lecture 10.11.2011

we had last week:

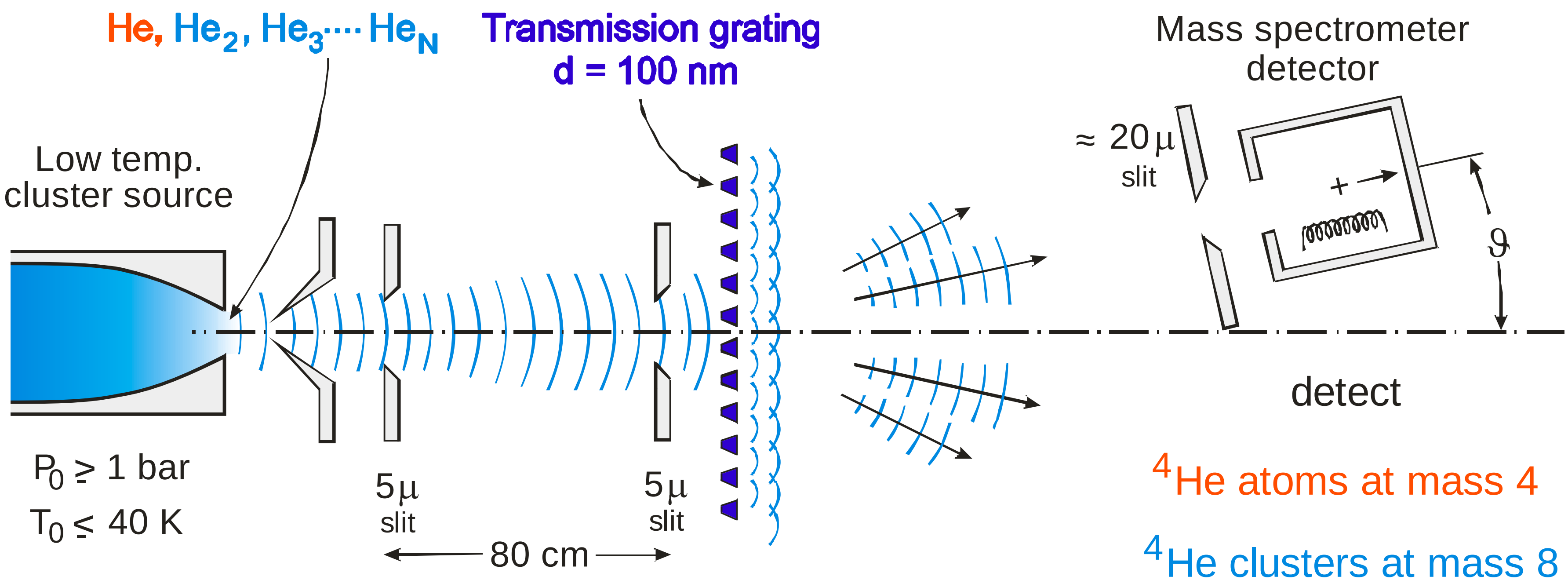
- atom beam diffraction

today:

- atom beam - surface diffraction
- radiation pressure as means to cool atom ensembles

Non - destructive Diffraction Grating "Mass Spectrometer"

