

THE DEVELOPMENT OF METHODS OF QUANTUM MEASUREMENTS (NOTES ABOUT A PART OF A. EINSTEIN LEGACY)

V. B. BRAGINSKY

DEPT. OF PHYSICS, MOSCOW STATE UNIVERSITY, MOSCOW, 119992, RUSSIA

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NOBEL COMMITTEE:

“THE PRIZE FOR 1921 AWARDED IN 1922 TO PROFESSOR A. EINSTEIN, BERLIN, FOR SERVICES TO THEORETICAL PHYSICS AND ESPECIALLY FOR HIS DISCOVERY OF THE LAW OF PHOTOELECTRIC EFFECT”

A. EINSTEIN, ANN. PHYS. 17, 132-148 (1905)

CHAPT. 8

“QUANTA PENETRATE INTO THE SURFACE LAYER OF A SOLID, AND THEIR ENERGY AT LEAST PARTIALLY IS TRANSFERRED IN ELECTRON KINETIC ENERGY, THE SIMPLEST CASE IS WHEN SINGLE QUANTUM OF LIGHT GIVES ALL ITS ENERGY TO SINGLE ELECTRON; WE SHALL ASSUME THAT THIS HAPPEN IN REALITY. BESIDE WE ASSUME, THAT EACH ELECTRON WHEN LEAVING THE SOLID HAS TO LOOSE CERTAIN ENERGY A (WHICH IS A PARAMETER OF THIS SOLID) ... KINETIC ENERGY OF THESE ELECTRONS IS:

$$\frac{m_e v_e^2}{2} = \hbar\omega - A'' \quad (1)$$

(IN HIGH SCHOOL TEXT BOOK FORM)

TODAY GRADUATED STUDENT:

(1) IS THE CONSERVATION OF ENERGY IN THE INTERACTION OF SINGLE PHOTON WITH SINGLE ELECTRON IN CASE WHEN PHOTON SEIZES TO EXIST (COLLAPSE OF WAVE FUNCTION)
(1) DESCRIBES A METHOD OF MEASUREMENT (OF ESTIMATE) PHOTON'S ENERGY.

SLOW “PACE” OF UNDERSTANDING

! (1905) A. EINSTEIN (LAW OF PHOTOELECTRIC EFFECT).
(1913) N. BOHR (EXPLANATION OF HYDROGENE LIKE ATOM RADIATION)
! (1922) A. COMPTON (PHOTON MAY SURVIVE, WHEN INTERACTING WITH ELECTRON; CONSERVATION OF ENERGY AND OF MOMENTUM)
(1926–1929) W. HEISENBERG, E. SCHRÖDINGER, P. A. M. DIRAC.
! (1958) R. MÖSSBAUER (LATTICE MAY BE INVOLVED IN PHOTON-NUCLEON INTERACTION)

GROUPS ("COMPANIES") OF PHOTONS

(1956) R. HANBURY BROWN AND R. Q. TWISS — CORRELATION !
 (1955–1956) C. TOWNES, N. BASOV, A. PROKHOROV — MASER
 (1961) T. MEIMAN — LASER

(1916) A. EINSTEIN: STIMULATED EMISSION
 CREATES DUPLICATE (CLONE) PHOTONS.

SINCE \simeq 1970: NEW TYPES (NEW TERMS) OF GROUPS ("COMPANIES") OF
 PHOTONS:

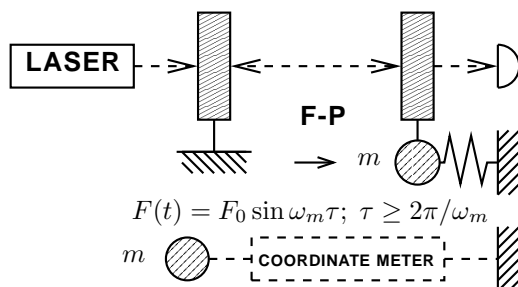
BUNCHING, ANTIBUNCHING, SQUEEZED STATES (QUADRATURE AMPLITUDE,
 ENERGY, PHASE) FREQUENCY ANTICORRELATED ???

