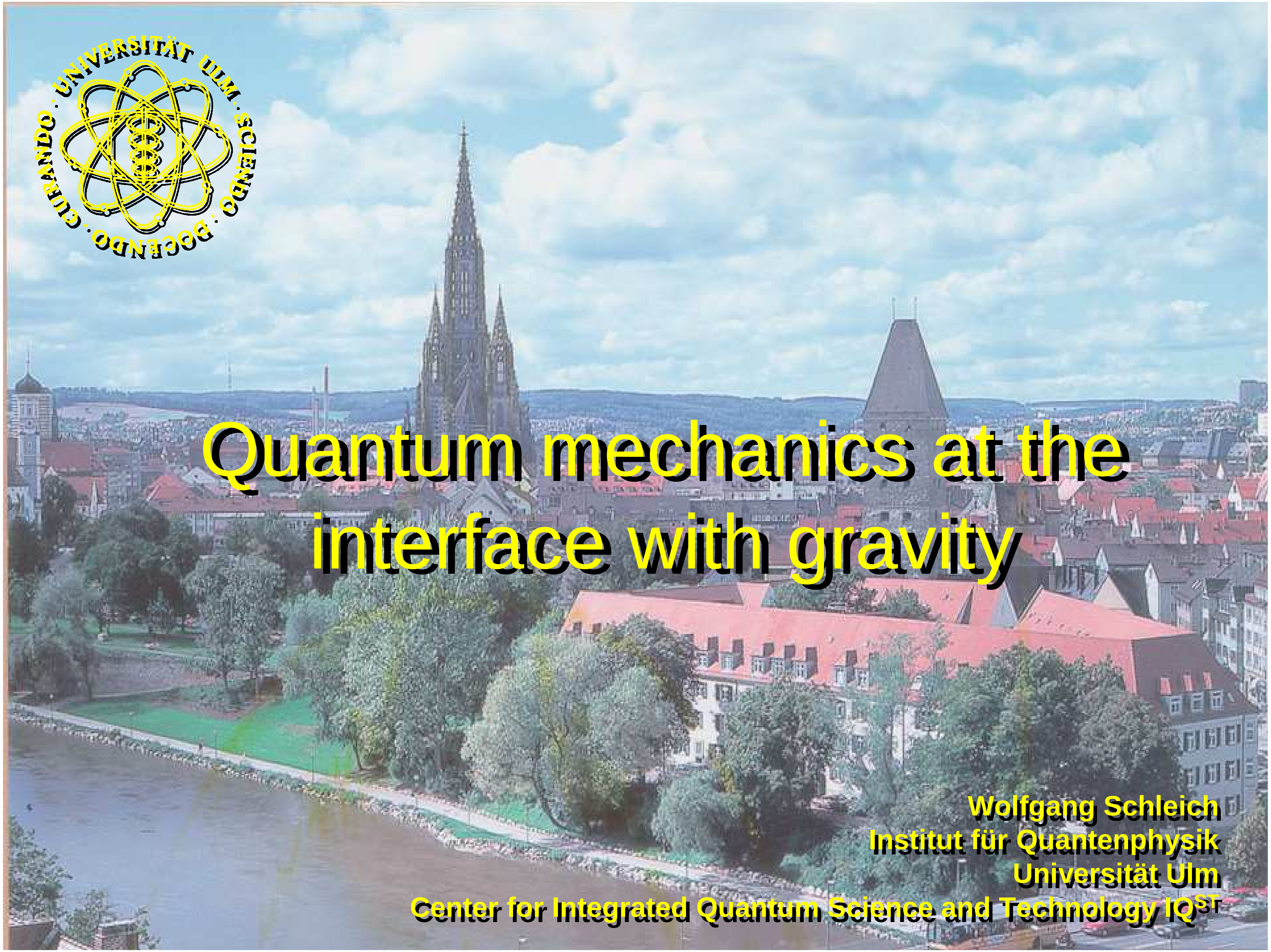

Quantum mechanics at the interface with gravity

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Bose-Einstein Condensation in Microgravity

