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CENTRE NATIONAL
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LPL
Laboratoire de
physique des lasers

UNIVERSITÉ PARIS 13
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IFRAF

The physics of Atom- Surface interactions and its applications

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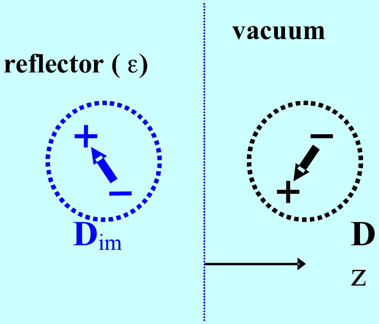
Critical Stability, Erice, Oct. 2008

ATOM-SURFACE VAN DER WAALS INTERACTION

The model of electrostatic images

(perturbative regime, non resonant coupling)



vdW potential
(interaction between
dipole and **dipole-image**)

$$H_{vdW} = -\frac{\varepsilon - 1}{\varepsilon + 1} \cdot \frac{D^2 + D_\perp^2}{16 z^3}$$

non-retarded and
near-field interaction: z^{-3}

D, atomic dipole operator

For a neutral atom , $\langle e|D|e\rangle = 0$, but $\langle e|D^2|e\rangle \neq 0$

(atomic dipole fluctuations)

$$\rightarrow < i|H|i > = - C_3(i) / z^3$$

Long-range interactions between atomic systems and surfaces

- Influence of the composite nature of the atomic system (internal energy level, ground/excited state, rotational symmetry, symmetry breaking…)

- "*real*" surfaces: dispersive materials, surface roughness

- Atom external dynamics: Quantum mechanical features of atomic motion (quantum reflection, bound states, interaction with "fast" (thermal) atoms…)

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Two experimental approaches

- Laser spectroscopy at vapor-dielectric interfaces (surface potential)

- Atom beam passing at surfaces (momentum spectroscopy- surface forces)

Long-range atom-surface interactions

OUTLINE

I. Introduction. Distance scaling

II. The surface response: material dispersion, temperature excitations…

III. Symmetry properties: symmetry break, inelastic vW reflection

IV. Quantum mechanical features. Conclusion

Spectroscopic Measurements

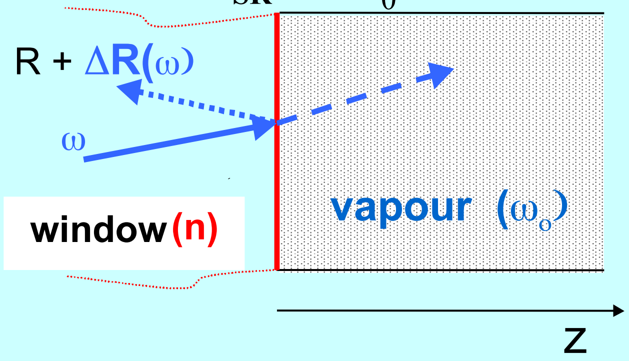
Optical Spectroscopy: DIFFERENCE between potentials $C_3(j) - C_3(i)$

Thermal vapours : spatial integration

Selective Reflection :

Resolution ~ $\lambda/2\pi$ ~ 100 nm

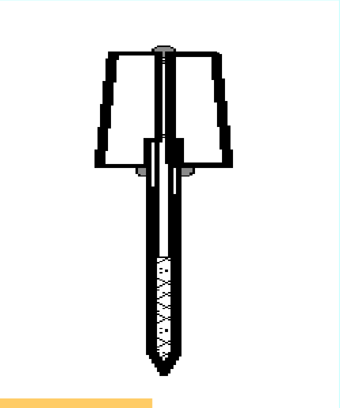
$$E_{SR} \propto \int_0^{+\infty} p(z)\, exp(2ikz)\, dz$$

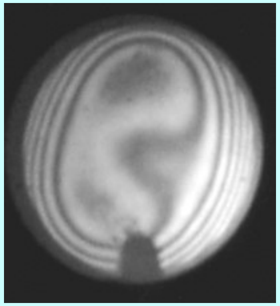


Thin Cells :

Mechanical confinement

thickness ~ 20-1000 nm



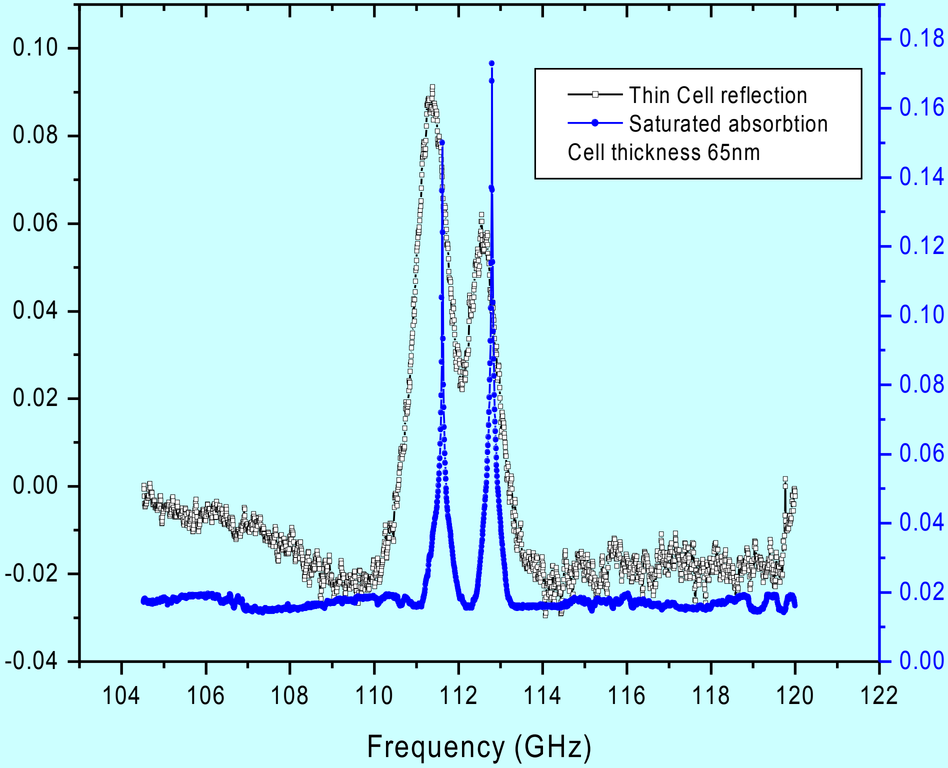


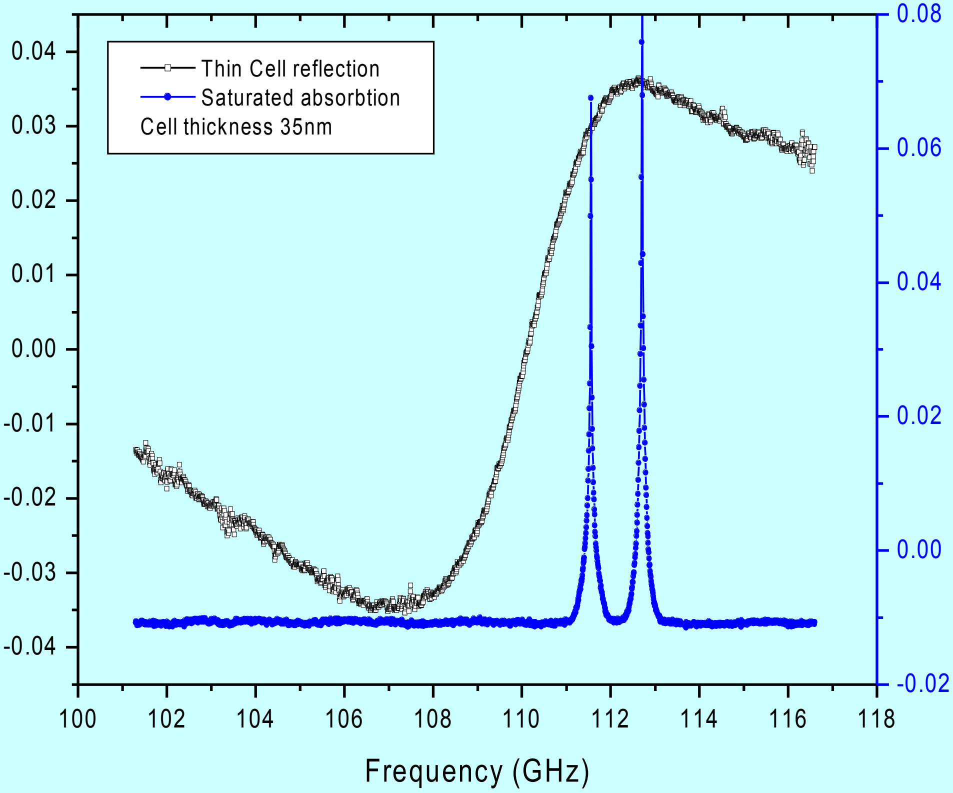
Cesium D_1 transition (894nm)

Reflection spectra on vapor nano-cells (FM mode)

65nm

35 nm





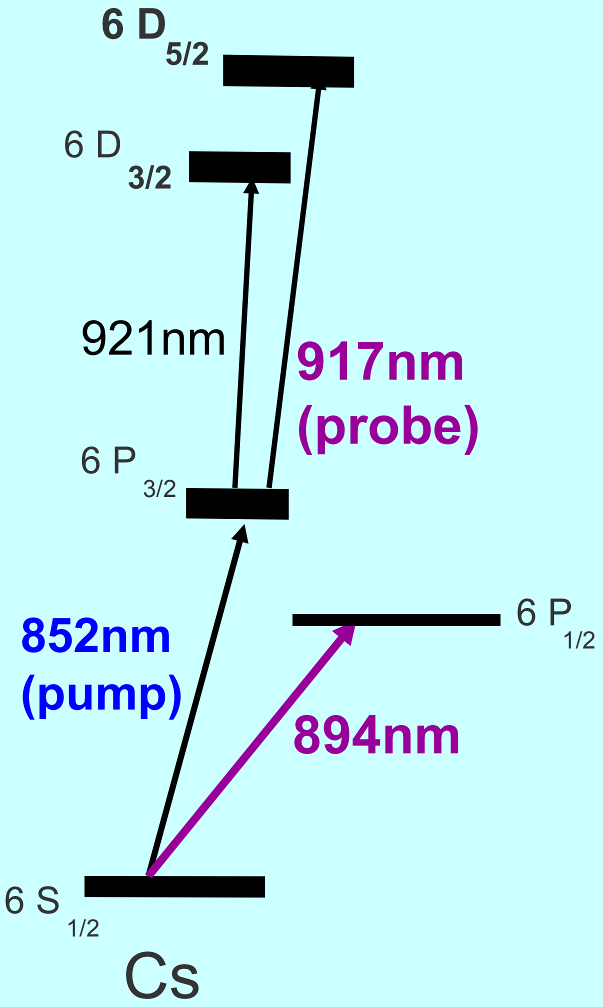
Modelling transmission spectra in nanocells

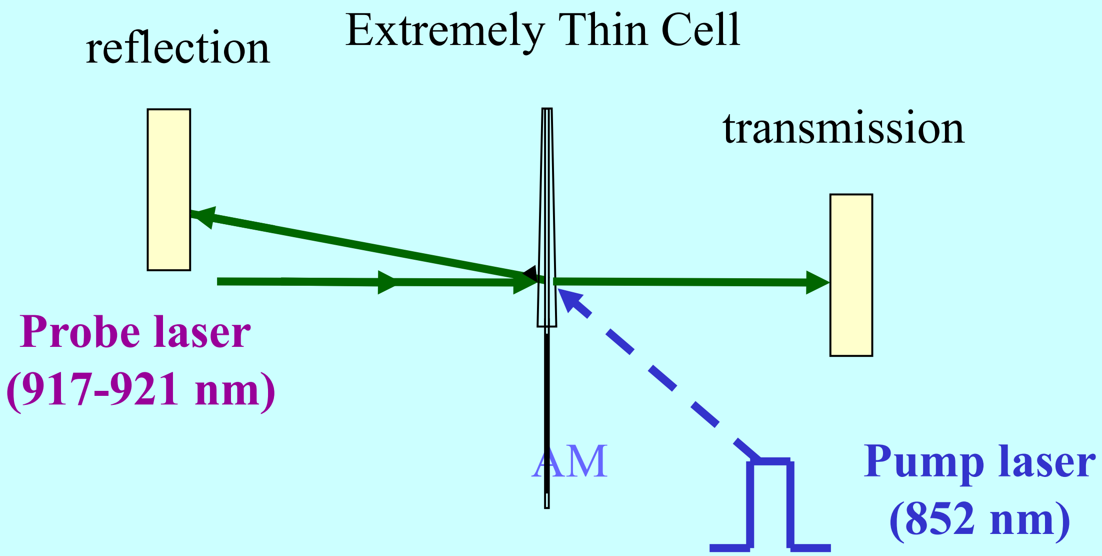
- **2-wall van der Waals potential** (adding 2 walls, or multiple image modeling)
- **Spatial integration** of transient interaction regimes in the nano-cell
- **Velocity distribution** *i.e.* distribution over atom-light interaction times
- **Pressure effects (**broadening, shift)

Transmission and Reflection spectra:

2 linearly **independent combinations** of
absorptive and dispersive properties

Experimental Principle

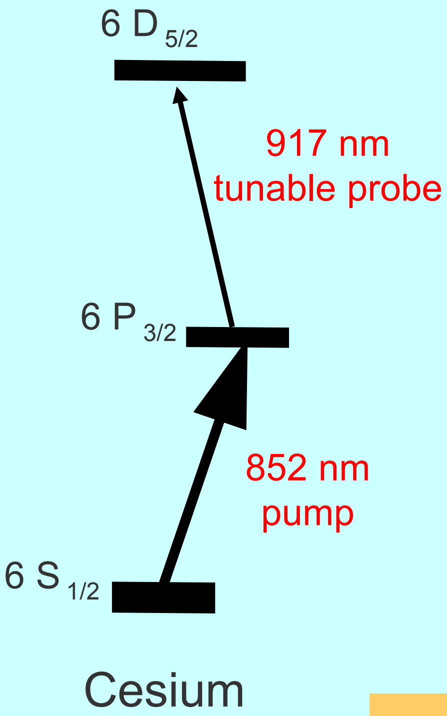


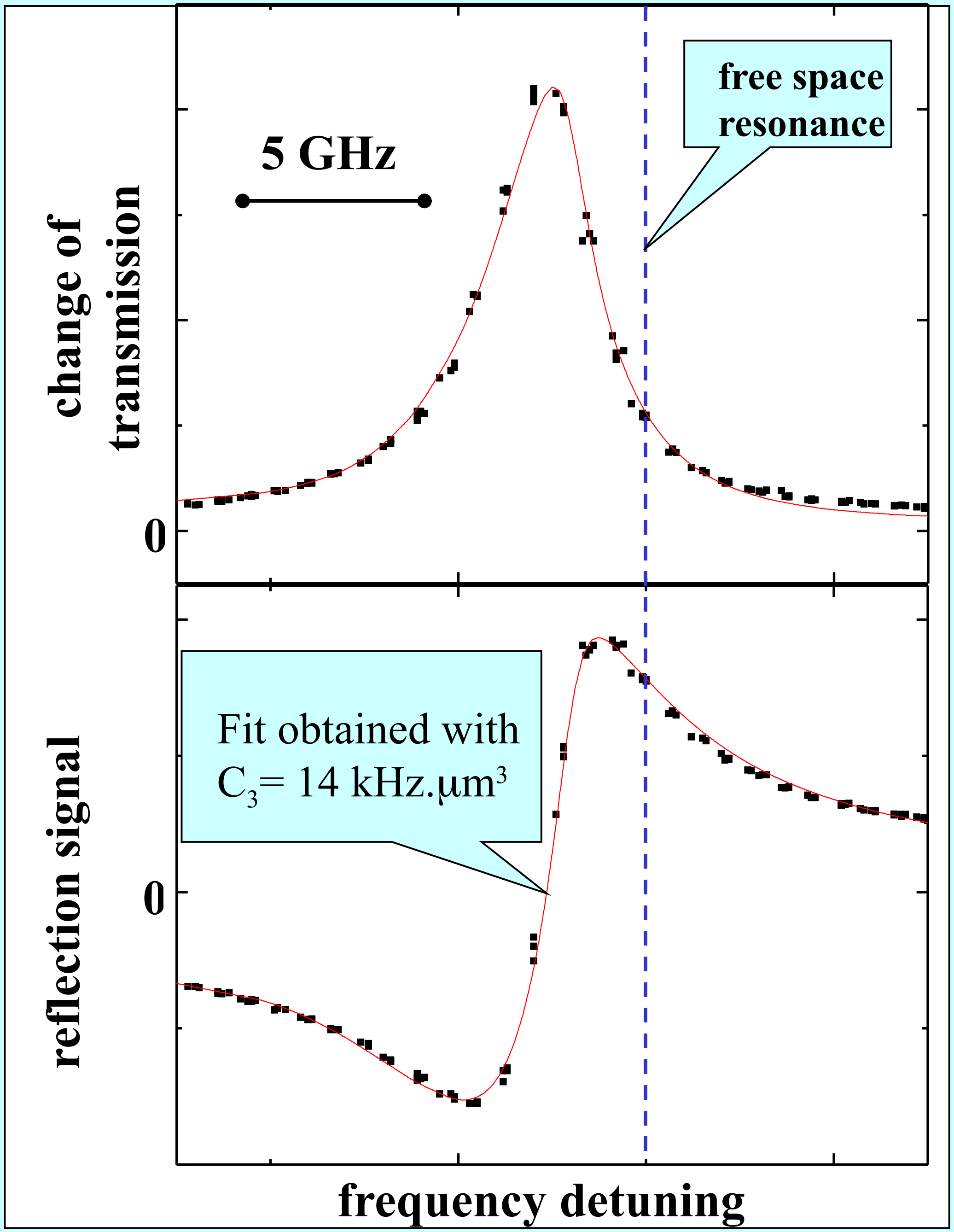


YAG/Cs thin cell transmission and reflection

strong red shift

L=50 nm
λ=917 nm
T=220°C,

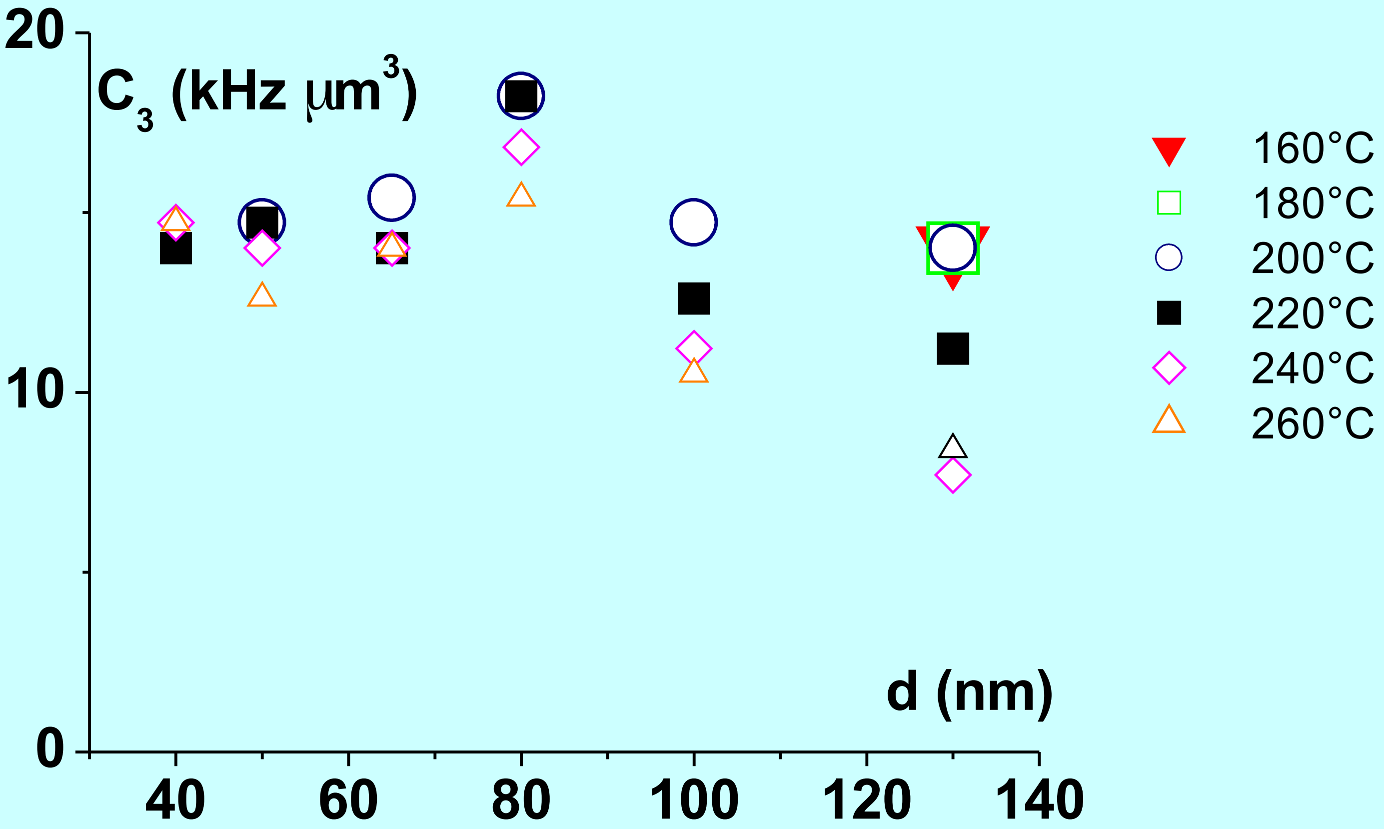




Fit obtained with C_3= 14 kHz.μm^3

YAG/Cs cell ; $6P_{3/2}$-$6D_{5/2}$ experiment

$\lambda = 917$ nm



$\nu = \nu_0 - C_3/z^3$

C_3 is found to be independent of thickness

M. Fichet *et al*, Europhysics Letters 77, 54001 (2007)

Long-range atom-surface interactions

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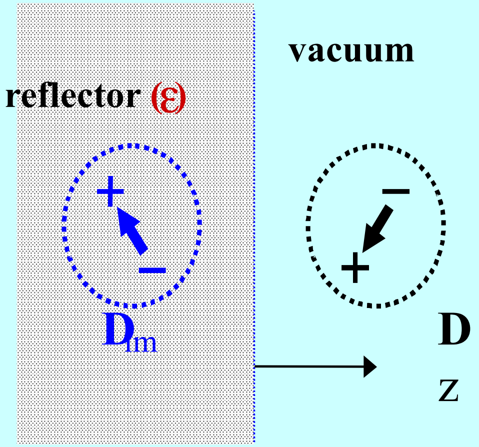
ATOM-SURFACE INTERACTION : *dielectric interface*

The model of Electrostatic images

vW potential : an interaction between **dipole** *and* **dipole-image**

$$H_{vw} = - \frac{\varepsilon - 1}{\varepsilon + 1} \frac{D^2 + D_z^2}{16 \, z^3}$$



A summing over virtual dipole transitions ω_{ij}

$$\langle i|D^2|i\rangle = \Sigma j \; r(\omega_{ij})\langle i|D|j\rangle \, \langle j|D|i\rangle$$

For $\varepsilon(\omega_{ij})$ ***complex*** (***i.e.*** **dispersion**)

How the image coefficient r behaves ?

IMAGE COEFFICIENT for DISPERSIVE DIELECTRICS

How (ε-1)/ (ε+1) is transformed ?

Virtual absorption

$\omega_0 \geq 0$

|g> Mac Lachlan or Mavroyanis 1963

$$r(\omega_0) = \frac{2}{\pi} \int_0^\infty \frac{\varepsilon(iu)-1}{\varepsilon(iu)+1} \frac{\omega_0}{\omega_0^2+u^2} du$$

$\boxed{0 \leq r \leq 1}$

Virtual emission

$\omega_0 \leq 0$

(concerns only ***excited*** atom)

Wylie & Sipe 1984-85, Fichet *et al* 1995

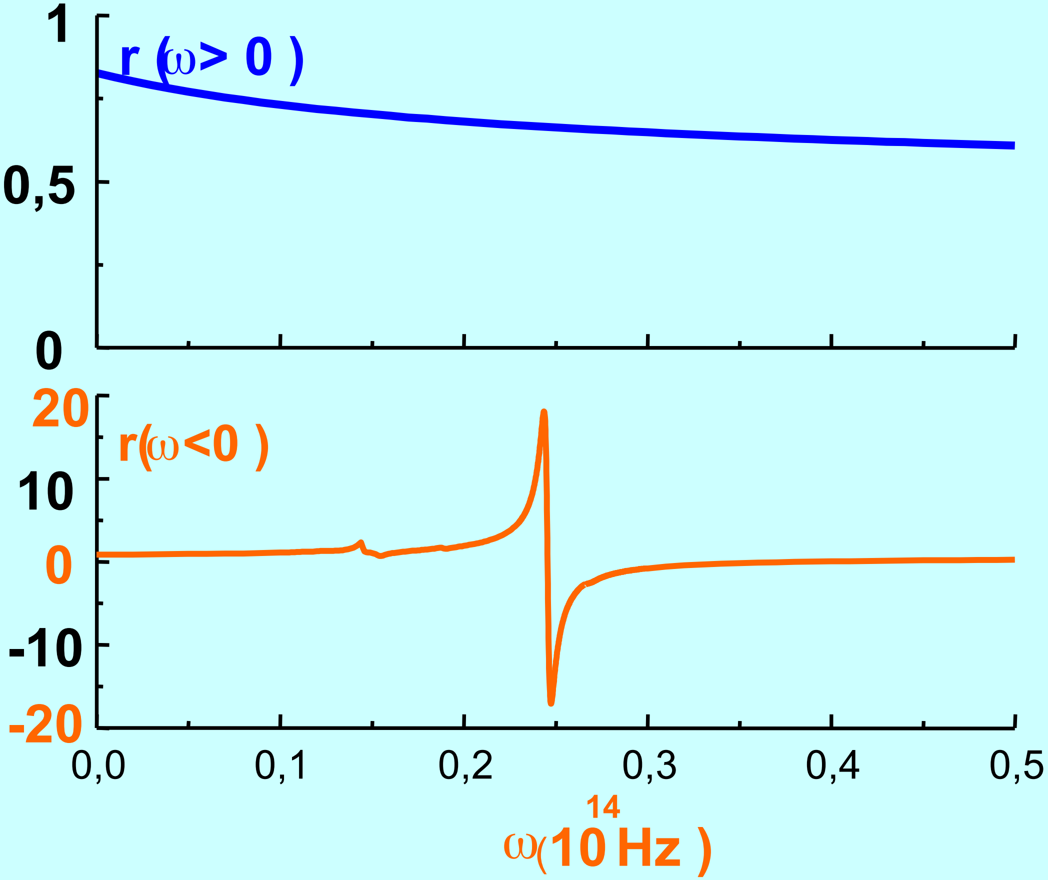
$$r(-|\omega_0|) = -\frac{2}{\pi} \int_0^\infty \frac{\varepsilon(iu)-1}{\varepsilon(iu)+1} \frac{|\omega_0|}{\omega_0^2+u^2} du + 2\,\mathrm{Re}\frac{\varepsilon(|\omega_0|)-1}{\varepsilon(|\omega_0|)+1} ,$$

r not bounded, r ≥0 or r ≤ 0

pole of [ε(ω)+1]→ resonant coupling *w/* surface mode (polariton)

