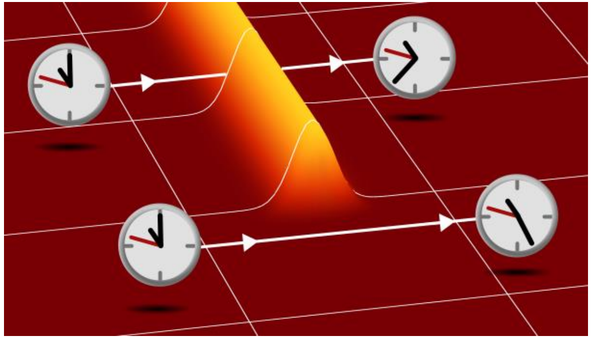
Quantum sensors based on tunneling

From Quantum to Cosmology - 6th June 2024 – Los Alamos



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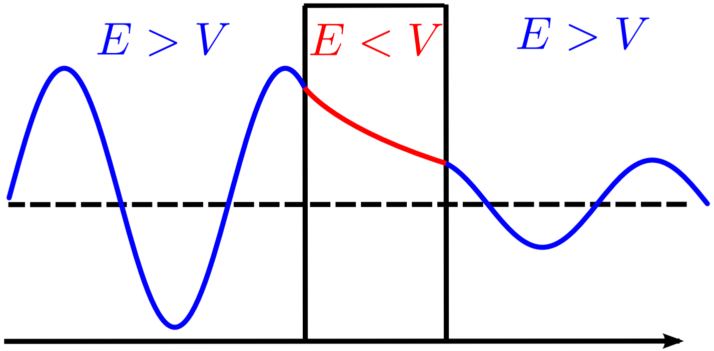
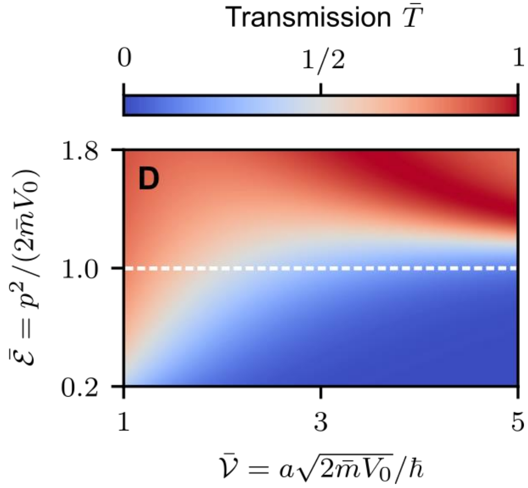
Quantum tunneling

- Transmission of plane waves
- Analytical solution available
- Decreasing probability amplitude
- Exponential decay within barrier region





Sci. Adv. **10**, eadl6078

Quantum tunneling for sensing

Applications

- Nuclear fusion

  Rev. Mod. Phys. **70**, 77

- Josephson junctions

  Phys. Rev. Lett. **95**, 010402

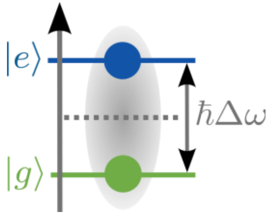
- Scanning tunneling microscopy

- Hawking radiation

  J. High Energy Phys. JHE09(2005)037

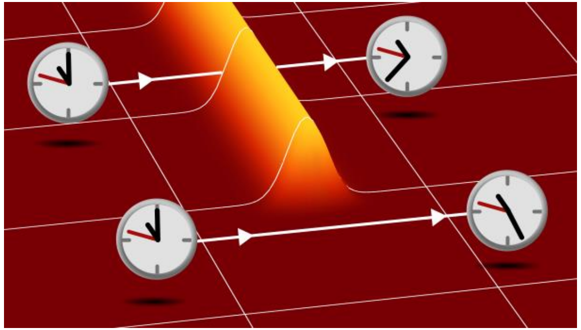
Quantum clocks

- Monitor transition frequency



- Operational approach

  Time is what you read off a clock



Inertial sensing

Atom interferometer

- ▶ Gyroscope
  - ▶ Sagnac effect

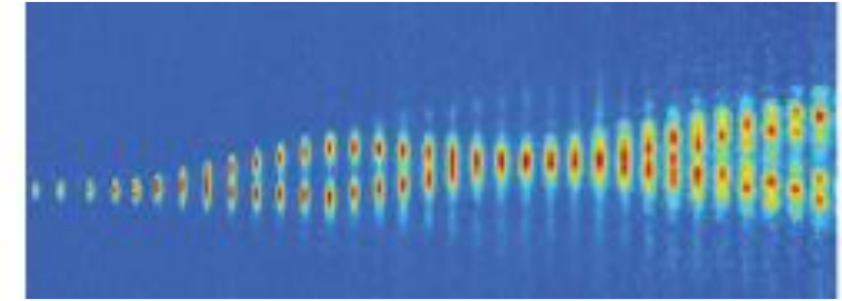
    Phys. Rev. A **80**, 063604

- ▶ Gravimeter
  - ▶ Linear acceleration

    Phys. Rev. Lett. **117**, 203003

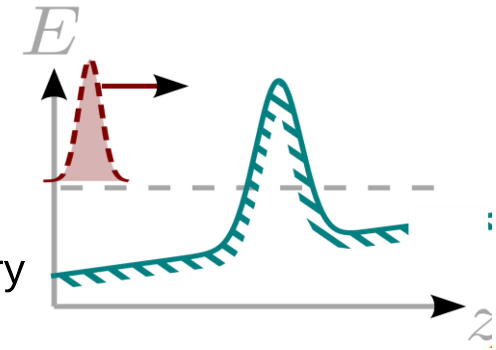
- ▶ Gradiometer
  - ▶ Curvature of gravity

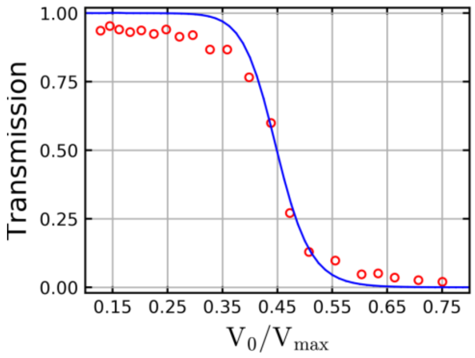
    Science **315**, 74



Phys. Rev. Lett. **110**, 093602

Idea: Quantum Tunneling for gravimetry





arXiv:2405.14466

Matter-wave Fabry-Pérot interferometer

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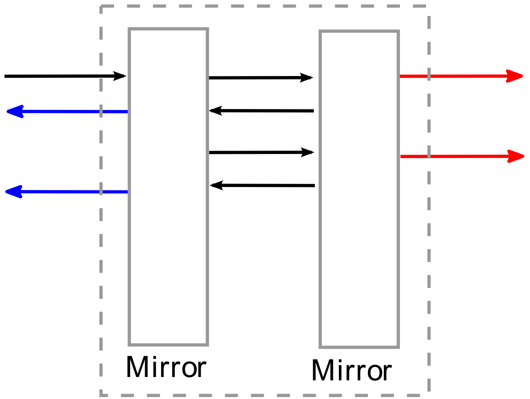