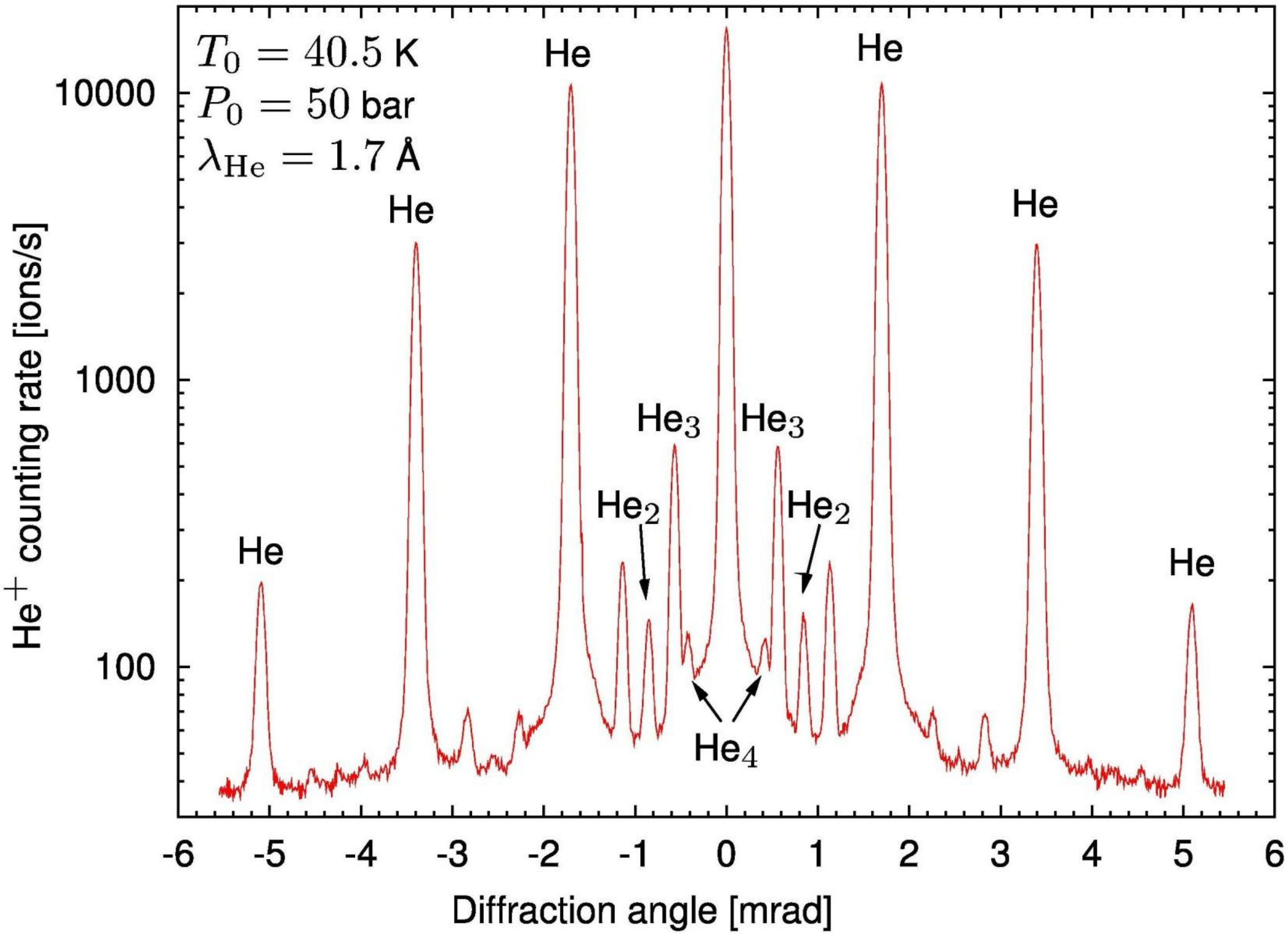
Previous: Na atoms, Pritchard et al (1988); He*, Mlynek et al (1991)



Can discriminate against atoms with mass spectrometer set at mass 8 and larger

from J. P. Toennies

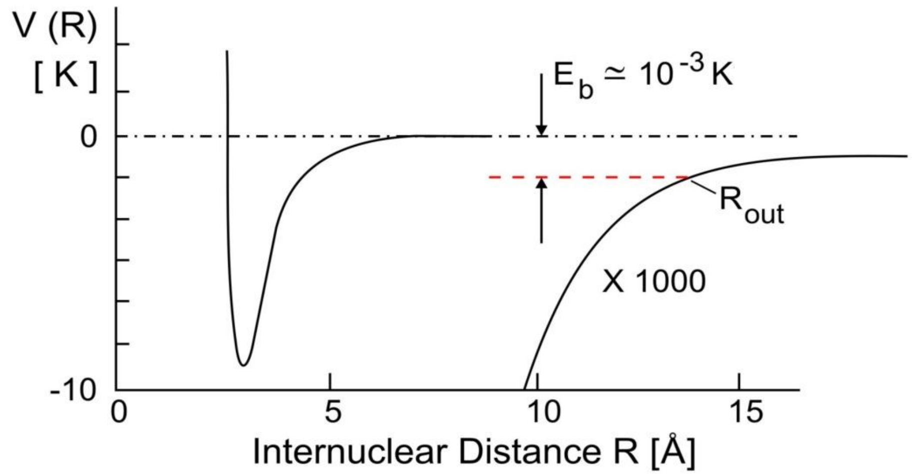
at low source temperatures new diffraction peaks appear