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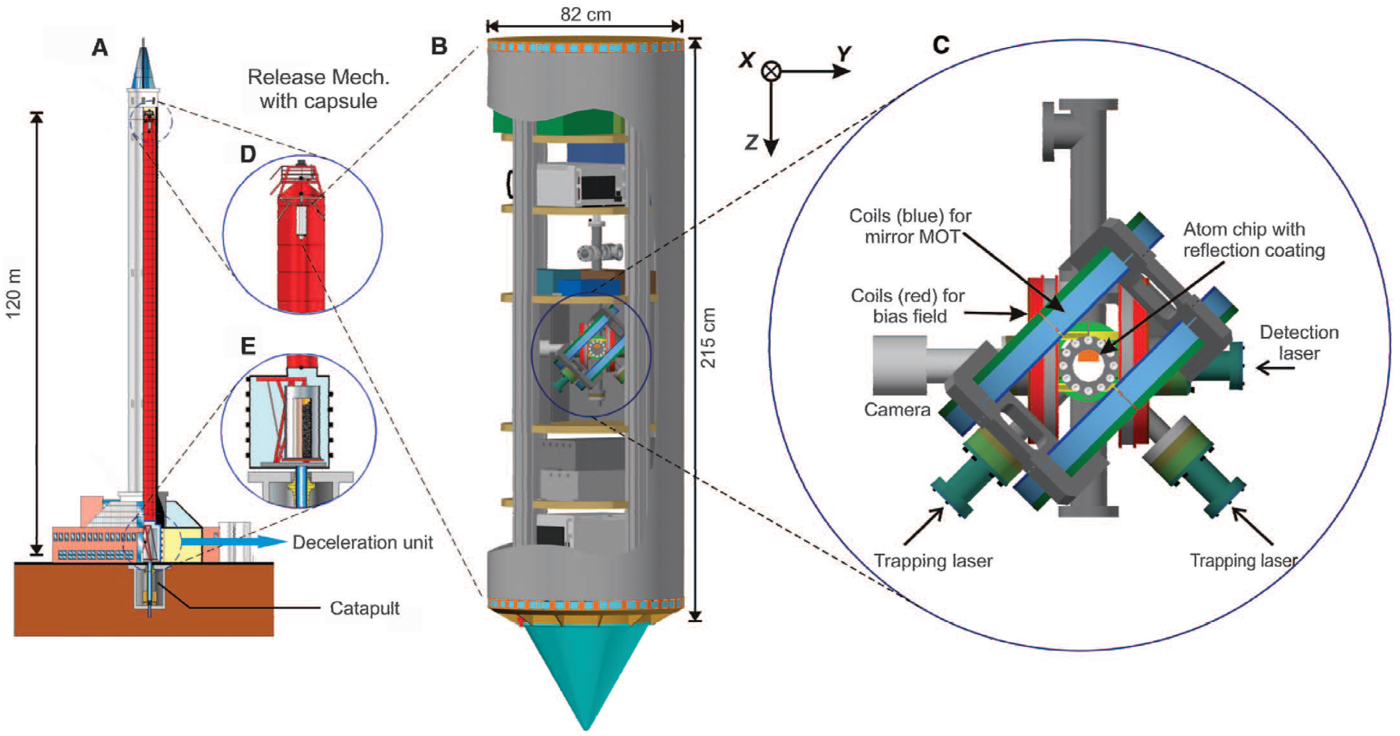

Selected for a Viewpoint in *Physics*
PRL **110,** 093602 (2013) PHYSICAL REVIEW LETTERS week ending 1 MARCH 2013