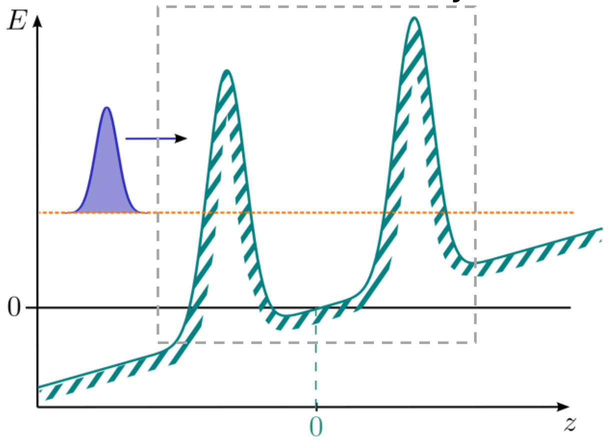

EPJ Quantum Technol. **9**, 20

Mirrors	⟷	Optical potential
Coherent light beam	⟷	Matter waves (e.g. BECs)

Matter-wave Fabry-Pérot interferometer

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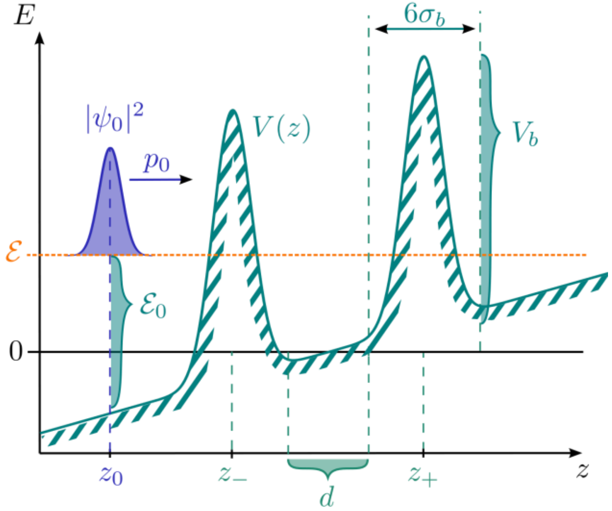
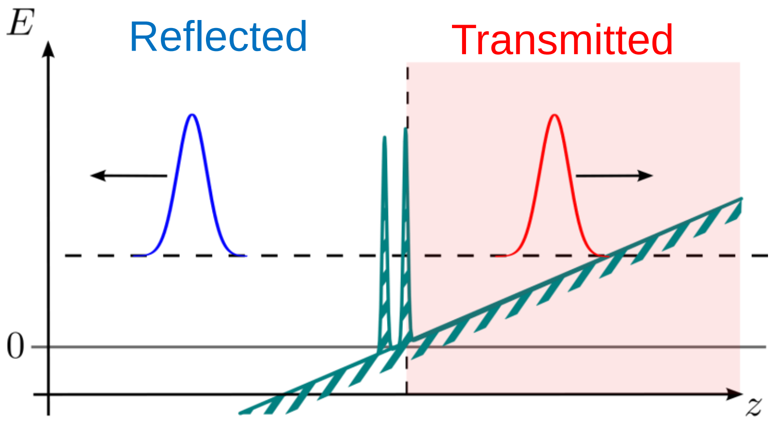
Initial condition





EPJ Quantum Technol. **9**, 20

- Center of cavity as reference for kinetic energy $\mathcal{E} = \mathcal{E}_0 - mg|z_0|$
- Accounts for effects of gravity prior to scattering

