Quantum reflection of antihydrogen from the Casimir-Polder potential above a material surface

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- Quantum reflection of antihydrogen from the Casimir potential above matter slabs – *Phys. Rev. A 87, 012901 (Jan 2013)*
- Quantum reflection of antihydrogen from nanoporous media – *Phys. Rev. A 87, 022506 (Feb 2013)*

Outline

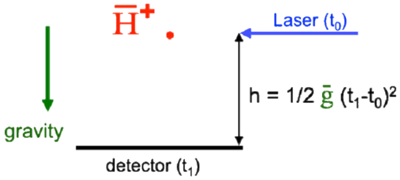
The GBAR experiment

Gravitational Behavior of Antihydrogen at Rest

Test the equivalence principle for antimatter by timing the free-fall of antihydrogen ($\overline{\mathrm{H}}$) dropped from $\sim$ 30 cm in the Earth's gravity field

The GBAR experiment

- initial state: $\overline{\mathrm{H}}^+$ in the ground state of a harmonic trap
- start: the extra e^+ is photodetached
- freefall of $\overline{\mathrm{H}}$
- stop: $\overline{\mathrm{H}}$ annihilates on the detector



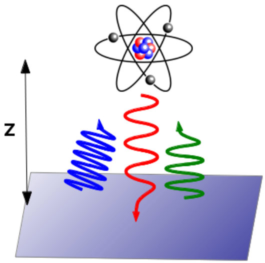
P. Perez & Y. Sacquin,
Class. Quantum Grav. 29 (2012) 184008

The free fall acceleration $\bar{g}$ of $\overline{\mathrm{H}}$ is deduced from the free fall time

Question: are there other forces than gravity acting on $\overline{\mathrm{H}}$?

The Casimir-Polder force

Electromagnetic (EM) modes are modified when the atom comes close to the detector:
$\Rightarrow$ the EM ground state (vacuum) energy changes
$\Rightarrow$ attractive Casimir-Polder force between atom and detector



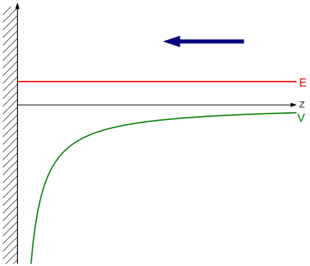
Casimir 1948 : long-range interaction energy between an atom and a perfectly conducting mirror:

$$V^*(z) = -\frac{3\hbar c}{8\pi z^4}\frac{\alpha(0)}{4\pi\epsilon_0} = -\frac{C_4^{perfect}}{z^4}$$

For H and $\overline{\mathrm{H}}$, $C_4^{perfect} \approx 73.6\ E_h a_0^4$
$V(35\text{ nm}) \approx$ - $mg \times 10$ cm

Scattering on the Casimir-Polder potential

What happens when the atom scatters on this potential ?



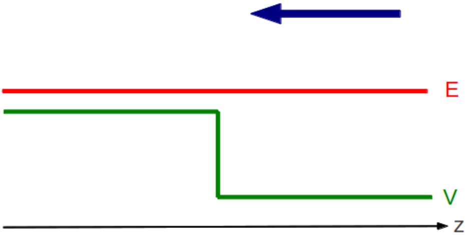
Length scales :

- free fall height : $h \approx 30$ cm
- quantum gravitational scale : $l_{grav} = \left(\hbar^2/2m^2 g\right)^{1/3} \approx 6\ \mu$m
- Casimir-Polder scale : $l_{CP} = \sqrt{2mC_4}/\hbar \approx 30$ nm

We can decouple the free-fall and the scattering on the potential: the incoming wavefunction is a plane wave with energy $E = mgh$.

Quantum reflection on a step

Schrödinger plane wave incident on a potential step:



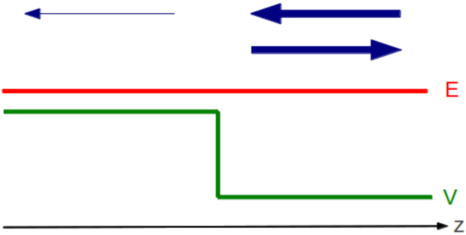
$$\psi_{in}(z) \propto \exp(-ikz)$$

with a wavevector

$$k = \sqrt{2m(E - V)}/\hbar$$

Quantum reflection on a step

The wavefunction is partly reflected, partly transmitted



Reflection:

