may be extended to the field of geodesy, with applications in geophysics and hydrology as well as in space-based tests of fundamental physics.

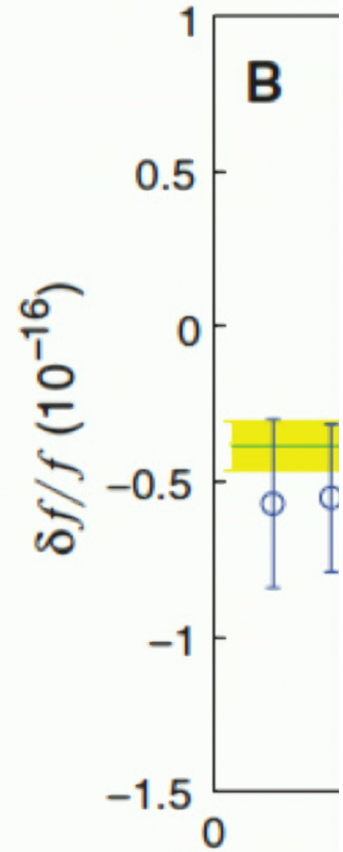




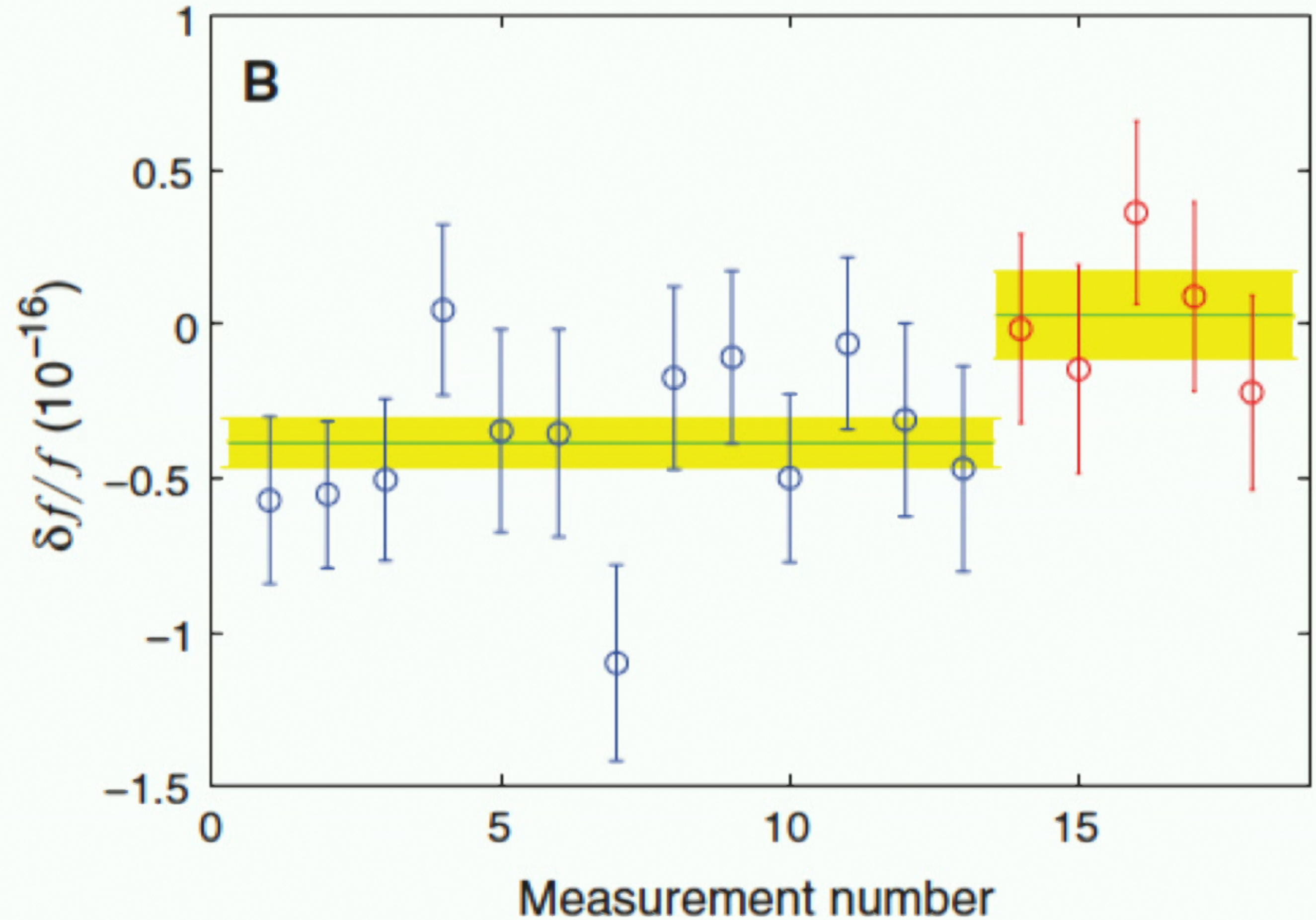
Atomic clocks: Frequency shift due to 33 cm lift in Earth's gravitational field

