安東研輪講

2013年5月15日

光子の過去を聞く

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東京大学大学院理学系研究科物理学専攻
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論文紹介

- The classical limit of quantum optics: not what it seems at first sight
  Y. Aharonov+: arXiv:1305.0168

- The past of a quantum particle
  L. Vaidman: arXiv:1304.7474 (→ PRA)
- Asking photons where have they been
  A. Danan+: arXiv:1304.7469

↑
今回はこちらをメインに紹介

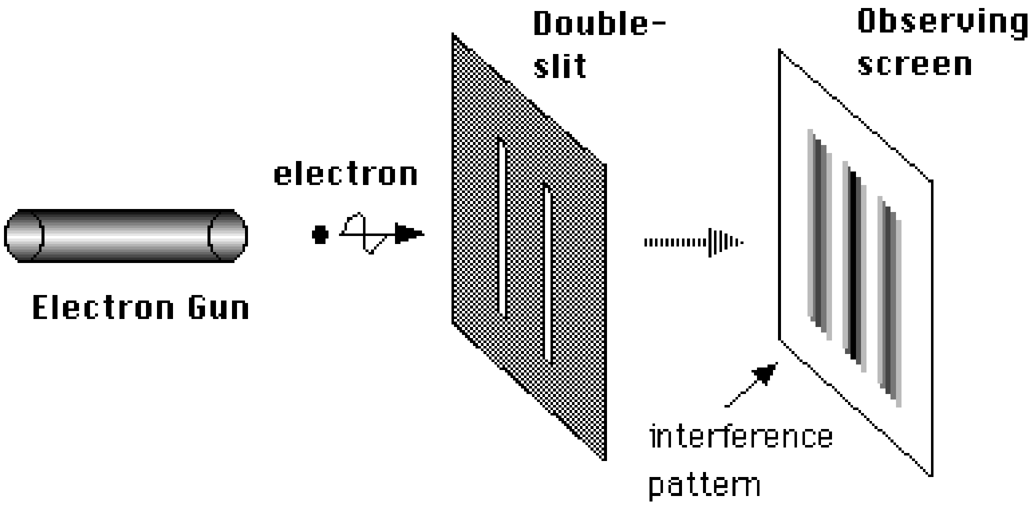
אוניברסיטת תל-אביב
TEL AVIV UNIVERSITY

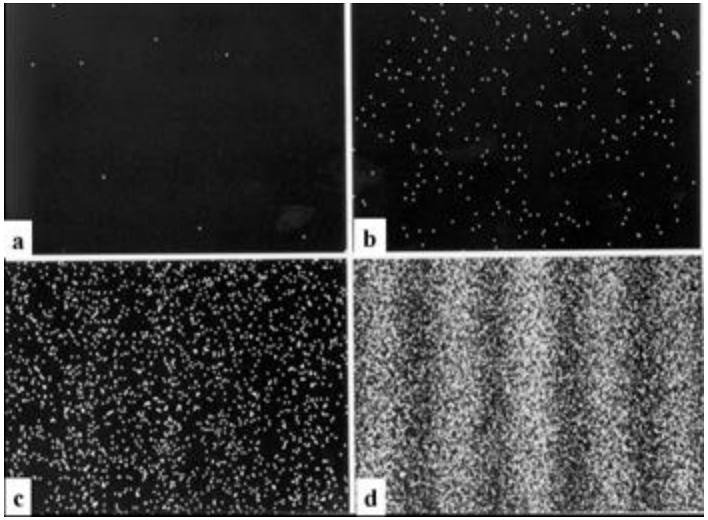
TIAU

Tel-Aviv University
http://www.tau.ac.il/~quantum/

二重スリット実験

- 電子を1個ずつ発射させても干渉縞が生じる
- 電子がどっちを通ったかはわからない
- 量子力学の確率的ふるまい

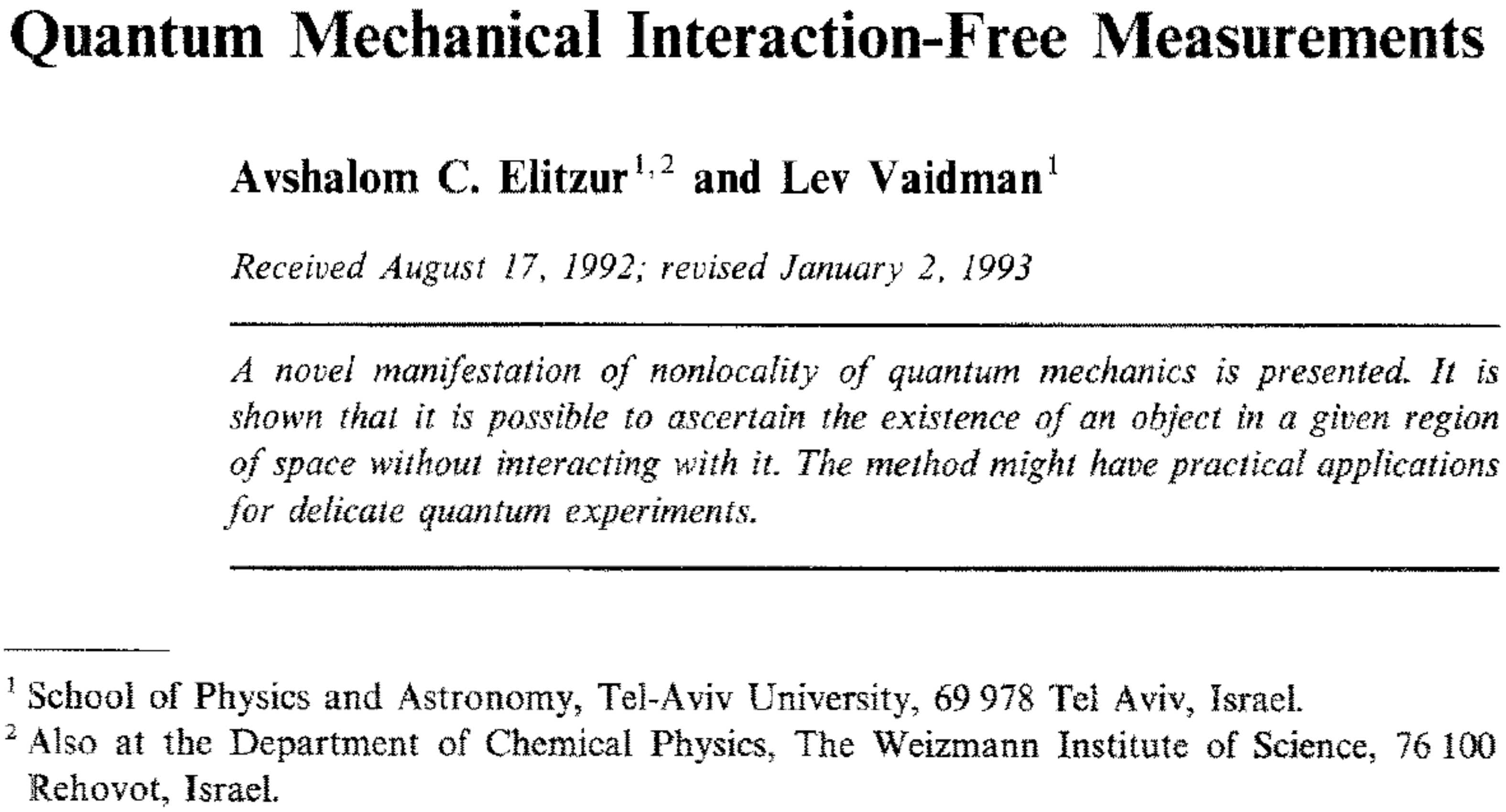




http://ja.wikipedia.org/wiki/二重スリット実験

Elitzur-Vaidmanの思考実験

- A. C. Elitzur & L. Vaidman: Found. Phys. 23, 987 (1993)



Quantum Mechanical Interaction-Free Measurements

Avshalom C. Elitzur[1,2] **and Lev Vaidman**[1]

Received August 17, 1992; revised January 2, 1993

A novel manifestation of nonlocality of quantum mechanics is presented. It is shown that it is possible to ascertain the existence of an object in a given region of space without interacting with it. The method might have practical applications for delicate quantum experiments.

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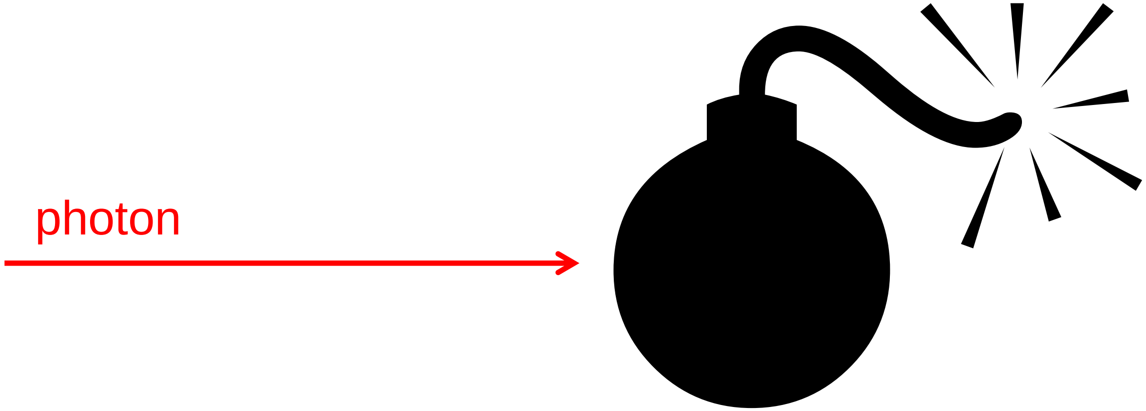
[2] Also at the Department of Chemical Physics, The Weizmann Institute of Science, 76 100 Rehovot, Israel.