Interferometry with Bose-Einstein Condensates in Microgravity

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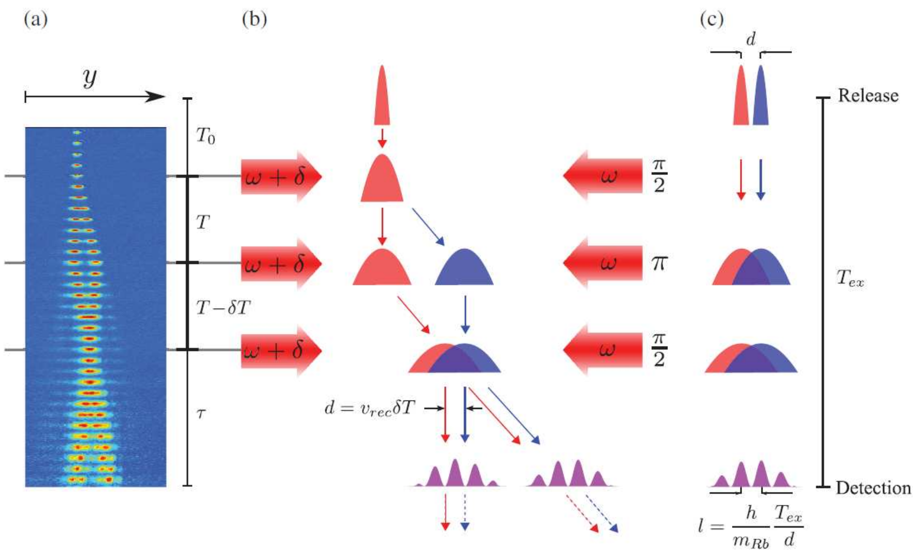
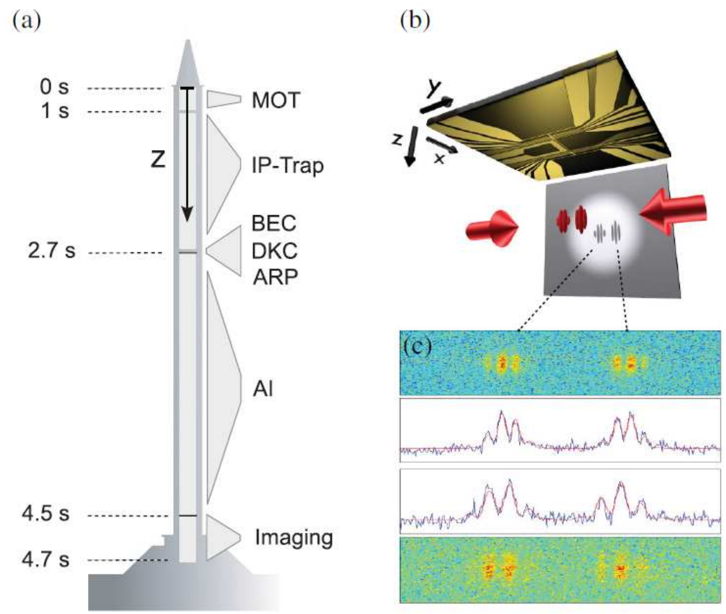
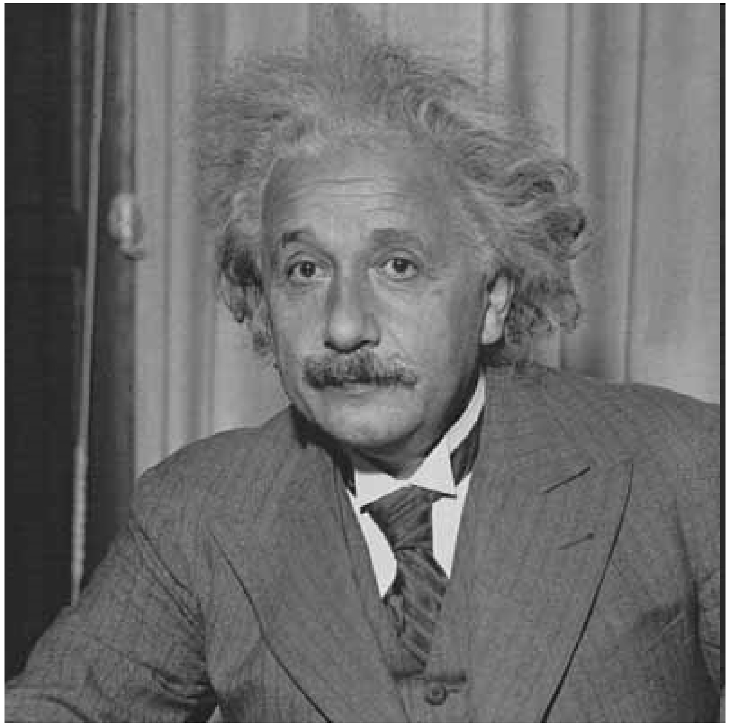






“ I was sitting on a chair in my patent office in Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his weight. I was taken aback. This simple thought experiment made a deep impression on me. This led to the theory of gravity.”

Albert Einstein, 1922

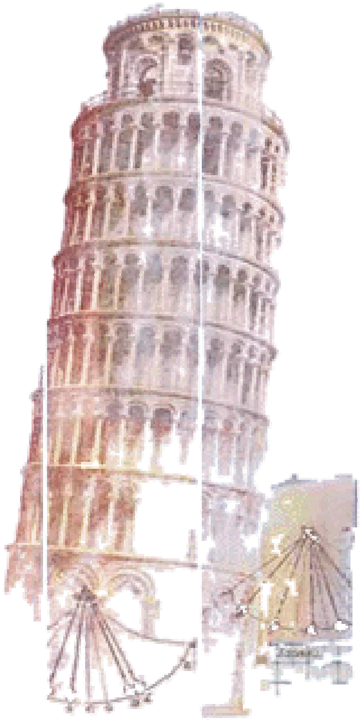
Equivalence Principle

- Weak EP: $$m_i \ddot{x} = eE \quad \rightarrow \quad \ddot{x} = \frac{e}{m_i} E$$

$$m_i \ddot{x} = m_g \mathcal{G} \quad \rightarrow \quad \ddot{x} = \mathcal{G}$$