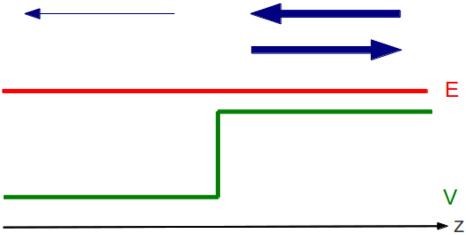
$$r_{12} = \frac{k_2 - k_1}{k_1 + k_2}$$

Transmission:

$$t_{12} = \frac{2\sqrt{k_1 k_2}}{k_1 + k_2}$$

Quantum reflection on a step

Reflection from an attractive potential: “quantum reflection”

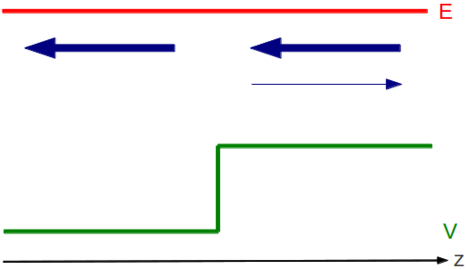


Reflection probability unchanged when $1 \leftrightarrow 2$:

$$|r_{12}|^2 = |r_{21}|^2$$

Quantum reflection on a step

No quantum reflection at large energies: classical regime



Reflection:

$$\frac{k_2 - k_1}{k_1 + k_2} \underset{E \to \infty}{\longrightarrow} 0$$

Transmission:

$$\frac{2\sqrt{k_1 k_2}}{k_1 + k_2} \underset{E \to \infty}{\longrightarrow} 1$$

Observation of quantum reflection

Shimizu 2001: Ne* on Silicon and BK7 glass, grazing incidence

VOLUME 86, NUMBER 6 PHYSICAL REVIEW LETTERS 5 FEBRUARY 2001

Specular Reflection of Very Slow Metastable Neon Atoms from a Solid Surface

Fujio Shimizu
Institute for Laser Science and CREST, University of Electro-Communications, Chofu-shi, Tokyo 182-8585, Japan
(Received 7 July 2000)

An ultracold narrow atomic beam of metastable neon in the $1s_3[(2s)^5 3p:{}^1P_0]$ state is used to study specular reflection of atoms from a solid surface at extremely slow incident velocity. The reflectivity on a silicon (1,0,0) surface and a BK7 glass surface is measured at the normal incident velocity between 1 mm/s and 3 cm/s. The reflectivity above 30% is observed at about 1 mm/s. The observed velocity dependence is explained semiquantitatively by the quantum reflection that is caused by the attractive Casimir–van der Waals potential of the atom-surface interaction.

DOI: 10.1103/PhysRevLett.86.987 PACS numbers: 34.50.Dy, 03.75.–b, 34.20.Cf

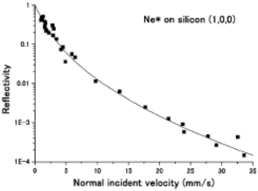


FIG. 3. The reflectivity vs the normal incident velocity on the Si(1,0,0) surface. The solid curve is the reflectivity calculated by using the potential Eq. (1) with $\lambda = 0.4\ \mu m$ and $C_4 = 6.8 \times 10^{-56}\ J\,m^4$, which corresponds to $\alpha = 2.0 \times 10^{-39}\ F\,m^2$ of Casimir's theory.

Observation of quantum reflection

Pasquini et al. 2004: dilute BEC of Na on silicon, normal incidence

PRL **93,** 223201 (2004) PHYSICAL REVIEW LETTERS week ending 26 NOVEMBER 2004

Quantum Reflection from a Solid Surface at Normal Incidence

T. A. Pasquini, Y. Shin, C. Sanner, M. Saba, A. Schirotzek, D. E. Pritchard, and W. Ketterle*
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and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA
(Received 15 June 2004; published 24 November 2004)

We observed quantum reflection of ultracold atoms from the attractive potential of a solid surface. Extremely dilute Bose-Einstein condensates of ^{23}Na, with peak density 10^{11}–10^{12} atoms/cm^3, confined in a weak gravitomagnetic trap were normally incident on a silicon surface. Reflection probabilities of up to 20% were observed for incident velocities of 1–8 mm/s. The velocity dependence agrees qualitatively with the prediction for quantum reflection from the attractive Casimir-Polder potential. Atoms confined in a harmonic trap divided in half by a solid surface exhibited extended lifetime due to quantum reflection from the surface, implying a reflection probability above 50%.

