Atom-surface interactions – (instead of) an introduction

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Cold atoms near surfaces

Casimir–Polder forces

Lifetimes etc.

van der Waals forces near surfaces
Cold atoms near surfaces

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Casimir–Polder forces

van der Waals forces and quantum reflection
Cold atoms near surfaces

ultracold atoms trapped in magnetic fields generated by current-carrying wires or (programmable) ferromagnetic structures

typical atom-surface distances $\lesssim 1 \ldots 100 \mu m$
Cold atoms near surfaces

magnetic-field imaging


cold atom scanning probe microscopy

M. Gierling et al., Nature Nanotechn. 6, 446 (2011).

cavity-mediated manipulation in waveguide chips

Cold atoms near surfaces

Lifetimes etc.

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Magnetic field noise

B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. Purcell, Harvard University.—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

\[ A_v = \left( \frac{8\pi^2}{c^2} \right) h \nu \left( \frac{8\pi^2 \mu^2}{3\hbar^3} \right) \text{sec}^{-1}, \]

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for \( \nu = 10^7 \text{ sec}^{-1} \), \( \mu = 1 \) nuclear magneton, the corresponding relaxation time would be \( 5 \times 10^8 \text{ seconds}! \)

However, for a system coupled to a resonant electrical circuit, the factor \( 8\pi^2/c^2 \) no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now one oscillator in the frequency range \( \nu/Q \) associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor \( f = 3Q\lambda^3/4\pi^2 V \), where \( V \) is the volume of the resonator. If \( \alpha \) is a dimension characteristic of the circuit so that \( V \sim \alpha^3 \), and if \( \delta \) is the skin-depth at frequency \( \nu \), \( f \sim \lambda^3/\alpha^3 \delta \). For a non-resonant circuit \( f \sim \lambda^3/\alpha^3 \), and for \( \alpha < \delta \) it can be shown that \( f \sim \lambda^3/\alpha^3 \delta^2 \).

If small metallic particles, of diameter \( 10^{-3} \text{ cm} \) are mixed with a nuclear-magnetic medium at room temperature, spontaneous emission should establish thermal equilibrium in a time of the order of minutes, for \( \nu = 10^7 \text{ sec}^{-1} \).

E.M. Purcell, Phys. Rev. 69, 681 (1946).
Magnetic field noise

\[ \Gamma = \frac{2(\mu_B g S) \mu_0}{\hbar} \langle \mathbf{S} \rangle \cdot \text{Im} \left[ \nabla \times \mathbf{G}(r_A, r_A, \omega_A) \times \nabla \right] \cdot \langle \mathbf{S} \rangle [\bar{n}_{\text{th}}(\omega_A) + 1] \]

superconducting materials with longer spin flip lifetimes, but generating vortex noise that could be detected with cold atoms

Electric dipole transitions in Rydberg atoms

- Rydberg atoms in free space: $\tau \propto n^3$
- in the near-field of a surface: $\tau \propto n^{-4}$

Cold atoms near surfaces

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Casimir–Polder forces

van der Waals forces and quantum reflection
Casimir–Polder forces on atoms

- Casimir–Polder force is strong enough to make atom trapping impossible
- can be measured by nano probes
- theory: nonequilibrium situation $\Rightarrow$ M. Antezza’s session

Casimir–Polder forces on atoms

reduction of field noise and dispersion forces by reducing material $\Rightarrow$ graphene (see also M. Bordag’s talk)

opens up opportunity to bring atoms closer to surface
- steeper trapping potentials
- possibility to measure gravity at short separations

Casimir–Polder potential of Rydberg atoms is strong enough to drive ripples in suspended graphene sheets $\Rightarrow$ mutual coupling between cold atoms and solid-state system (see also D. Chang’s talk)

Casimir-Polder interaction of Rydberg atoms

CP potential $\sim$GHz expected for Rydberg atoms at $\mu$m distances
$\Rightarrow$ shift of EIT peak observed, but with different scaling for different Rydberg states

