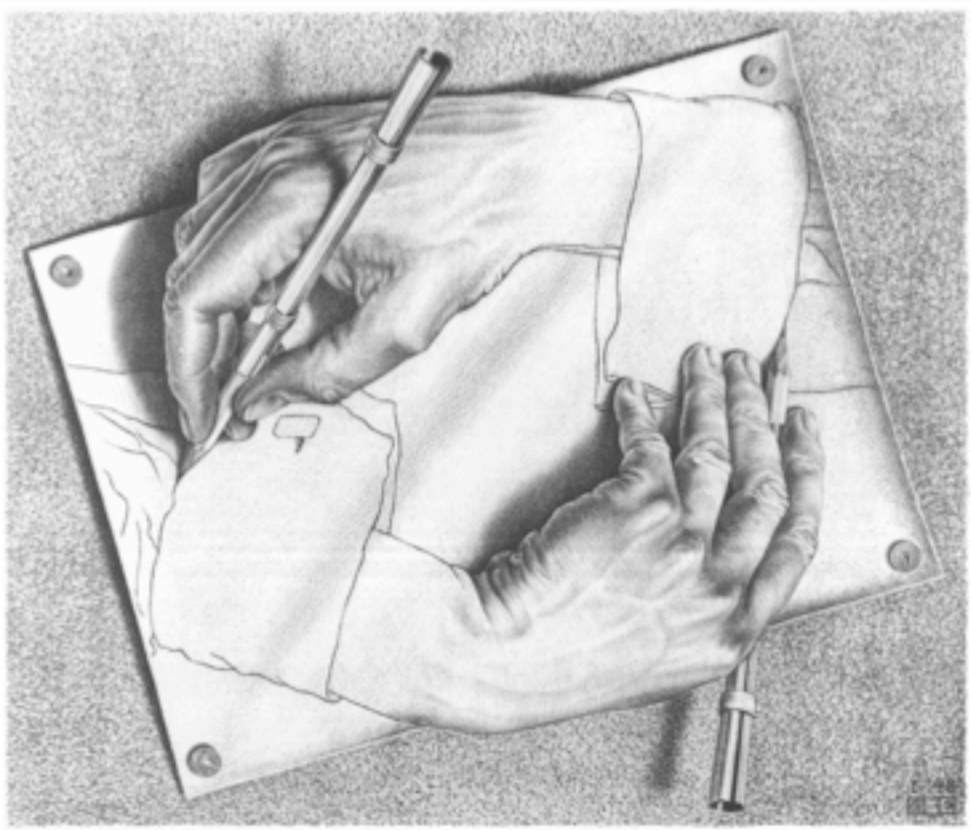
H Atom, show Weakness !!

Parity Violation

in

Atomic Hydrogen

revisited !



Maarten
DeKieviet

Universität Heidelberg

Physikalisches Institut

Bar Harbor, June 2009

or ...

... P-Violation Experiments

with an Atomic Beam Interferometer !

Contents:

- Introduction to Atomic Beam Spin Echo
    - Principle
    - Quantum Reflection
    - Casimir Force and QED-Tests
- Parity Violation Experiments
    - Basic Ingredients
    - Hydrogen Interferometry
    - Berry Phase

Maarten F.M. DeKieviet

Motivation for APV in times of LHC

FUNDAMENTAL INTERACTIONS AND THEIR SYMMETRIES:
HIGH-PRECISION EXPERIMENTS AT LOWEST ENERGIES

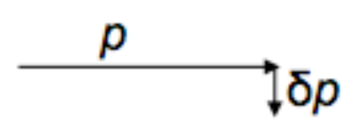
- **LOWEST ENERGIES:**

Particle energies down to $E \sim 10^{-12}$ eV = pico-eV
(cf. HEP: energies up to $E \sim 10^{+12}$ eV = Tera-eV)

When an unknown process is at $M \sim 10^{5...19}$ GeV,
then a propagator like $(p^2+M^2)^{-1}$ becomes $1/M^2$,
whether one works at 0 GeV or at several 100 GeV − what counts is:

- **HIGHEST PRECISION:**

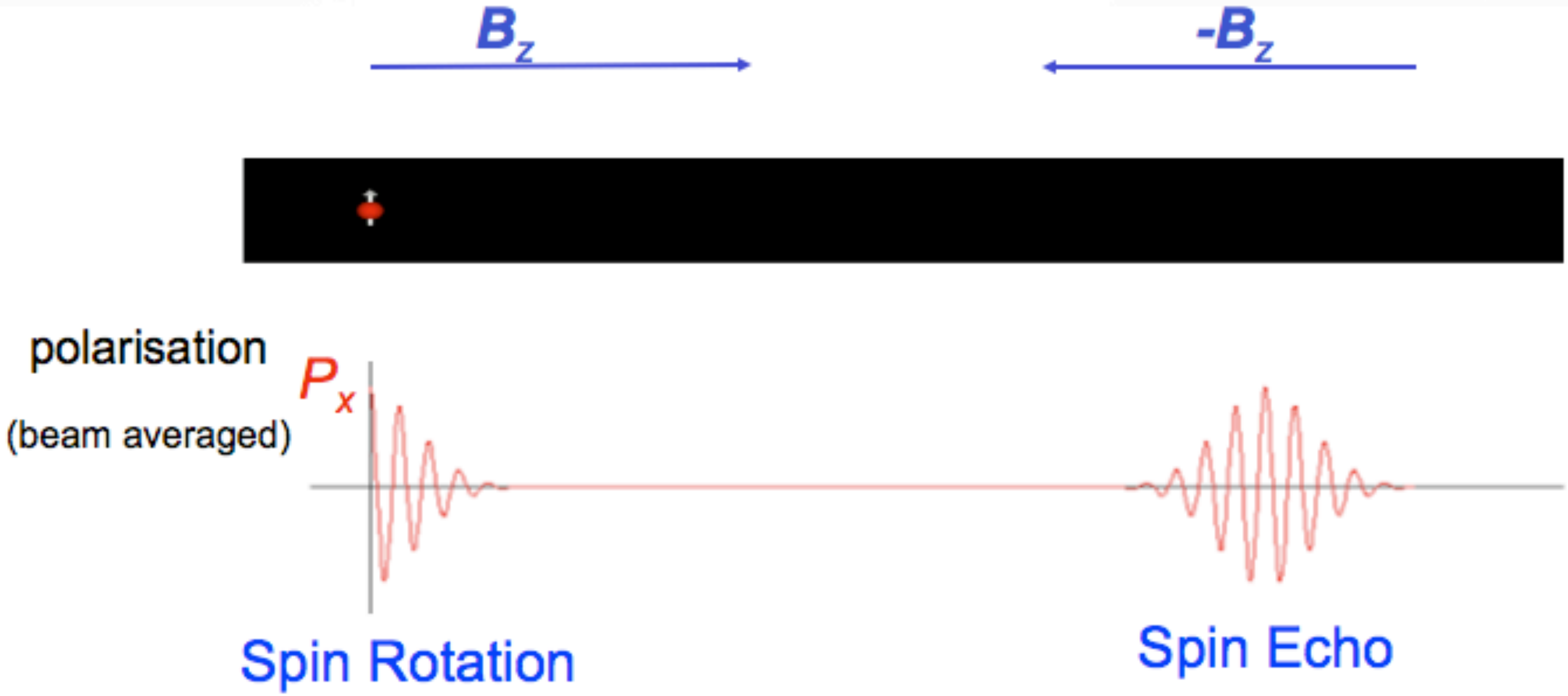
in energy: $\delta E = \pm 10^{-23}$ eV = ± 0.000 000 000 000 000 000 000 01 eV
in momentum: $\delta p/p = \pm 10^{-11}$: 1Å/10m
in mass: $\delta m/m = \pm 10^{-11}$