DOI: 10.1103/PhysRevLett.93.223201 PACS numbers: 34.50.Dy, 03.75.Be

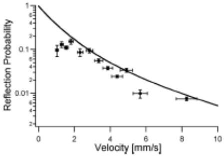


FIG. 3. Reflection probability vs incident velocity. Data were collected in a magnetic trap with trap frequencies $2\pi \times (3.3, 2.5, 6.5)$ Hz. Incident and reflected atom numbers were averaged over several shots. Vertical error bars show the standard deviation of the mean of six measurements. Horizontal error bars reflect the uncertainty in deducing $v_\perp$ from the applied magnetic field $B_\perp$. The solid curve is a numerical calculation for individual atoms incident on a conducting surface as described in the text.

Effect of the atom-detector interaction

Attractive Casimir-Polder interaction between atom and detector :

- no noticeable change in time of fall
- BUT part of the atomic wavepacket is reflected

Quantum reflection : classically forbidden reflection of a matter wave
from an attractive potential

Need to estimate and master this bias :

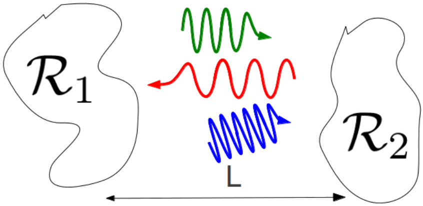
- How much quantum reflection can we expect?
- How does it depend on the atom's velocity?
- How is this affected by the materials used?

Scattering approach to Casimir forces

Scattering formula for Casimir energy (here at $T = 0$)

$$V = \hbar \int_0^\infty \frac{\mathrm{d}\xi}{2\pi} \mathrm{Tr} \log \left(1 - \mathcal{R}_1 e^{-\kappa L} \mathcal{R}_2 e^{-\kappa L} \right)$$

Objects described by EM reflection matrices $\mathcal{R}_1, \mathcal{R}_2$

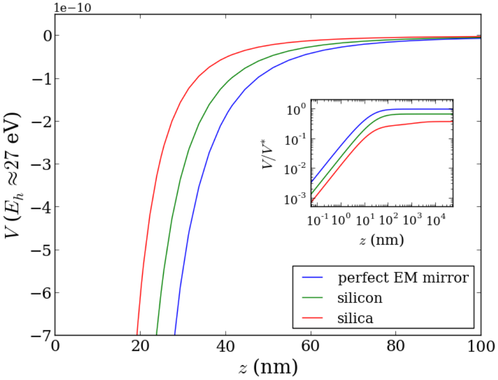


- $\mathcal{R}_{atom}$ function of the dynamic polarizability of the atom
- $\mathcal{R}_{plane}$ function of Fresnel reflection coefficients on the surface, which depend on the permittivity of the material

R. Messina, D.A.R. Dalvit, P.A. Maia Neto, A. Lambrecht, S. Reynaud, *Phys. Rev. A 80 (2009) 022119*

Calculation of the Casimir-Polder potential

Casimir-Polder potential above various semi-infinite media, numerical results (inset : normalized potential V/V^*):



- long distance (retarded regime): $V(z) \simeq -C_4/z^4$
- short distance (van der Waals regime): $V(z) \simeq -C_3/z^3$
- weaker potential for materials weakly coupled to the EM field

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Reflection equations and boundary conditions

Exact wavefunction written as a sum of up- and downward semiclassical (WKB) waves with non-constant coefficients :

$$\psi(z) = b_+(z)\frac{\exp(+i\phi(z))}{\sqrt{p(z)}} + b_-(z)\frac{\exp(-i\phi(z))}{\sqrt{p(z)}}$$

$$p(z) = \sqrt{2m(E - V(z))}, \qquad \hbar\phi(z) = \int^z p(z')\mathrm{d}z'$$

Schrödinger's equation $\Rightarrow$ coupled equations for $b_\pm(z)$

M.V. Berry and K.E. Mount, *Rep. Prog. Phys. 35 (1972) 315*

Annihilation of $\overline{\mathrm{H}}$ on the surface: no reflected wave $b_+(z=0) = 0$
$\Rightarrow$ different from matter atoms & less sensitive to surface physics

Reflection and transmission probabilities

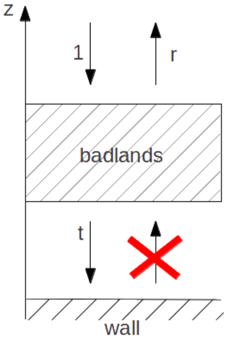
The WKB approximation becomes exact

- as $z \to \infty$ since the potential goes to 0
- as $z \to 0$ because the momentum becomes very large