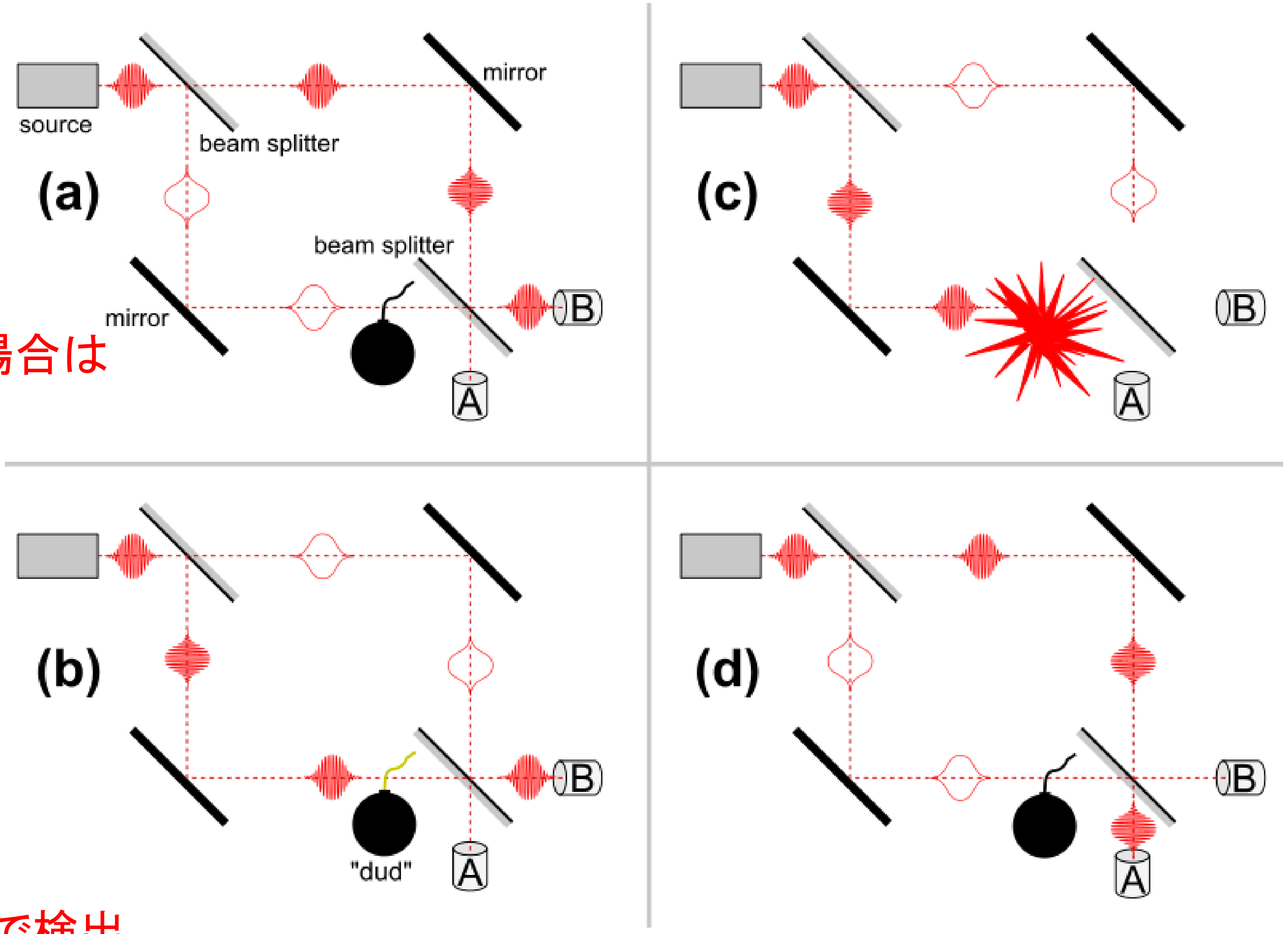
Elitzur-Vaidman Bomb Tester

- 光子を吸収して爆発する爆弾がたくさんある
- その中のいくつかは光子を吸収できず、爆発しない不発弾
- どうやって使える爆弾を選別するか？
(爆発していない状態で取り出したい)



MZIを使えば選別可能

- 1光子のMach-Zehnder干渉計
- Aに光子が来たら使える爆弾(一部は爆発してしまうが)



1光子源

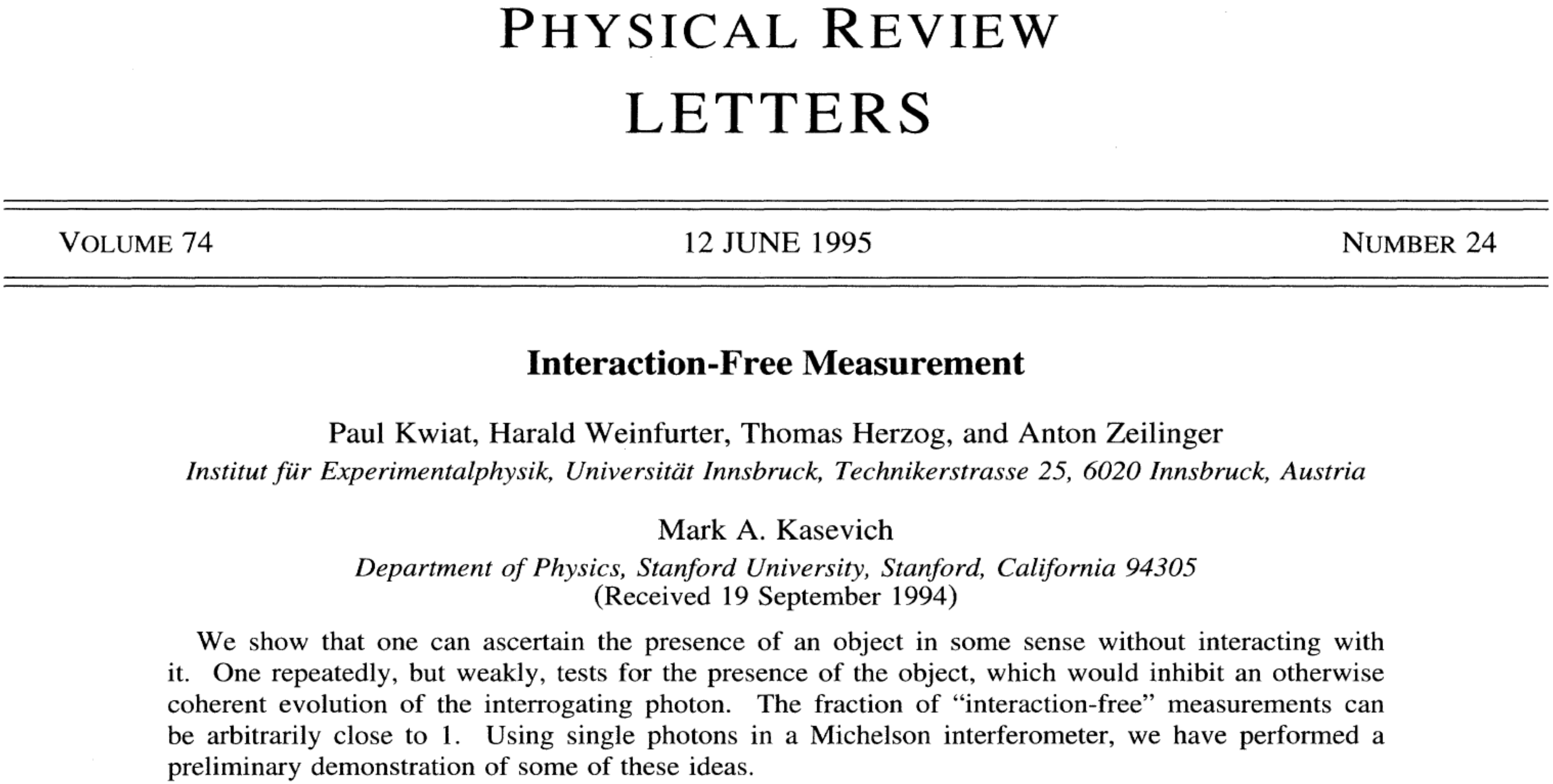
Bがbright fringe
Bで光子検出された場合は
どちらかわからない

使える爆弾の場合は
波動関数が収縮
下を通ったら爆発
上を通ったらAかBかで検出

http://en.wikipedia.org/wiki/Mach%E2%80%93Zehnder_interferometer

Kwiatらの実証実験

- P. Kwiat+: Ann. N. Y. Acad. Sci. 755, 383 (1995)
- P. Kwiat+: Phys. Rev. Lett. 74, 4763 (1995)



PHYSICAL REVIEW
LETTERS

VOLUME 74 12 JUNE 1995 NUMBER 24

Interaction-Free Measurement

Paul Kwiat, Harald Weinfurter, Thomas Herzog, and Anton Zeilinger
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Mark A. Kasevich
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(Received 19 September 1994)

We show that one can ascertain the presence of an object in some sense without interacting with it. One repeatedly, but weakly, tests for the presence of the object, which would inhibit an otherwise coherent evolution of the interrogating photon. The fraction of "interaction-free" measurements can be arbitrarily close to 1. Using single photons in a Michelson interferometer, we have performed a preliminary demonstration of some of these ideas.

Kwiatらの実証実験

- 鏡で爆弾を模したMichelson干渉計
- “爆弾”を判別できる割合ηが理論と一致

Darkでの検出数
(鏡が入ったとわかった数)

$$\eta = \frac{P(\mathrm{det})}{P(\mathrm{det}) + P(\mathrm{abs})}$$

Objでの検出数
(爆発数)

$$= RT/(RT + R) = (1 - R)/(2 - R)$$

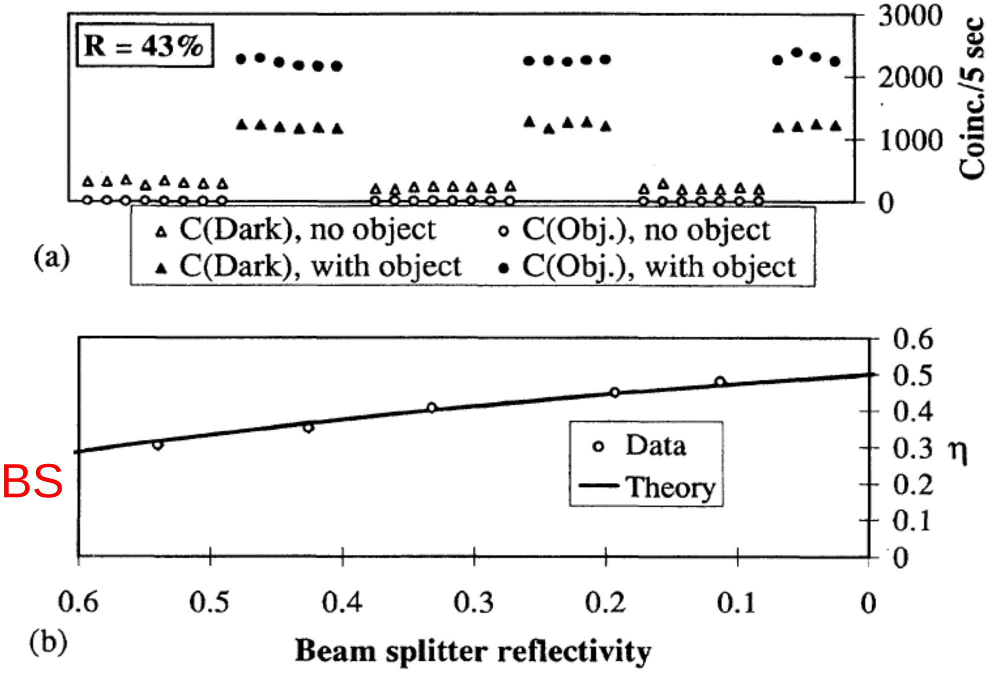


FIG. 5. (a) Typical experimental results for an interaction-free measurement. The beam splitter reflectivity for this data set was 43%. (b) Experimental and theoretical values for the figure of merit η in the Michelson-interferometer scheme, as a function of beam splitter reflectivity.

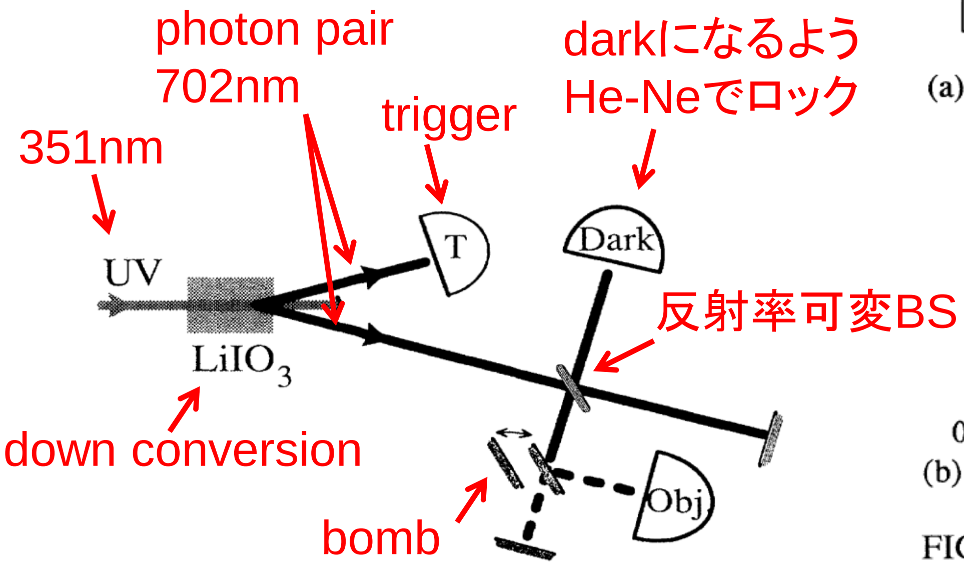


FIG. 4. Schematic of the down-conversion experiment demonstrating the principle of an interaction-free measurement.