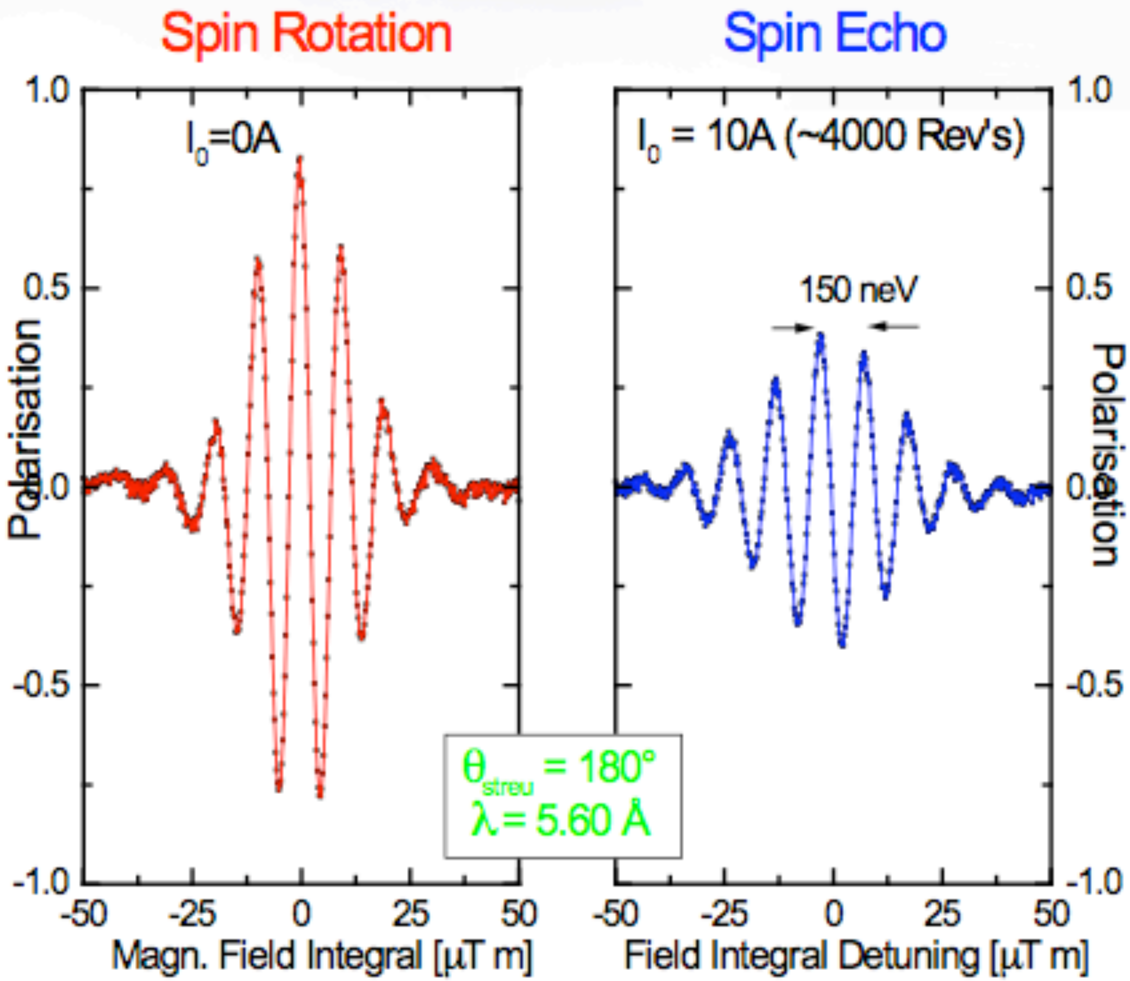
all with 1st particle family: abundant, long-lived, useful