SEE IN TEXT BOOKS:

(E.G. L. MANDEL + E. WOLF; G. AULETTA)

STANDARD QUANTUM LIMITS

Sov. Phys. JETP, 53, 1435 (1967)



$$\underline{\underline{F_{SQL} \simeq \frac{2}{\tau} \sqrt{\hbar m \omega_m}; \quad W_{optim!} \quad (2)}}$$

$$\Delta x_{SQL} \simeq \sqrt{\frac{\hbar \tau}{2m}}; \quad \Delta P_{SQL} \simeq \sqrt{\frac{\hbar m}{2\tau}} \quad (3)$$

SIMILAR SQL IN OPTICAL DOMAIN,
 "FAMILY" OF SQL (MECHANICAL AND OPTICAL)

QUANTUM-NON-DEMOLITION MEASUREMENTS PERMIT TO CIRCUMVENT SQL

Sov. Phys. JETP, 73, 705 (1977)

K. THORNE ET AL, PHYS. REV. LETT. 40, 667 (1978)

Sov. Phys. JETP LETT. 27, 296 (1978)

W. UNRUH, PHYS. REV. D, 18, 1764 (1978)

QND MEASUREMENTS REALIZED IN OPTICAL DOMAIN

SEE REVIEW BY P. GRANGIER ET AL, NATURE, 396, 537 (1998)

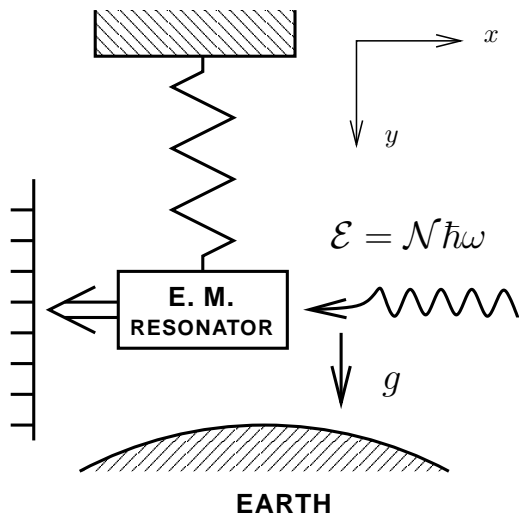
QND MEASUREMENTS REALIZED IN MICROWAVE DOMAIN (ENS)

SEE G. NOGUES ET AL, NATURE, 400, 239 (1999)

NO QND MEASUREMENTS WITH MECHANICAL OBJECTS YET

II QND MEASUREMENTS AND BOHR-EINSTEIN DISPUTE

N. BOHR "DISCUSSION WITH EINSTEIN ON EPISTEMOLOGICAL PROBLEMS IN ATOMIC PHYSICS" (1949), [AVAILABLE IN "QUANTUM THEORY AND EXPERIMENT", EDS. J. WHEELER, W. ZUREK, (1983) PRINCETON SERIES IN PHYSICS]



$$P_y = \frac{\mathcal{E}}{c^2}g\tau; \quad \Delta\mathcal{E} = \frac{c^2}{g\tau}\Delta P_y$$

BUT $\Delta P_y \cdot \Delta y \geq \hbar$

AND $\frac{\Delta\mathcal{E}}{\mathcal{E}} = \frac{g\Delta y}{c^2};$ **[GR !!!]**