Transmission spectrum

Transmission spectrum for plane waves

Sci. Rep. **10**, 15052

Momentum representation

$$T_R = \int_{-\infty}^{\infty} \mathrm{d}p \, T(p) |\psi_0(p)|^2$$

Transmission amplitudes

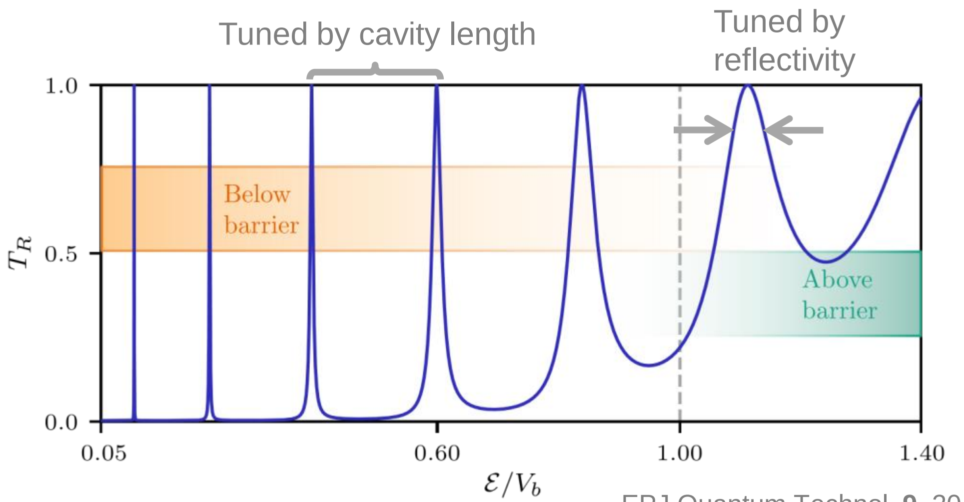
Initial wave packet

➔ Momentum filtering

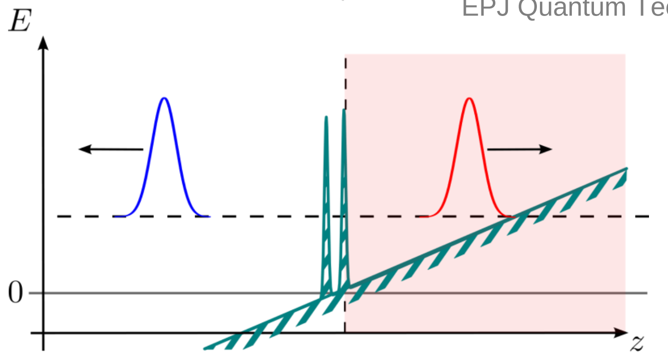
Position representation

$$T_R = \int_{z_+}^{\infty} \mathrm{d}z \, |\psi_f(z)|^2$$

Scattered wave packet



EPJ Quantum Technol. **9**, 20



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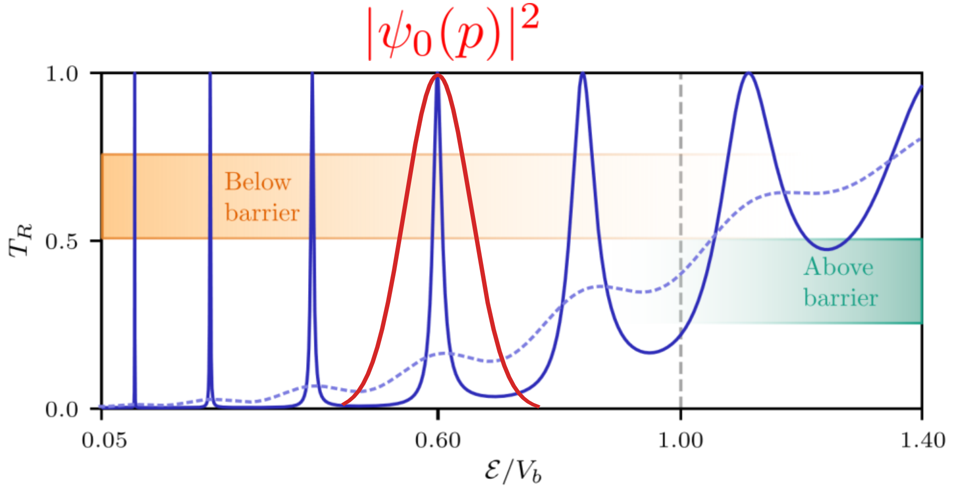

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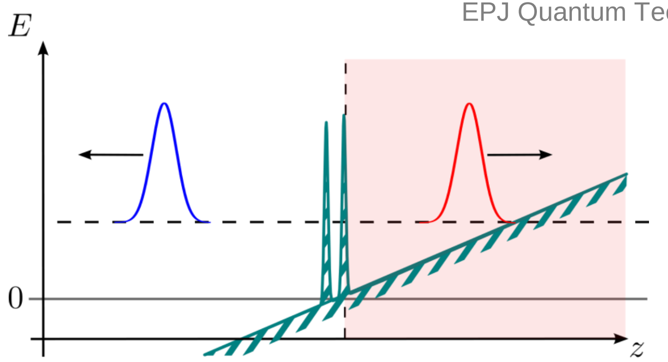

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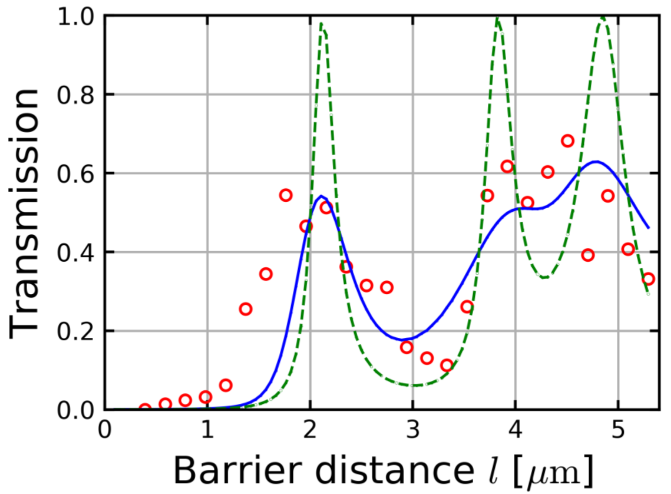
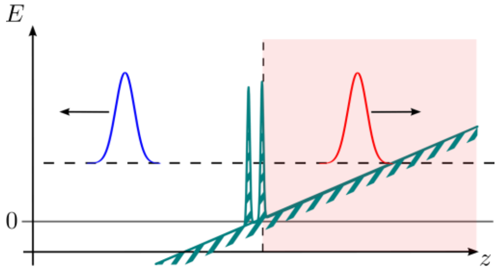


arXiv:2405.14466



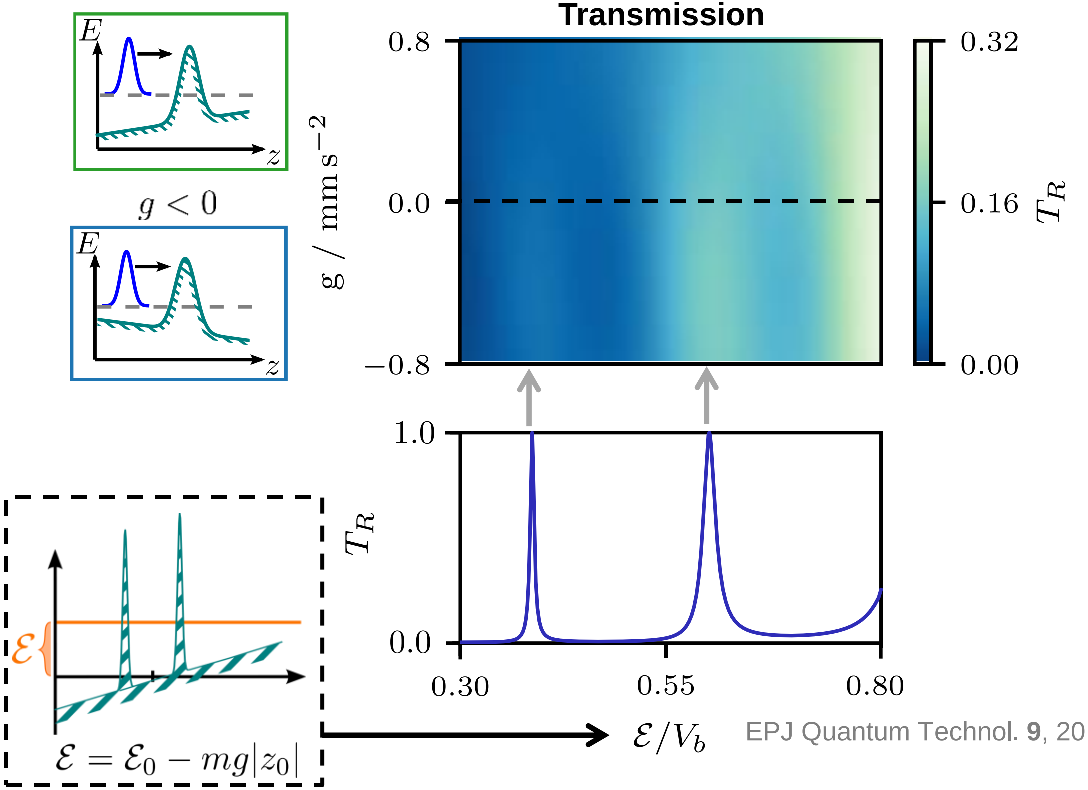
Transmission of a wave packet

Observable:

Fraction of transmitted atoms

- Resonances depend on gravity

- Main effects prior to scattering
  1) Acceleration of wave packet
     ➔ Shift of resonances
  2) Wave packet deformation