ABSE principle semi-classical - cartoon

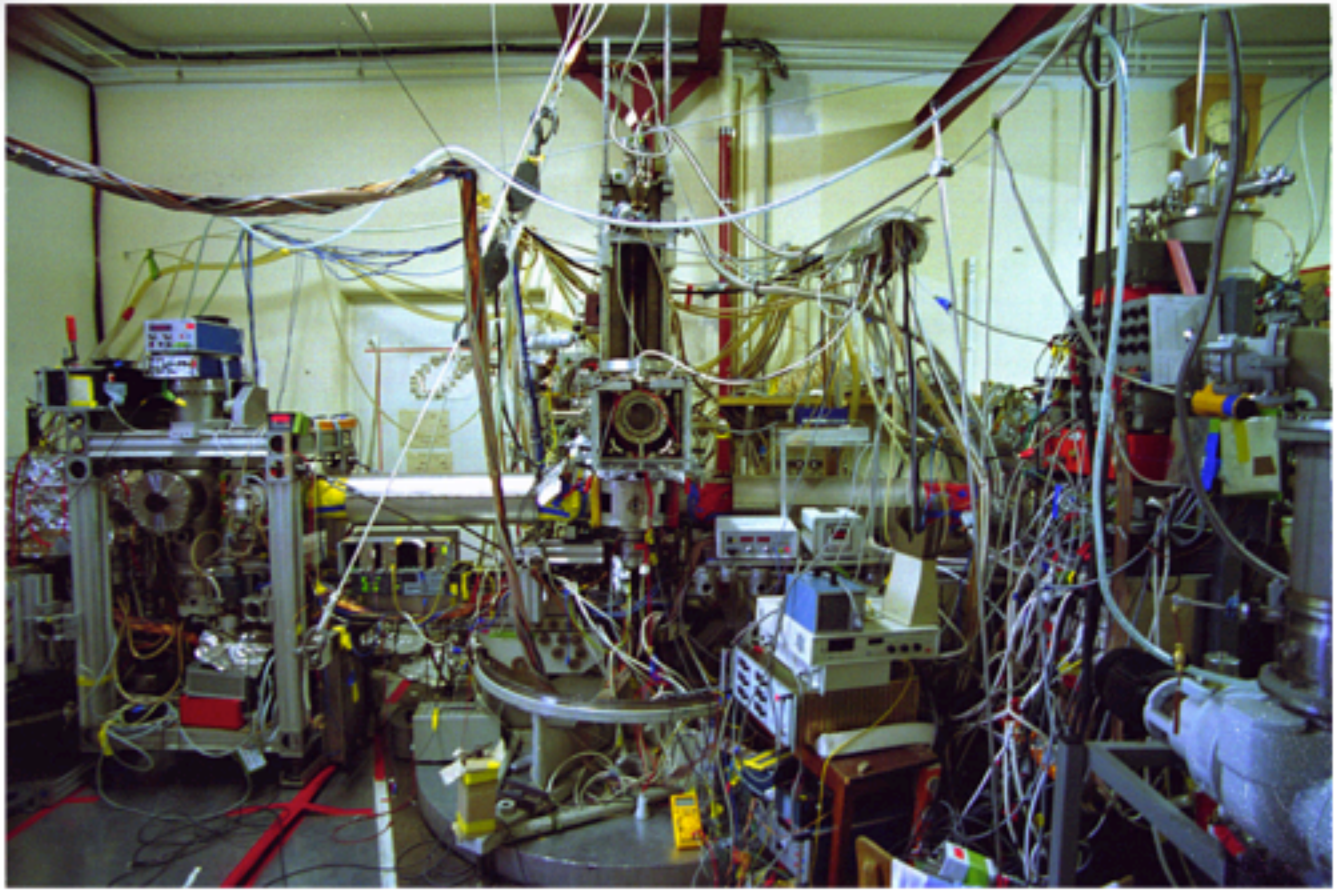
Larmor precession of spin vector



Spin Rotation vs Spin Echo

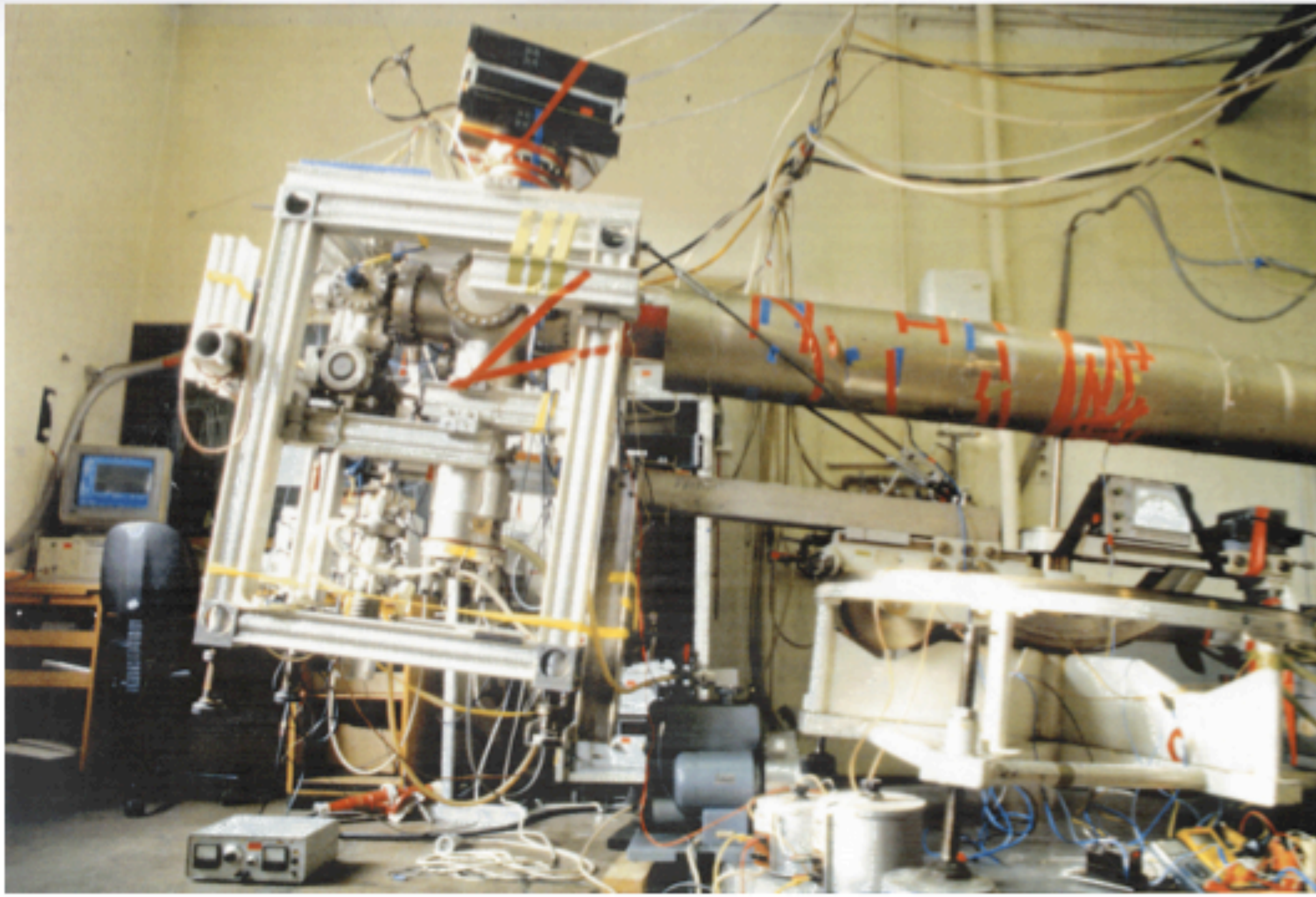


^{3}He Spin Echo Spectrometer ...



… works much better than it looks !!

Energy Loss in Gravitational Field



$\Delta E = m\, g\, \Delta h$

$m = 3$ amu
$\Delta h = 11$ cm
$g = 9.81$ m/s^2

$\Delta E = 33 \pm 1$ neV !

Maarten F.M. DeKieviet

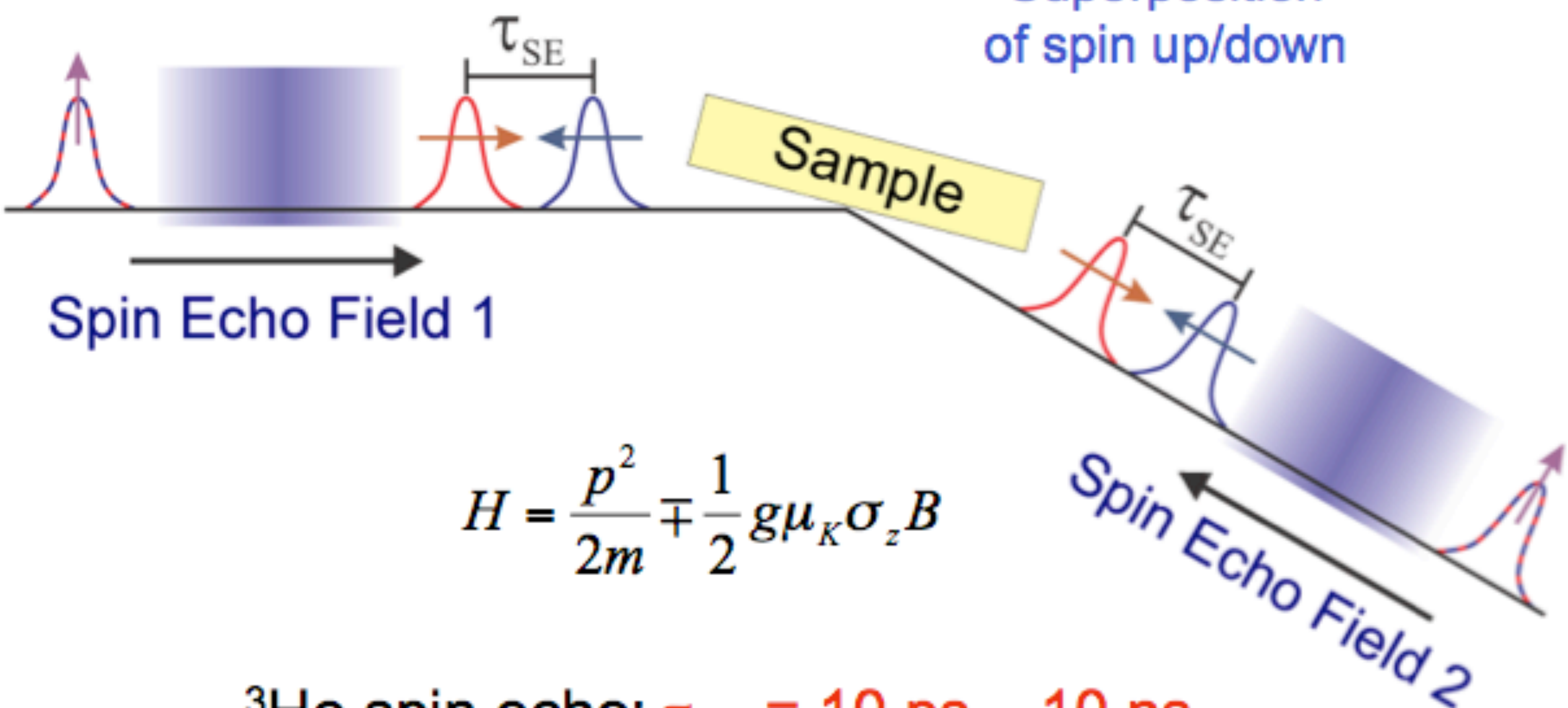
The Principle – quantum mechanically

Spin polarized in *x* direction

$$|\uparrow_x\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow_z\rangle + |\downarrow_z\rangle\right)$$