Kwiatらの実証実験

- 無相互作用測定
- BSの反射率Rが低いほど判別できる割合が高い
- η=50%が最高
  R~0にしても、使える爆弾のうち半分は爆発させてしまう
- 量子Zeno効果を用いると100%にすることが可能

判別割合が最大でも50%

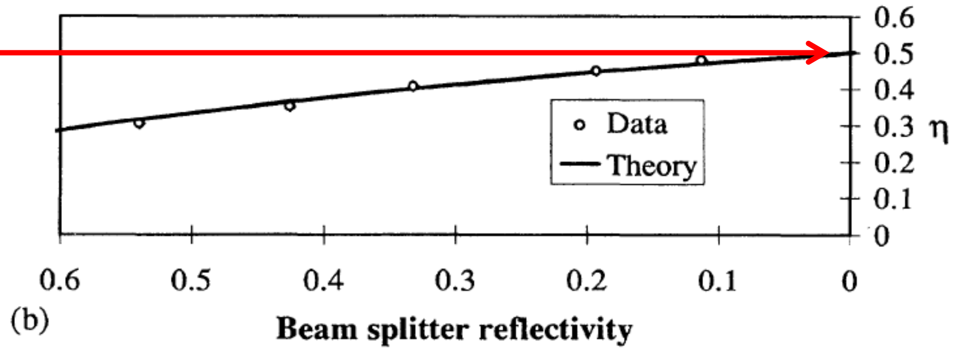
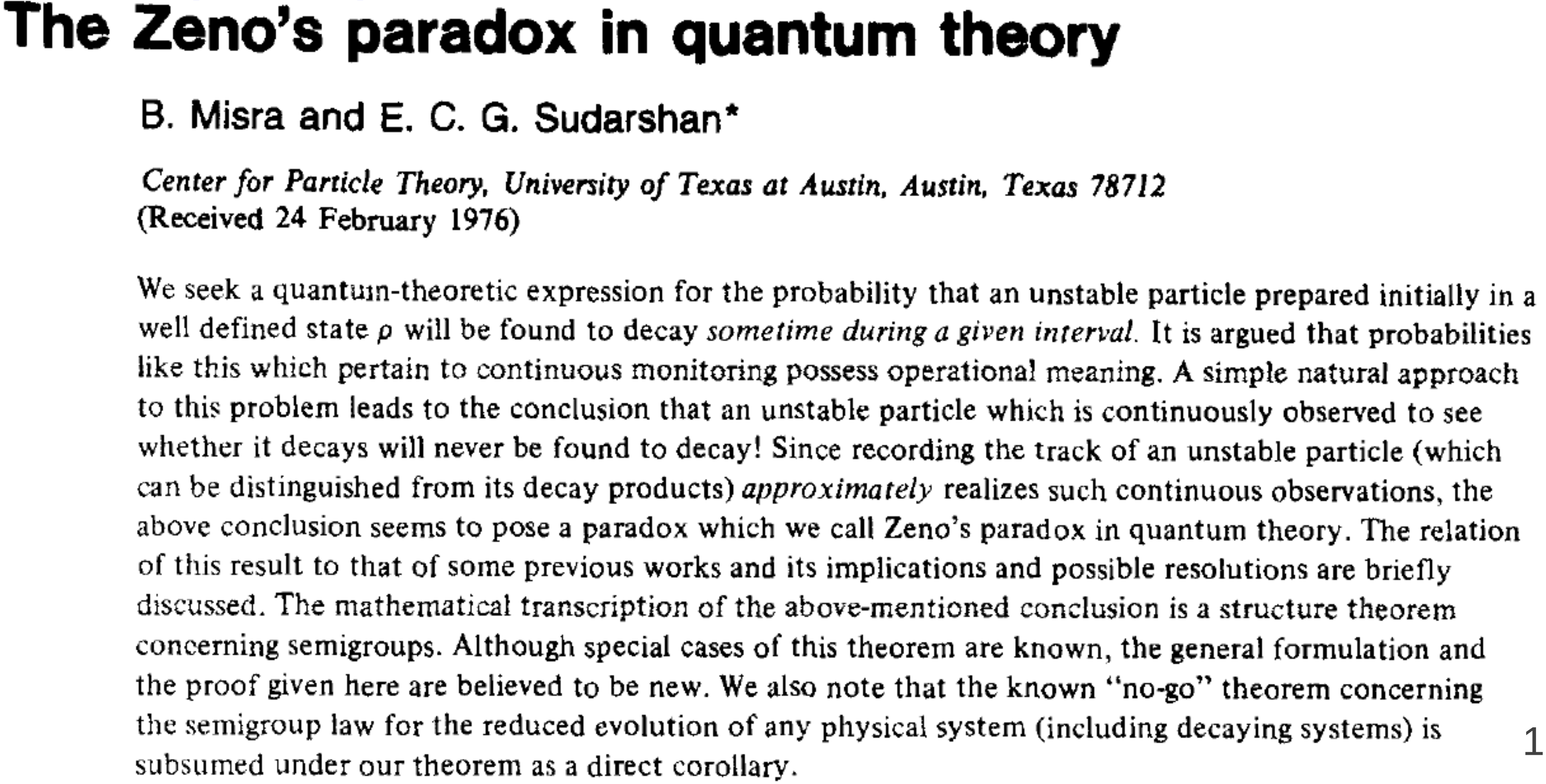


FIG. 5. (a) Typical experimental results for an interaction-free measurement. The beam splitter reflectivity for this data set was 43%. (b) Experimental and theoretical values for the figure of merit η in the Michelson-interferometer scheme, as a function of beam splitter reflectivity.

量子Zeno効果(QZE)

- 測定を頻繁に行うと、量子系の時間発展を制御することができる
- B. Misra & E. C. G. Sudarshan: J. Math. Phys. 18, 756 (1977)



The Zeno's paradox in quantum theory

B. Misra and E. C. G. Sudarshan*

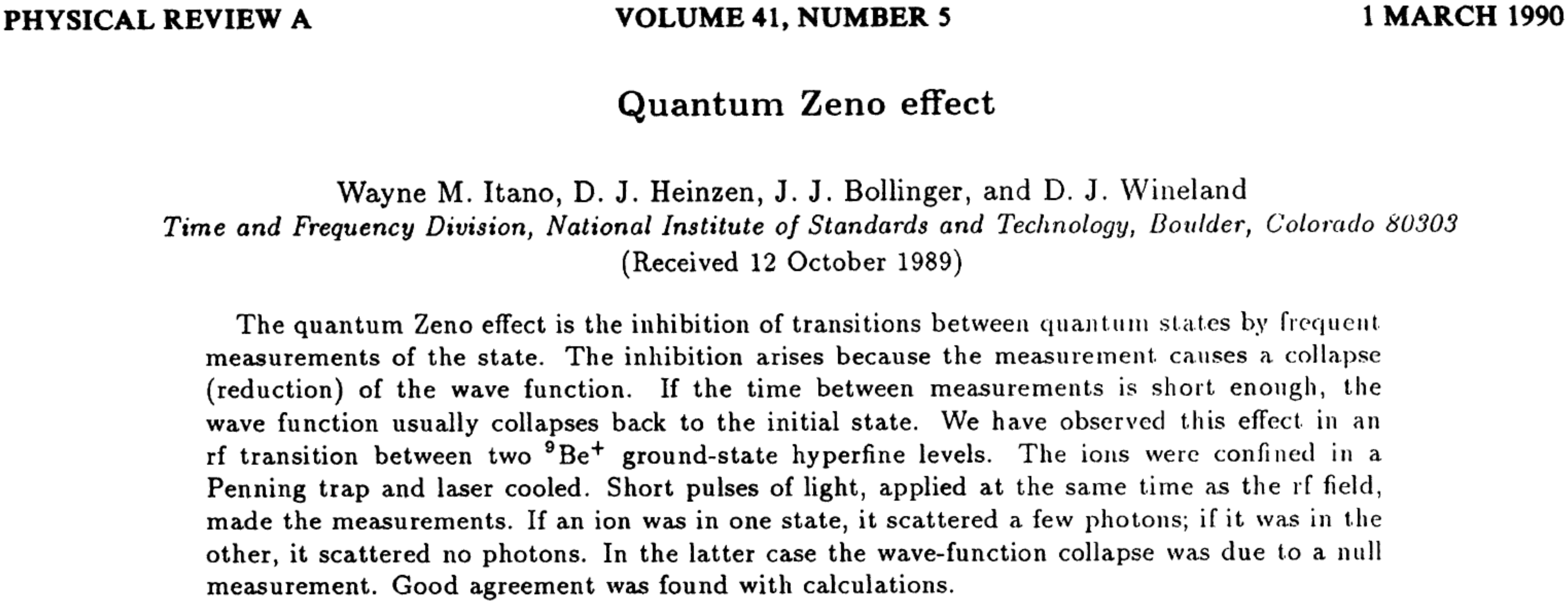
Center for Particle Theory, University of Texas at Austin, Austin, Texas 78712

(Received 24 February 1976)

We seek a quantum-theoretic expression for the probability that an unstable particle prepared initially in a well defined state ρ will be found to decay *sometime during a given interval*. It is argued that probabilities like this which pertain to continuous monitoring possess operational meaning. A simple natural approach to this problem leads to the conclusion that an unstable particle which is continuously observed to see whether it decays will never be found to decay! Since recording the track of an unstable particle (which can be distinguished from its decay products) *approximately* realizes such continuous observations, the above conclusion seems to pose a paradox which we call Zeno's paradox in quantum theory. The relation of this result to that of some previous works and its implications and possible resolutions are briefly discussed. The mathematical transcription of the above-mentioned conclusion is a structure theorem concerning semigroups. Although special cases of this theorem are known, the general formulation and the proof given here are believed to be new. We also note that the known "no-go" theorem concerning the semigroup law for the reduced evolution of any physical system (including decaying systems) is subsumed under our theorem as a direct corollary.

誘導遷移系での実証例

- W. N. Itano+: Phys. Rev. A 41, 2295 (1990)



PHYSICAL REVIEW A VOLUME 41, NUMBER 5 1 MARCH 1990

Quantum Zeno effect

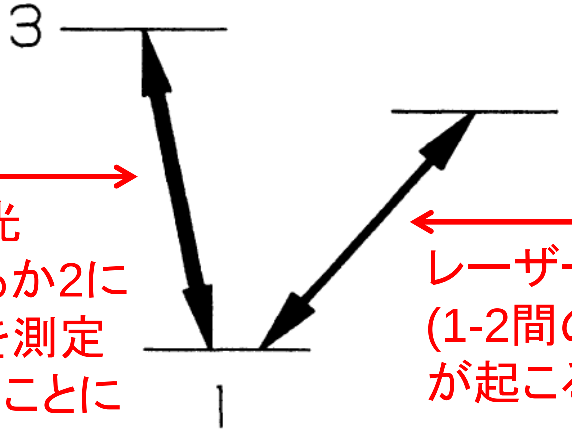
Wayne M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303

(Received 12 October 1989)

The quantum Zeno effect is the inhibition of transitions between quantum states by frequent measurements of the state. The inhibition arises because the measurement causes a collapse (reduction) of the wave function. If the time between measurements is short enough, the wave function usually collapses back to the initial state. We have observed this effect in an rf transition between two $^9Be^+$ ground-state hyperfine levels. The ions were confined in a Penning trap and laser cooled. Short pulses of light, applied at the same time as the rf field, made the measurements. If an ion was in one state, it scattered a few photons; if it was in the other, it scattered no photons. In the latter case the wave-function collapse was due to a null measurement. Good agreement was found with calculations.