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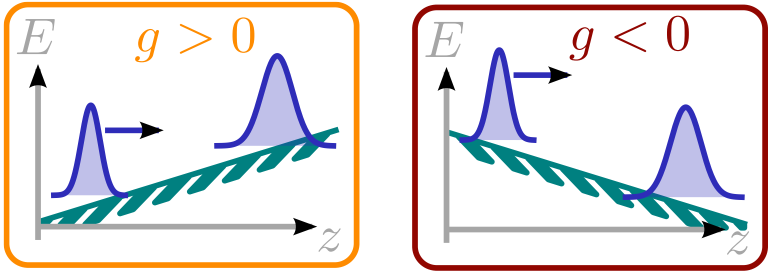
Wave packet deformation

- Linear potential $V(z) = mgz$

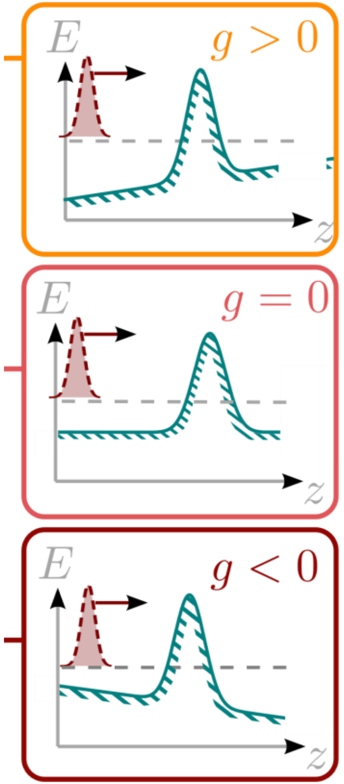
  ➔ No effect on width of wave packet



Wave packet deformation

- Linear potential $V(z) = mgz$
  ➔ No effect on width of wave packet

- Gaussian barriers $V(z) = mgz + V_{\text{Gauss}}$
  ➔ Deformation of wave packet



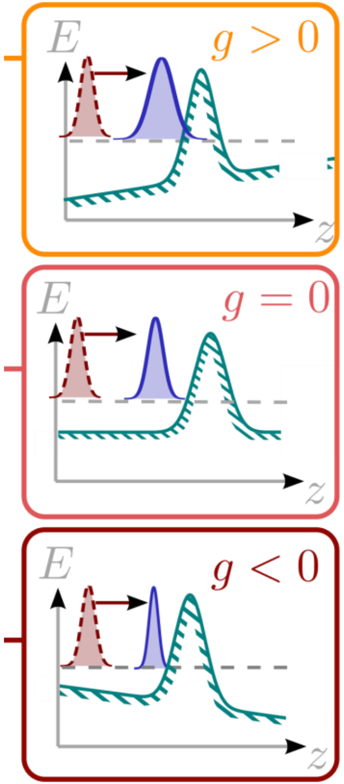
EPJ Quantum Technol. **9**, 20

Wave packet deformation

- Linear potential $V(z) = mgz$
  ➔ No effect on width of wave packet

- Gaussian barriers $V(z) = mgz + V_{\text{Gauss}}$
  ➔ Deformation of wave packet

- Prominence of resonances modified



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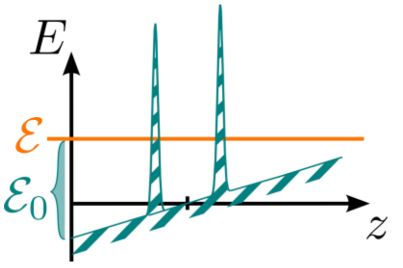
Sensitivity of a wave packet

Gaussian error propagation $\quad T_R = T_R(g, \mathcal{E})$

$$\Delta T_R^2 = |\partial_g T_R|^2 \Delta g_R^2 + |\partial_\mathcal{E} T_R|^2 \Delta \mathcal{E}^2$$

$$\Delta \mathcal{E} = |m z_0| \Delta g_R$$



$$\mathcal{E} = \mathcal{E}_0 - mg|z_0|$$

Relative uncertainty

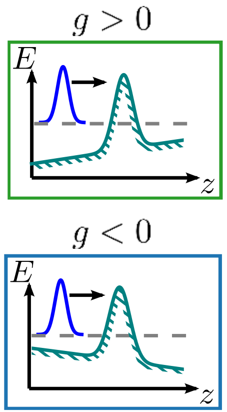
$$\delta g_R = \frac{\Delta g_R}{\sqrt{\nu}\sqrt{N} g} = \frac{1}{\sqrt{\nu}\sqrt{N}} \frac{\Delta T_R}{\sqrt{\underbrace{|g \partial_g T_R|}_{\text{Sensitivity of transmission coefficient}}{}^2 + \underbrace{|m g z_0 \partial_\mathcal{E} T_R|}_{\text{Propagation prior to impact}}{}^2}}$$

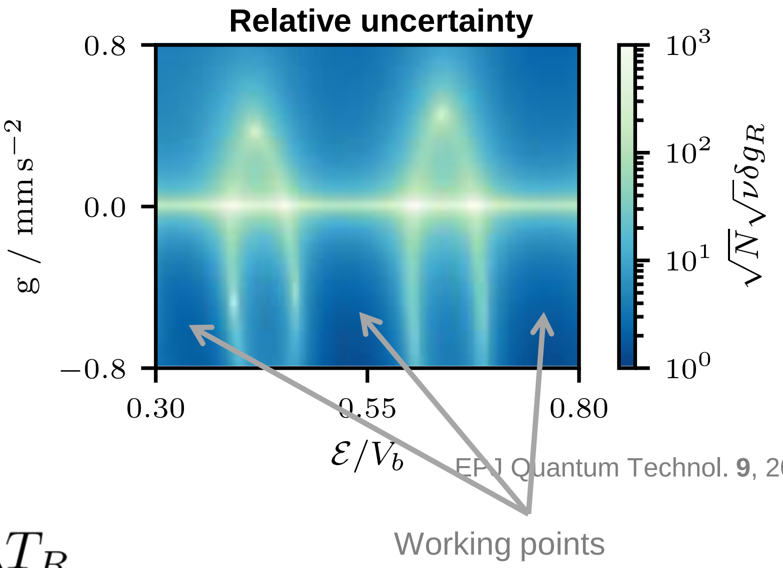
Number of measurements

Particle number

Sensitivity of a wave packet

Observable: Fraction of transmitted atoms





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Relative uncertainty

$$\delta g_R = \frac{\Delta g_R}{\sqrt{\nu}\sqrt{N} g} = \frac{1}{\sqrt{\nu}\sqrt{N}} \frac{\Delta T_R}{\sqrt{\underbrace{|g\partial_g T_R|^2}_{\text{Sensitivity of transmission coefficient}} + \underbrace{|mgz_0\partial_{\mathcal{E}} T_R|^2}_{\text{Propagation prior to impact}}}}$$