in magnetic field in *z* direction

Superposition of spin up/down



$$H = \frac{p^2}{2m} \mp \frac{1}{2} g \mu_K \sigma_z B$$

^3He spin echo: τ_{SE} = 10 ps – 10 ns

Surface Dynamics Experiments

- 3D Gas → Noble Gases → 3-D Brownian Motion
- 2D Gas → Xe / Au(111) → 2-D Phases
- Phonons
- Jump Diffusion
- Continuous Diffusion

(Phonons, Jump Diffusion, Continuous Diffusion) → $C_{24}H_{12}$ / Au(111) → "Slow" Motion

- 2D Structure Growth → Thiols / Au(111) → Spatial Resolution
- Soft Matter → Thiols / Si(111) → Collective Motion
- Phase Transitions → Si(111) 7x7 → Critical Behavior

ABSE beyond Surface Science ...

- we study surfaces
- to resolve structures, dynamics, reactivity, etc.
- under well-defined conditions
- to reduce spurious environmental influences
- typical: Ultra High Vacuum conditions

Surface = break of symmetry
(e.g. bulk -> vacuum)

common: what does vacuum do to the surface?

now: what does the surface do to the vacuum?

The QED-Vacuum

the void is not empty !

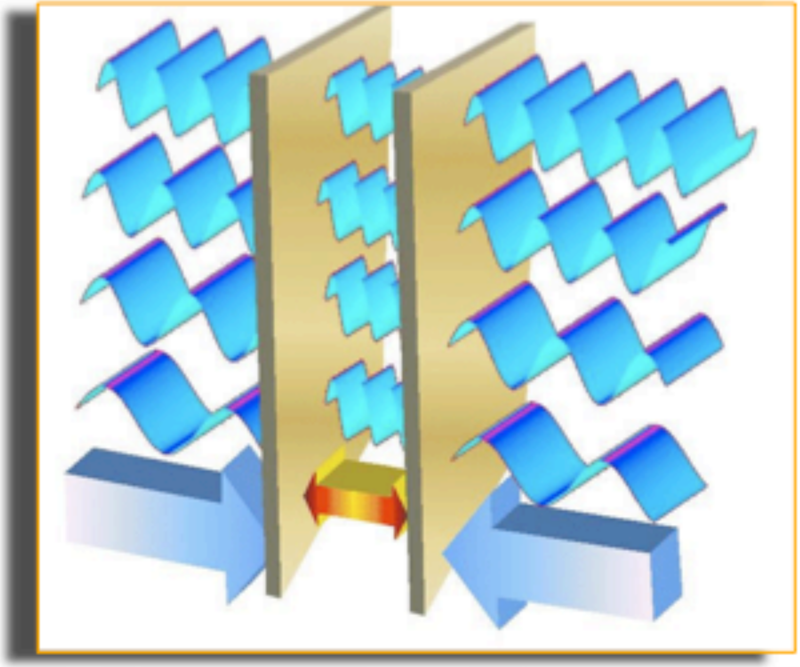
- Quantization of the Electromagnetic Field
- Bath of Harmonic Oscillators in 3-D, of all freq., pol.
- each having Zero-Point Energy $\frac{1}{2}\hbar\omega$
- "Vacuum Fluctuations" within the vacuum

What happens to the vacuum fluctuations, when there is a surface in the vacuum?

Casimir Force

Motivation:

- 1948 Hendrik Casimir prediction
- 1958 attractive force between two flat surface



Hendrik Brugt Gerhard Casimir
(1909 – 2000)

The Casimir Force – Semi-Classical

Atom – Atom: $V^{ret.}_{atom-atom}(r) = -\frac{23\hbar c \alpha_1 \alpha_2}{4\pi r^7}$

Atom – Surface: $V^{ret.}_{atom-surface}(r) = -\frac{3\hbar c \alpha}{8\pi r^4}$

for $r_{ret.} >> \lambda_{|g\rangle \to |e\rangle}$

α : atomic polarizability

Quantum mechanical effect!

retardation

reduced strength

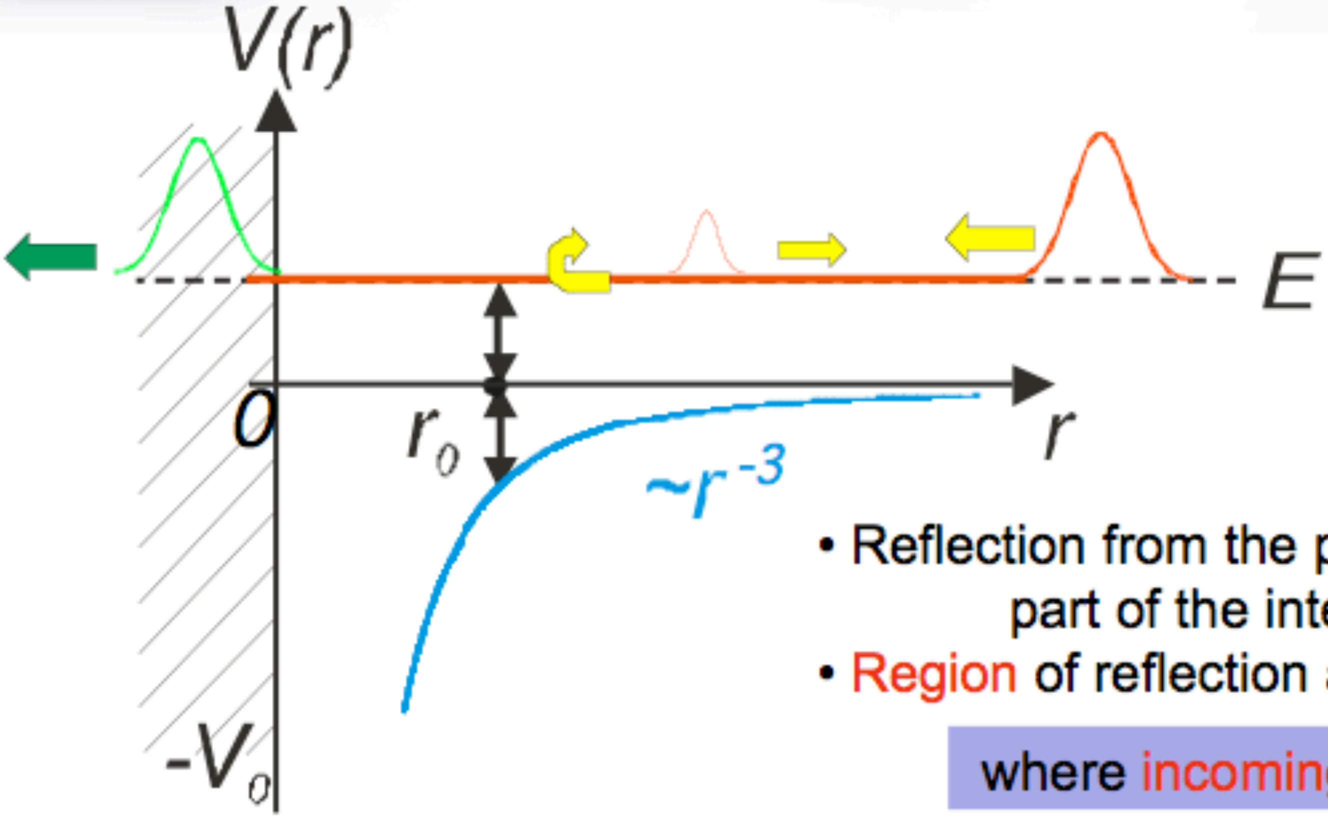
(even weaker than the v/d Waals force and that at large distances!)