誘導遷移系での実証例

- 1→3のパルス光を頻繁に照射すると、1-2間のラビ振動が抑えられた



パルス光
(1にあるか2にあるかを測定していることに相当)

レーザー光
(1-2間のラビ振動が起こる)

FIG. 1. Energy-level diagram for Cook's proposed demonstration of the quantum Zeno effect.

測定頻度が高い(nが大きい)ほど遷移確率が小さくなる

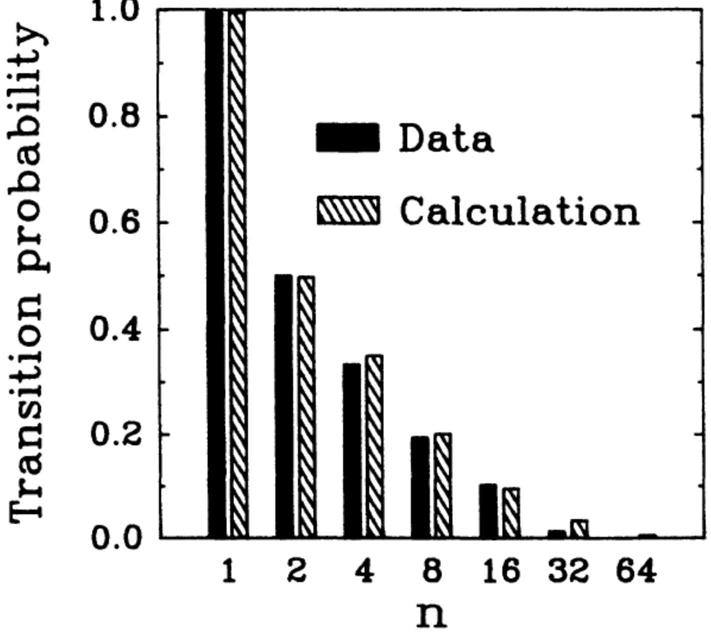
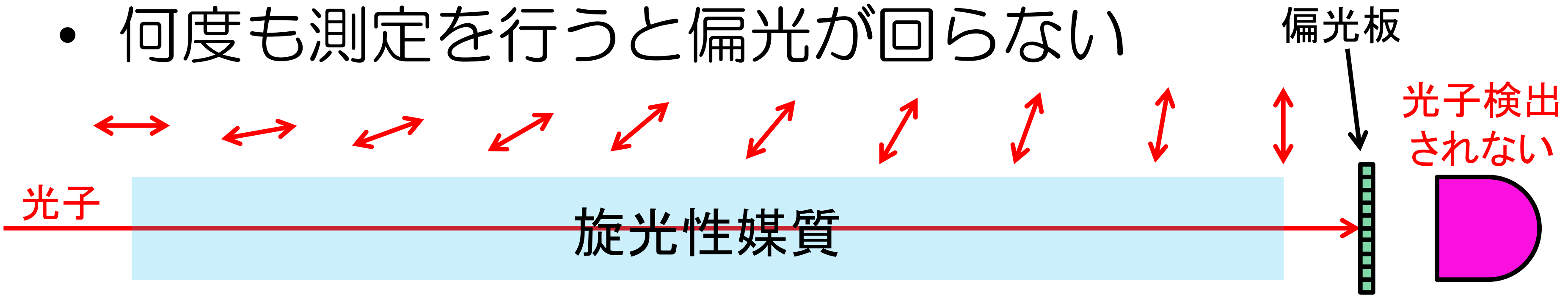


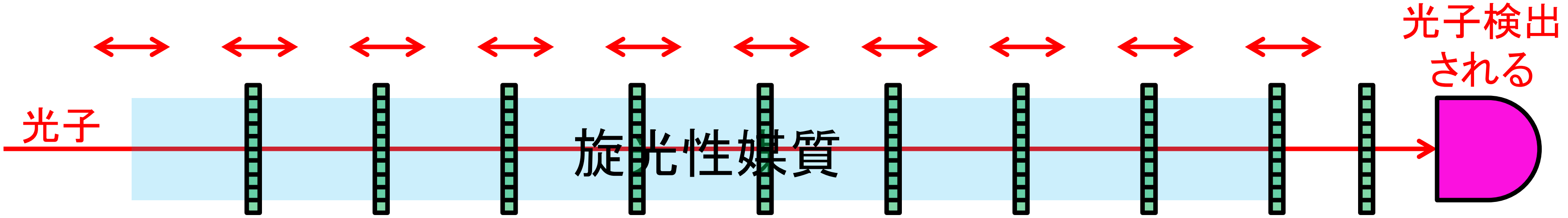
FIG. 3. Graph of the experimental and calculated 1 → 2 transition probabilities as a function of the number of measurement pulses n. The decrease of the transition probabilities with increasing n demonstrates the quantum Zeno effect.

偏光光学系でのQZE

- 何度も測定を行うと偏光が回らない



$$A = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$



$$A = \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cos(\theta/N) & -\sin(\theta/N) \\ \sin(\theta/N) & \cos(\theta/N) \end{pmatrix}\right]^N = \begin{pmatrix} \cos^N(\theta/N) & -\sin^N(\theta/N) \\ 0 & 0 \end{pmatrix}$$

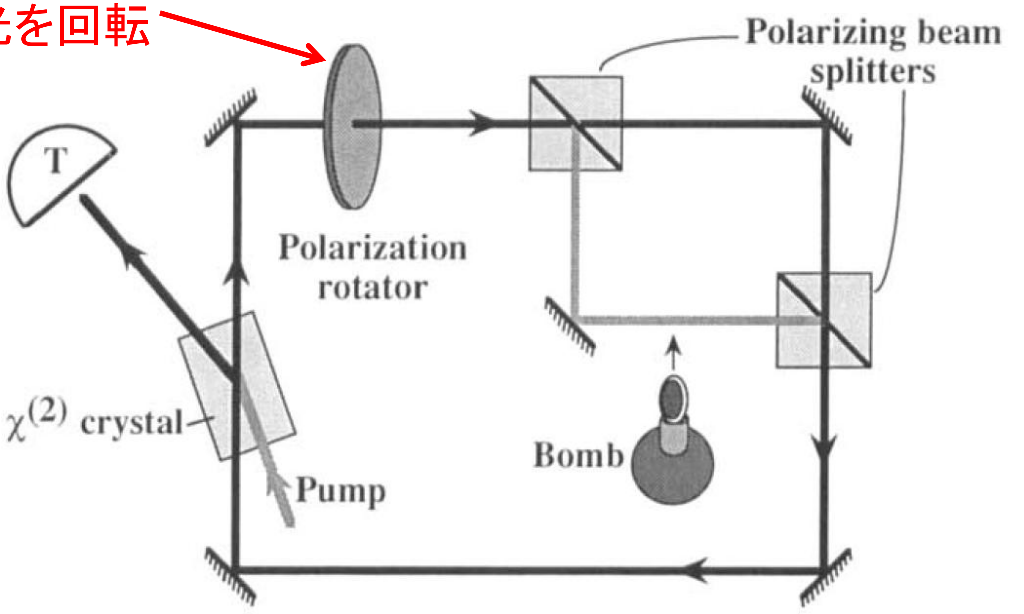
↑
偏光板

↑
N分割した
旋光性媒質

$$\xrightarrow[N\to\infty]{} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

QZEを利用した無相互作用測定

- N週後の光子を取り出す(delay-line風にするなどで)
  - p偏光なら使える爆弾
    N→∞だと量子Zeno効果により爆発しない
  - s偏光なら不発弾



π/(2N)
偏光を回転

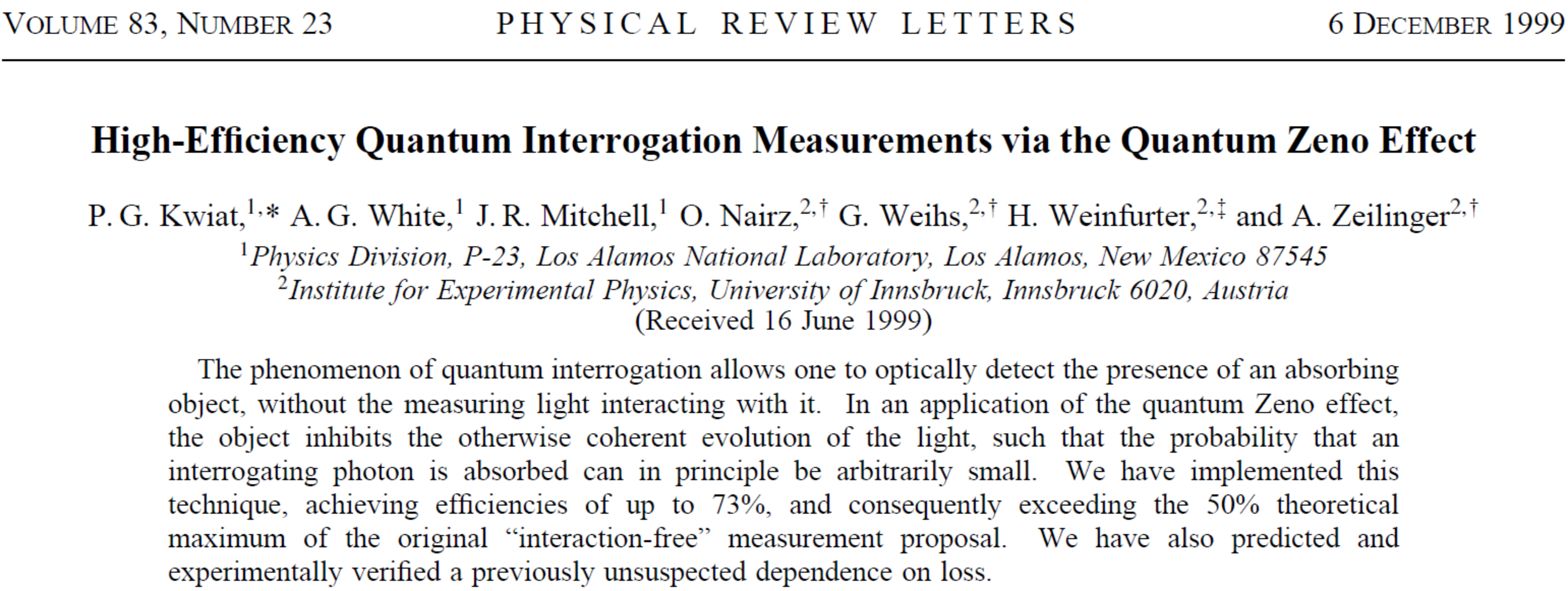
trigger→

FIGURE 6. Simplified schematic of one method to observe a greater than 50% interaction-free measurement. The downconversion photon makes N cycles before being removed (due to geometry or a fast switch) and its polarization measured.