- Redshift: $$\frac{\nu_2}{\nu_1} = 1 - \frac{U_2 - U_1}{c^2}$$

- Einstein EP

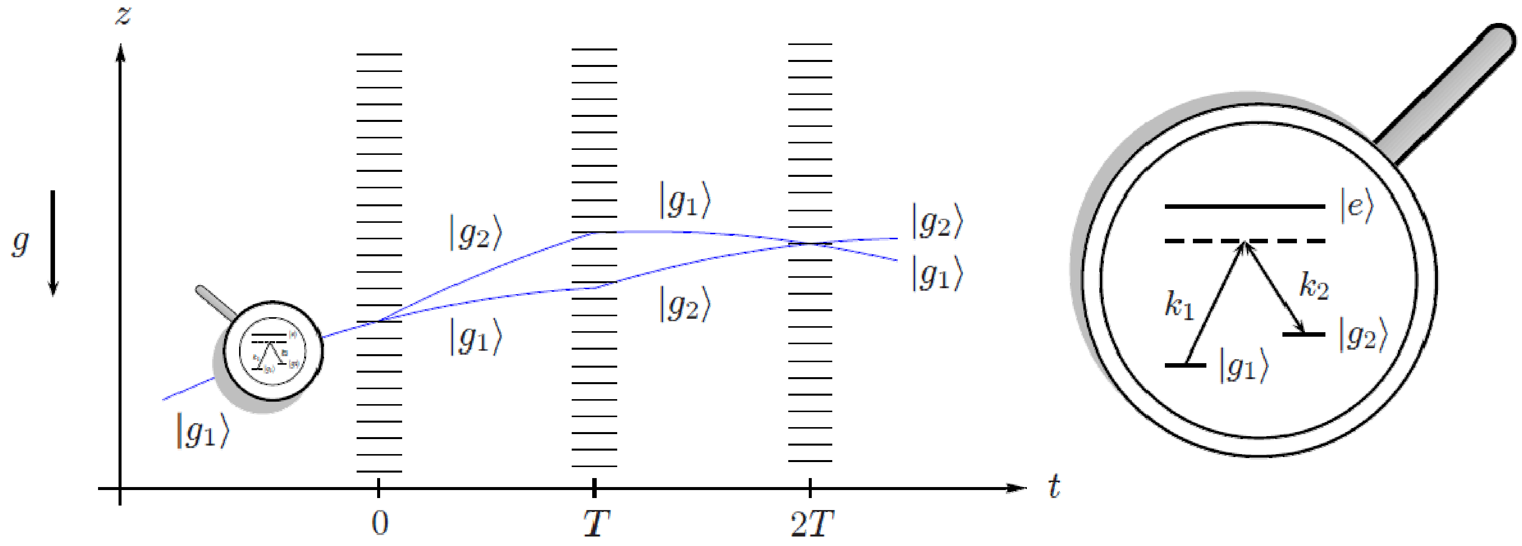


Overview

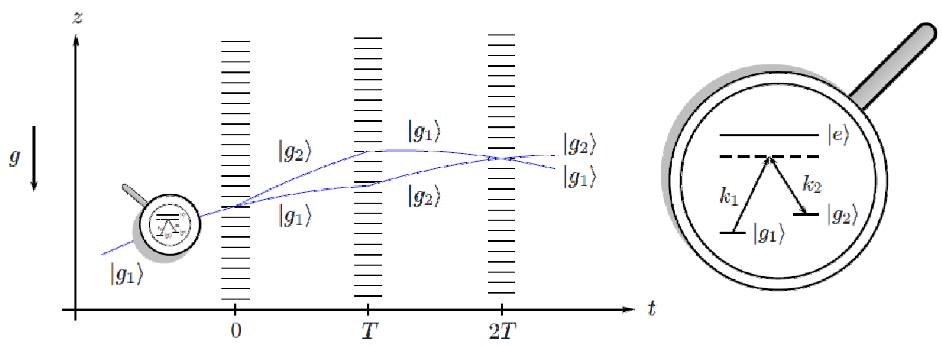
- representation-free description of Kasevich-Chu interferometer
- proper time and interferometers
- interference of proper time