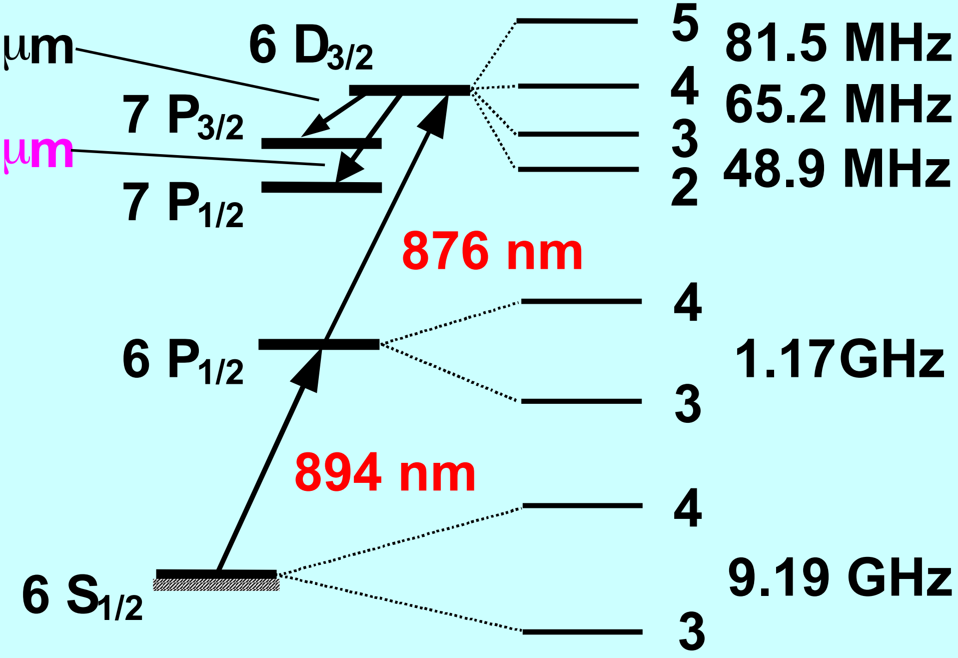
THE DIELECTRIC IMAGE COEFFICIENT

The case of **SAPPHIRE**

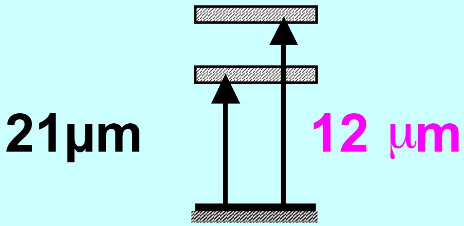


Virtual ABSORPTION of the atom (always **non resonant**)

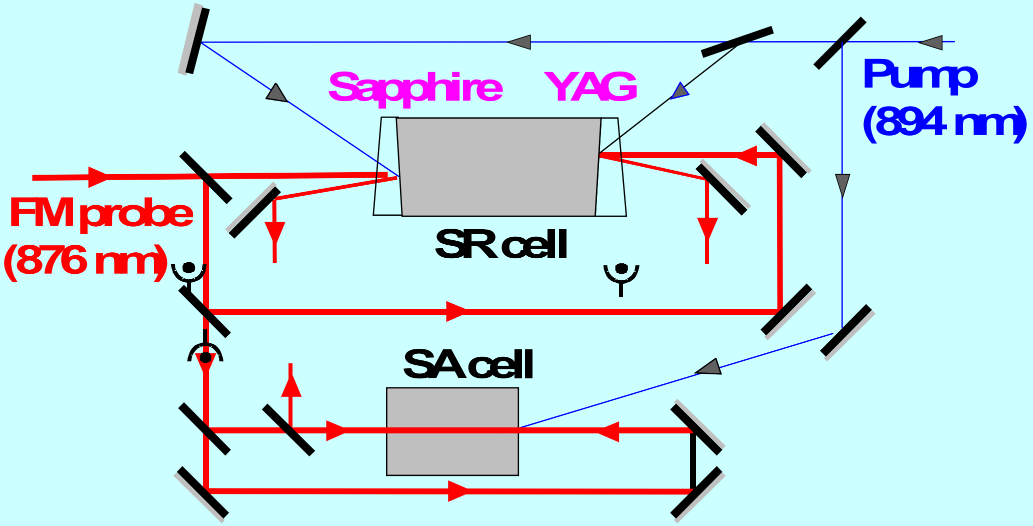
Virtual *EMISSION* of the atom : resonant COUPLING to a **ABSORPTION in a SURFACE POLARITON MODE: enhancement, van der Waals repulsion?**

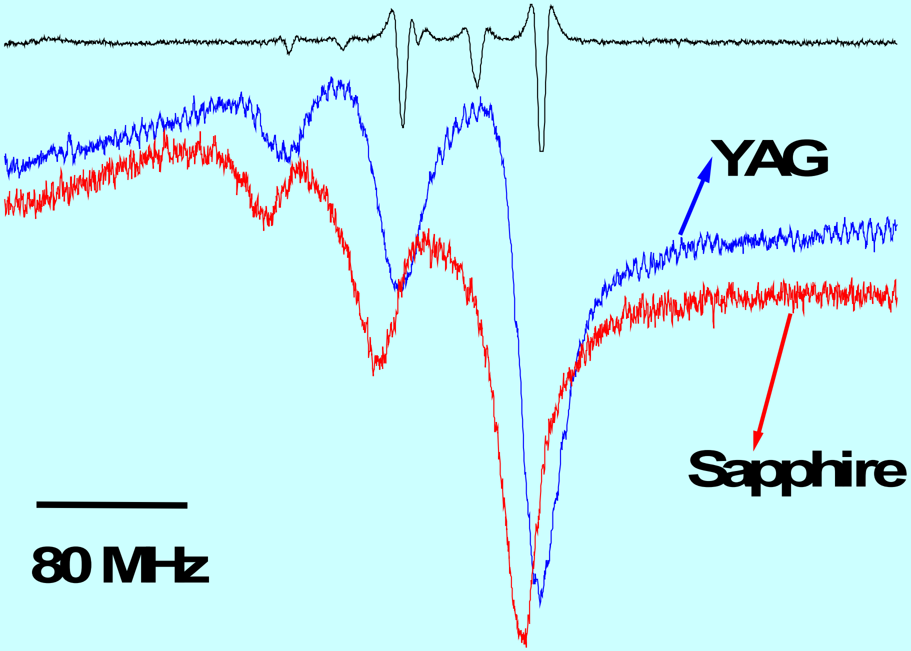


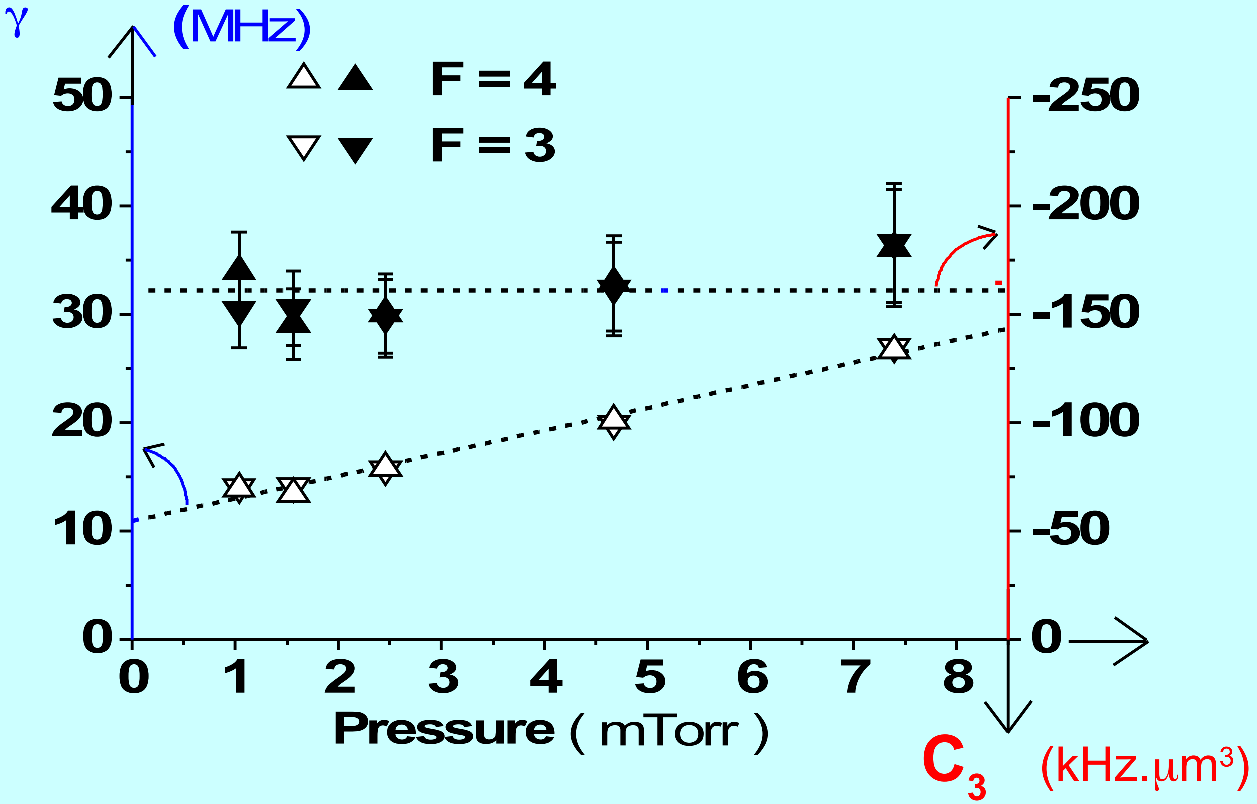
Cs



Sapphire surface polaritons




YAG
Sapphire
80 MHz



Cs $(6D_{3/2})$ and sapphire interface

Evidence of a vW surface repulsion ($C_3<0$) consistent with pressure broadening in spite of phenomenological changes in the line-shapes

Failache et al, PRL, **83**, 5467 (1999)

van der Waals energy shift at non-zero temperature

$$\delta E_a = -\frac{1}{12z^3}\sum_n \left|\langle a|D|n\rangle\right|^2 \left(\mathbf{r}_1^{\mathbf{an}} + \mathbf{r}_2^{\mathbf{an}} + \mathbf{r}_3^{\mathbf{an}}\right)$$

$$r_1(\omega_{na}, T) = -2\mathrm{Re}\, \frac{\varepsilon(\omega_{na}) - 1}{\varepsilon(\omega_{na}) + 1} \frac{e^{-\frac{\hbar\omega_{na}}{K_B T}}}{1 - e^{-\frac{\hbar\omega_{na}}{K_B T}}}$$

virtual *absorption* contribution

(null for **T=0)**

$$r_2(\omega_{an}, T) = +2\mathrm{Re}\, \frac{\varepsilon(\omega_{an}) - 1}{\varepsilon(\omega_{an}) + 1} \frac{1}{1 - e^{-\frac{\hbar\omega_{an}}{K_B T}}}$$

virtual *emission* contribution
increases with T

[stimulated emission ~<N>]

$$r_3(\omega_{na}, T) = +\frac{4k_B T}{\hbar}\sum_p^{\infty}{}' \frac{\varepsilon(i\xi_p) - 1}{\varepsilon(i\xi_p) + 1} \frac{\omega_{na}}{\omega_{na}^2 + \xi_p^2}$$