P. Kwiat+: Ann. N. Y. Acad. Sci. 755, 383 (1995)

QZE無相互作用測定の実証

- P. G. Kwiat+: Phys. Rev. Lett. 83, 4725 (1999)



VOLUME 83, NUMBER 23 PHYSICAL REVIEW LETTERS 6 DECEMBER 1999

High-Efficiency Quantum Interrogation Measurements via the Quantum Zeno Effect

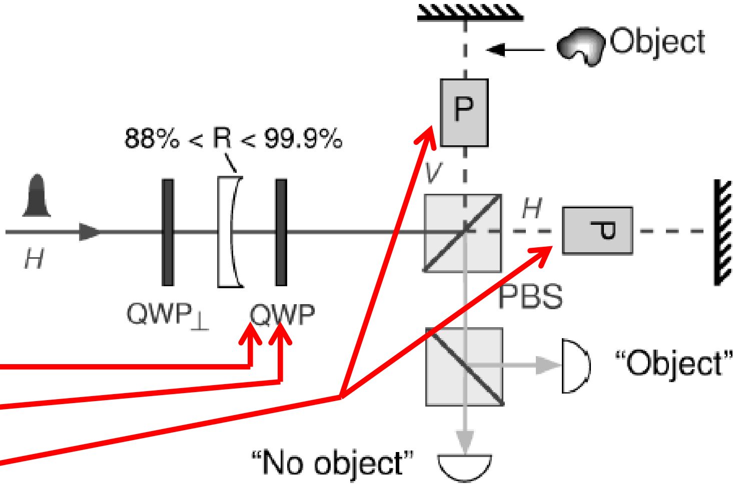
P. G. Kwiat,[1,*] A. G. White,[1] J. R. Mitchell,[1] O. Nairz,[2,†] G. Weihs,[2,†] H. Weinfurter,[2,‡] and A. Zeilinger[2,†]
[1] *Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[2] *Institute for Experimental Physics, University of Innsbruck, Innsbruck 6020, Austria*

(Received 16 June 1999)

The phenomenon of quantum interrogation allows one to optically detect the presence of an absorbing object, without the measuring light interacting with it. In an application of the quantum Zeno effect, the object inhibits the otherwise coherent evolution of the light, such that the probability that an interrogating photon is absorbed can in principle be arbitrarily small. We have implemented this technique, achieving efficiencies of up to 73%, and consequently exceeding the 50% theoretical maximum of the original "interaction-free" measurement proposal. We have also predicted and experimentally verified a previously unsuspected dependence on loss.

QZE無相互作用測定の実証

- 判別の効率を最大73%まで上げることに成功



パルス光(670nm)

PRM透過後の光子数は0.1-0.3/pulse

1往復でπ/(2N)だけ偏光を回転

Pockels cell
(N往復目の光子の偏光をπ/2回転させ、
光子を干渉計の外に出す)

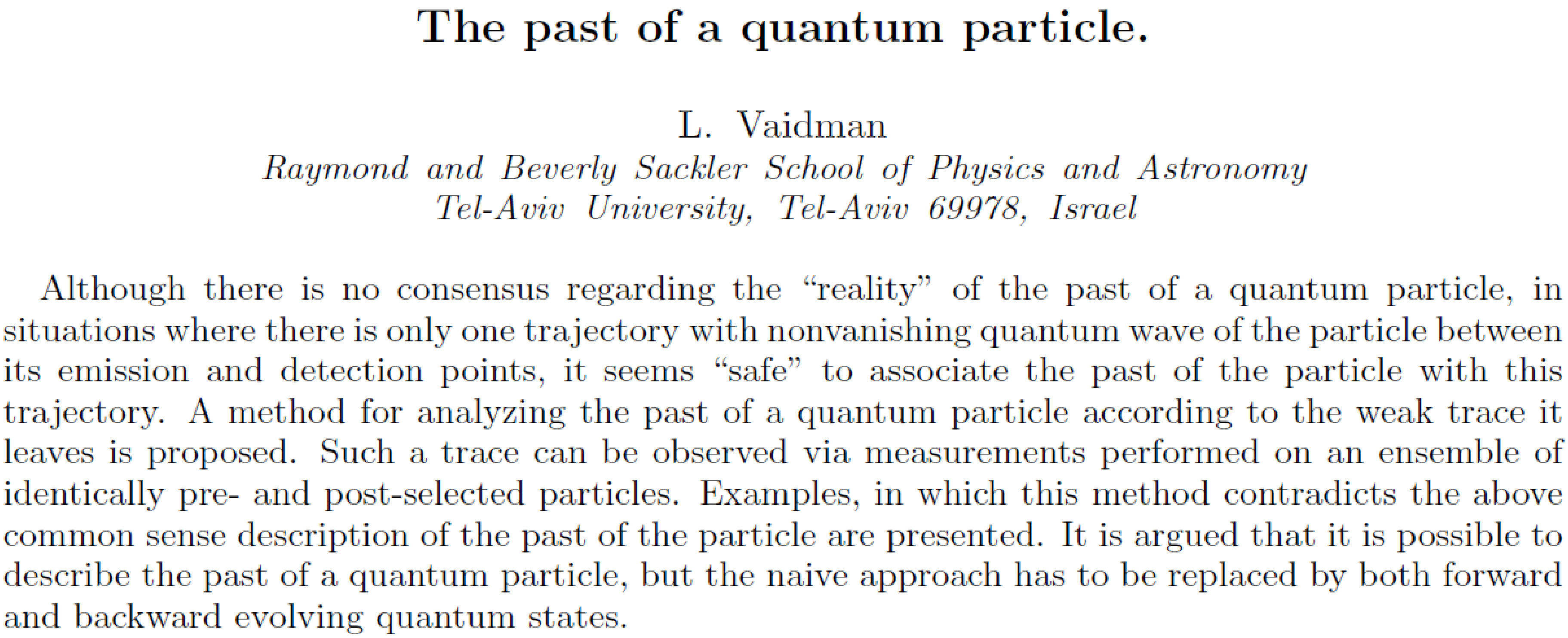
- N=15だったが、ロスを減らしてN~100にすればη>93%はいける見込み
- 応用すると走らせなくても結果が出る量子コンピュータ

O. Hosten+: [Nature 439, 949 (2006)]

FIG. 2. Experimental system to demonstrate high-efficiency quantum interrogation. Photons from a pulsed laser at 670 nm are coupled into the recycling system via a high-reflectivity recycling mirror (initially flat, later curved; see Fig. 3). A double pass through the quarter wave plate (QWP) served to rotate the polarization by a fixed amount during each cycle; an extra wave plate ($QWP_\perp$) in the entrance beam was used to compensate for the initial pass. On each cycle the photon passed through a polarization interferometer [with a polarizing beam splitter (PBS)]; to fine-tune the interferometer phase, one mirror was mounted on a piezoelectric “bimorph.” The Pockels cells (P) were used to switch the photons out after a desired number of cycles—a ~3 kV pulse was applied, which after the double pass rotated the polarization of the photon by 90°, so that it exited via the other port of the PBS. The exiting photon was then analyzed by the adjustable polarizer and single-photon detector [EG&G No. SPCM-AQ-141, preceded by an interference filter (10 nm FWHM, centered at 670 nm) to reduce background]. The final polarization of the detected photon indicates the presence (**V** polarized) or absence (**H** polarized) of an object in the reflected arm of the interferometer. (Not shown: an active feedback helium neon laser which ran below the plane of the 670 nm light, to stabilize the interferometer.)

光子の過去の軌跡

- L. Vaidman: arXiv:1304.7474 (28 Apr 2013; →PRA)



The past of a quantum particle.

L. Vaidman
Raymond and Beverly Sackler School of Physics and Astronomy
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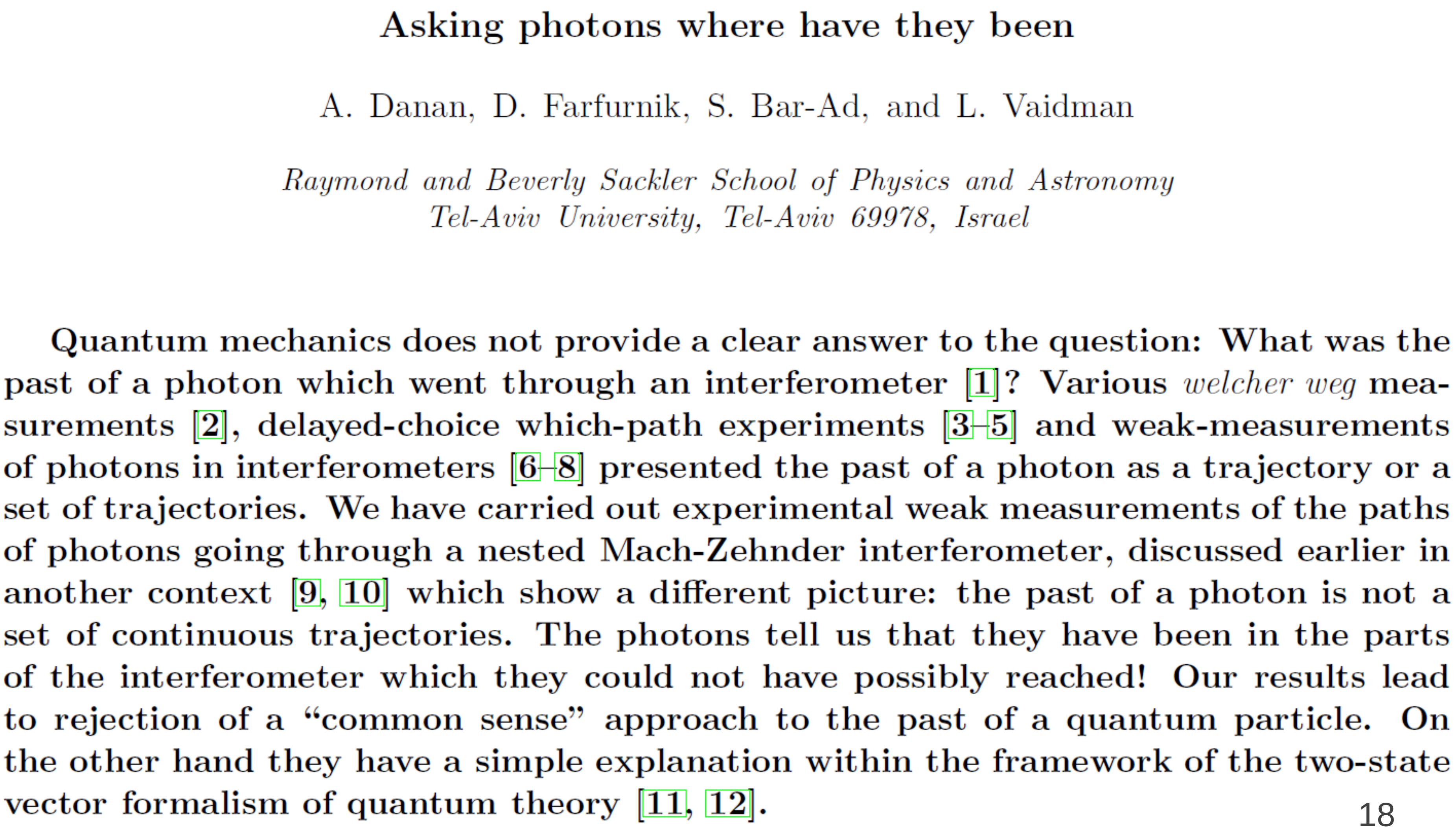
Although there is no consensus regarding the "reality" of the past of a quantum particle, in situations where there is only one trajectory with nonvanishing quantum wave of the particle between its emission and detection points, it seems "safe" to associate the past of the particle with this trajectory. A method for analyzing the past of a quantum particle according to the weak trace it leaves is proposed. Such a trace can be observed via measurements performed on an ensemble of identically pre- and post-selected particles. Examples, in which this method contradicts the above common sense description of the past of the particle are presented. It is argued that it is possible to describe the past of a quantum particle, but the naive approach has to be replaced by both forward and backward evolving quantum states.