THUS $\Delta\mathcal{E} \cdot \tau \geq \hbar$ **(QND SCHEME!)**

MEASUREMENT OF FREE MASS KINETIC ENERGY \mathcal{E}_{kin} BY MEASUREMENT OF THE MOMENTUM

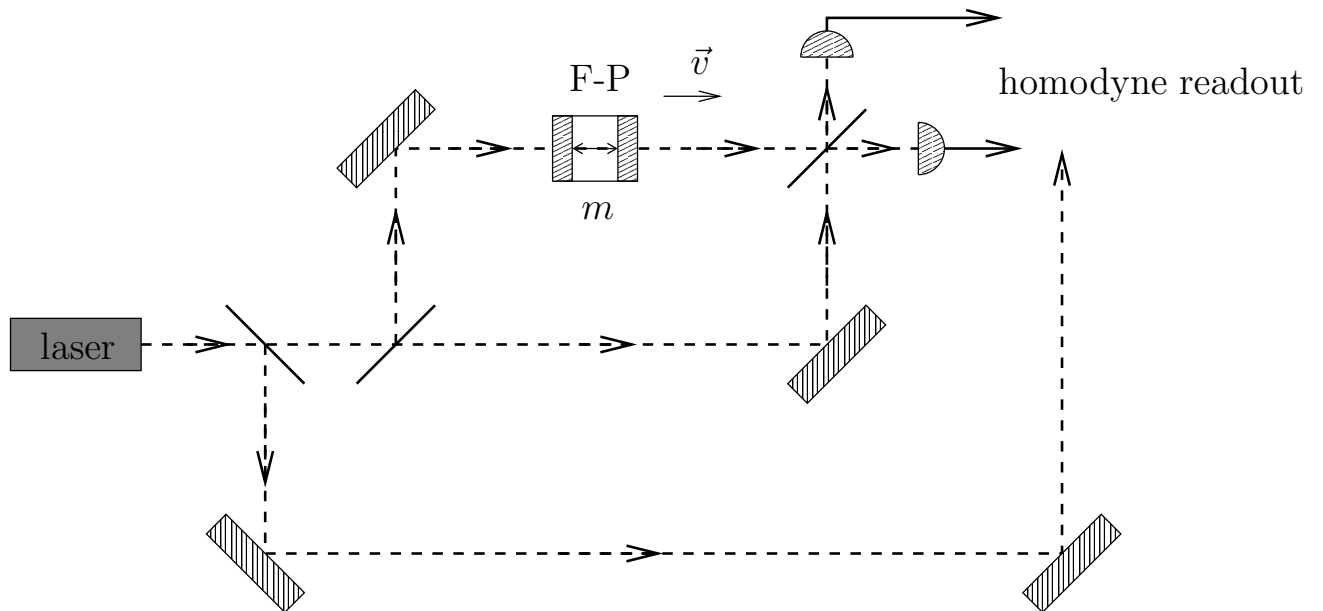
IF $\Delta P = \Delta P_{SQL} = \sqrt{\frac{\hbar m}{2\tau}}$, **THEN** $\Delta\mathcal{E}_{kin} = \frac{\Delta P_{SQL}^2}{m} = \frac{\hbar}{2\tau};$ $\Delta\mathcal{E}_{kin} \cdot \tau = \frac{\hbar}{2}$

BUT(!) IF $\Delta P = \Delta P_{QND} = \xi \sqrt{\frac{\hbar m}{2\tau}};$ $\Delta\mathcal{E}_{kin} = \xi^2 \frac{\hbar}{2\tau};$ $\xi \ll 1 !!$

THE "FEE": $\Delta y = \frac{1}{\xi} \sqrt{\frac{\hbar\tau}{2m}}$
SEE SPIE, 3516, 421 (1999)

THE IMPLEMENTATION OF SPEED METER

GEDANKEN VERSION: F-P RESONATOR INSIDE M-Z INTERFEROMETER



$$\Delta\varphi = \frac{v}{c} \cdot Q_{F-P}$$

IF $(1 - R) = 10^{-6}$, $m = 1 \text{ gram}$, $W_{SQL} = 4 \cdot 10^{12} \text{ erg/sec!}$