ABSE and Casimir II

How can He atom scattering contribute?

- Probe atom – Surface interaction potential
- Over a long range 0.1 nm – 10 μm (!)
- van der Waals vs. Casimir
- High spatial and energy resolution 1 neV – 1 meV (!)
-
-
- very special tool: Quantum Reflection !

Quantum Reflection – *Where ?*



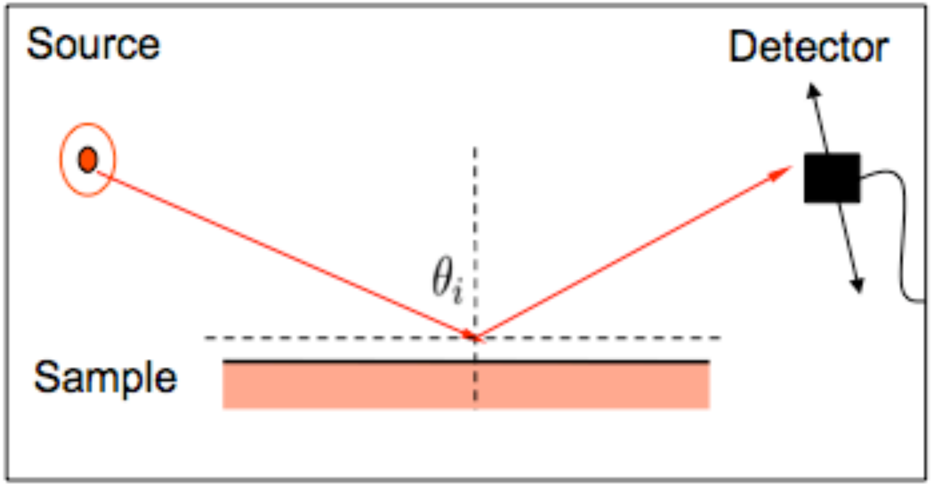
- Reflection from the purely attractive part of the interaction potential
- Region of reflection at r_0

where incoming energy $E_i \sim |V(r_0)|$

=> QR = very sensitive probe of potential shape far out

Quantum Reflection – setup

=> measure specularly reflected ^3He intensity as a function of incident angle



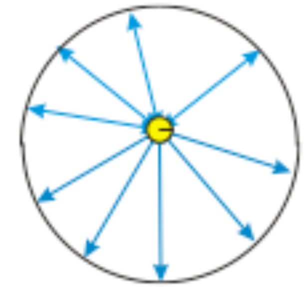
- low beam energy (< 1meV)
- $\Delta v/v \approx 15\%$
- grazing incidence (70º - 90º)
- huge $\lambda_{De\ Broglie} \perp$ surface (1 nm - 1 μm)
- perpendicular energy (neV - 100 μeV)
- Specular Reflection

Phys. Rev. Lett. 91(19), 06 Nov. 2003

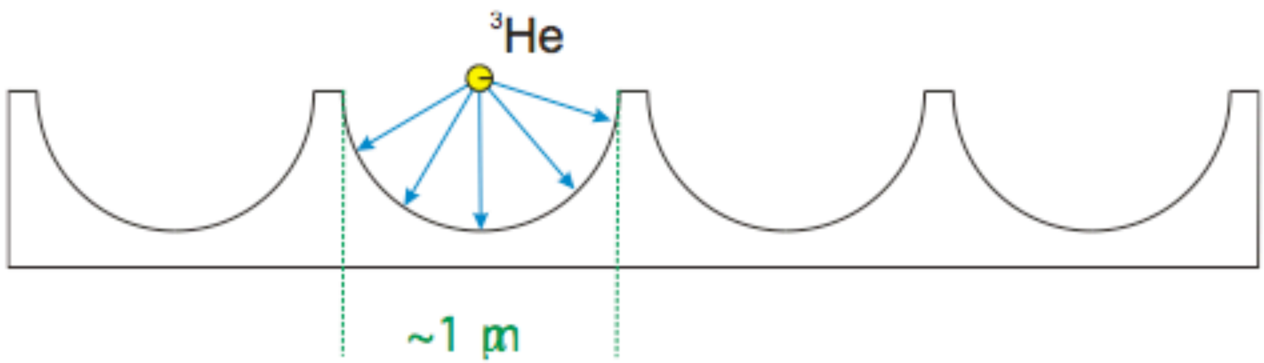
Current Casimir-Polder Experiments

Fundamental issues:

- Temperature Dependence
- Morphology:
    - Boundary Conditions
    - Casimir focussing

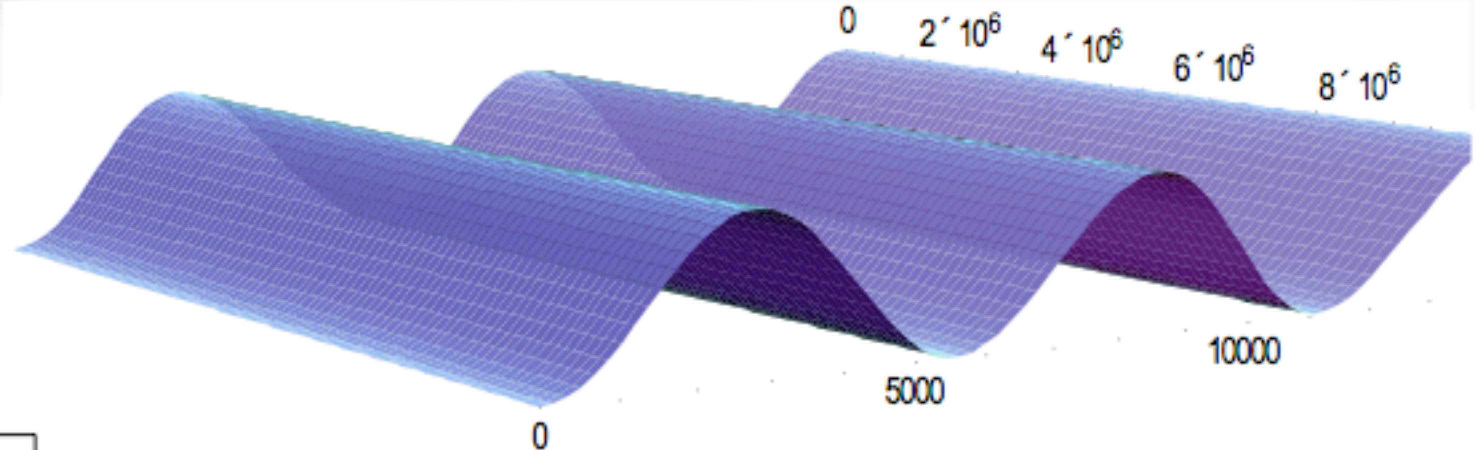


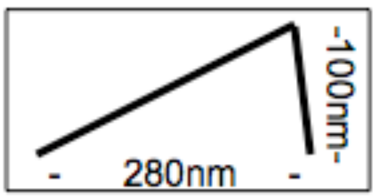
$F_{Casimir} = \not{?} > 0$ (!)