non-resonant contribution

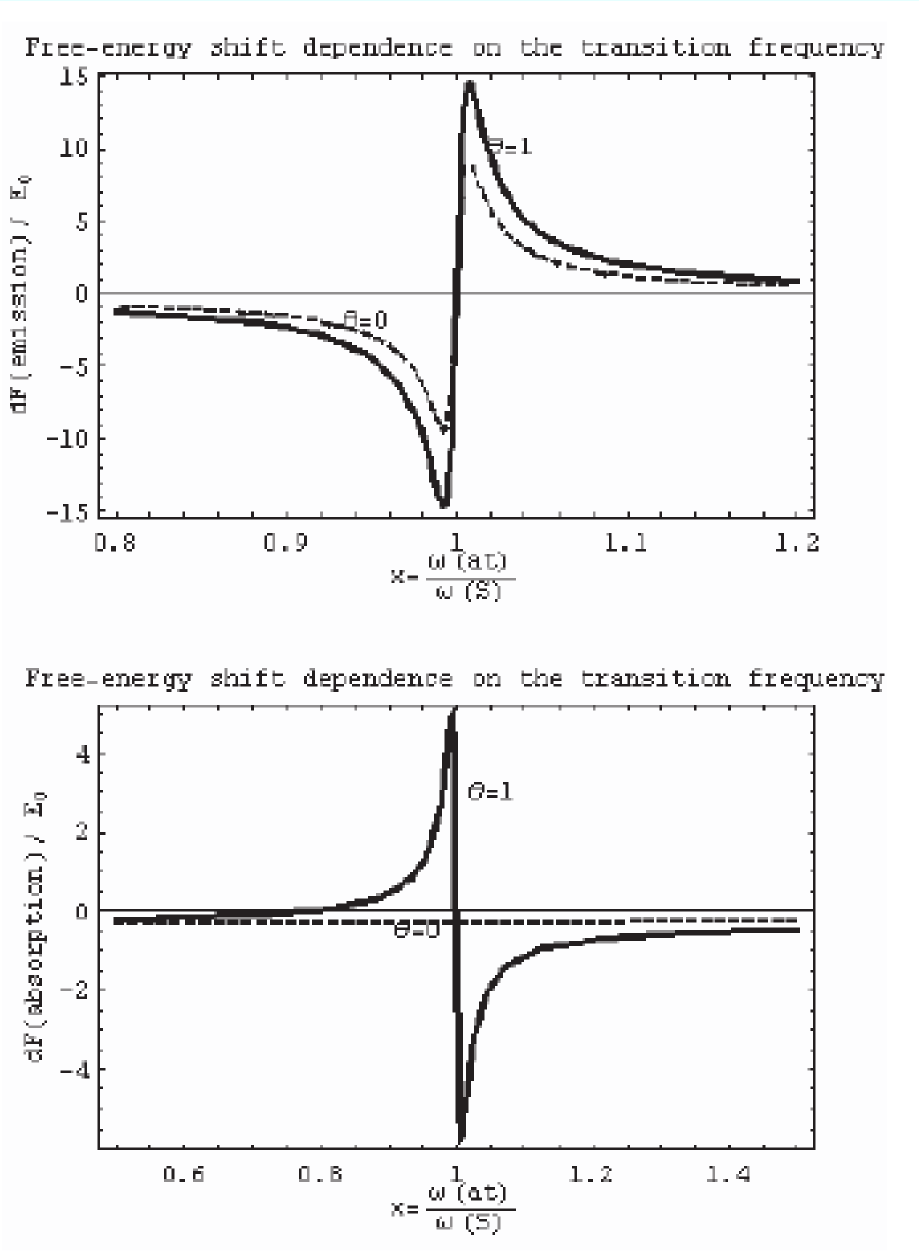
(known since Mac Lachlan 1963)

with $\xi_p = 2\pi k_B T/\hbar$

← **Matsubara frequency**

*M-P Gorza & M Ducloy, Eur. Phys. J. D **40**, 343 (2006)*

$$\theta = k_B T/\hbar\omega_S$$



Influence of surface thermal excitations

M-P Gorza & M Ducloy, Eur. Phys. J. D ***40****, 343 (2006)*

Long-range atom-surface interactions

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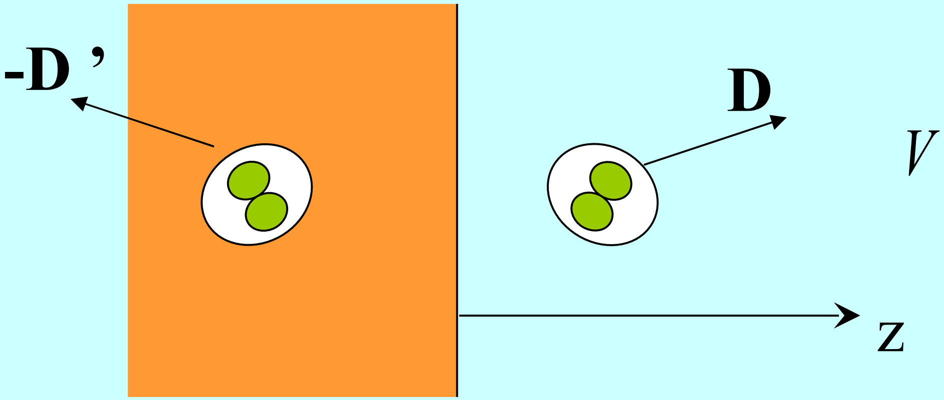
Non scalar van der Waals potential : a “prism” for atoms



$$V_{vdW} = -\frac{1}{4\pi\varepsilon_0}\left[\frac{(4/3)D^2}{16\,z^3} + \frac{D_Z^2 - D^2/3}{16\,z^3}\right]$$

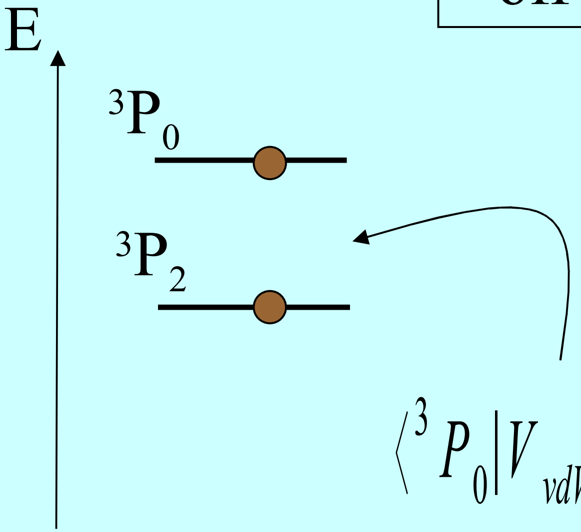
Scalar T^0_0

Anisotropic T^2_0
off-diagonal

$$\langle {}^3P_0 | V_{vdW} | {}^3P_2 \rangle \neq 0$$

Ar*, Kr*

2 metastable states, ${}^3P_2$ and ${}^3P_0$



Boustimi *et al.*, PRL, **86**, 2766 (2001)

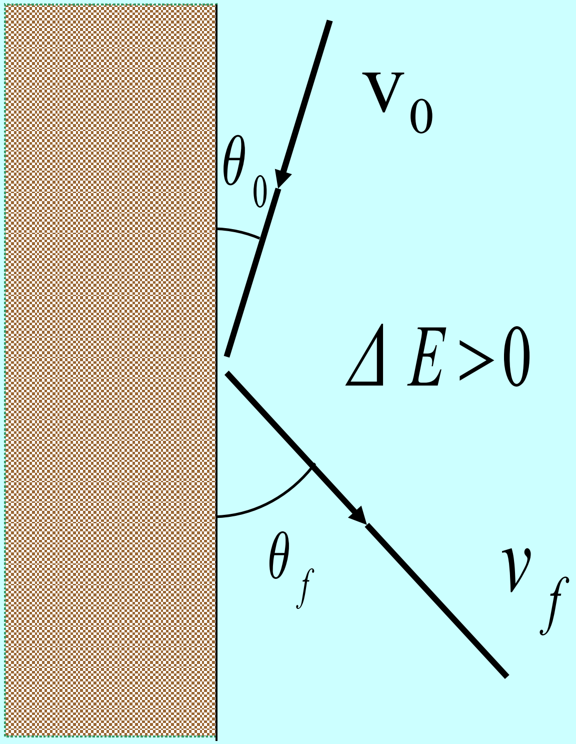
Kinematics of inelastic transitions

Conservation of total Energy of the atom:

$$v_f = \left[v_0^2 + \frac{2\Delta E}{m} \right]^{1/2}$$

Conservation of the linear momentum in the plane // to the surface:

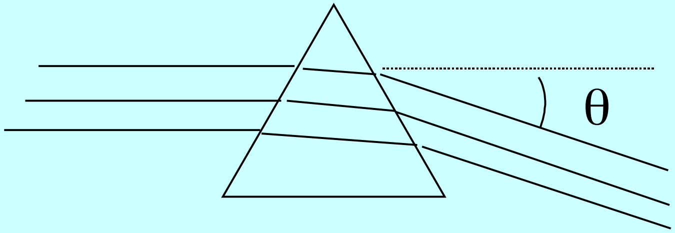
$$v_0 \cos\theta_0 = v_f \cos\theta_f$$



$$\cos\theta_f = \frac{\cos\theta_0}{\sqrt{1 + \frac{\Delta E}{E_0}}}$$

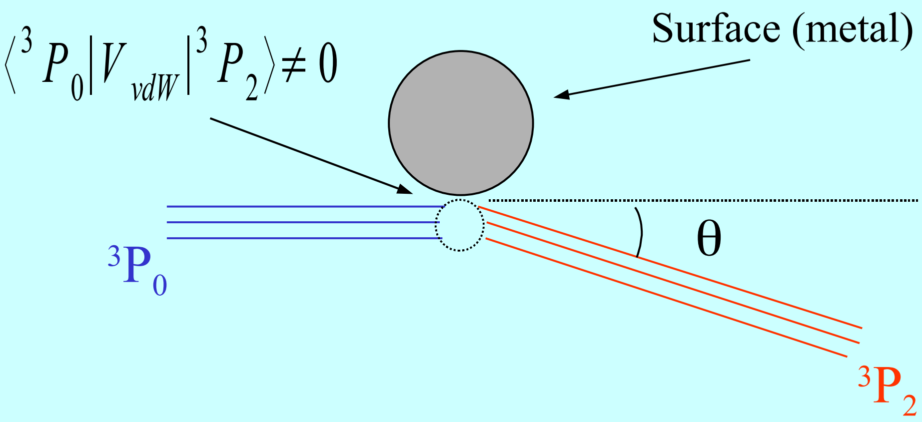
M. Ducloy, Critical Stability, Erice

Light Optics



θ

Atom Optics



$\langle {}^3P_0 | V_{vdW} | {}^3P_2 \rangle \neq 0$

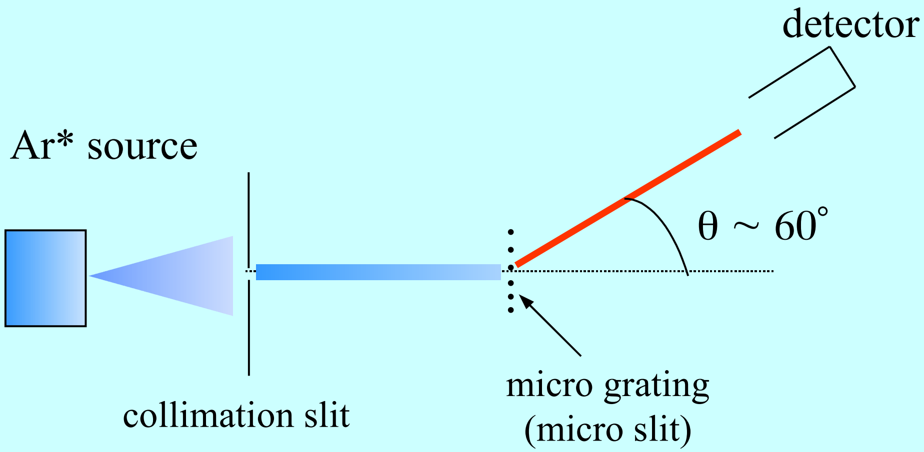
Surface (metal)

θ

${}^3P_0$

${}^3P_2$

Experiment



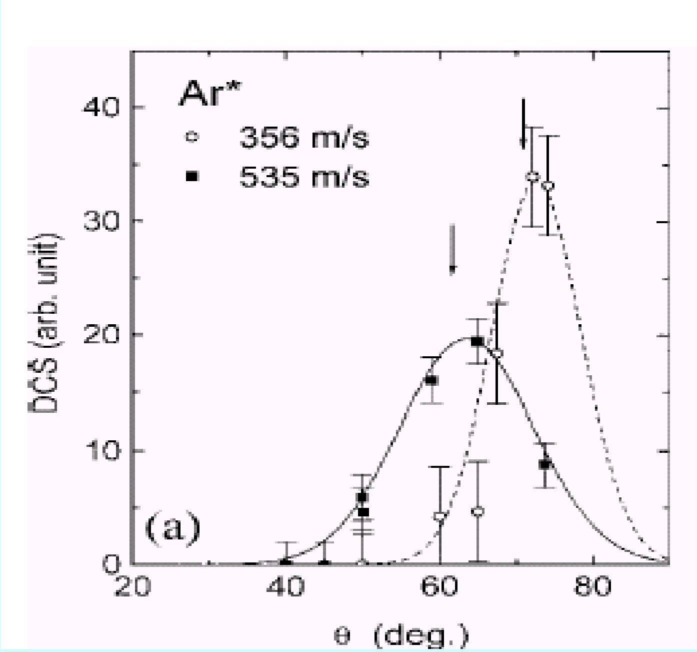
detector

Ar* source

θ ~ 60°

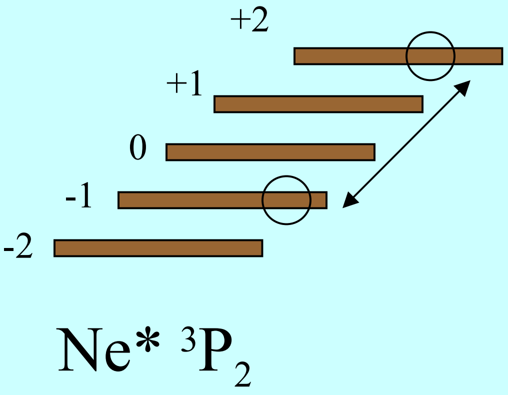
collimation slit

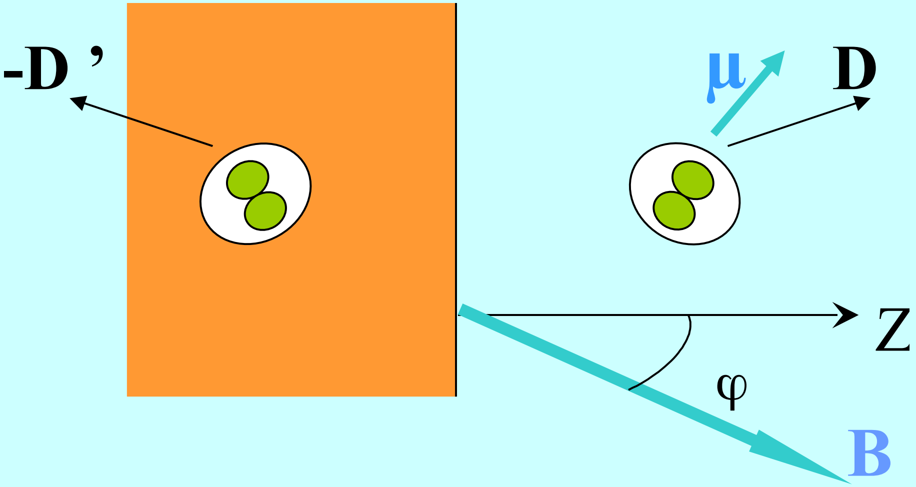
micro grating
(micro slit)