et al.,





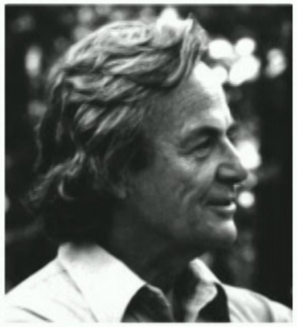
Atomic clocks: Frequency sh



clocks: Frequency shift due to 33 cm lift

e.g. Belenchia, Wald, et al., *Phys. Rev. D* **98**, 126009 (2018)

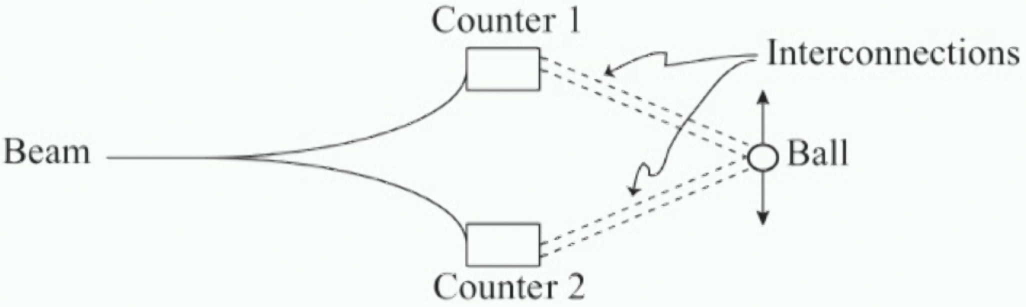
How does gravity react to quantum systems?



R P Feynman

"One should think about designing an experiment which uses a gravitational link and at the same time shows quantum interference"

Chapel Hill Conference 1957



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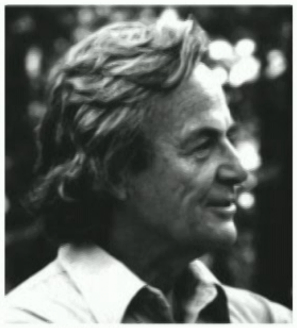

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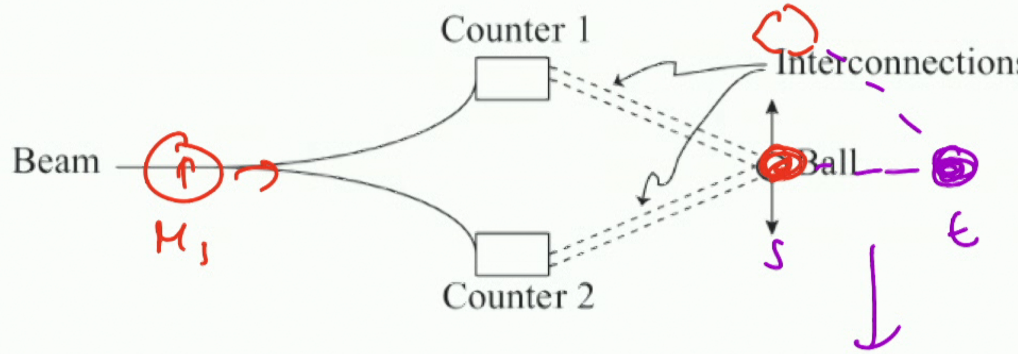

$$\left(|x_{\bar u}\rangle_s + |x_d\rangle_s\right) \otimes |x_0\rangle_t$$

$$t \downarrow \quad a_G^{I,II} = G\frac{m_s}{d^2_{I,II}}$$

$$|x_{\bar u}\rangle_s |x_{\bar u}\rangle_t + |x_d\rangle_s |x_d\rangle_t \qquad \langle x_{\bar u}|x_d\rangle_t \ll 1$$