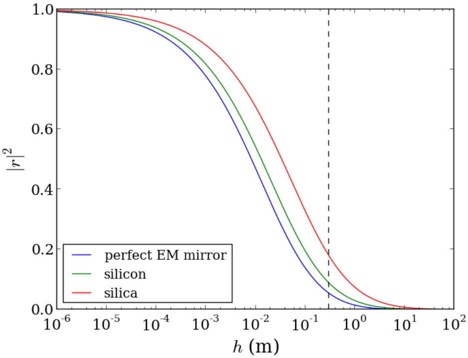
$\Rightarrow$ reflection only occurs in an intermediate region, the "badlands"

reflection probability:
$|r|^2 = |b_+(\infty)/b_-(\infty)|^2$

transmission/annihilation probability:
$|t|^2 = |b_-(0)/b_-(\infty)|^2$



Reflection probability versus energy



Atomic reflection probabilities for a free fall height $h = 30$ cm

surface	$\|r\|^2$
perfect EM mirror	5%
silicon	9%
silica	18%

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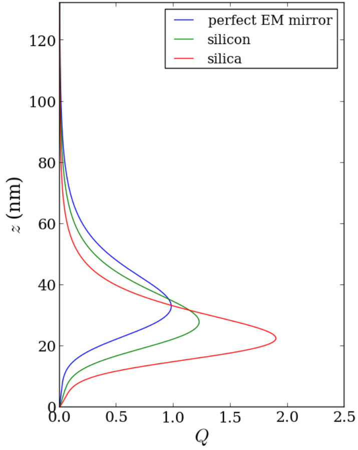
Atomic reflection probability:

- significant for GBAR fall heights
- bias : high energy atoms more likely to be detected
- weaker reflectors of EM field are better reflectors of atoms !

Explanation of the "paradox"



Badlands function Q for h=10cm

"Badlands" function:

$$Q(z) = \hbar^2 \left| \frac{p''(z)}{2p(z)^3} - \frac{3p'(z)^2}{4p(z)^4} \right|,$$

indicates regions where the semiclassical approximation breaks down

For the Casimir-Polder potential, reflection is localized in the region where $|V(z)| \simeq E$

$\Rightarrow$ For weaker Casimir potentials, the atom comes closer to the surface and quantum effects are enhanced.

Interest and general idea

Increasing quantum reflection opens many possibilities:

$\Rightarrow$ storing antimatter: antimatter bottles, pipes, ...

$\Rightarrow$ levitation of anti-atoms above a surface

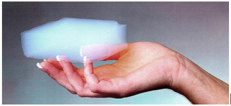
A.Yu. Voronin, P. Froelich, *J. Phys. B 38 (2005) L301*
A.Yu. Voronin, P. Froelich, B. Zygelman, *Phys. Rev. A 72 (2005) 062903*
A.Yu. Voronin, P. Froelich, V.V. Nesvizhevsky, *Phys. Rev. A 83 (2011) 032903*

We can use our understanding of quantum reflection to enhance it :
to increase reflection, weaken the Casimir-Polder interaction

- thin slabs
- graphene
- nanoporous materials that incorporate a large fraction of gas or vacuum

Nanoporous materials

Examples : silica aerogels, powders of nanodiamonds and porous silicon have pore sizes in the 10-100 nm range.


NASA

Atoms that are slow enough are reflected far from the surface and are not affected by inhomogeneities:
⇒ Bruggeman effective permittivity model to describe the porous medium.

Lifetime of 1st quantum state

surface (porosity)	Lifetime (s)
perfect conductor	0.11
bulk silicon	0.14
bulk silica	0.22
diamond powder (95%)	0.89
porous silicon (95%)	0.94
silica aerogel (98%)	4.6

Phys. Rev. A 87 (Feb 2013) 022506

Conclusions

- The Casimir-Polder interaction between $\overline{\mathrm{H}}$ and the detector can cause a significant amount of reflection
  - $\rightarrow$ lower statistics
  - $\rightarrow$ bias towards high energy atoms.
- Importance of the choice of material : bad reflectors of the EM field cause more quantum reflection.
- Quantum reflection can be increased by reducing the Casimir interaction : a new way to trap and manipulate antimatter.

The end

Thank you for your attention

Any questions?