F. KHALILI, YU. LEVINE, PHYS. REV. D, 54, 4735 (1996)

REALISTIC SCHEME OF A SPEED METER

**TWO HIGH Q VALUES COUPLED MICROWAVE RESONATORS:
ONE "WALL" OF ONE RESONATOR IS MOVABLE (TEST MASS)**

$$\underline{Q_{e.m.} \geq 5 \cdot 10^9} \quad \underline{T = 1 \text{ K}} \quad \underline{W_{SQL} \simeq 10^2 \text{ erg/sec}, \omega \simeq 10^{11} \text{ sec}^{-1}}$$

PHYS. REV. D 61, 044002 (2000)

THIS TYPE (OR SIMILAR) METER MAY BE REALIZED IN NOT A DISTANT FUTURE.

THE NET RESULT OF THE BOHR-EINSTEIN DISPUTE:

BOTH WERE CORRECT.

III POTENTIAL RESERVES OF SENSITIVITY IN MEASUREMENTS OF OBSERVABLE OF MACROSCOPIC MASSES

TODAY QND METERS IN OPTICAL AND MICROWAVE DOMAINS ARE BEAUTIFUL TOYS (NOT TOOLS YET): SOPHISTICATED, EXPENSIVE

IN THE J. WEBER "TASK": DETECT ON EARTH BURSTS OF GRAV. WAVES FROM ASTROPHYSICAL CATASTROPHES, THE COST AND SOPHISTICATION ARE LESS IMPORTANT.

LIGO, GEO-600, VIRGO, TAMA SOONER OR LATER WILL "MEET" SQL. (LIGO WILL BE THE FIRST)

TODAY LIGO I: HAS REACHED $h \simeq 10^{-21}$ (REPORT BY B. BARISH)

$$F_{grav} = \frac{1}{2} h L \omega_{grav}^2 m \simeq \frac{1}{2} \cdot 10^{-21} \cdot 4 \cdot 10^5 \cdot 10^6 \cdot 10^4 \simeq 2 \cdot 10^{-6} \text{ dyn}$$

$$\Delta L \simeq \frac{1}{2} h L = 2 \cdot 10^{-16} \text{ cm}, \quad \tau \simeq 10^{-2} \text{ sec}, \quad \bar{\omega}_{grav} \simeq 2\pi \cdot 10^2 \text{ sec}^{-1}$$

$t \simeq 2010$ (?) IN ADVANC. LIGO $h \simeq 10^{-22}$ THIS VALUE IS CLOSE TO

$$h_{SQL} = \frac{1}{L} \sqrt{\frac{8\hbar}{m\omega_{grav}^2 \tau}} \simeq 2 \cdot 10^{-23} \times \left(\frac{m}{10^4 \text{ gram}}\right)^{-1/2} \times \left(\frac{\omega_{grav}}{10^3 \text{ s}^{-1}}\right)^{-1} \times \left(\frac{L}{4 \cdot 10^5 \text{ cm}}\right)^{-1} \times \left(\frac{\tau}{10^{-2} \text{ s}}\right)^{-1/2} \quad (4)$$

**HOW TO "BEAT" SQL?
(ONE EXAMPLE ALREADY MENTIONED ABOVE)**

THE "ENEMIES"

THERMOELASTIC NOISE

THERMOREFRACTIVE NOISE

PARAMETRIC INSTABILITY

LOW Q_{susp}, Q_{mirror}

? HUGE FLUX OF $W = 10^6$ WATT ?

THE "FRIENDS"

LARGE CAUSTIC

LOW NOISE TRANQUILISER

PURE FUSED SiO_2

$\tau_{susp}^* > 5 \text{ years}, Q_{mech} > 2 \cdot 10^8$

ADVANCED LIGO: $\mathcal{E} = 4 \cdot 10^8 \text{ erg}$ ($N = 2 \cdot 10^{20}$) $W = 10^6 \text{ Watt}$;