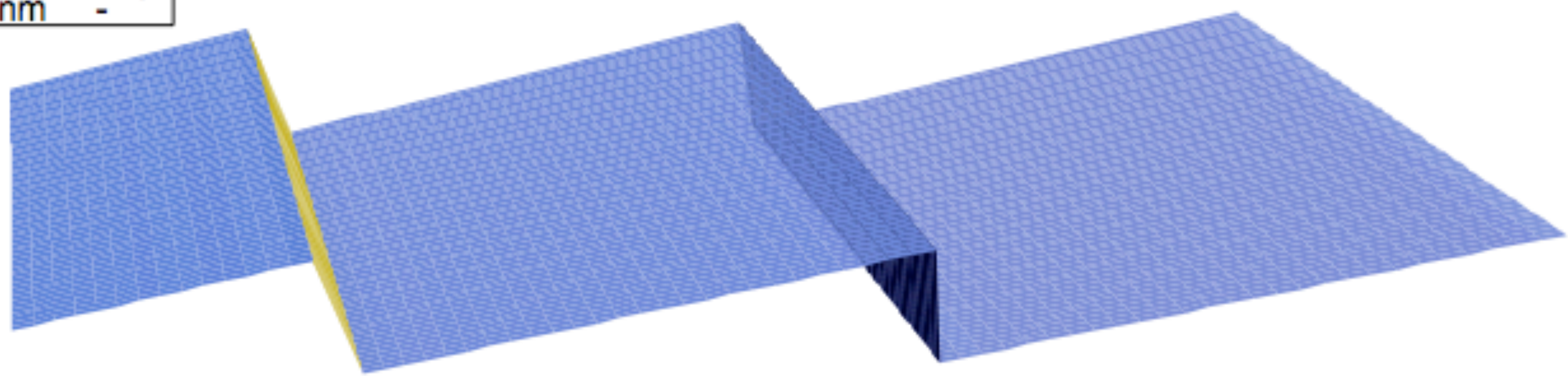
Nano-Structured Surfaces

Au





Al



nano structuring --> huge increase in reflectivity!

New impulse for Hydrogen

Experiment:

(DeKieviet et al. 1994 -)

Theory:

(Nachtmann et al. 1994 -)

Atomic Beam Spin Echo

sensitve interferometer

Quantum Reflection

atom-surface interaction

Casimir-Polder

vacuum QED

Sokolov results

Casimir-like 2S-2P mixing

$\Delta E_{Weak} \sim 100$ Hz

?

PNC pitfalls

$\sim (H_{Weak})^2$, when T-symmetric

Chiral Boxes

$\sim H_{Weak}$, when T-violation

Complex Degeneracy

$\sim \sqrt{H_{Weak}}$, when $|\Delta E_{Lamb}| \approx 0$

Geometric phases:

H_{Weak} $\Delta\phi_{PNC}$ <=> $\Delta\phi_{Berry}$!

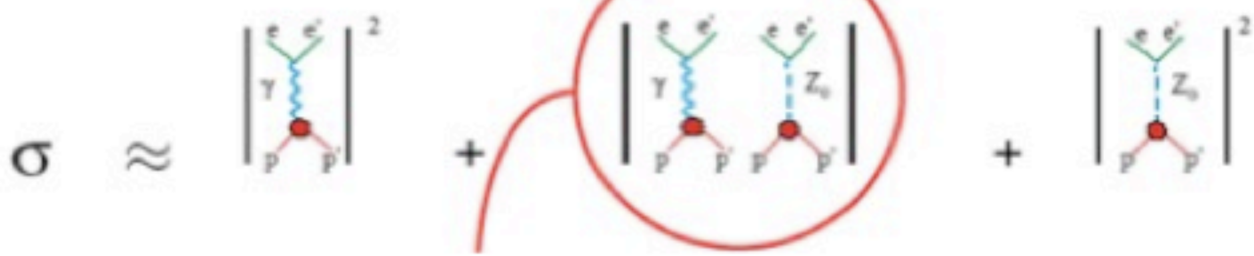
traditional Weak enhancement in H(2S)

- (nearly) degenerate levels of opposite parity:

$$|\psi_{2S}{}^{*}\rangle \approx |\psi_{2S}\rangle + \frac{\langle\psi_{2S}|H^{Weak}|\psi_{2P}\rangle}{|E_{2S} - E_{2P}|}|\psi_{2P}\rangle$$

⇔ small Lamb shift ⇒ large mixing ! !

- Stark interference (EM and Weak amplitude):

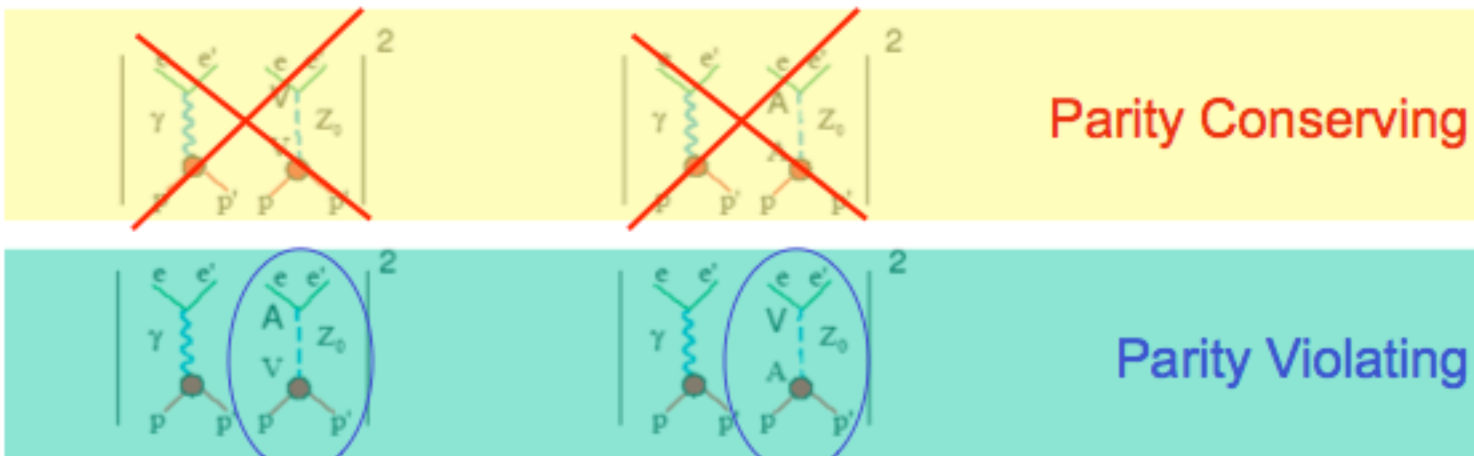


~1 ~10^{-6} ~10^{-12}

enhancement factor !