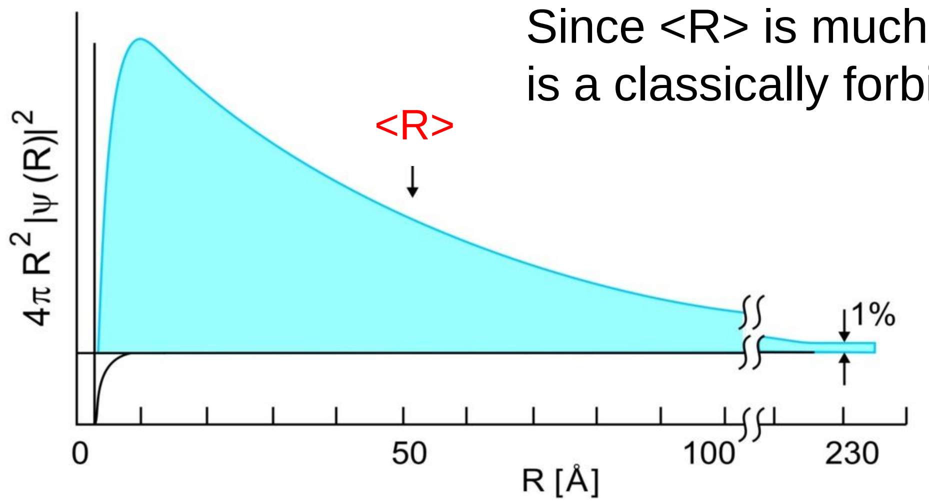
The first unambiguous detection of ^{4}He dimer ($E_b = 1.3$ mK)

W. Schöllkopf and J. P. Toennies, Science **266**, 1345 (1994)

the ^{4}He dimer: the world‘s weakest bound and largest ground state molecule



Since <R> is much greater than R_{out} the dimer is a classically forbidden molecule



Scattering length: $a \simeq 2 <R> \approx 100$ Å

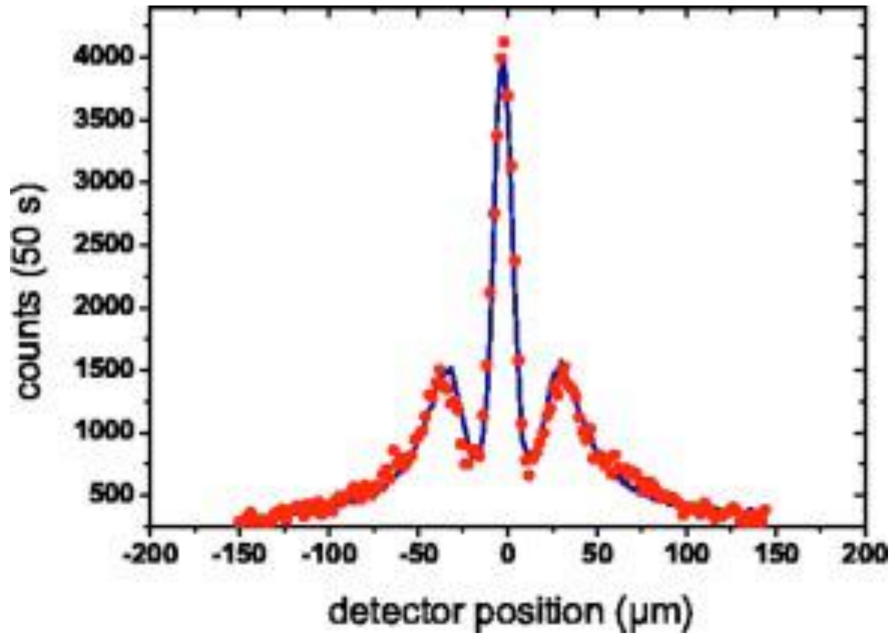
Cross section: $\sigma (T \to 0) = 8 \pi a^2 = 259{,}000$ Å^2

A frail GIANT!