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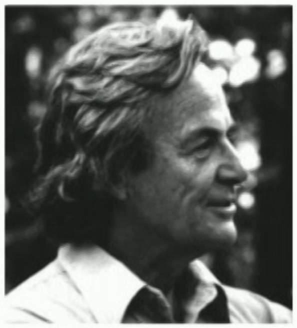

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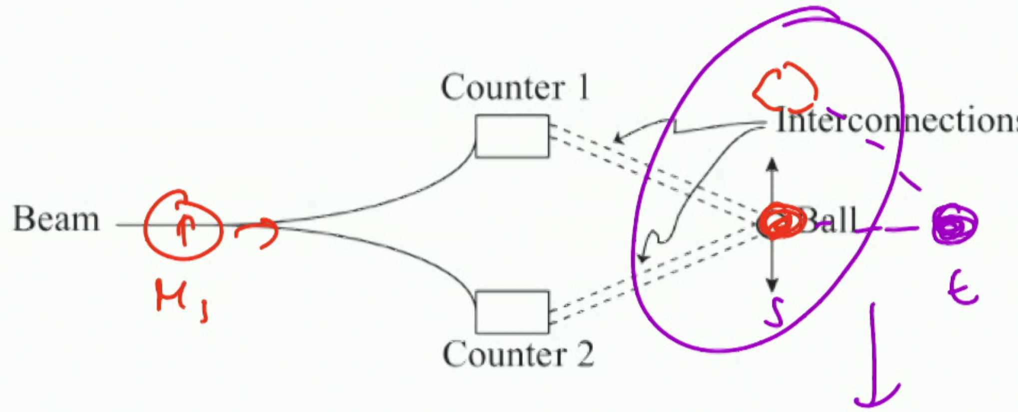

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$$t \downarrow \quad a_G^{I,II} = G\,\frac{m_s}{d^2_{I,II}}$$

$$|x_u\rangle_s |x_u\rangle_t + |x_d\rangle_s |x_d\rangle_t$$

ENTANGLED iff $\langle x_u | x_d \rangle_t \ll 1$

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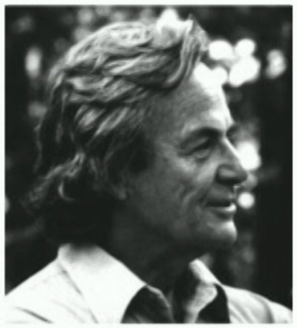

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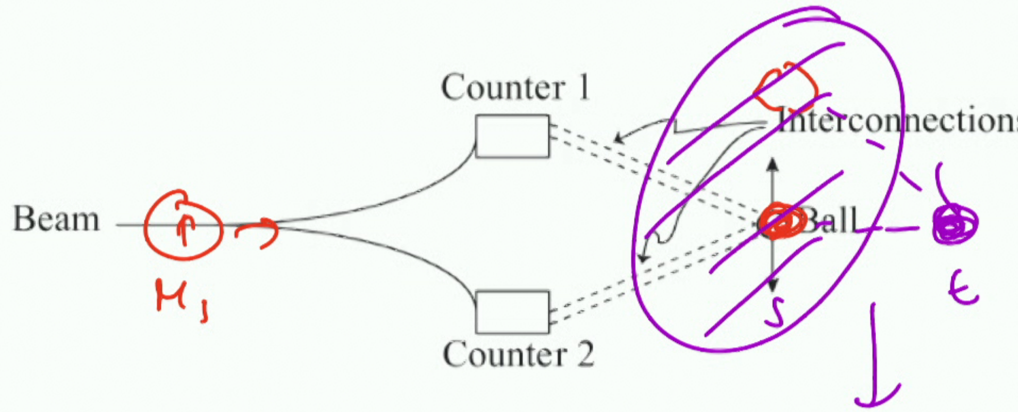

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