Boustimi *et al.*, PRL, **86**, 2766 (2001)

van der Waals – Zeeman Transitions



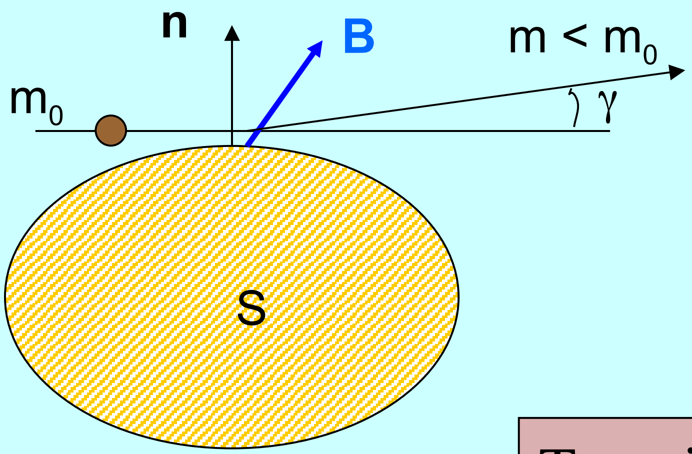


$$V = \underbrace{-\frac{C_3}{Z^3} + g\ \mu_B\ B(J\,.\,u_B)}_{\boxed{\text{diagonal}}} + \eta\ \underbrace{\left(J_Z^2 - \frac{1}{3}\ J^2\right)/Z^3}_{\boxed{\text{quadrupolar}}}$$

$$\left\langle {}^3P_2, m_i \middle| V \middle| {}^3P_2, m_j \right\rangle \neq 0$$

Karam *et al.*, Europhys. Lett., **74**, 36 (2006)

van der Waals-Zeeman transitions



Two quantisation axes :

- scalar + quadrupolar vW interaction (**n**)

- magnetic interaction (**B**)

Transitions among Zeeman sublevels $m_0 \rightarrow m$

For $m < m_0$, repulsive deflection by an angle:

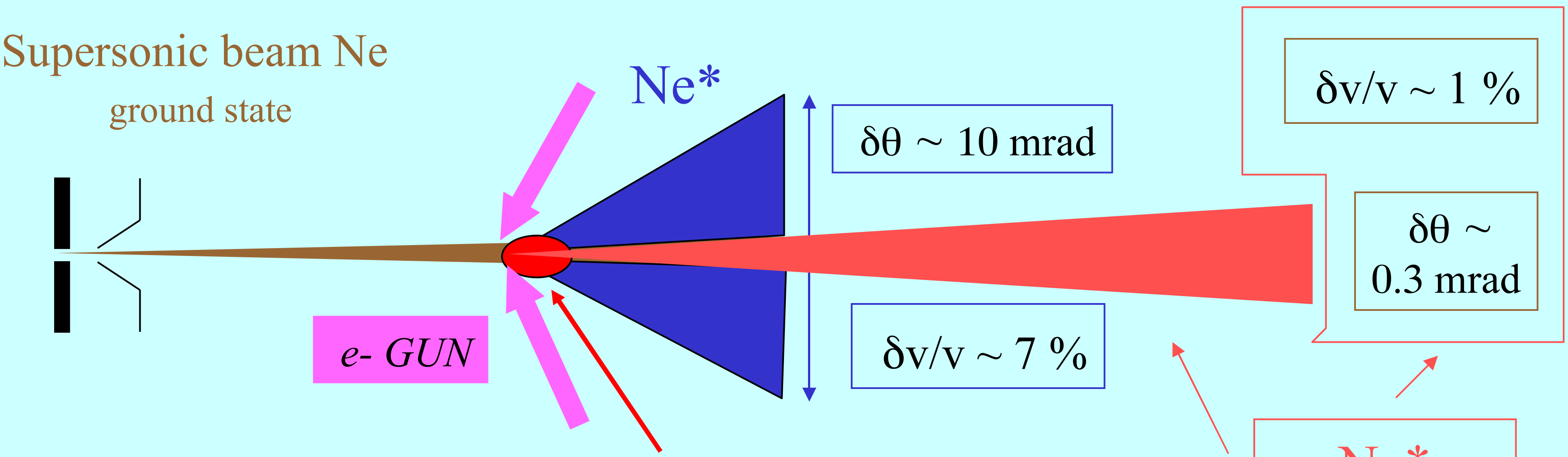
$\gamma \approx \mathbf{(\Delta E / E_0)}^{1/2}$, where $\Delta E = g\mu_B B \,|\Delta m|$ (internal energy defect)

γE_0 = incident kinetic energy

typically: $\gamma \sim$ mrad $\longrightarrow$ $\delta\theta$ (beam) < mrad

Karam *et al.*, Europhys. Lett., **74**, 36 (2006)

Ultra narrow metastable Ne* atoms Beam



Supersonic beam Ne

ground state

e- GUN

Ne*

δθ ~ 10 mrad

δv/v ~ 7 %

δv/v ~ 1 %

δθ ~ 0.3 mrad

Ne*

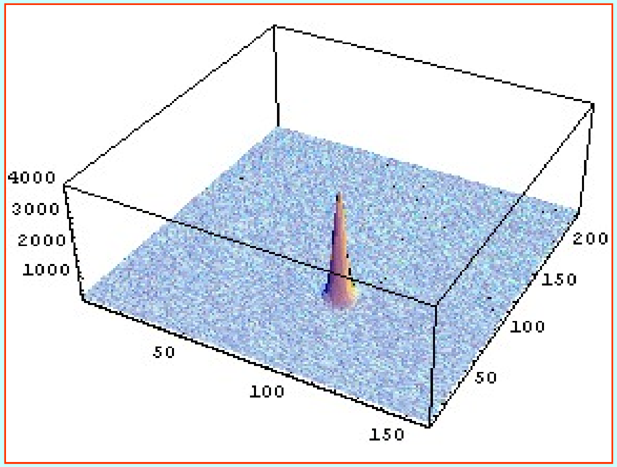
Metastable

+

Initial beam qualities

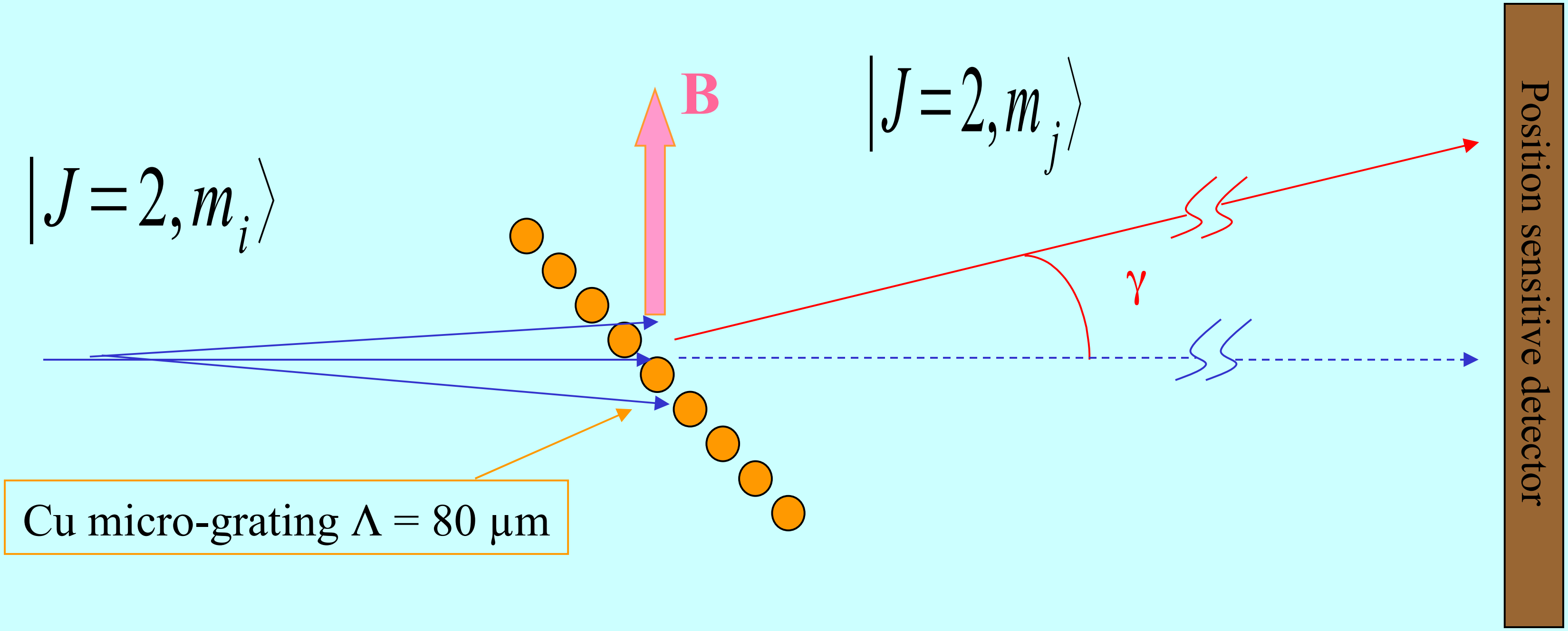
Metastability Exchange

Ne* + Ne → Ne + Ne*



Karam *et al,* J. Phys. B, 2005

Experiment



$|J=2,m_i\rangle$

B

$|J=2,m_j\rangle$

γ

Cu micro-grating Λ = 80 µm

Position sensitive detector

B = 100 to 600 G

Grating → several slits covered : larger available surface

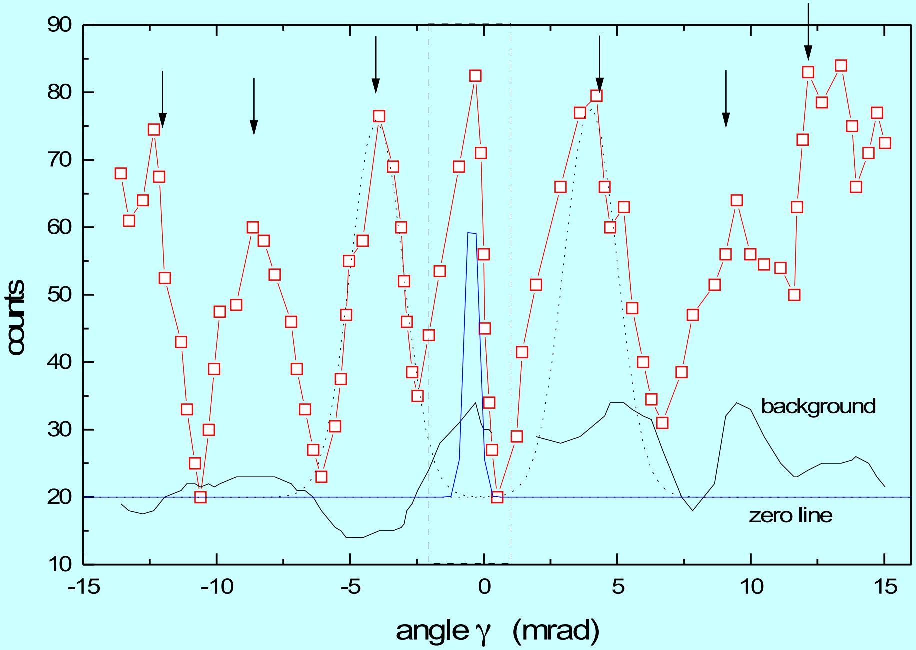
Tilted Grating → Better contrast of scattered signal