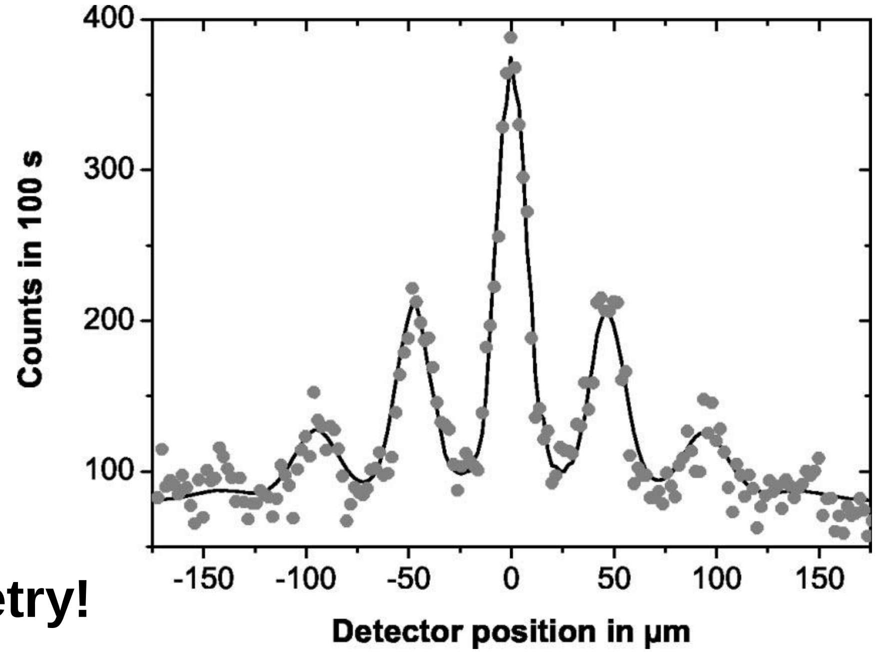
from J. P. Toennies

C_{60} diffraction pattern with

thermal beam
v_{mean} = 200 m/s



with slotted disk velocity selector
v_{mean} = 117 m/s



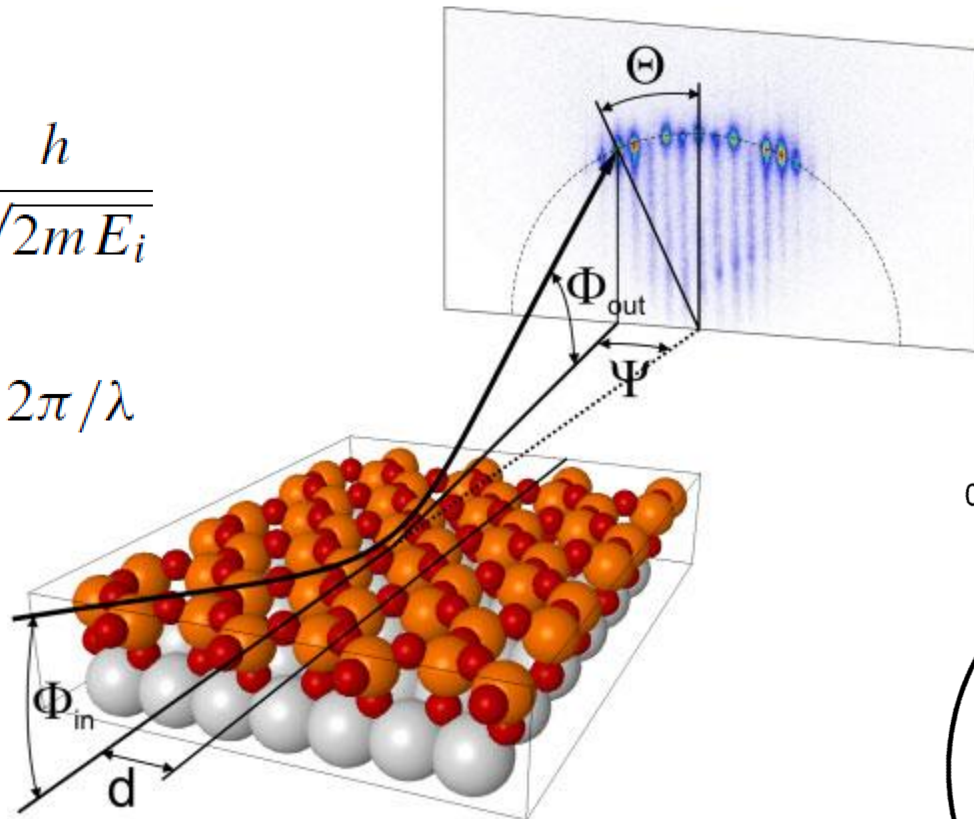
single particle interferometry!