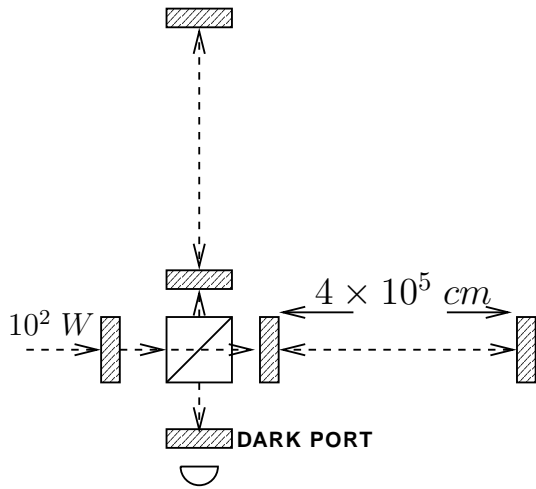
$$\tau_{FP}^* = \frac{L}{c(1-R)} \simeq 1 \text{ sec}$$

$$h \simeq 10^{-22} \Rightarrow \Delta\varphi \simeq 4 \cdot 10^{-10} \text{ rad}$$

COHERENT STATE

$$\Delta\varphi = \frac{1}{2\sqrt{N}} \simeq 3 \cdot 10^{-11} \text{ rad}$$

"USED" PHOTONS $\simeq 10^{10}$



IF QND WITH SQUEEZED PHASE: $\Delta\varphi \simeq \frac{1}{2N}$; $N \simeq 10^9$

POTENTIAL GAIN: 11 ORDERS!

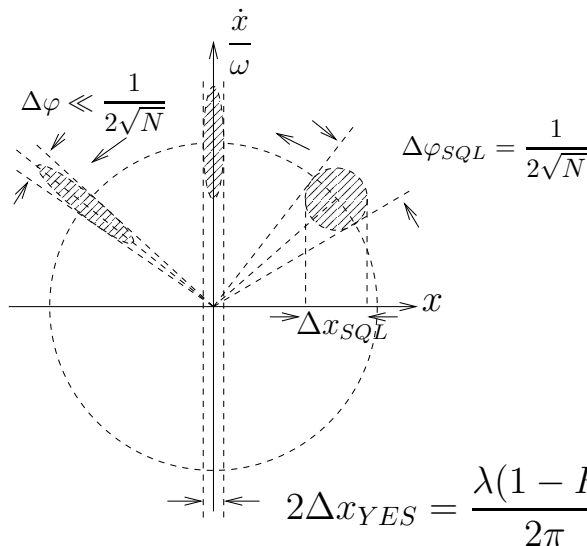
CONDITION FOR LOSSES: $\tau_{FP}^* \simeq 10^7 \text{ sec! (4 MONTHS)}$

J-M. MAKOWSKY PROMISE: $(1-R) = 10^{-9} \Rightarrow \tau_{FP}^* \simeq 10^4 \text{ sec}$

STILL 3 ORDERS

HOW TO IMPLEMENT?

MECH. OSCILLATOR WITH "YES-NO" DETECTOR



$$m = 10^{-9} \text{ gram} \quad \omega_m = 1 \text{ sec}^{-1}$$

$$\Delta x_{SQL} = \sqrt{\frac{\hbar}{2m\omega_m}} = 7 \cdot 10^{-10} \text{ cm}$$

squeezing factor 70

$$2\Delta x_{YES} = \frac{\lambda(1-R)}{2\pi} = \frac{6 \cdot 10^{-5} \cdot 10^{-6}}{6} \simeq \underline{\underline{10^{-11} \text{ cm}}}$$

PHYS. LETT. A, 202, 1 (1995)