ANGULAR SPECTRA

B = 289 Gauss

In blue: incident beam profile (δθ = 0.35 mrad)

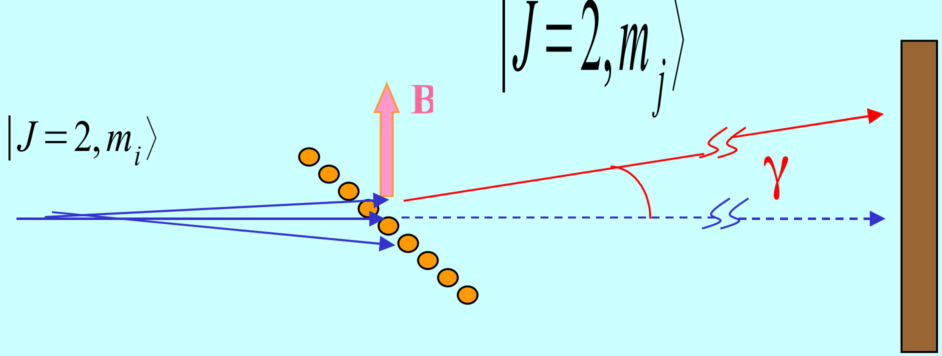
Peaks are widened by diffraction (dotted line)



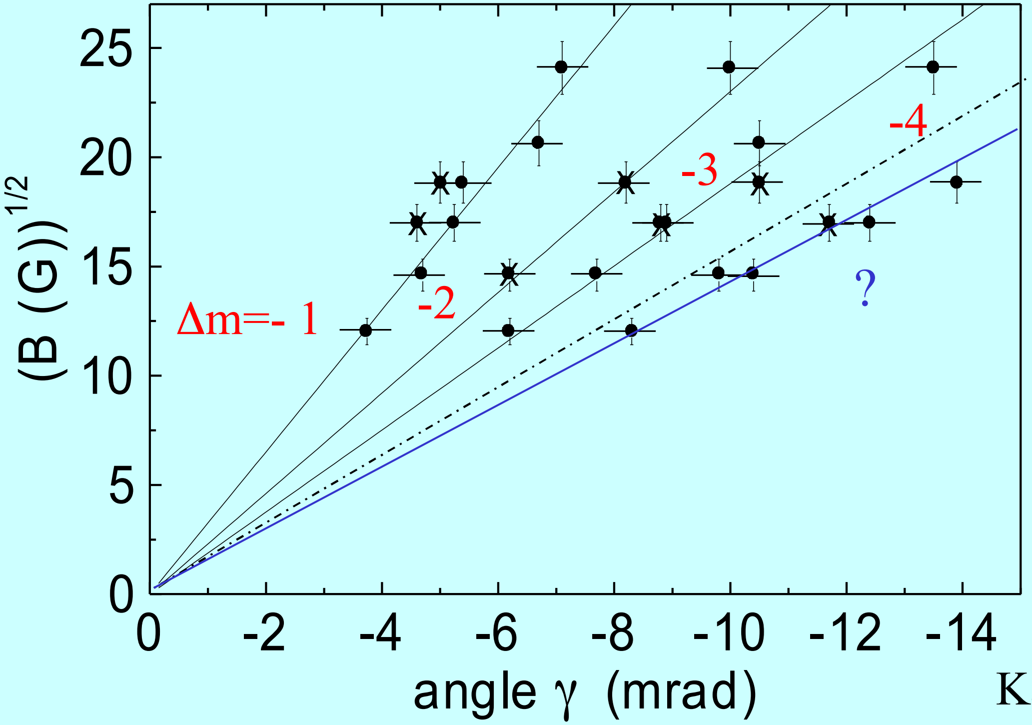
Metastable Ne*($^3P_2$) atoms traverse a micrometric copper grating

submitted to a static magnetic field B. Exo-energetic transitions (Δ m = -1, -2, -3, -4) are identified by the deflection angles γ

This is a multiple & tunable beam splitter



$$\gamma \approx \sqrt{\Delta E / E_0} = \sqrt{g\mu_B / E_0}\,\sqrt{B}\,\sqrt{|\Delta m|} \Longrightarrow \sqrt{B} \propto \frac{1}{\sqrt{|\Delta m|}}\gamma$$



No adjustable parameter

Evidence
for vdW – Zeeman
transitions

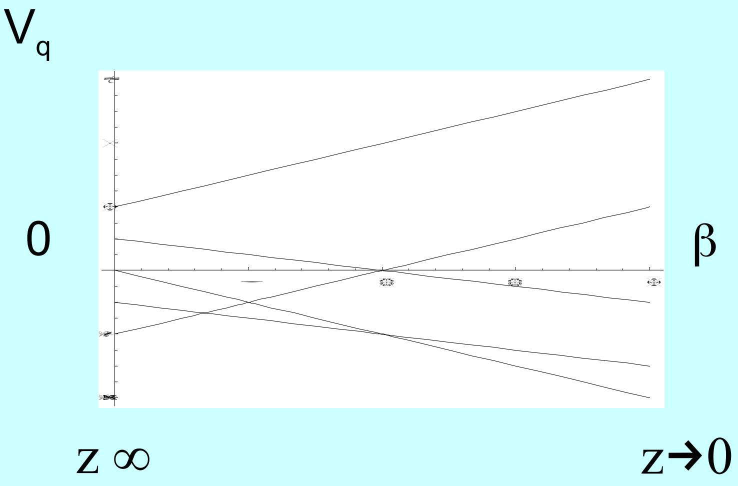
Karam *et al.*, Europhys. Lett., **74**, 36 (2006)

Avoided crossings between Zeeman sublevels of Ar (J=2)

$$V = -\frac{C_3}{z^3} + g\ \mu_B\ B(J\,.\,u_B) + \eta\ (J_Z^2 - \frac{1}{3}\ J^2)/z^3$$

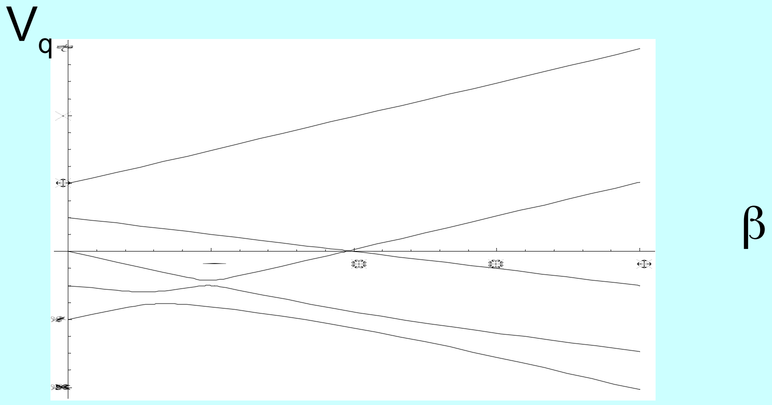
B strictly normal to the surface (θ=0)

Level crossings for β=1/3, 1/2,1



B off-normal

Avoided crossings
$\theta = (\mathbf{u}_B, \mathbf{u}_S) = 17°$



For B=1G, the first level crossing appears at z~20 nm

$$\beta = \frac{-\eta}{g\ \mu_B\ B\ z^3}$$

Theoretical description of vW-Z transitions

- Large velocity: short interaction time (<0.1ns), sudden approximation for the vW potential

- Small velocity: potential energy surfaces with anticrossings explored in the adiabatic regime

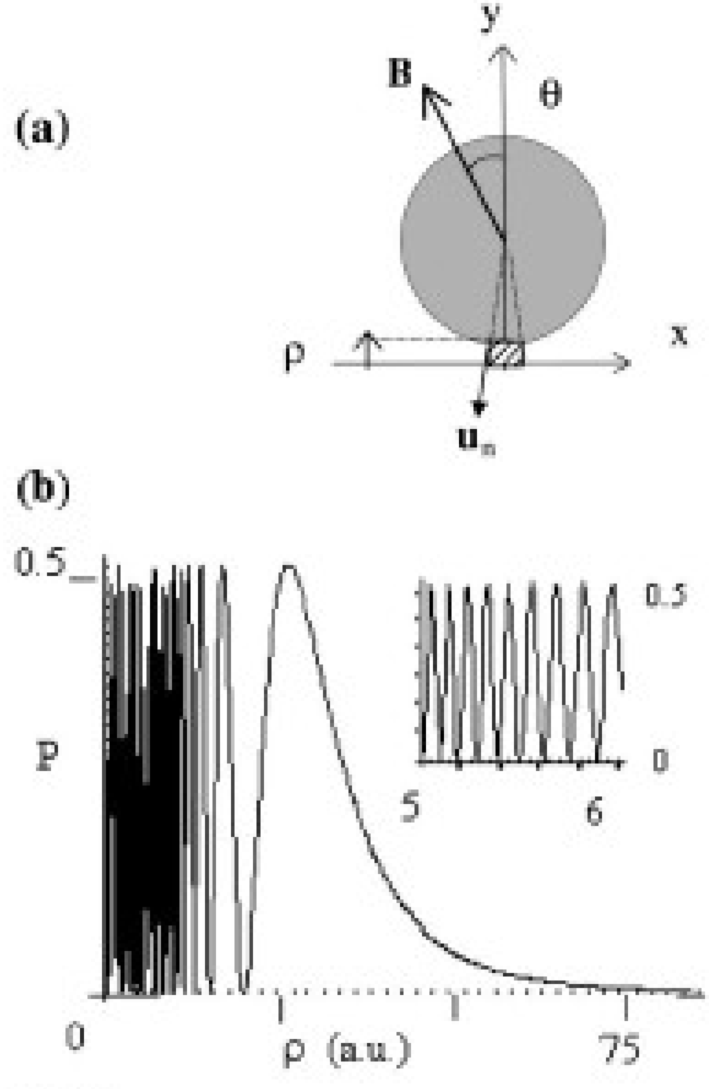


Fig. 4

Karam *et al.*, Europhysics Letters, **74**, 36 (2006)

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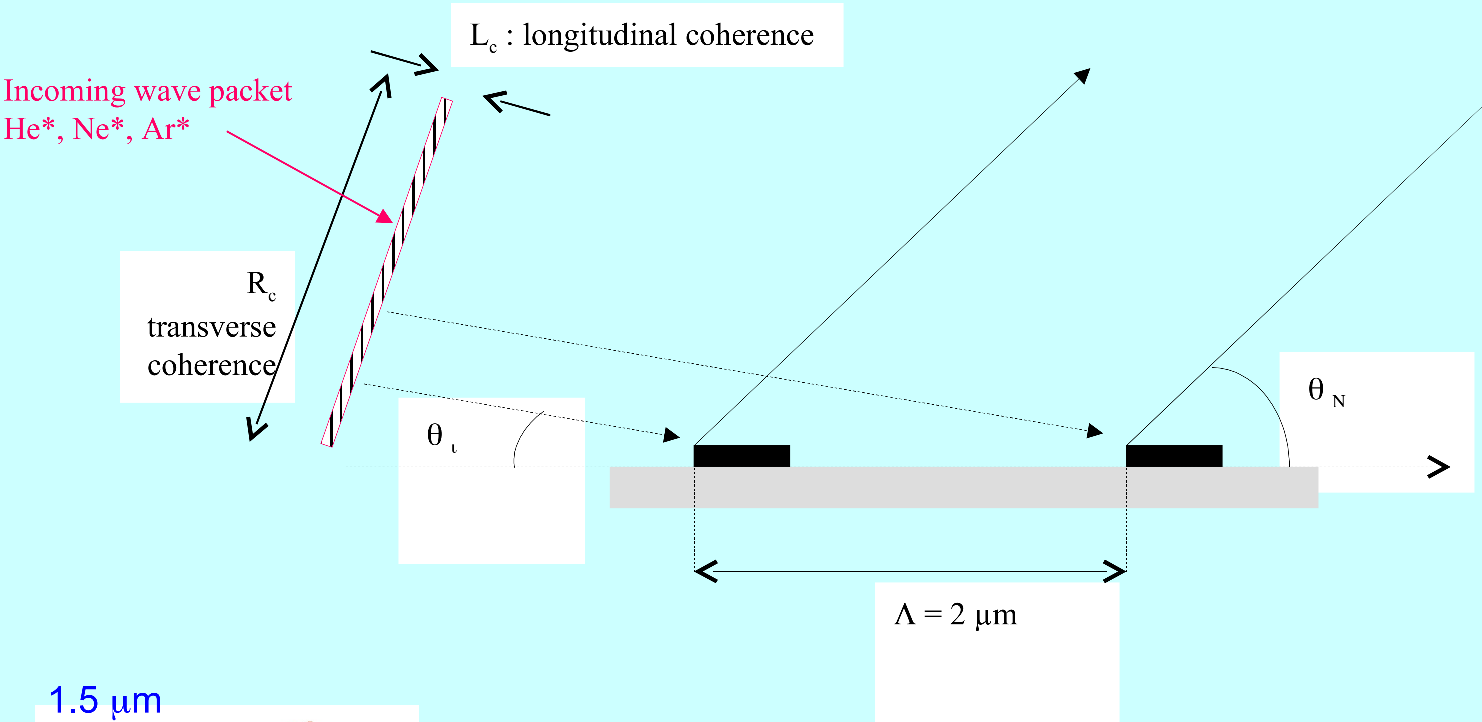
Diffraction experiment with 1D *reflection* grating
Fast metastable atoms: v ~ 1000m/s
Elastic scattering