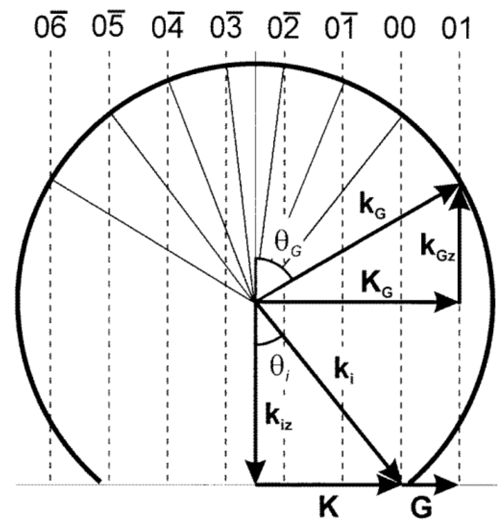
200 μm separation, 174 diff. vibrational modes, thus distinguishable

using the wave nature of atoms for surface investigations

$$\lambda = \frac{h}{\sqrt{2mE_i}}$$

$$|\boldsymbol{k}_i| = 2\pi/\lambda$$





Ewald construction like electron diffraction

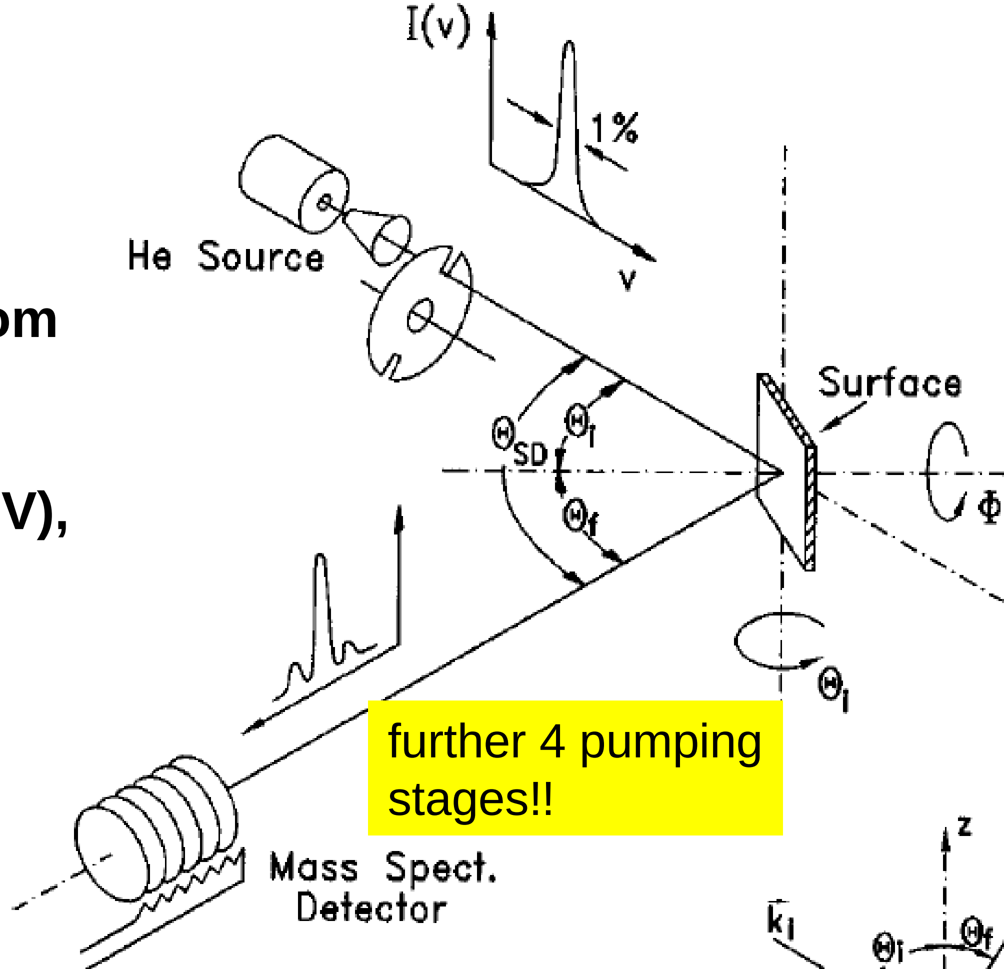
Helium atom scattering for surface analysis