Atomic Interferometry Using Stimulated Raman Transitions

Mark Kasevich and Steven Chu
Departments of Physics and Applied Physics, Stanford University, Stanford, California 94305
(Received 23 April 1991)



Unitary evolution in interferometer



$$\hat{U}_{\mathrm{u}} \equiv \hat{U}_g \, \hat{U}^{(-)}(T) \, \hat{U}_g \, \hat{U}^{(+)}(0)$$

$$\hat{U}_{\mathrm{l}} \equiv \hat{U}^{(-)}(2T) \, \hat{U}_g \, \hat{U}^{(+)}(T) \, \hat{U}_g$$

$$P_1 = \frac{1}{2}\left[1 + \frac{1}{2}(\langle\psi_i|\hat{U}_{\mathrm{l}}^{\dagger}\hat{U}_{\mathrm{u}}|\psi_i\rangle + \mathrm{c.c.})\right]$$

Phase shift operator

$$P_1 = \frac{1}{2}\left[1 + \frac{1}{2}(\langle\psi_i|\hat{U}_1^\dagger \hat{U}_\mathrm{u}|\psi_i\rangle + \mathrm{c.c.})\right]$$

$$\hat{U}_\mathrm{u} = \mathrm{e}^{\mathrm{i}[-\phi(T)+\phi(0)]} \exp\left(-\frac{\mathrm{i}}{\hbar}\hat{H}T\right) \exp\left(-\frac{\mathrm{i}}{\hbar}\hat{H}^{(+)}T\right)$$

$$\hat{U}_1 = \mathrm{e}^{\mathrm{i}[-\phi(2T)+\phi(T)]} \exp\left(-\frac{\mathrm{i}}{\hbar}\hat{H}^{(+)}T\right) \exp\left(-\frac{\mathrm{i}}{\hbar}\hat{H}T\right)$$

Commutation relations

$$\hat{H} \equiv \frac{\hat{p}^2}{2m} + V(\hat{z})$$

$$\hat{H}^{(+)} \equiv \frac{\left(\hat{p} + \hbar k\right)^2}{2m} + V(z) = \hat{H} + \frac{(\hbar k)^2}{2m} + \frac{\hbar k}{m}\hat{p}$$

$$[\hat{H}, \hat{H}^{(+)}] = \frac{\hbar k}{m}[\hat{H}, \hat{p}]$$

$$[\hat{H}, \hat{H}^{(+)}] = -\mathrm{i}\hbar^2 k \ddot{\hat{z}}$$

Constant gravitational field

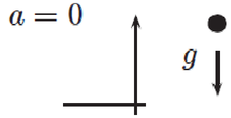
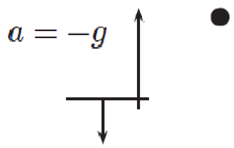
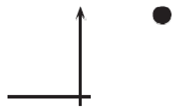
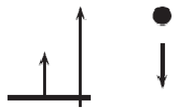
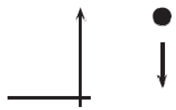
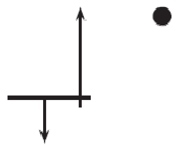
$$V_g(z) \equiv mgz$$

$$\hat{U}_{\mathrm{l}}^{\dagger}\hat{U}_{\mathrm{u}} = \mathrm{e}^{\mathrm{i}\alpha}$$

$$\alpha \equiv \delta\phi + \delta\varphi$$

$$\delta\phi \equiv \phi(2T) - 2\phi(T) + \phi(0)$$

$$\delta\varphi = -\delta\varphi_g \equiv -kgT^2$$

Scenarios	Frame used in analysis	Accelerations of coordinate system and atom	Phase $\delta\phi$ due to acceleration of pulses	Phase $\delta\varphi$ due to acceleration of atom	Total Phase $\alpha \equiv \delta\phi + \delta\varphi$
Accelerometer (I)	lf		0	$-\delta\varphi_g$	$-\delta\varphi_g$
	af		$-\delta\varphi_g$	0	$-\delta\varphi_g$
Inertial motion (II)	lf		0	0	0
	af		$\delta\varphi_g$	$-\delta\varphi_g$	0
Einstein equivalence principle (III)	lf		$\delta\varphi_g$	$-\delta\varphi_g$	0
	af		0	0	0