L_c : longitudinal coherence

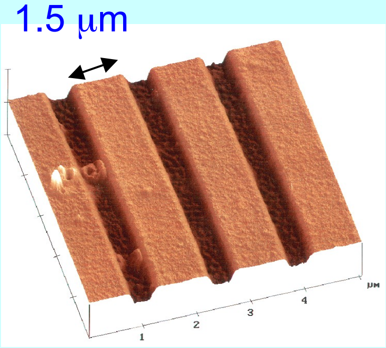
Incoming wave packet
He*, Ne*, Ar*

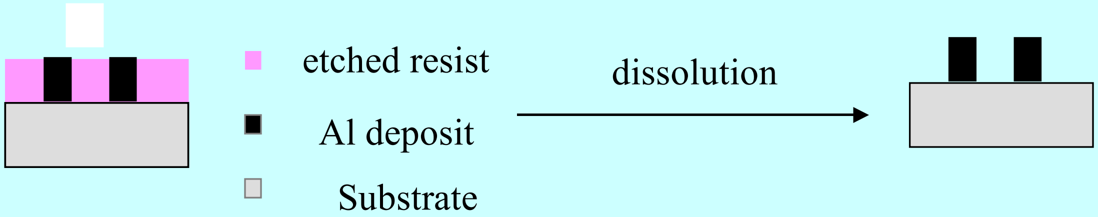
R_c
transverse
coherence

θ_ι

θ_N

$\Lambda = 2\ \mu m$





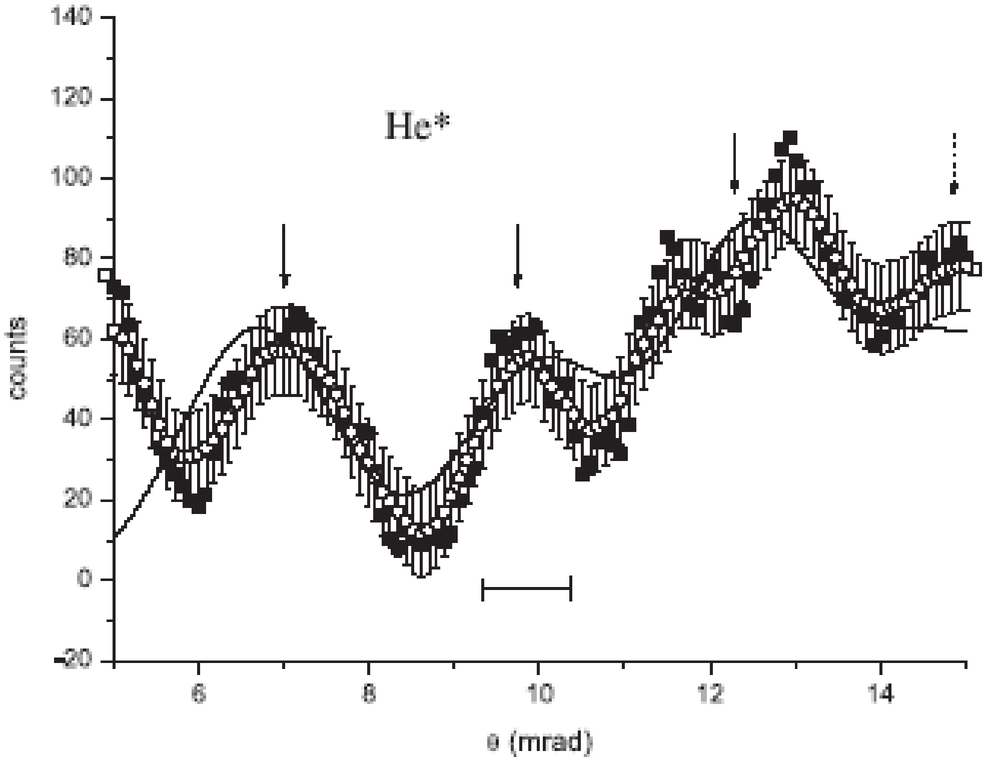
- ▨ etched resist
- ■ Al deposit
- □ Substrate

dissolution

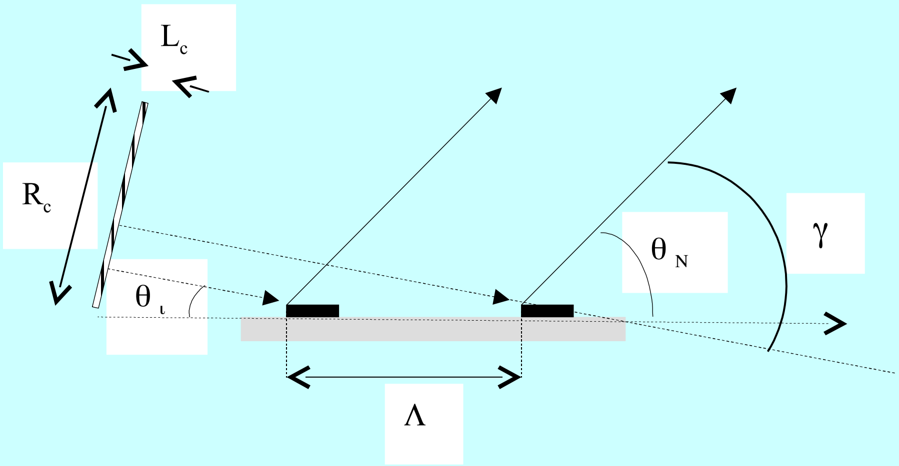
Difficulties

- High Quenching factor (He* → He) ⇨ 10^{-4} of metastable atoms survive
- $\lambda_{//} \sim 10^{-2}$ nm compared to $\Lambda = 2000$ nm ⇨ Grazing incidence
- Small angles between diffracted peaks, $\theta_N \sim 10$ mrad ⇨ Good angular definition

J. Grucker et al.: Diffraction of fast metastable atoms by micrometric reflection gratings

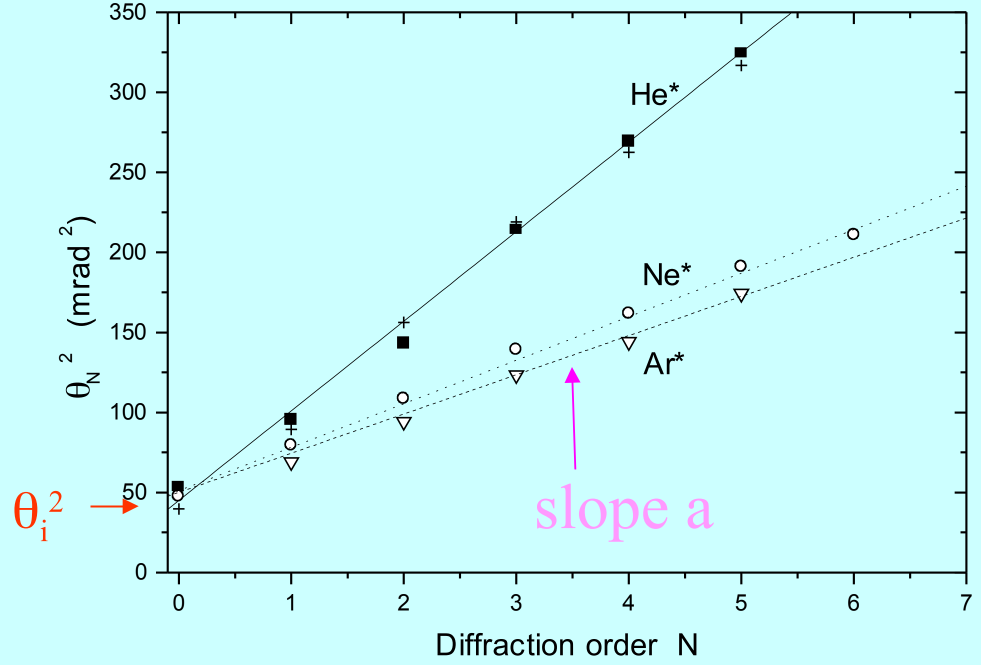


Grucker *et al*, Eur. Phys. J. D, **41**, 467 (2007)



$$\cos\theta_N = \cos\theta_i - N\frac{\lambda_{//}}{\Lambda}$$

$$\theta_N^2 \approx \theta_i^2 + 2N\frac{\lambda_{//}}{\Lambda}$$



$$\frac{a_{He*¿}}{a_{Ne*¿}} \approx 2.05$$ (+/- 0.5)

¿

¿

$$\frac{\lambda_{//He*¿}}{\lambda_{//Ne*¿}} \approx 2.3$$

¿

¿

$$\frac{a_{He*¿}}{a_{Ar*¿}} \approx 2.5$$ (+/- 0.5)

¿

¿

$$\frac{\lambda_{//He*¿}}{\lambda_{//Ar*¿}} \approx 3.1$$

¿

¿

M. Ducloy, Critical Stability, Erice

Conclusion

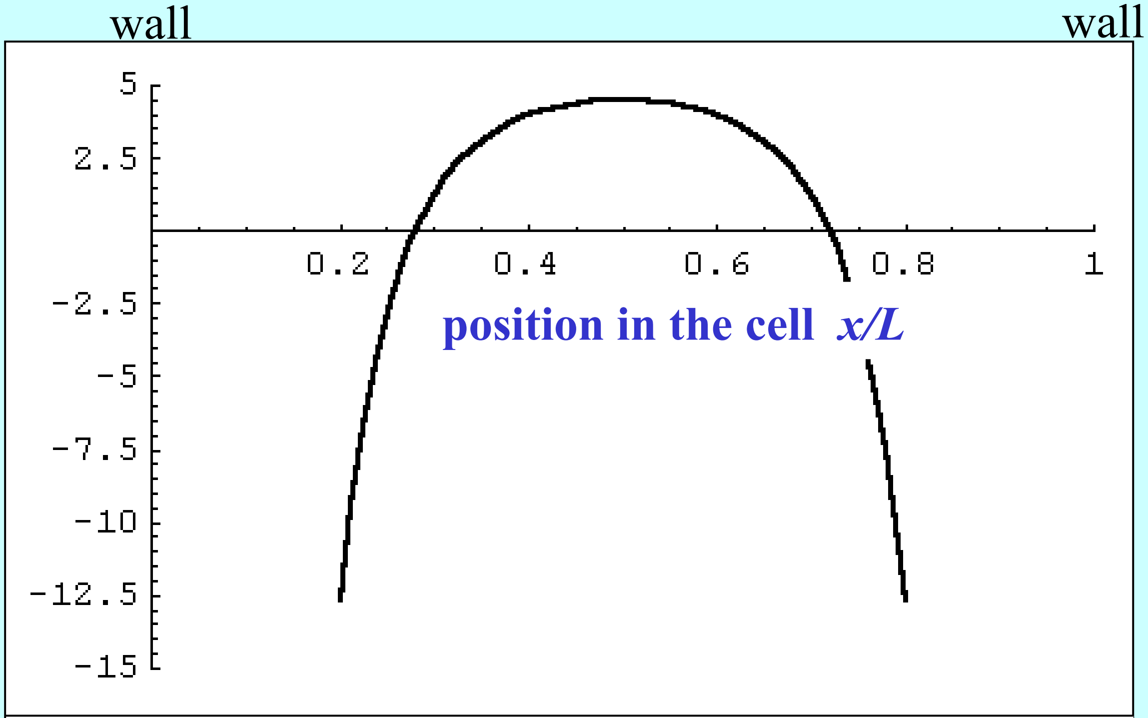
* New experimental approaches allow one to study the non-retarded long-range (~1-100 nm) interactions between atoms in selected internal state, and dielectric or metallic surfaces, with observations of :

- *resonant atom-surface coupling*
- *atom symmetry break and transitions between internal energy levels*
- *atom diffraction via quantum reflection*

* Most of the work performed up-to-date is about free atoms interacting with surfaces (continuum states). Observation of long-range atom-surface bound states (≠ adsorbed atoms) is hindered by overall attractive character of forces, short-range atom perturbations, surface irregularities…