Resonant interaction with surface plasmons

Example: initial state $32S_{1/2}$: Peak position $\sim d^{-1}$

initial state $43S_{1/2}$: Peak position $\sim d^{-3}$

need polariton $\Omega_2$ to be thermally occupied to drive resonant transition $\Rightarrow$ depends in details of initial atomic state (available transitions) and material properties (SPP resonances)

resonant interaction: degenerate perturbation theory

$$\Delta E = -|\langle e, 0_1, 1_2 | \hat{H}_{\text{eff}} | g, 1_1, 0_2 \rangle| \sqrt{(\bar{n}_{\text{th}}(\Omega_1) + 1)\bar{n}_{\text{th}}(\Omega_2)}$$

- same power laws as nonresonant interaction ($z^{-3}$ nonretarded, $z^{-4}$ retarded), magnitude of $C_3/z^3$ can exceed several MHz for close resonances
- for increasing temperature new decay channels open up

Chiral Casimir–Polder force and enantiomer separation

- Curie principle: enantiomer selective force between chiral molecule and chiral body
- choose parameters such that resonant and nonresonant electric forces cancel
- possible route to enantiomer separation in the gas phase

Casimir–Polder forces in molecular interferometry

Casimir–Polder potential in Talbot–Lau-Interferometer

Casimir–Polder forces in molecular interferometry

- new developments: higher detection yield with Phthalocyanine
- quantum chemistry calculation of molecular polarisability needed (courtesy O. Bokareva)
- molecular size taken into account by Gaussian model of electron density
- internal temperature $\sim 600$ K, vibrational and rotational states in thermal nonequilibrium
- $\Rightarrow$ full calculation of all material properties and retardation effects needed
- $\Rightarrow$ tomographic reconstruction of (some) parameters possible (see J. Fiedler’s poster)

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van der Waals interaction

van der Waals potential from perturbation theory
with interaction Hamiltonian $\hat{H}_{\text{int}} = \hat{H}_{AF} + \hat{H}_{BF}$

$$\Delta E = \sum_{I,II,III\neq G} \frac{\langle G | \hat{H}_{\text{int}} | III \rangle \langle III | \hat{H}_{\text{int}} | II \rangle}{(E_G - E_{III})}$$

$$\times \frac{\langle II | \hat{H}_{\text{int}} | I \rangle \langle I | \hat{H}_{\text{int}} | G \rangle}{(E_G - E_{II})(E_G - E_I)}$$

for isotropic atoms:

$$U(r_A, r_B) = -\frac{\hbar \mu_0^2}{2\pi} \int_0^\infty d\xi \xi^4 \alpha_A(i\xi)\alpha_B(i\xi) \text{Tr} [G(r_A, r_B, i\xi)G(r_B, r_A, i\xi)]$$
van der Waals interactions in clusters

Helium dimer near a metallic surface (quantum reflection)
He dimer: largest ground-state molecule ($\langle r \rangle = 52\,\text{Å}$, $E_0 = -1.1\,\text{mK}$)

surface influences vdW potential $\Rightarrow$ massiv change in bond length at distances $\lesssim 10\,\text{nm}$

van der Waals interactions in semiconductor excitons

giant Rydberg excitons in thin cuprous oxide plates and first observation of Rydberg blockade in semiconductor systems

Manipulation of vacuum fluctuations

Vacuum fluctuations and hence dispersion force depend on

- material properties
- geometry and structure of macroscopic bodies
- temperature
- spectroscopic properties of atoms/molecules

Vacuum fluctuations are there to be manipulated!
Running order

1. Carsten Henkel (Potsdam):
   *Simple model systems and current questions*

2. Darrick Chang (Barcelona):
   *Trapping atoms with nanoscale quantum vacuum forces*

3. Peter Krüger (Nottingham):
   *Cold atoms at (sub)micron distances from atom chip surfaces*

4. Claudia Eberlein (Sussex):
   *Magnetic moments of electrons interacting with surfaces*

5. Andreas Günther (Tübingen):
   *Cold-Atom Scanning Probe Microscopy near Nanostructures*
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The University of Rostock...

PhD/Postdoc positions available!

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