30 to 200 bar Helium,
10 µm nozzle

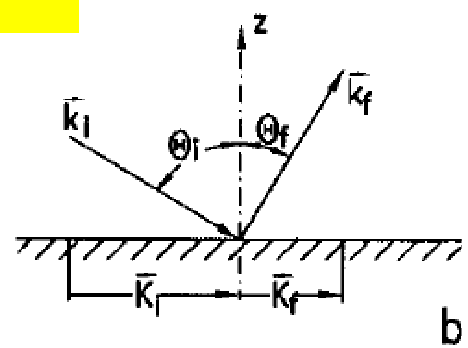
temperature variation from 300 K to 40 K leads to a variation from
v_{mean} = 3000 m/s (120 meV),
$k_i = 16$ Å^{-1}, $\lambda_{dB} = 0.3$ Å
to
v_{mean} = 700 m/s (8 meV),
$k_i = 4$ Å^{-1}, $\lambda_{dB} = 1.5$ Å

<u>**measure**</u>

- scattering angular distribution
- with pulsed sources: inelastic processes

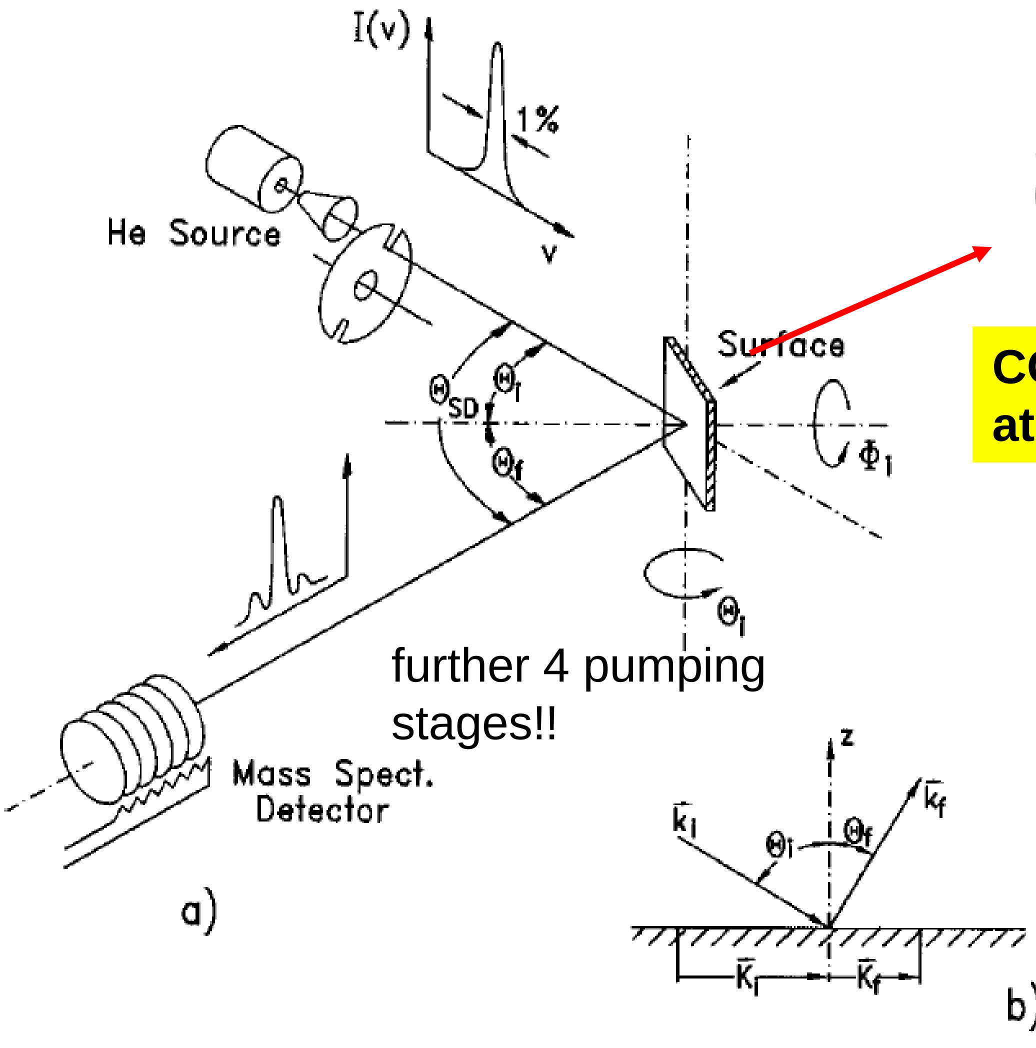


further 4 pumping stages!!