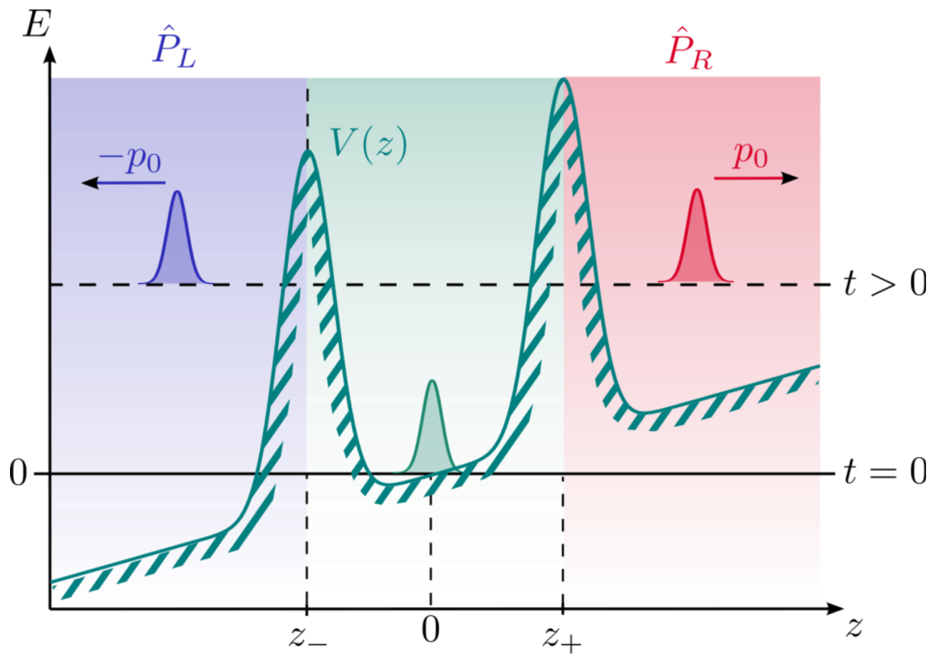
Number of measurements

Particle number

Asymmetric transmission

- Initial state: Kicked wave packet
- Momentum transfer via Double Bragg
  Phys. Rev. A **88**, 053608
- No acceleration
  ➔ Symmetric motion
- Observable: Asymmetry

$$T_- = T_L - T_R$$



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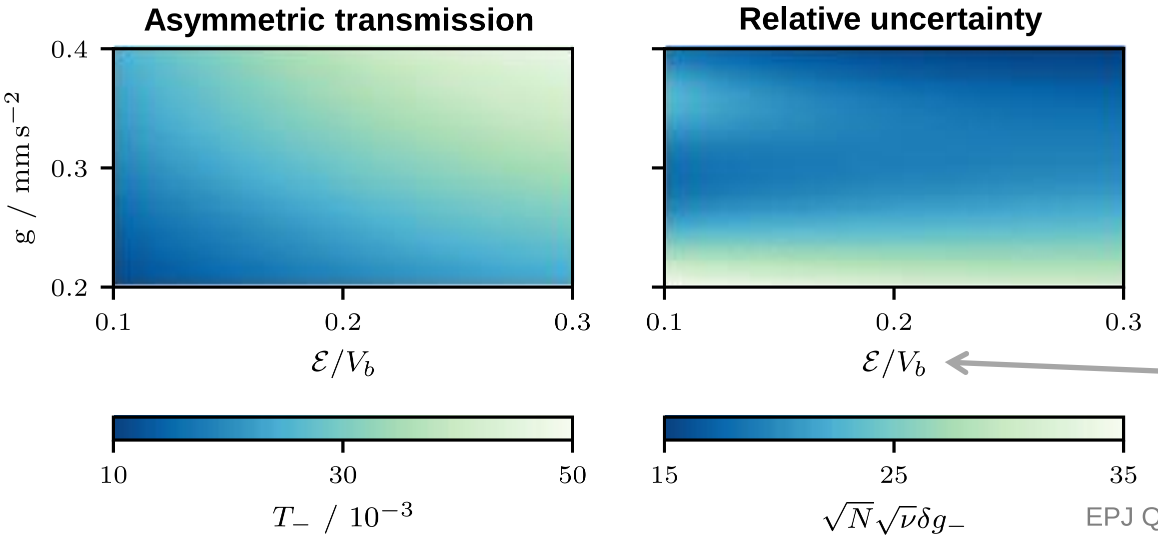
Asymmetric transmission



$\mathcal{E} = p_0^2/(2m)$

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- No structure of transmission spectrum visible
- Sensitivity one order of magnitude smaller than for T_R measurement

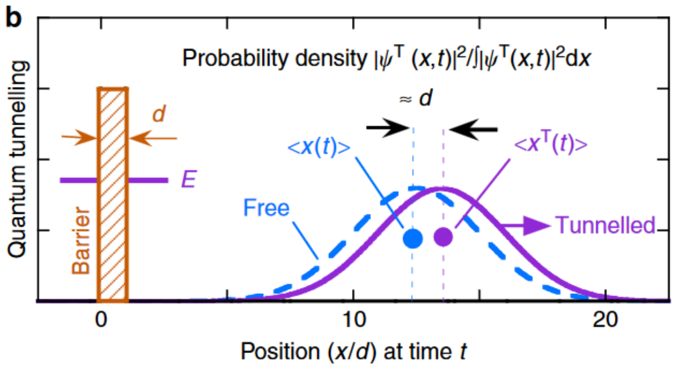
Concept on tunneling times

- Relativity: Proper time measured by an ideal clock along a worldline
- Quantum tunneling
  - Impossible to assign a worldline
- Arrival time

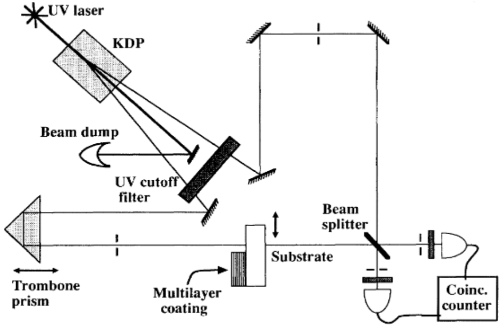
  Phys. Rev. Lett. **49**, 1739
  Rev. Mod. Phys. **61**, 917
  Commun. Phys. **1**, 47
  - Shift in position upon arrival
  - Hong-Ou-Mandel setup

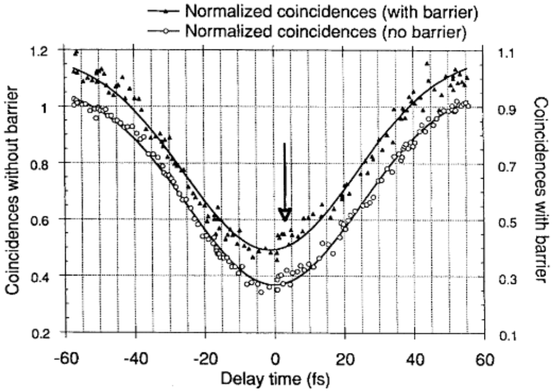
    Phys. Rev. Lett. **71**, 708
  - Attoclock experiments