Observation of Gravitationally Induced Quantum Interference*

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and

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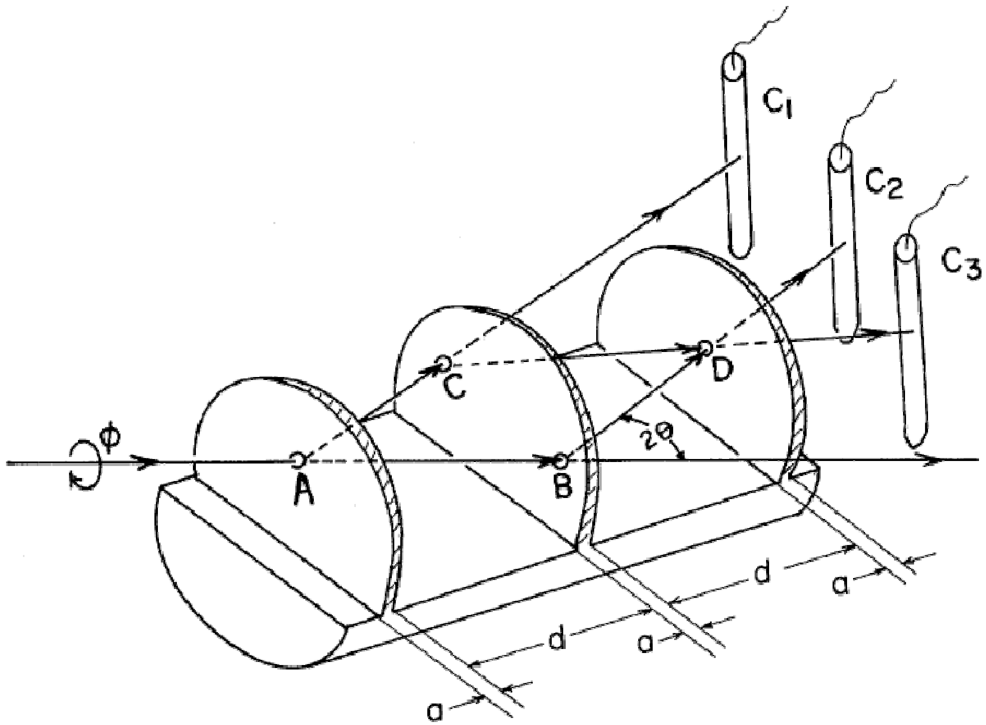
(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.



Appl. Phys. B 54, 321–332 (1992)

Applied Physics B Photophysics and Laser Chemistry

Measurement of the Gravitational Acceleration of an Atom with a Light-Pulse Atom Interferometer

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$$\Delta\phi_{\mathrm{f}} = \int_{\Gamma} \mathbf{k}_{\mathrm{a}} \cdot d\mathbf{x} - \omega_{\mathrm{a}} dt \,, \tag{17}$$

where Γ is the circuit describing the path of the wavepackets, $\mathbf{k}_{\mathrm{a}}$ =(wavepacket's mean momentum $\mathbf{p})/\hbar$, and ω_{a} =(total mean energy of wavepacket)/$\hbar$.

Evaluation of (16) for the gravitationally perturbed wavepacket trajectories which occur in a $\pi/2$–π–$\pi/2$ pulse sequence yields the result obtained in Sect. 3.1. The free evolution contribution from (17) turns out to be zero if there is no violation of the equivalence principle: the contribution from the asymmetry in de Broglie wavelengths is canceled by the changes in the atom's total energy. This is in contrast to neutron interferometers of the type described in [7], where the free evolution contribution *is* the dominant phase shift [22]. The distinguishing feature between the two cases is that the energy of the particle is not conserved during the light pulses of our interferometer while it is conserved during the Bragg reflection processes of neutron interferometers.

Proper time

$$c^2 \mathrm{d}\tau^2 = \mathrm{d}s^2 = g_{\mu\nu} \mathrm{d}x^\mu \mathrm{d}x^\nu$$

$$\mathrm{d}\tau \cong \left[1 - \frac{2}{c^2}\left(\frac{1}{2}\mathbf{v}^2 - \Phi\right)\right]^{1/2} \mathrm{d}t$$

PHYSICAL REVIEW A **86**, 063622 (2012)

Relativistic effects in atom and neutron interferometry and the differences between them