New Info from H(2S)

$\psi_{|2S\rangle}(r=0) \neq 0 \Rightarrow$ many point-like e^- - p^+ interactions:



Vector-Form Factor   Axial-Form Factor

$Q_W^{(1)} \approx 0$ $Q_W^{(2)} \neq 0$

not measured in APV yet!

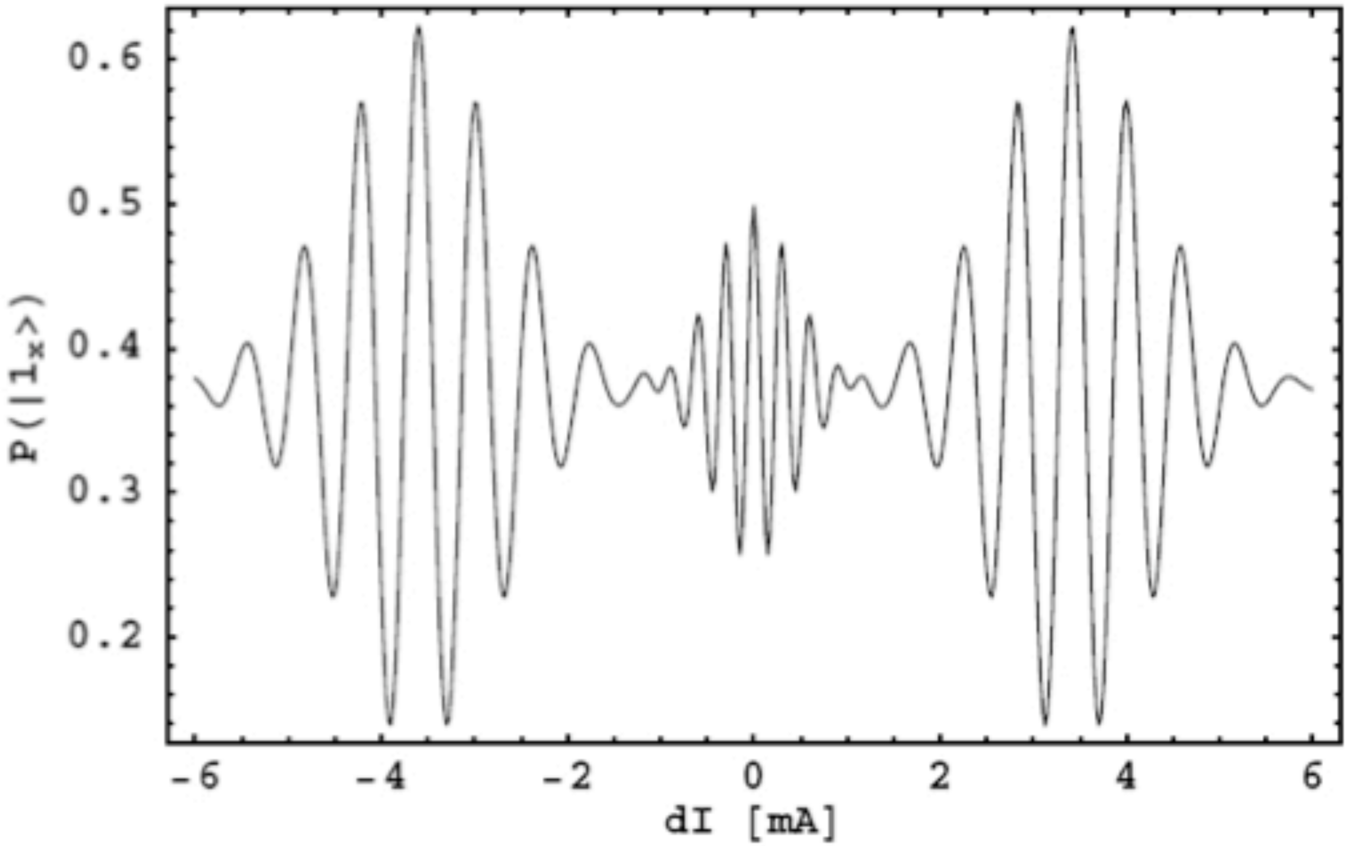
The Heidelberg approach

Berry Phases in the Quantum Reflection of H(2S) atoms from a diffraction grating

1. Atom Interferometry
   - H(2S) Atomic Beam Spin Echo => QM phases => „chiral boxes"
   - Multiple Spin Echo Groups => systematics => separation of PNC from PC effects

H(n=1) Spin Echo - dynamic phase

3 Spin Echo Groups!



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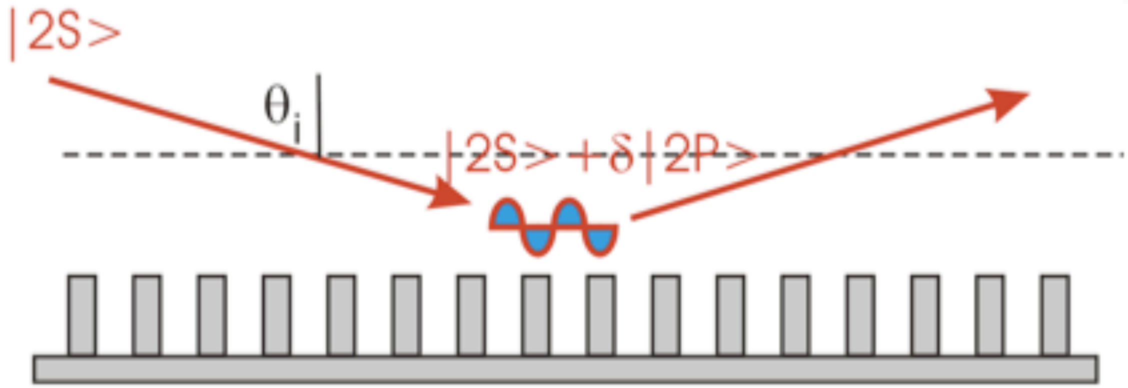
2. Atom-Surface interaction
   - Chirality => (v, B, E_{eff}) => PV Signature
   - Quantum Reflection => H(2S) survival => Intensity
   - Admixture (2S+δ2P) => enhancement of PNC over PC contributions => Intensity
   - Grating => many interactions => accumulated phase

Experimental Scheme II

Quantum Reflection of H(2S) from a diffraction grating



- Atom - Surface interaction ⇒ "E_{eff}"
- close to surface => large 2S-2P state mixing!
- Casimir-like interaction
- Quantum Reflection (at distance ≈ 1 μm) => avoid "touch-down"
- acquire geometric (Berry) phase => accumulative!