    Science **322**, 1525
    Nature **446**, 627



Commun. Phys. **1**, 47





Phys. Rev. Lett. **71**, 708

Concept on tunneling times

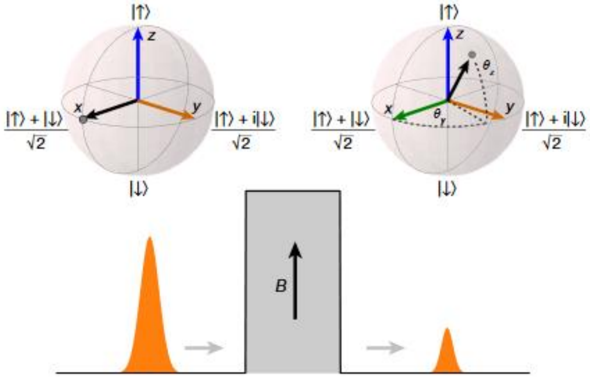
- Interaction (dwell) time

  Phys. Rev. A **107**, 042216

  Phys. Rev. B **27**, 6178

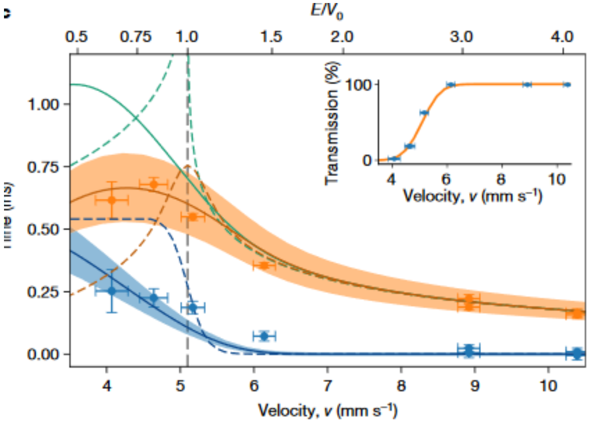
  Nature **583**, 529

  - Time spent in barrier
  - Larmor clock Phys. Rev. Lett. **127**, 133001
  - Phase shift acquired while in barrier



Nature **583**, 529

Phys. Rev. Lett. **71**, 708



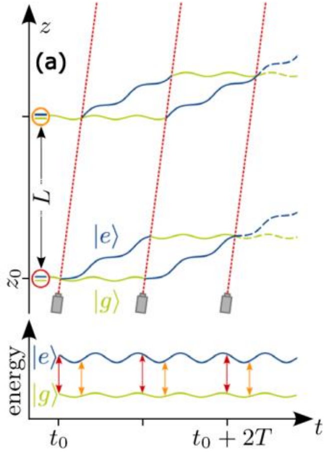
Nature **583**, 529

Time is what you read off a clock

Atom with internal structure

Relativistic effects

- Atom interferometers for relativistic physics
  - Violations of equivalence principle
    Phys. Rev. D **107**, 064007
  - Gravitational waves
    Phys. Rev. Lett. **110**, 171102
  - Dark matter candidates
    AVS Quantum Sci. **5**, 044404



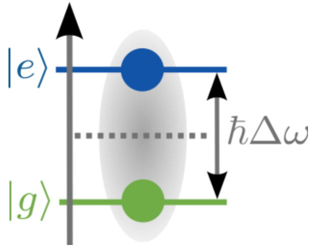
AVS Quantum Sci. **5**, 044404

- Mass defect $E = mc^2$
  - Different internal states have different mass

PRX Quantum **5**, 020322
Laser Phys. Lett. **15**, 035703
Phys. Rev. A **98**, 042106
Phys. Rev. A **100**, 052116

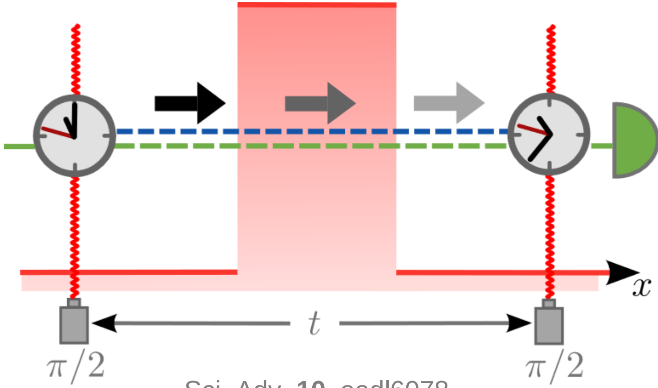
$$m_{e/g} = \bar{m} \pm \frac{\Delta m}{2} = \bar{m} \pm \frac{\hbar \Delta\omega}{2c^2}$$

clock frequency



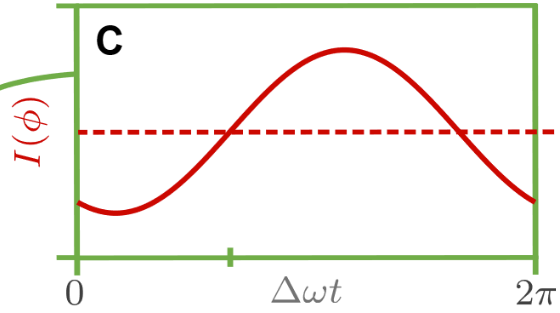
Ramsey Clock

Ramsey sequence



Sci. Adv. **10**, eadl6078

Interference signal



$$I = \frac{N_T}{2}\left[1 + \underbrace{\frac{|\langle e_T|g_T\rangle|}{N_T}}_{\text{Contrast}}\cos\left(\arg\langle e_T|g_T\rangle\right)\right]$$

Number of transmitted atoms

Contrast

Measured phase

State of transmitted atoms

$$|e_T/g_T\rangle = t_{e/g}(E)\exp\left[-\mathrm{i}\left(\omega_{e/g}t - \frac{p^2}{2m_{e/g}\hbar}t\right)\right]|e_{\mathrm{in}}/g_{\mathrm{in}}\rangle$$

Transmission coefficient $\quad |t_{e/g}|\mathrm{e}^{\mathrm{i}\varphi_{e/g}} \cong \sqrt{\bar{T}}\mathrm{e}^{\mathrm{i}\bar{\varphi}\pm\mathrm{i}\Delta\omega\tau}$