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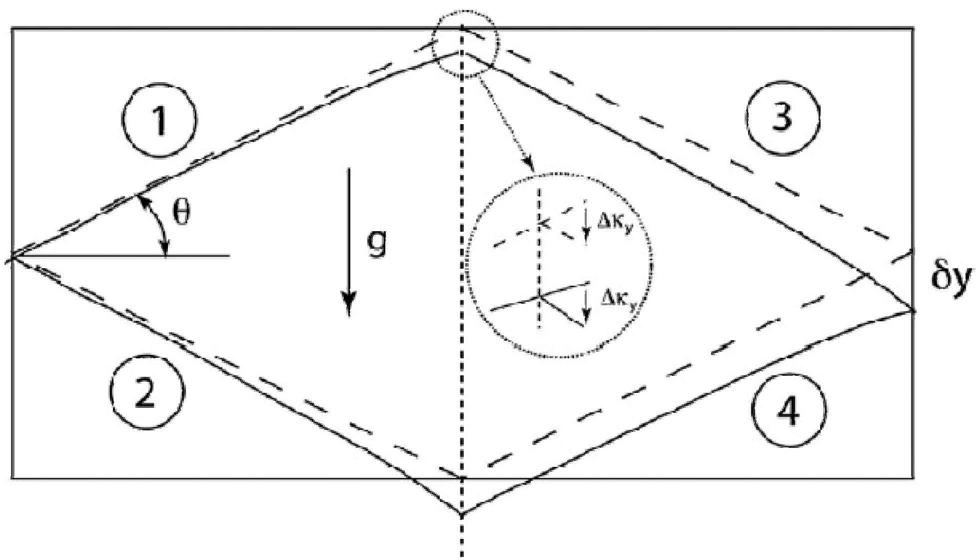
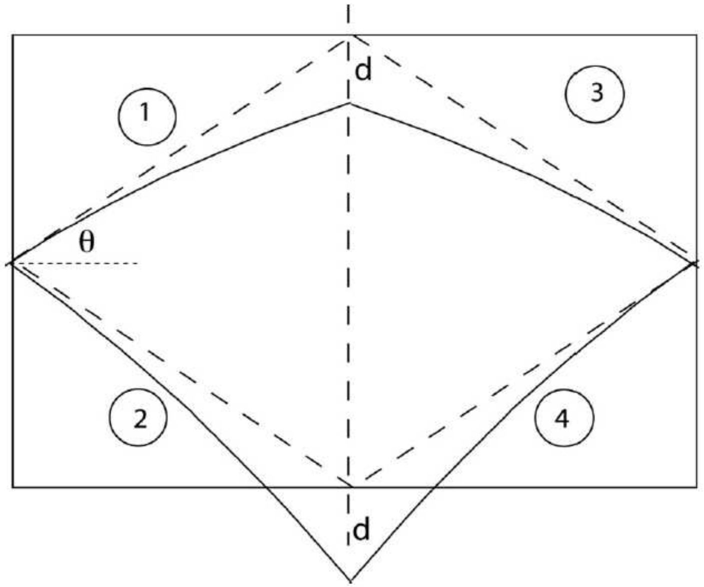
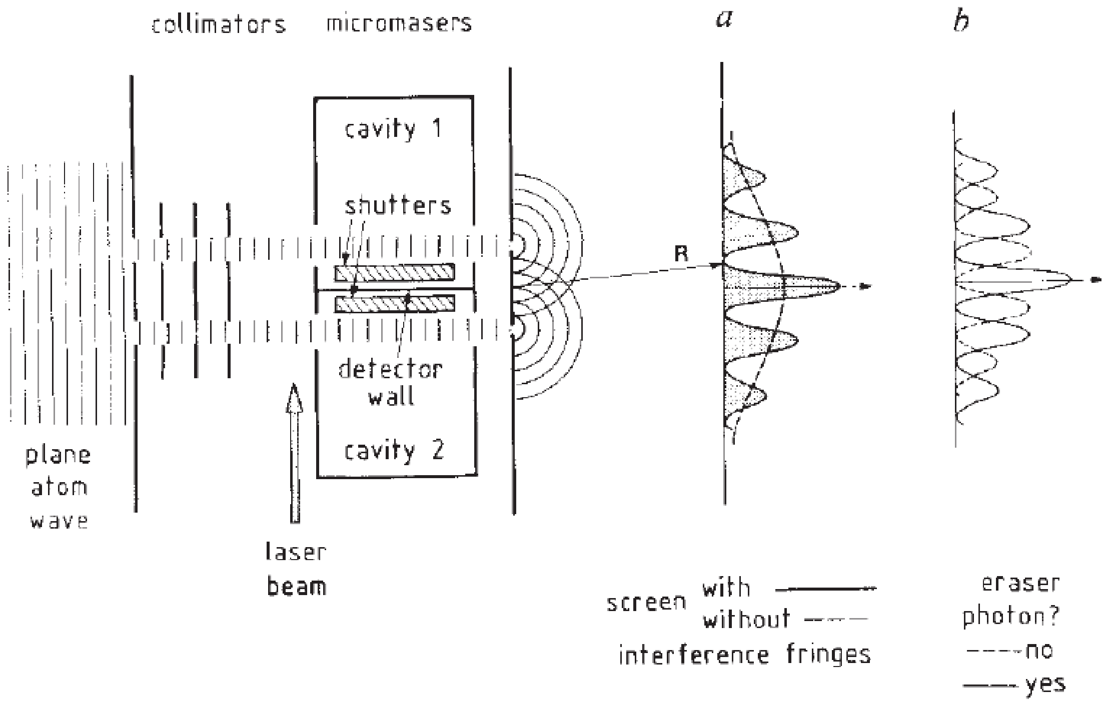