- ここからが今回の紹介論文

入れ子になったMZIでの実測

- A. Danan+: arXiv:1304.7469 (28 Apr 2013)



Asking photons where have they been

A. Danan, D. Farfurnik, S. Bar-Ad, and L. Vaidman

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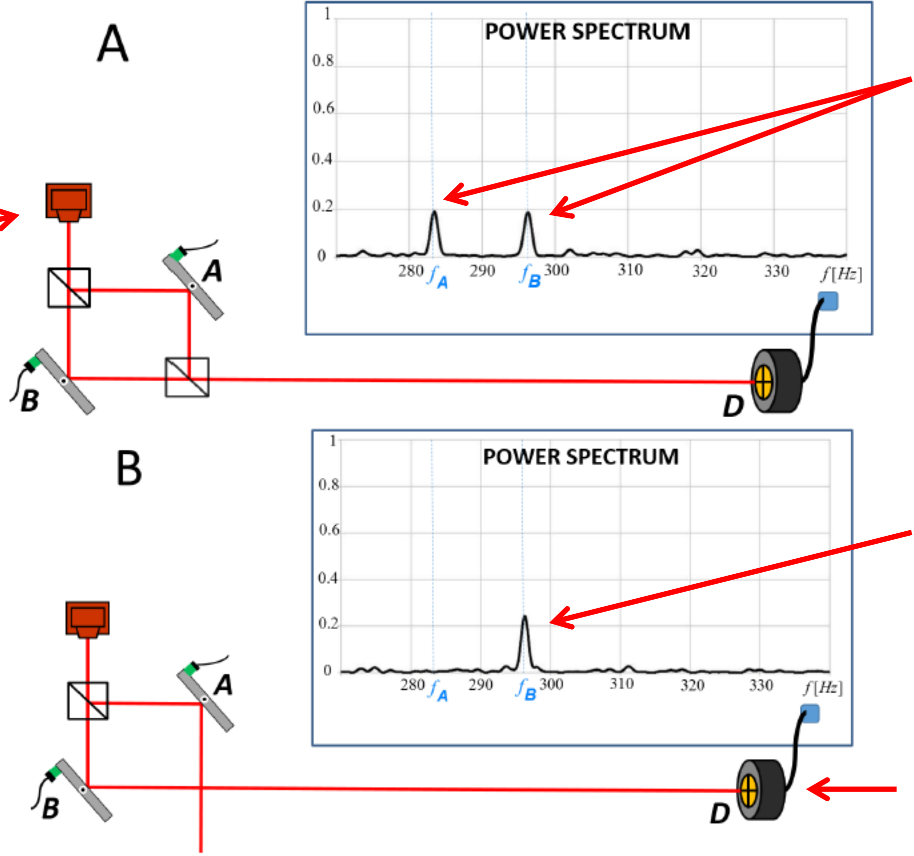
Tel-Aviv University, Tel-Aviv 69978, Israel

Quantum mechanics does not provide a clear answer to the question: What was the past of a photon which went through an interferometer [1]? Various *welcher weg* measurements [2], delayed-choice which-path experiments [3–5] and weak-measurements of photons in interferometers [6–8] presented the past of a photon as a trajectory or a set of trajectories. We have carried out experimental weak measurements of the paths of photons going through a nested Mach-Zehnder interferometer, discussed earlier in another context [9, 10] which show a different picture: the past of a photon is not a set of continuous trajectories. The photons tell us that they have been in the parts of the interferometer which they could not have possibly reached! Our results lead to rejection of a "common sense" approach to the past of a quantum particle. On the other hand they have a simple explanation within the framework of the two-state vector formalism of quantum theory [11, 12].

光子がどこを通ったか

- 鏡を異なる周波数で揺らすことで光子がどこを通ったかわかる



CWレーザー
(785nm)

AとBの周波数が出る
(当たり前)

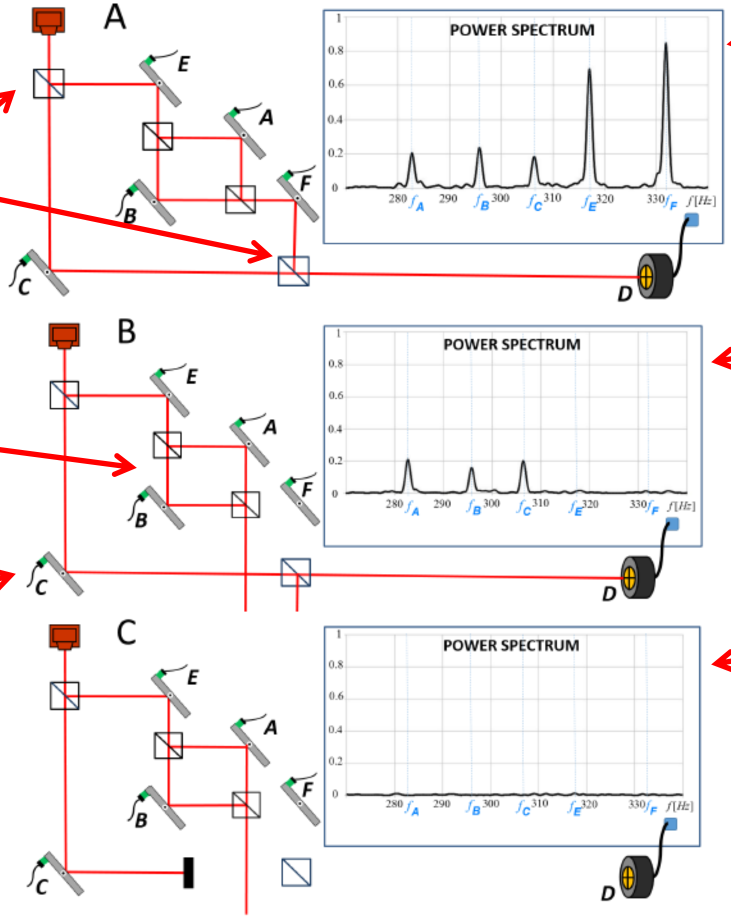
Bの周波数しか出ない
(当たり前)

QPD出力のスペクトル
を見る

FIG. 1: (A) Measured power spectrum of the signal from the quad-cell photo-detector shows frequencies of oscillation of internal mirrors *A* and *B* of the Mach-Zehnder interferometer. (B) Only the frequency of the mirror *B* remains in the power spectrum of the signal when the second beam splitter of the interferometer is taken out.

光子がどこを通ったか

- 通ったはずのない鏡の周波数が出る



PBS
(2:1に光を分岐)

F側がdarkに
なるよう制御

それぞれの鏡は
~150nrad揺らす

全ての鏡の周波数が
出る
EとFは高い
(当たり前)

Cは出る
AとBもなぜか出る！
EとFは出ない

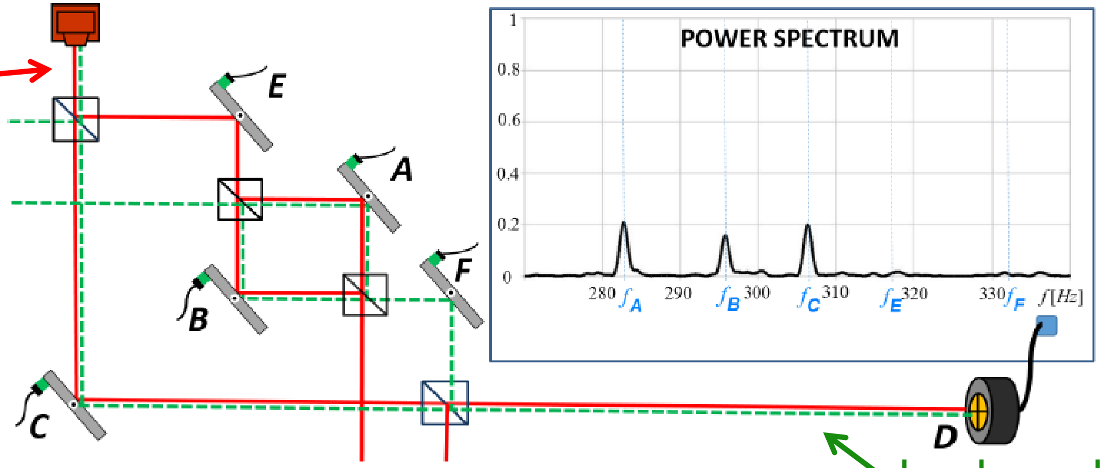
Cからの光をブロック
すると何もでない
(つまり内側のMZからの
漏れが原因ではない)

FIG. 2: (A) Measured power spectrum of the signal from the quad-cell photo detector shows frequencies of oscillation of all internal mirrors of the interferometer. (B) When the inner interferometer is tuned in such a way that the beam of light passing through it does not reach the photo-detector, the power spectrum of the signal in the photo-detector still shows frequencies of the mirrors of this interferometer. (C) These frequencies (and all other signals) disappear when we, without changing anything in the upper arm, block the lower arm of the large interferometer.

TSVFによる説明

- TSVF = two-state vector formalism
  Y. Aharonov+: Phys. Rev. 134, B1410 (1964)
  Y. Aharonov & L. Vaidman: Phys. Rev. A 41, 11 (1990)
- 逆行する量子状態と重なる部分の鏡だけ出る (真空場の混入ってこと？)

forward evolving state



backward evolving state

FIG. 3: The two-state vector description of the photon inside the interferometer includes the standard forward evolving quantum state (red line) and backward evolving quantum state (green dashed line) of the photon detected by the quad-cell photo-detector. It provides an explanation of the observed power spectrum: frequencies f_C, f_A and f_B are present while f_E and f_F are not. The photon was present only where both forward and backward quantum wave functions do not vanish.

TSVFとは

- 新しい量子力学の形式
- 通常の形式では、量子系の時間発展は過去のある時点での状態|Ψ>のみで記述される
  → 測定するまでどんな物理量かわからない
- TSVFでは未来の状態<Φ|も含めて、その量子系の時間発展がわかる
  何を測定するかが原因になって時間発展が確定する
  測定する物理量だけあらかじめ決まっている
- 逆向き因果の存在を認める
- TSVFだと先の実験のような結果が簡単に説明可能

- 弱測定や量子コンピュータに繋がるらしい

TSVFによる説明

- two-state vectorは

$$\langle\Phi|\ |\Psi\rangle = \frac{1}{\sqrt{3}}(\langle A| - \langle B| + \langle C|)\ \ \frac{1}{\sqrt{3}}(|A\rangle + |B\rangle + |C\rangle)$$

forward evolving state

backward evolving state

- 例えば、検出された光子がAを通っていた割合は

$$P_A^w = \frac{\langle\Phi|P_A|\Psi\rangle}{\langle\Phi|\Psi\rangle} = \frac{\langle\Phi|A\rangle\langle A|\Psi\rangle}{\langle\Phi|\Psi\rangle} = 1$$