Phase contribution

Phase difference measured by a tunneled clock

$$|e_T/g_T\rangle = t_{e/g}(E)\exp\left[-\mathrm{i}\left(\omega_{e/g}t - \frac{p^2}{2m_{e/g}\hbar}t\right)\right]|e_{\mathrm{in}}/g_{\mathrm{in}}\rangle$$

$$\arg\langle e_T|g_T\rangle = \Delta\omega(t+\delta t+\tau) - \underbrace{[\phi(t)-\phi(0)]}_{\text{e.g. laser phase}}$$

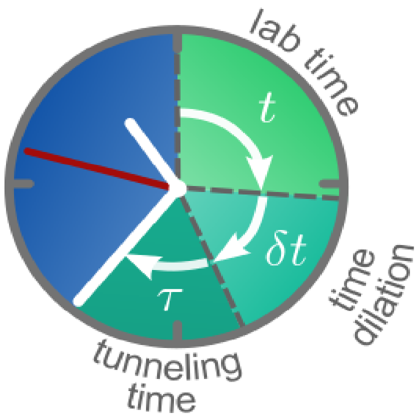
Lab time Time dilation Tunneling time

$$\delta t = \frac{1}{2}\left(\frac{p}{\bar{m}c}\right)^2 t$$

Tunneling time

$$\tau = \frac{\bar{\mathcal{V}}\bar{T}}{4\bar{\omega}\sqrt{\bar{\varepsilon}}(\bar{\varepsilon}-1)}\left[(2\bar{\varepsilon}-1) - \frac{\sinh\left(2\bar{\mathcal{V}}\sqrt{1-\bar{\varepsilon}}\right)}{2\bar{\mathcal{V}}\sqrt{1-\bar{\varepsilon}}}\right]$$

incoming energy $\bar{\mathcal{E}} = \frac{p^2}{2\bar{m}V_0}$ barrier parameter $\bar{\mathcal{V}} = a\frac{\sqrt{2\bar{m}V_0}}{\hbar}$



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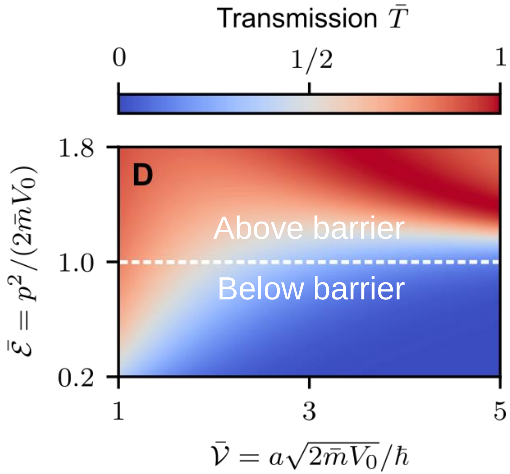

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Tunneling time

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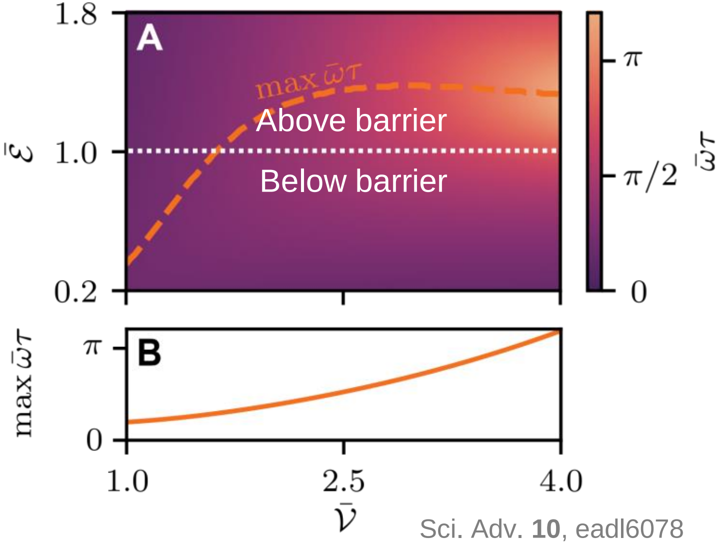
incoming energy $\bar{\varepsilon} = \frac{p^2}{2\bar{m}V_0}$

barrier parameter $\bar{\mathcal{V}} = a\frac{\sqrt{2\bar{m}V_0}}{\hbar}$

Tunneling time



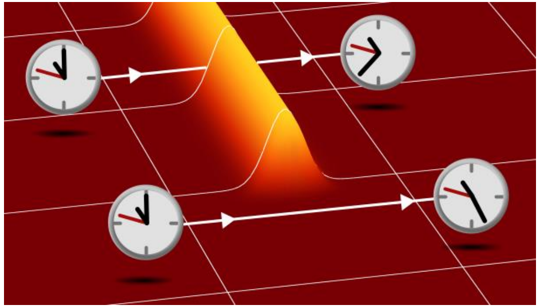
Sci. Adv. **10**, eadl6078

- Short tunneling times for
  - small tunneling probabilities
  - far above barrier

- No clear distinction between tunneling and classical regime

Differential measurement

- Differential measurement scheme to isolate tunneling phase
- Initial state: Cold atomic cloud
- Measurement of ground-state population

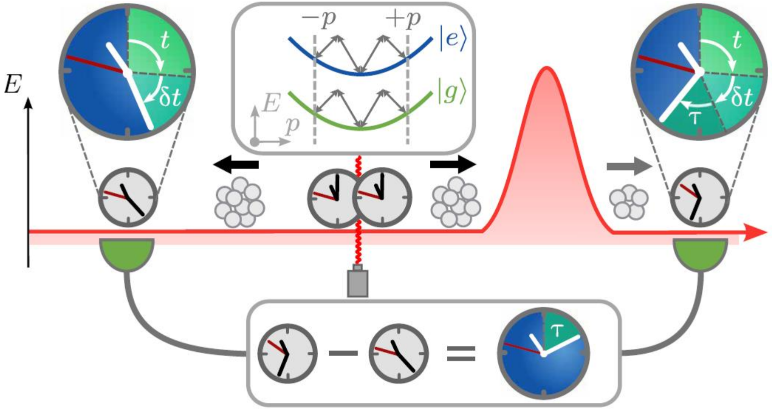


Time dilation

$$\delta t = \frac{t}{2N_T}\int \mathrm{d}p\, \bar{T}(p)|\psi_0(p)|^2 \left(\frac{p}{\bar{m}c}\right)^2$$

Tunneling time

$$\tau = \frac{1}{N_T}\int \mathrm{d}p\, \bar{T}(p)|\psi_0(p)|^2 \tau(p)$$



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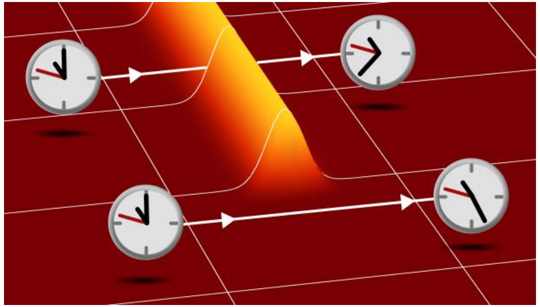
Differential measurement