Quantum optical tests of complementarity

Marlan O. Scully, Berthold-Georg Englert & Herbert Walther

Simultaneous observation of wave and particle behaviour is prohibited, usually by the position–momentum uncertainty relation. New detectors, constructed with the aid of modern quantum optics, provide a way around this obstacle in atom interferometers, and allow the investigation of other mechanisms that enforce complementarity.



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ARTICLE

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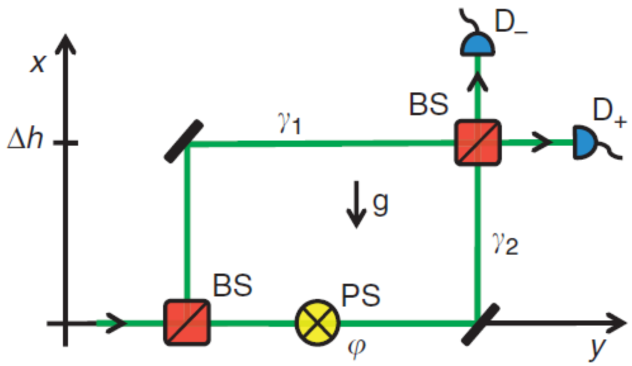
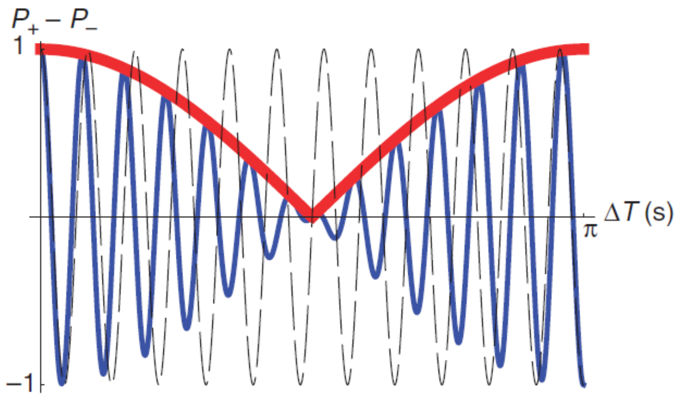
Quantum interferometric visibility as a witness of general relativistic proper time

Magdalena Zych[1], Fabio Costa[1], Igor Pikovski[1] & Časlav Brukner[1,2]

$$|\Psi_{MZ}\rangle = \frac{1}{\sqrt{2}}\left(ie^{-i\Phi_1}|r_1\rangle|\tau_1\rangle + e^{-i\Phi_2+i\varphi}|r_2\rangle|\tau_2\rangle\right)$$



$$P_{\pm} = \frac{1}{2} \pm \frac{1}{2}|\langle\tau_1|\tau_2\rangle|\cos(\Delta\Phi + \alpha + \varphi)$$



PRL **110,** 010401 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

Redshift Controversy in Atom Interferometry: Representation Dependence of the Origin of Phase Shift

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New Journal of Physics

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A representation-free description of the Kasevich–Chu interferometer: a resolution of t... redshift controversy

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New Journal of Physics **15** (2013) 013007 (48pp)

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Relativistic effects in atom and neutron interferometry and the differences between them

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QUANTUS

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Overview

- representation-free description of Kasevich-Chu interferometer
- proper time and interferometers
- interference of proper time