**HOW TO TRANSFER INTO OPTICAL DOMAIN?
("DORMANT" RESERVE OF SENSITIVITY)**

50 YEARS OF COMPETITION BETWEEN ATOM CLOCKS AND HIGH Q SELF SUSTAINED OSCILLATORS

TODAY: $\frac{\Delta\omega}{\omega} \simeq \underline{\underline{10^{-17} - 10^{-16}}}$ ← Al_2O_3 **WHISP. GAL. MODE**

$$\left(\frac{\Delta\omega_{osc}}{\omega_{osc}}\right)_{SQL} \simeq \sqrt{\frac{\hbar}{VY\tau}} = \underline{\underline{5 \cdot 10^{-24}}} \times \left(\frac{Y}{4 \cdot 10^{12}}\right)^{-1/2} \times \left(\frac{V}{10^4}\right)^{-1/2} \times \left(\frac{\tau}{10^3}\right)^{-1/2}$$

$$W_{optim} \simeq \frac{VY\omega_{osc}}{Q_{e.m.}^2} \simeq 10^3 \text{ erg/sec [6 ORDERS!]}$$

SOV. PHYS. JETP, 74, 828, (1978)

$$\omega_{osc} \simeq 10^{11} \text{ sec}^{-1}, \quad Q_{e.m.} = 10^{12}$$

$(Q_{e.m.})_{Al_2O_3} \gtrsim 10^9$ **OBTAINED 1987(PHYS. LETT. A)**

WHISPERING GALLERY MODE, $T \simeq 10K$

PREDICTION: BY PURIFICATION $Q \simeq 10^{15}$ FOR Al_2O_3 RESONATOR

ANOTHER PREDICTION:

$$\left(\frac{\Delta\omega_{osc}}{\omega_{osc}}\right)_{QND} < \left(\frac{\Delta\omega_{osc}}{\omega_{osc}}\right)_{SQL}$$

SOV. PHYS. DOKLADY, v 247, 583, (1979)

IF NONLINEARITY OF PONDERMOTIVE ORIGIN IS COMPENSATED BY ANOTHER ONE

ANOTHER "DORMANT" RESERVE

WHAT LIGO MAY GIVE?

1. DENSITY OF NS AND BH (FRACTION OF DARK MATTER?)
2. EQUATION OF STATE OF NS
3. TEST OF GR WHEN $(1 - \Phi/c^2) \ll 1$
4. RELIC GRAVITATIONAL RADIATION?
5. DISCOVERY OF SPACE-TIME FOAM (UNIVERSAL DECOHERENCE)?

S. HAWKING. PHYS. REV. D, 37, 904 (1988)

IV CONCLUSION

1. THE ABOVE NOTES ABOUT THE PROSPECTS IN QUANTUM MEASUREMENTS ARE ONLY ABOUT ONE TYPE OF INDIRECT QUANTUM MEASUREMENTS; THERE ARE OTHER ONES

(E. G. S. P. VYATCHANIN, PHYS. LETT. A, 231, 38 (1997))

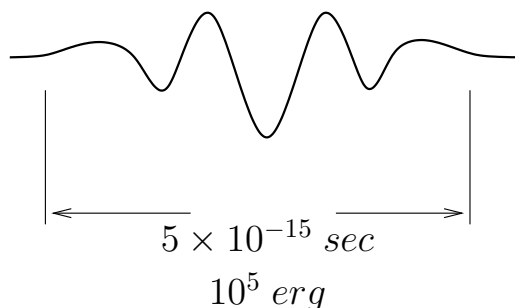
2. THE PROBE QUANTUM OBJECT (PHOTONS) MAY BE SUBSTITUTED BY OTHERS (E. G. BY NEUTRONS, MUONS ...)

(E. KARLSSON, S. LOVESEY PHYS. REV. A 61, 062714 (2000))

3. ANY TEST HAVE TO BE EXPANDED IN SPACE-TIME VOLUME

E. G. F. KRAUSZ, MPQ GARCHING

[R. KIENBERGER ET AL, SCIENCE 297, 1144 (2002)]



+ BEAM OF ATOMS = BURST OF SHORT X-RAYS ($10 \times 10^{-18} \text{ sec!}$)
A VERY LONG "ROUTE" TILL

$$\tau_{Planck} = \sqrt{\frac{\hbar G}{c^5}} = 5 \cdot 10^{-44} \text{ sec}$$