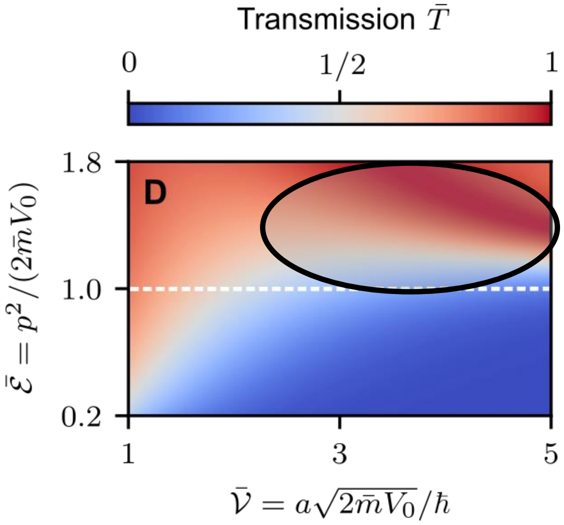


- Differential measurement scheme to isolate tunneling phase
- Insensitive to position uncertainties
- Velocity uncertainty → additional contributions
- But for $|\partial_p \bar{T}|_{p_0} \delta p| \ll 1$

$\bar{T}(p) \approx 1$

Momentum width
→ Delta-kick collimation

Phys. Rev. Lett. **78**, 2088



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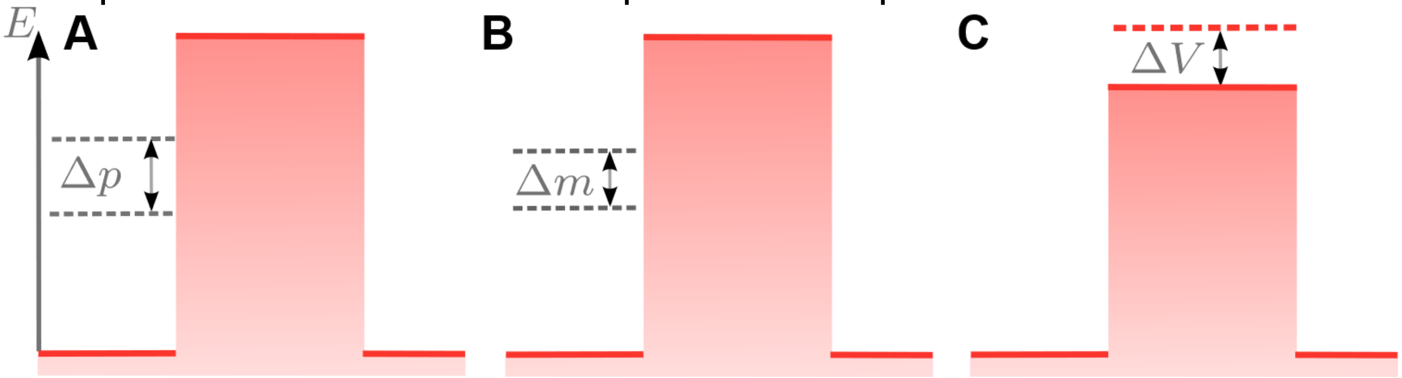
Time dilation

$$\delta t = \frac{t}{2\cancel{N_T}} \int \mathrm{d}p\, \cancel{\bar{T}(p)} |\psi_0(p)|^2 \left(\frac{p}{\bar{m}c}\right)^2$$

Experimental imperfections

▶ Additional phase contributions from experimental imperfections



Sci. Adv. **10**, eadl6078

Differential Doppler time

$$\tau_D \frac{\bar{p}\Delta p}{\hbar \bar{m}} = \left[\frac{t}{2} + \tau_P\right] \frac{\bar{p}\Delta p}{\hbar \bar{m}}$$

Wigner phase time

$$\tau_P = \hbar \partial_{\bar{E}} \bar{\varphi}$$

Phys. Rev. **98**, 145

Time dilation

$$\Delta\omega\delta t$$

Tunneling time

$$\tau\Delta\omega$$

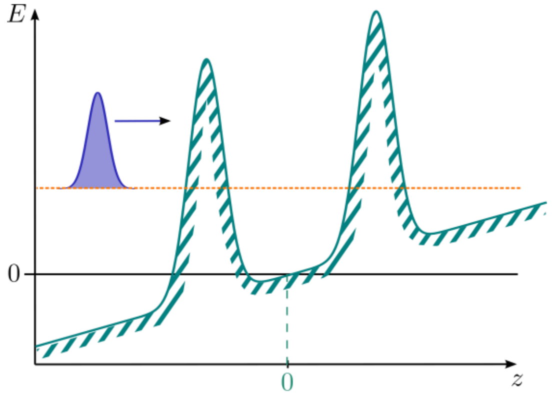
Larmor time

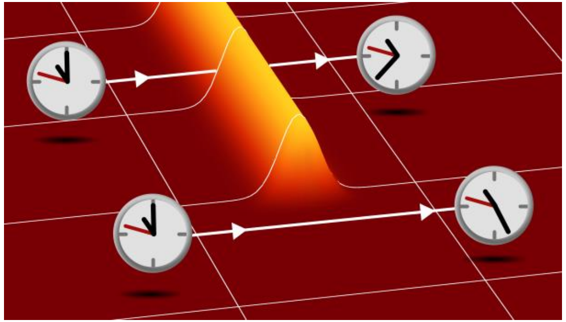
$$\tau_L \omega_L = \frac{\hbar |\Phi_V|}{\bar{V}} \omega_L$$

Larmor frequency

Conclusion

- Experiments currently performed
- „Time is what you read off a clock“
  - No superluminal or instantaneous tunneling
- Unification of definition of tunnelling times





Thank you for your attention

P. Schach, A. Friedrich, J. R. Williams, W. P. Schleich & E. Giese

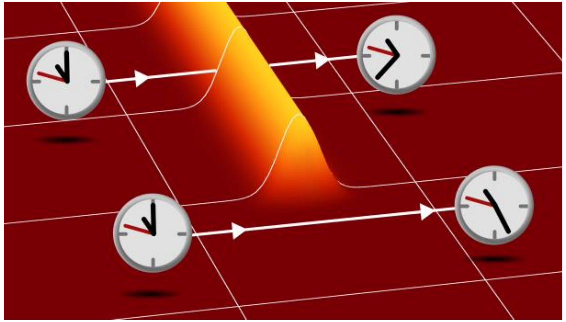
Tunneling gravimetry

EPJ Quantum Technology **9**, 20 (2022)

P. Schach & E. Giese

A unified theory of tunneling times promoted by Ramsey clocks

Science Advances **10**, eadl6078 (2024)



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Theoretical Quantum Optics

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