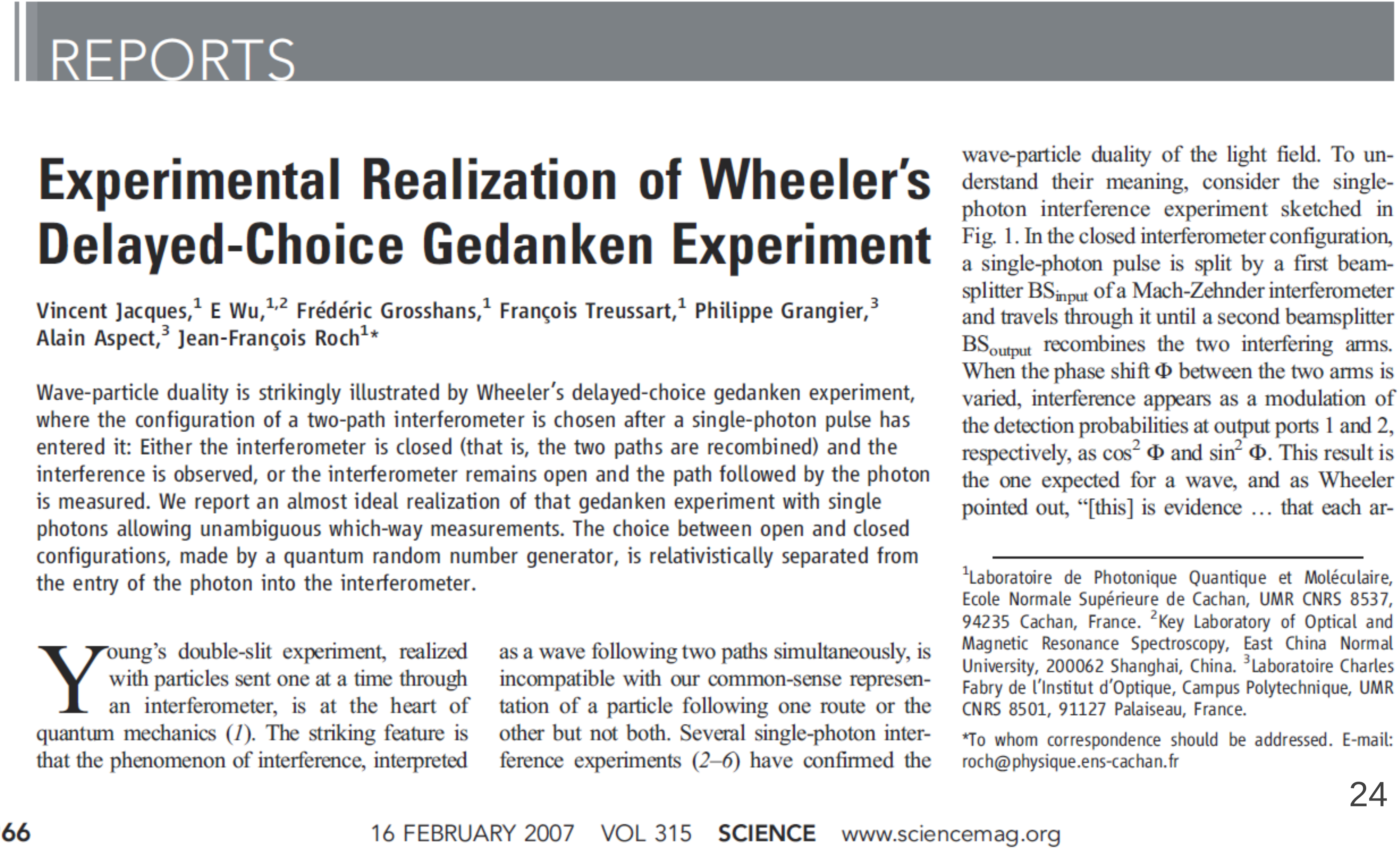
$\rightarrow$ ゼロでないのでAの周波数が検出される

- 実はこれが弱値らしい

(この計算だとCのパスをブロックすると弱値が無限大になりそう??)

Wheeler’s Delayed-Choice実験

- 測定の選択が過去を決定する
- V. Jacques+: Science 315, 966 (2007)



REPORTS

Experimental Realization of Wheeler’s Delayed-Choice Gedanken Experiment

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Wave-particle duality is strikingly illustrated by Wheeler’s delayed-choice gedanken experiment, where the configuration of a two-path interferometer is chosen after a single-photon pulse has entered it: Either the interferometer is closed (that is, the two paths are recombined) and the interference is observed, or the interferometer remains open and the path followed by the photon is measured. We report an almost ideal realization of that gedanken experiment with single photons allowing unambiguous which-way measurements. The choice between open and closed configurations, made by a quantum random number generator, is relativistically separated from the entry of the photon into the interferometer.

Young’s double-slit experiment, realized with particles sent one at a time through an interferometer, is at the heart of quantum mechanics (*1*). The striking feature is that the phenomenon of interference, interpreted as a wave following two paths simultaneously, is incompatible with our common-sense representation of a particle following one route or the other but not both. Several single-photon interference experiments (*2*–*6*) have confirmed the wave-particle duality of the light field. To understand their meaning, consider the single-photon interference experiment sketched in Fig. 1. In the closed interferometer configuration, a single-photon pulse is split by a first beamsplitter BS_{input} of a Mach-Zehnder interferometer and travels through it until a second beamsplitter BS_{output} recombines the two interfering arms. When the phase shift Φ between the two arms is varied, interference appears as a modulation of the detection probabilities at output ports 1 and 2, respectively, as $\cos^2 \Phi$ and $\sin^2 \Phi$. This result is the one expected for a wave, and as Wheeler pointed out, “[this] is evidence … that each ar-

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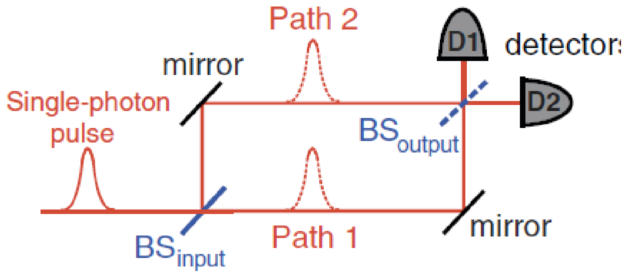
Wheeler's Delayed-Choice実験

- $\mathrm{BS}_{\mathrm{output}}$をなくすと光子の軌跡が一意に決まる
- $\mathrm{BS}_{\mathrm{input}}$通過時、$\mathrm{BS}_{\mathrm{output}}$の有無は不明のはずなのに

Fig. 1. Wheeler's delayed-choice gedanken experiment proposal. The choice to introduce or remove beamsplitter $\mathrm{BS}_{\mathrm{output}}$ (closed or open configuration) is made only after the passage of the photon at $\mathrm{BS}_{\mathrm{input}}$, so that the photon entering the interferometer "cannot know" which of the two complementary experiments (path difference versus which-way) will be performed at the output.



$\mathrm{BS}_{\mathrm{output}}$がないとD1とD2のどちらで光子検出されるかで軌跡がわかる(干渉が起こらない)

$\mathrm{BS}_{\mathrm{output}}$があると干渉が起こる

$\mathrm{BS}_{\mathrm{input}}$通過後に$\mathrm{BS}_{\mathrm{output}}$の有無がランダムに決まる

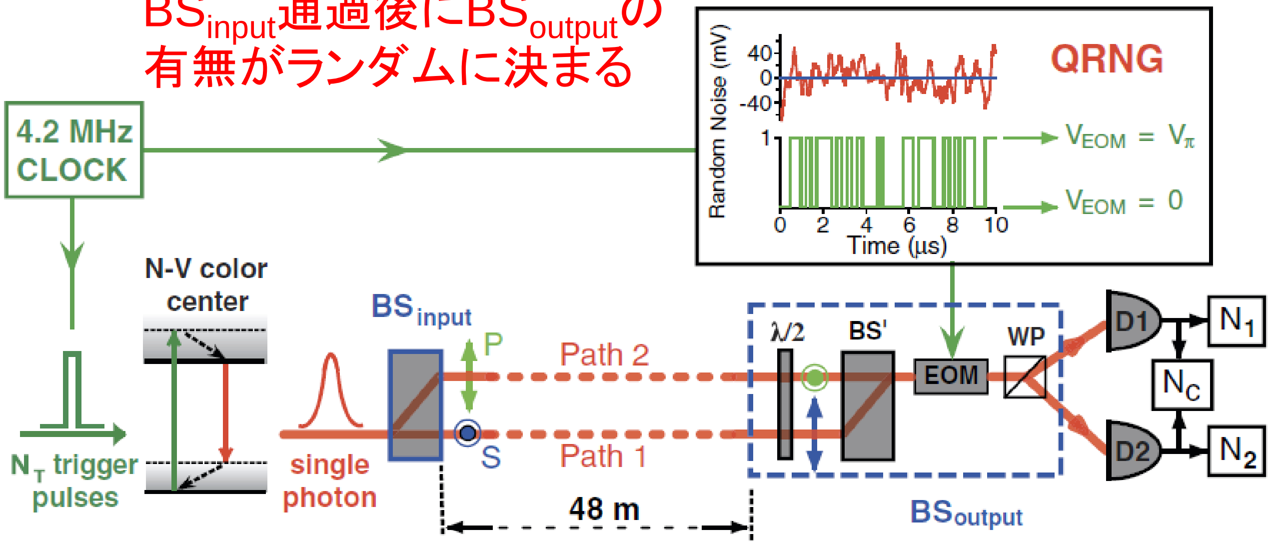


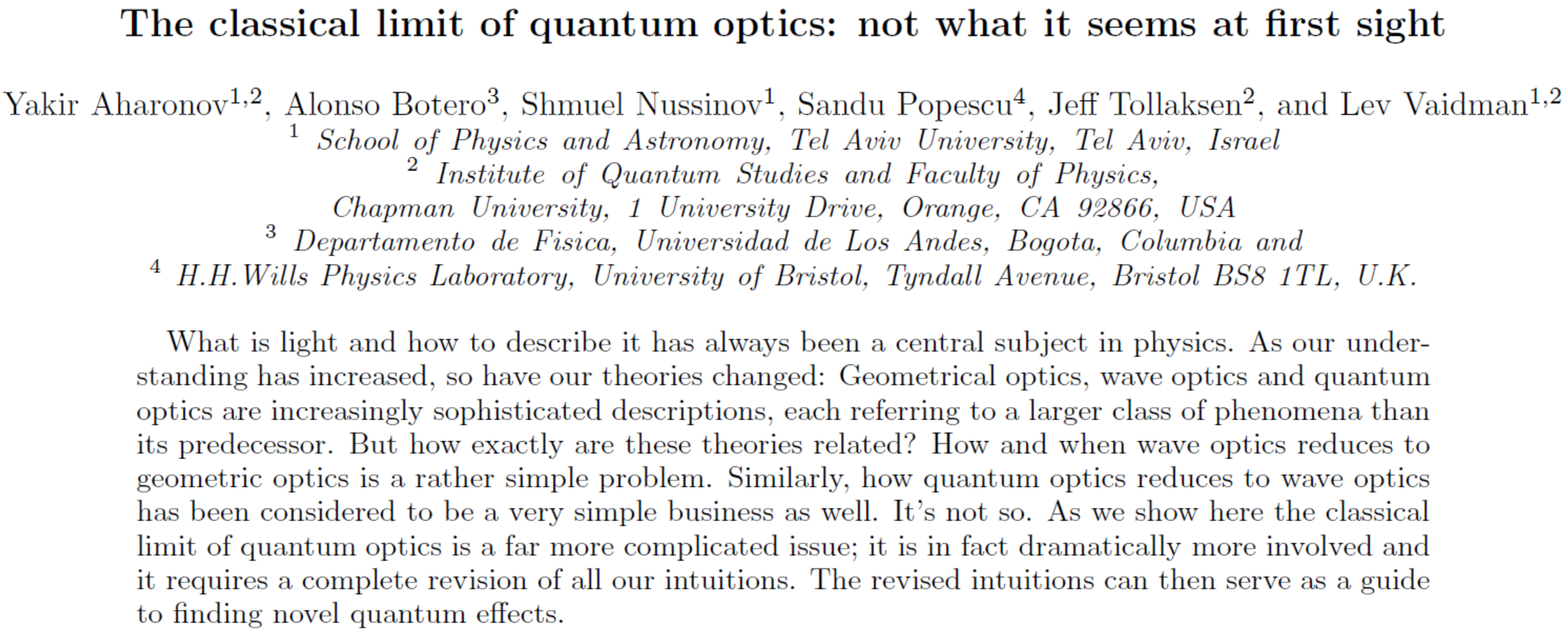
Fig. 2. Experimental realization of Wheeler's gedanken experiment. Single photons emitted by a single N-V color center are sent through a 48-m polarization interferometer, equivalent to a time of flight of about 160 ns. A binary random number 0 or 1, generated by the QRNG, drives the EOM voltage between $V = 0$ and $V = V_\pi$ within 40 ns, after an electronic delay of 80 ns. Two synchronized signals from the clock are used to trigger the single-photon emission and the QNRG. In the laboratory frame of reference, the random choice between the open and the closed configuration is made simultaneously with the entry of the photon into the interferometer. Taking advantage of the fact that the QNRG is located at the output of the interferometer, such timing ensures that the photon enters the future light cone of the random choice when it is at about the middle of the interferometer, long after passing $\mathrm{BS}_{\mathrm{input}}$.