The Heidelberg approach

Berry Phases in the Quantum Reflection of H(2S) atoms from a diffraction grating

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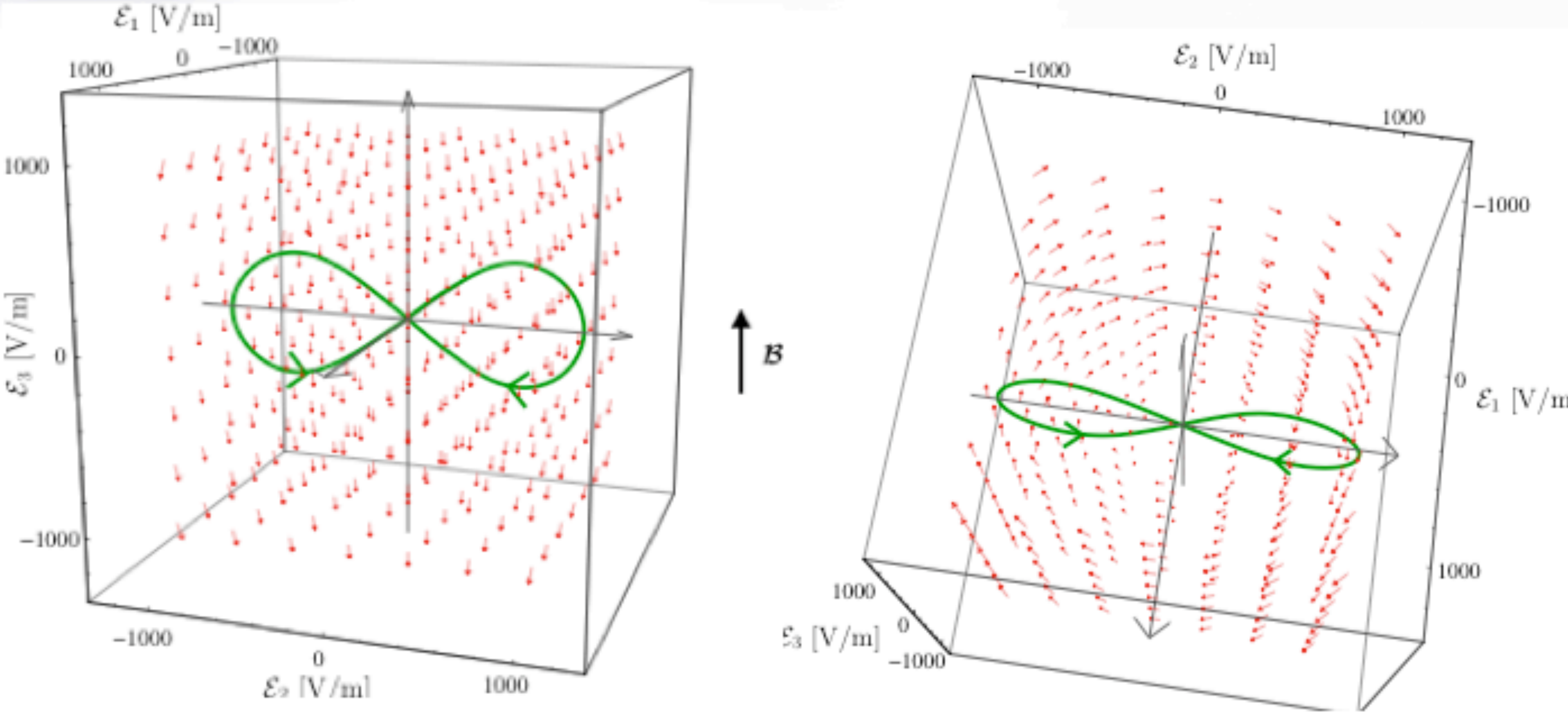
   - Grating => many interactions => accumulated phase

3. Geometric Berry Phase
   - Robustness => coherence time => resolution
   - Selected Trajectories => separation of PNC from PC phases => clear Signature

Calculated Signal

trajectories in (**E**,**B**)-parameter space
-> geometric phases



Parity Conserving

Parity NonConserving

ABSE & PNC: putting it all together ...

☑ 1. Atom Interferometry

- H(2S) Atomic Beam Spin Echo => QM phases => „chiral boxes"
- Multiple Spin Echo Groups => systematics => separation of PNC from PC effects

☑ 2. Atom-Surface interaction

- Chirality => (v, B, E_{eff}) => PV Signature
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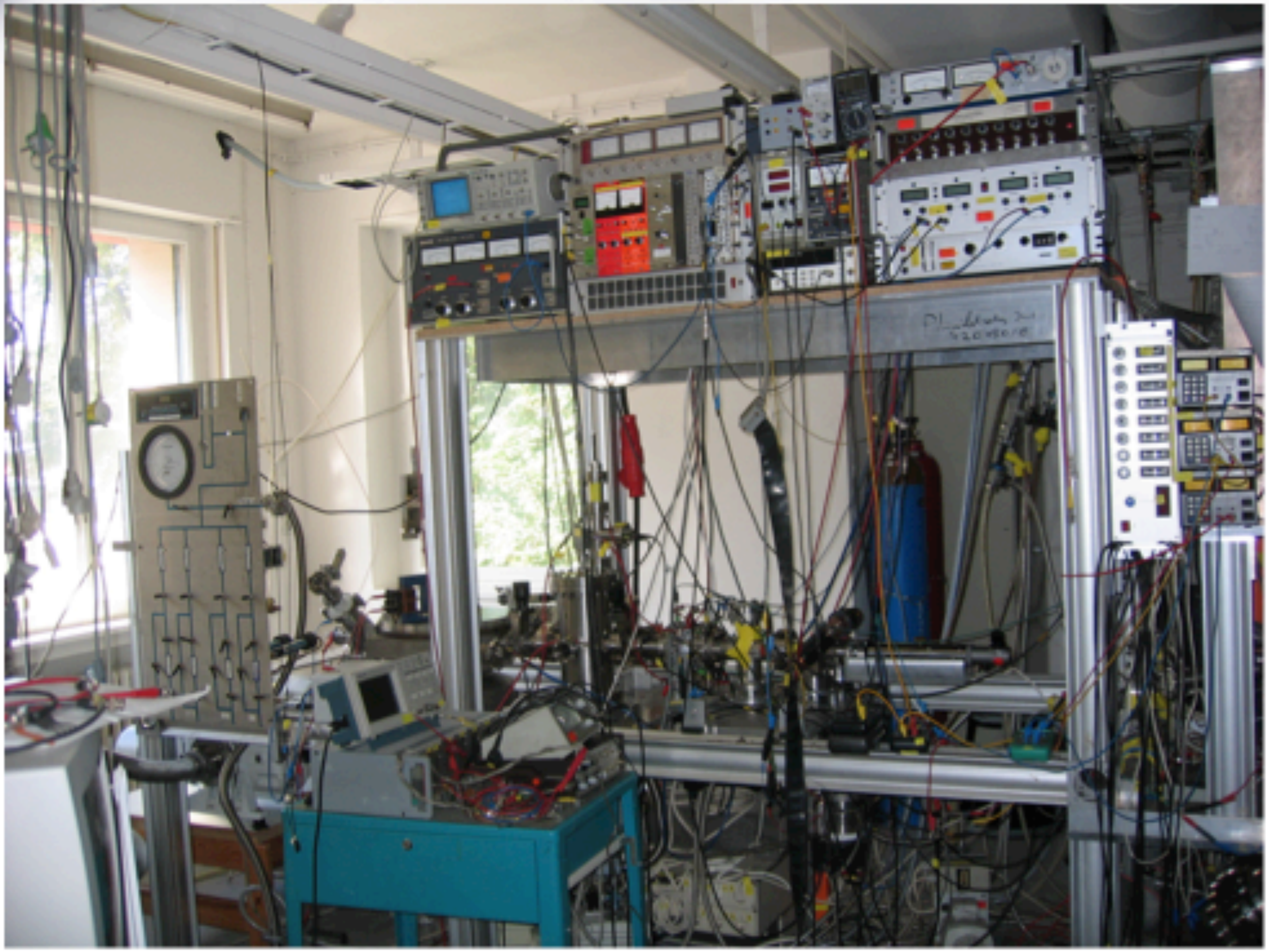
Berry Phases in the Quantum Reflection of H(2S) atoms from a diffraction grating

Experimental Setup



The Search for Parity Violation

in atomic hydrogen ...

… is to be continued !

for details see Eur. Phys. J. D (accepted)

Thanks !

Special thanks to:

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