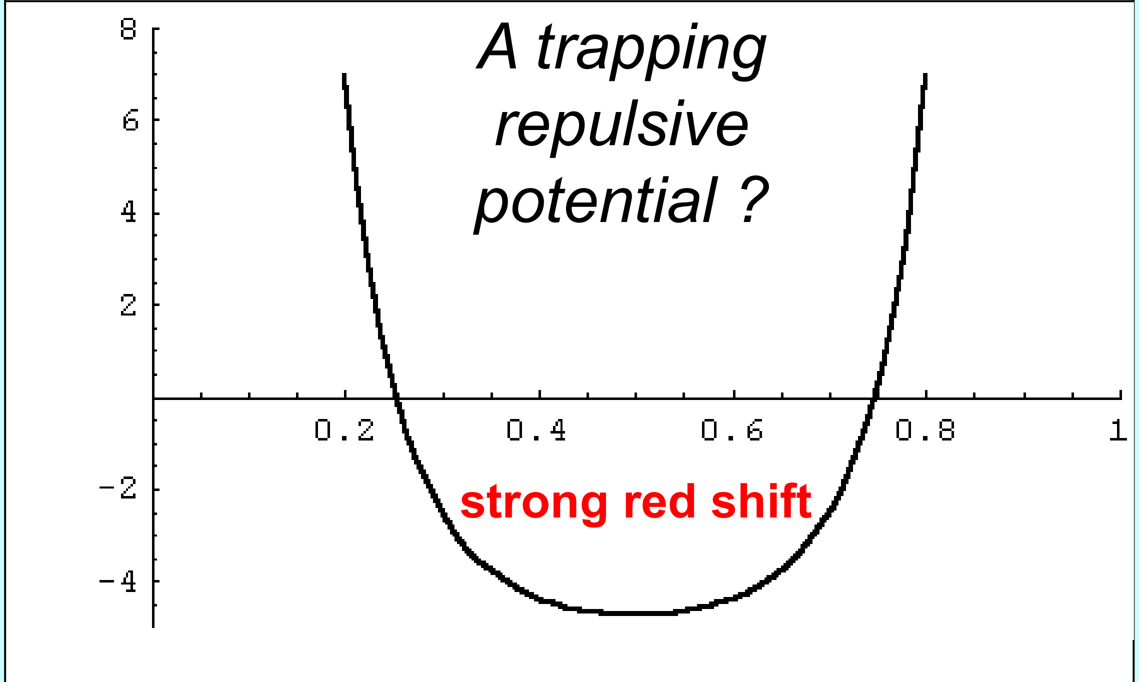
- *Necessity of one additional potential imposed by an applied field (one wall)*
- *Possibility of atom bound state in a thin cell with (resonant) repulsive walls*

vW shift for
$\omega/\omega_S = 0.999$ for $\mu_\perp$



vW shift for

$\omega/\omega_S = 1.001$ for $\mu_{||}$



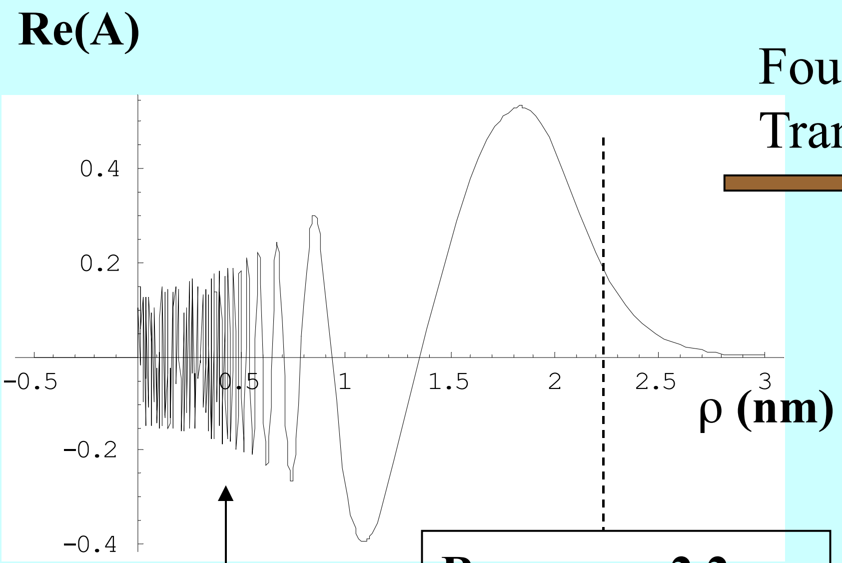
A trapping repulsive potential ?

Ultra-thin cells with repulsive walls, close to resonant coupling

(M.P. Gorza, Laser Physics 2005, and unpublished)

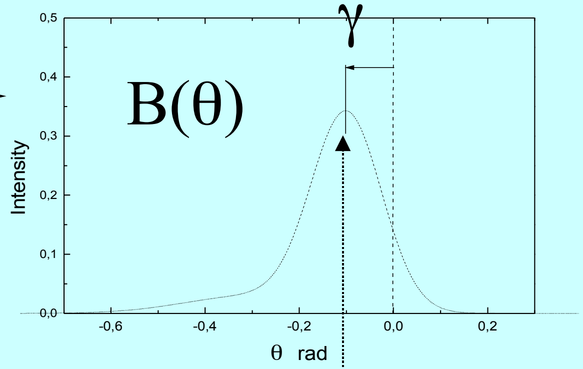
G. Dutier, A. Laliotis, M. P. Gorza, I. Maurin, M. Fichet, D. Bloch,
M. Hamamda, J. Grucker, J.C. Karam, F. Perales, J. Baudon
(Lab. Physique des Lasers, University Paris 13, Villetaneuse, F.)
S. Saltiel (Sofia University, Bulgaria)
T. Varzhapetyan, D. Sarkisyan (Institute for Physical Research, Armenia)
V. V. Klimov (Lebedev Physical Institute, Moscow, Russia)
V. Bocvarski (Institute of Physics, Belgrade, Serbia)

Fraunhofer diffraction from one inelastic (vdW-Z) complex ***transition*** amplitude A(ρ)



slit
surface

Fourier
Transform



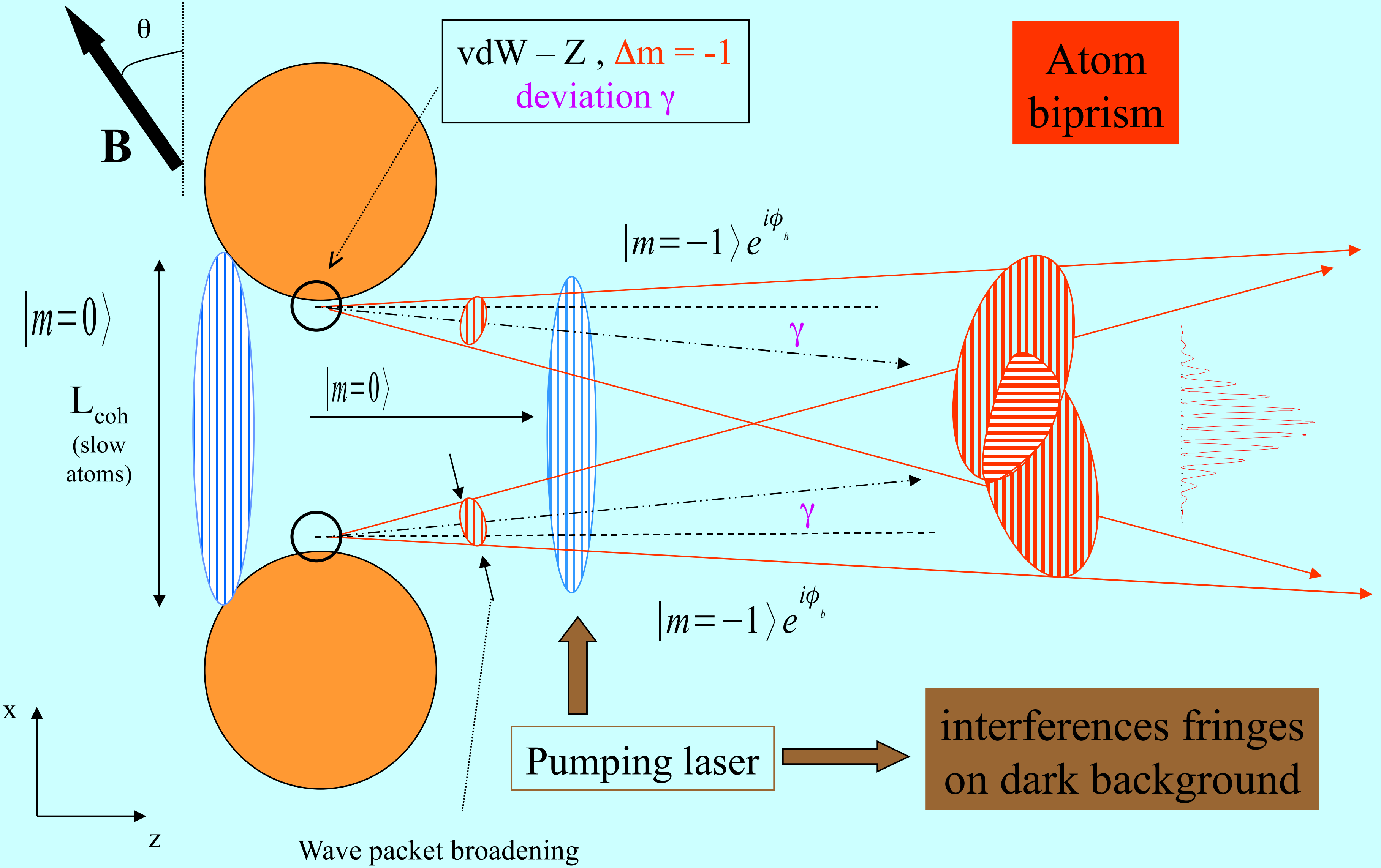
Range a ≈ 2.2 nm ⟷ **Angular aperture δθ ≈ λ / a**

Mean spatial frequency Ω ⟷ **Angular shift by γ = Ω / k = Ω λ / (2π)**

$$\mathbf{\Omega = (2\,M\,g\,\mu_B\,B\,|\Delta m|)^{1/2} / \hbar}$$ independent of velocity

Principle of Fresnel atomic bi-prism

Grucker *et al*, Eur. Phys. J. D **47**, 427 (2008)



vdW – Z , Δm = -1
deviation γ

Atom biprism

Pumping laser

interferences fringes on dark background

Wave packet broadening
for scattered atoms

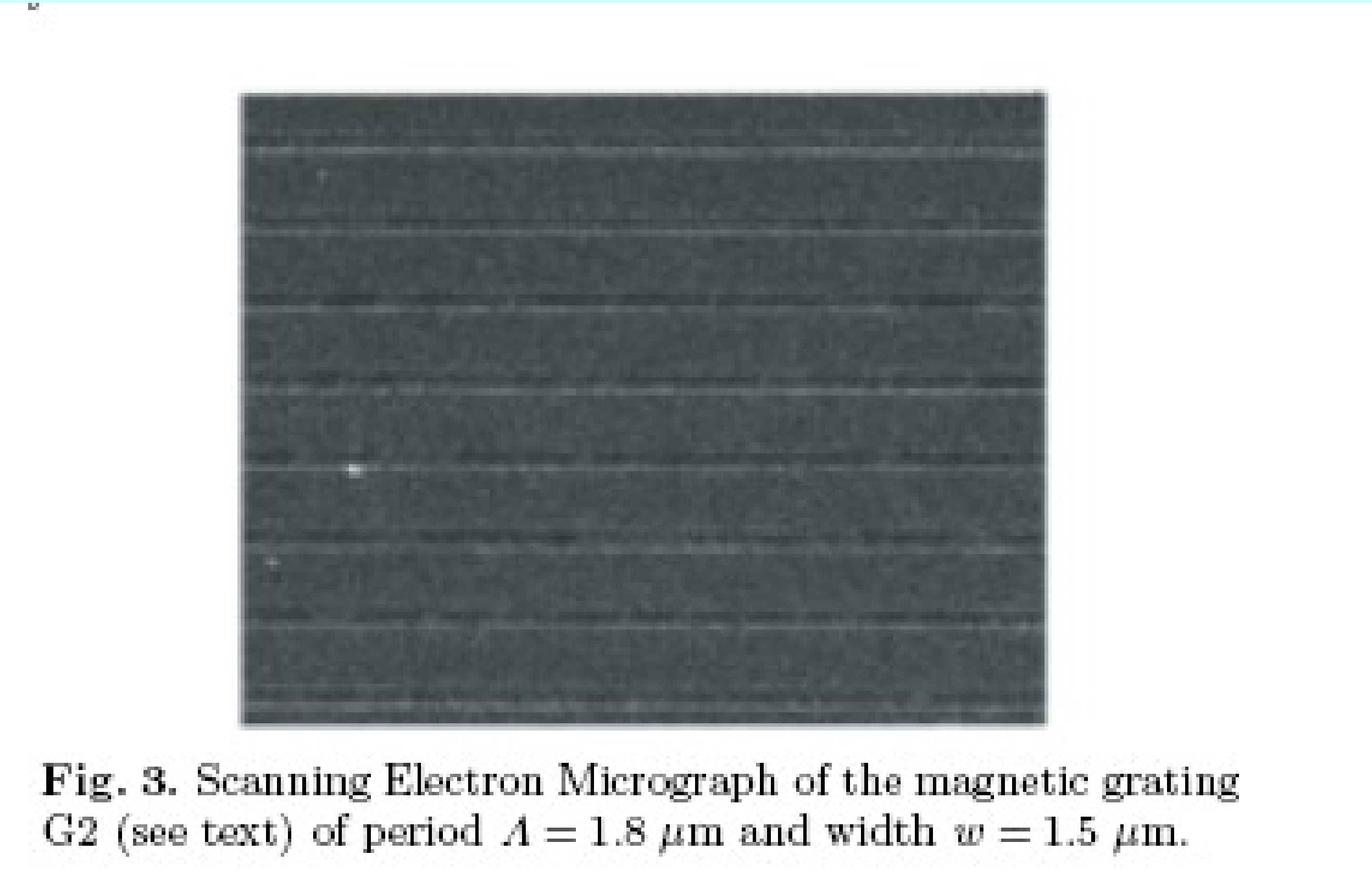


Fig. 3. Scanning Electron Micrograph of the magnetic grating G2 (see text) of period $\Lambda = 1.8\ \mu\text{m}$ and width $w = 1.5\ \mu\text{m}$.

Grucker *et al*, Eur. Phys. J. D, **41**, 467 (2007)