紹介できなかった関連論文

- A. Peruzzo+: Science 338, 634 (2012)
  A Quantum Delayed-Choice experiment
- F. Kaiser+: Science 338, 637 (2012)
  Entanglement-Enabled Delayed-Choice experiment
- S. Kocsis+: Science 223 1170 (2011)
  Observing the average trajectories of single photons in a two-slit interferometer
- T. J. Herzog+: Phys. Rev. Lett. 75, 3034 (1995)
  Complementarity and the Quantum Eraser
- O. Hosten+: Nature 439, 949 (2006)
  Counterfactual quantum computation through quantum interrogation
- L. Vaidman: Phys. Rev. Lett. 98, 160403 (2007)
  Impossibility of the Counterfactual Computation for All Possible Outcomes

量子光学の古典極限

- Y. Aharonov+: arXiv:1305.0168 (1 May 2013)
- 量子力学の古典極限が古典力学と一致しない例



The classical limit of quantum optics: not what it seems at first sight

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What is light and how to describe it has always been a central subject in physics. As our understanding has increased, so have our theories changed: Geometrical optics, wave optics and quantum optics are increasingly sophisticated descriptions, each referring to a larger class of phenomena than its predecessor. But how exactly are these theories related? How and when wave optics reduces to geometric optics is a rather simple problem. Similarly, how quantum optics reduces to wave optics has been considered to be a very simple business as well. It's not so. As we show here the classical limit of quantum optics is a far more complicated issue; it is in fact dramatically more involved and it requires a complete revision of all our intuitions. The revised intuitions can then serve as a guide to finding novel quantum effects.

- せっかくなので軽く

MZIの例

- MZIの一方の出力光を裏側からもう一度鏡Mに当てて、D1で検出

- Mへの入射角

$$\cos\beta = \frac{1}{2}\cos\alpha$$

- 2つのBS

$$r^2 + t^2 = 1, \quad r > t$$

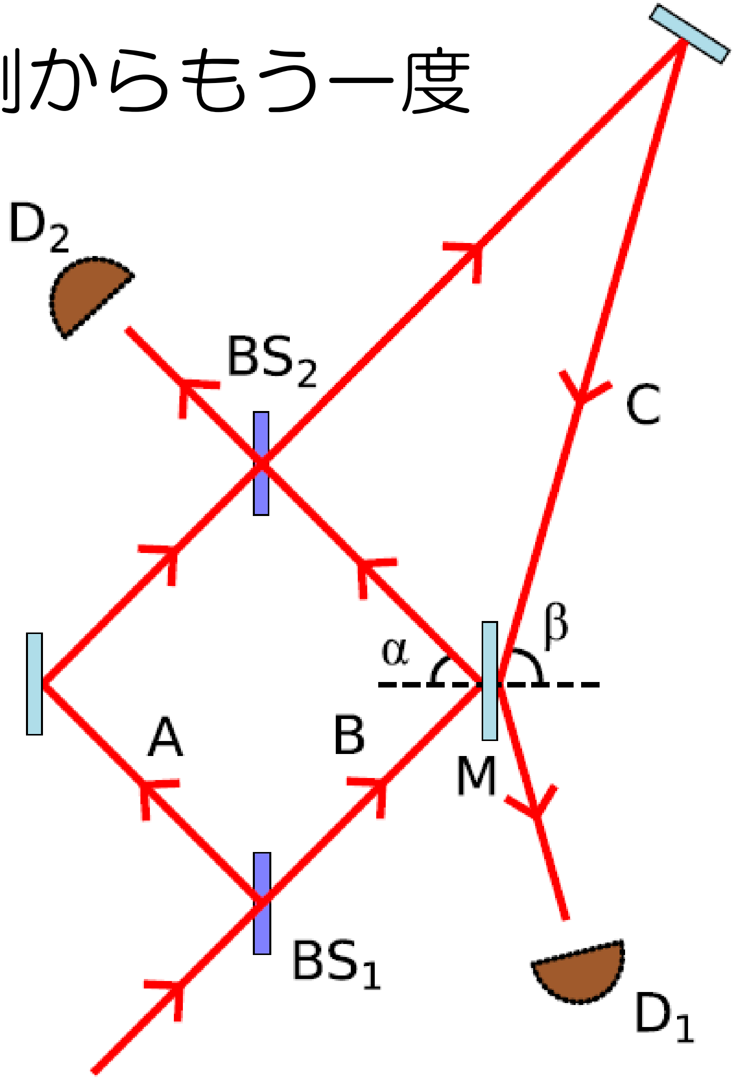

FIG. 2: Mach-Zehnder interferometer with one output beam reflected back onto the exterior side of mirror M.

Mに加わる運動量

- 古典的に計算した場合

$$\begin{aligned}\delta p_M &= 2\cdot t^2 I\cdot\cos\alpha - 2\cdot 4t^2r^2\cdot\cos\beta\\ &= -2t^2 I(r^2-t^2)\cos\alpha\end{aligned}$$

→r>t より鏡は内側に押される
「外側からの運動量の方が
大きいため」と考えられる

- 量子的にcoherent stateとして
計算した場合も同じ結果になる
($I=\bar{n}\hbar\omega$ が成り立つため)

↑

平均光子数

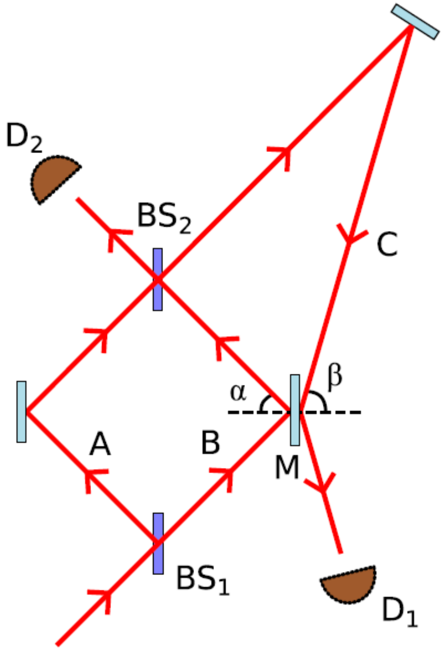

FIG. 2: Mach-Zehnder interferometer with one output beam reflected back onto the exterior side of mirror M.

Mに加わる運動量

- single photonの場合

  - D1に入った光子による運動量

D1での検出終状態

D1で検出された光子がBを通っていた割合(弱値)

初期状態

$$P_B^w = \frac{\langle\Phi_1|P_B|\Psi\rangle}{\langle\Phi_1|\Psi\rangle} = \frac{(t\langle A| + ir\langle B|)P_B(ir|A\rangle + t|B\rangle)}{(t\langle A| + ir\langle B|)(ir|A\rangle + t|B\rangle)}$$

$$= \frac{rt}{tr + rt} = \frac{1}{2}$$

より

$$\delta p_M = \hbar\omega\cos\alpha - 2\hbar\omega\cos\beta = 0$$

重ね合わせにより1/2になっている

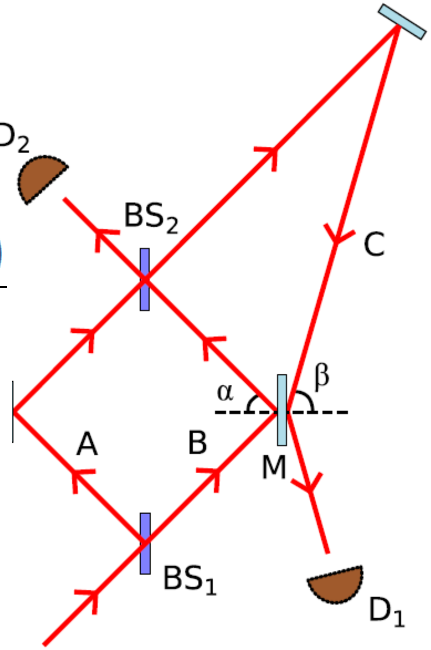

FIG. 2: Mach-Zehnder interferometer with one output beam reflected back onto the exterior side of mirror M.

  - D2に入った光子による運動量

$$P_B^w = \frac{\langle\Phi_2|P_B|\Psi\rangle}{\langle\Phi_2|\Psi\rangle} = \frac{(ir\langle A| + t\langle B|)P_B(ir|A\rangle + t|B\rangle)}{(ir\langle A| + t\langle B|)(ir|A\rangle + t|B\rangle)}$$

$$= -\frac{t^2}{r^2 - t^2}.$$

(r=tだったら無限大なの??)

より

$$\delta p_M = P_B^w \delta = -\frac{t^2}{r^2 - t^2} 2\hbar\omega\cos\alpha$$

Mに加わる運動量

- single photonの場合
  - D1に入った光子は何もしない
  - D2に入った光子が内側に押していることになる！

    → negative pressure

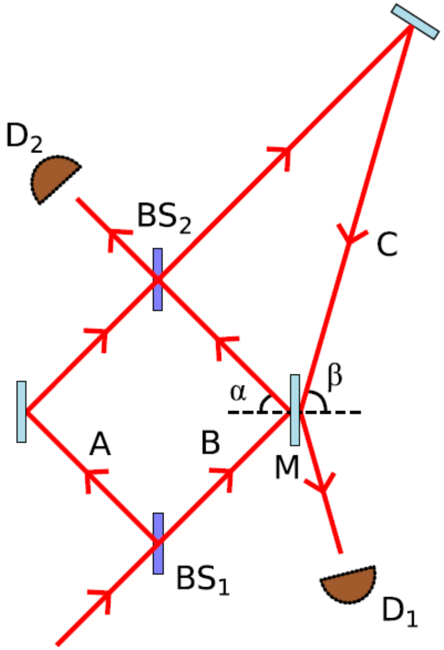

FIG. 2: Mach-Zehnder interferometer with one output beam reflected back onto the exterior side of mirror M.

- 入射する光子数を $\bar{n}$ 個にすると外側から当たる光子数より

$$\delta p_M = \overline{n}(r^2 - t^2)^2 \frac{-t^2}{r^2 - t^2} 2\hbar\omega\cos\alpha = -2t^2\hbar\omega\overline{n}(r^2 - t^2)\cos\alpha$$

→ 古典的な結果と一致

(Cのパスをブロックしたらどうなるの??)

まとめ

- Vaidman, Aharonovの最新の論文を読んだ
- なんとなく彼らが何やってるのかわかった
- 弱値のさわりを見た
- 詳しくは何もわかってない
- TSVFなど勉強する必要あり
- 1光子実験は面白そう
- 量子情報的な応用ではなく、精密測定への応用、理学的実験への応用ができるか
- 6月10日から15日まで分子研の鹿野研に行きます