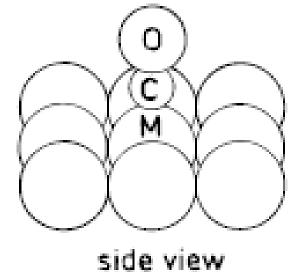


Hofmann, Toennies, Chemical Reviews 96, 1996, 1307

Helium atom scattering



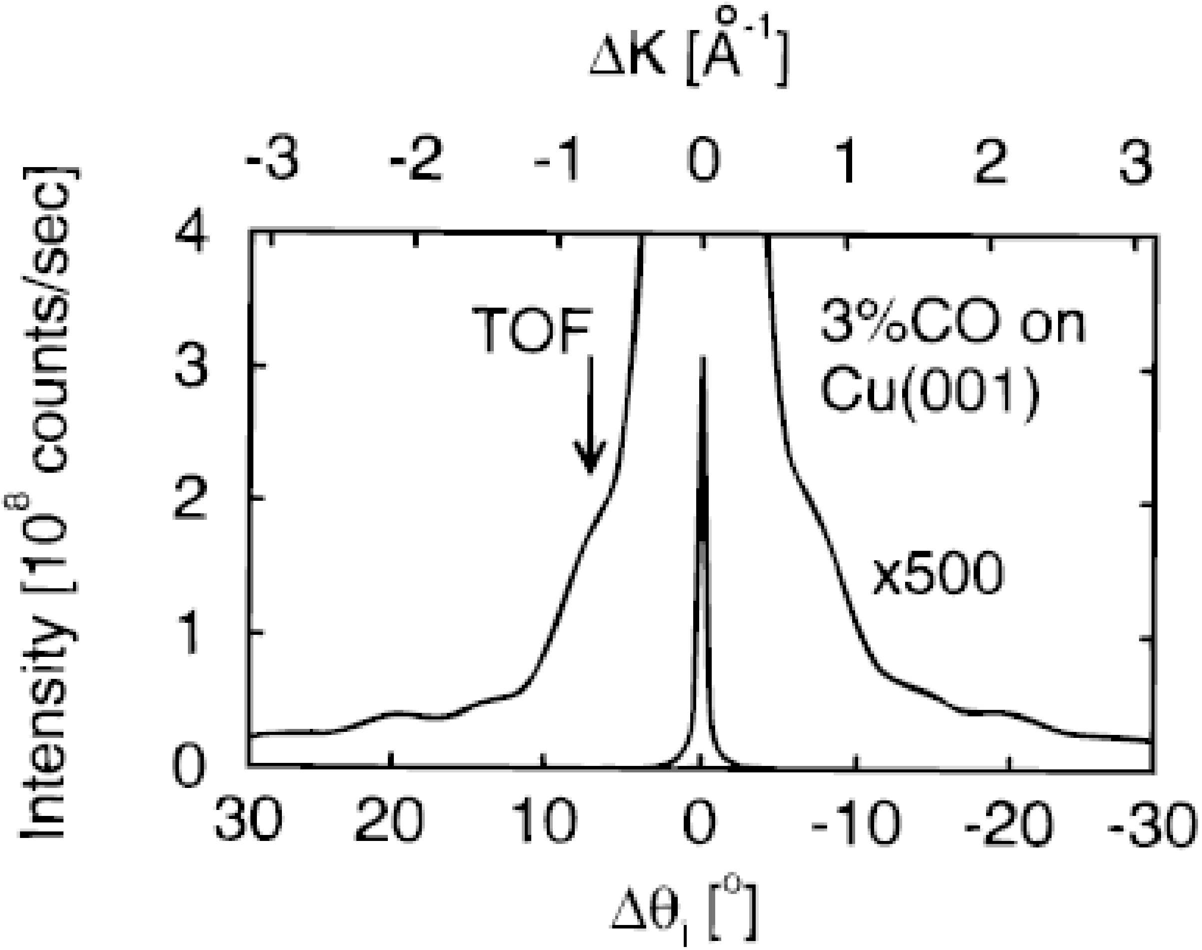
further 4 pumping
stages!!



CO on fcc(001) Cu at 10^{-11} mbar!!

Hofmann, Toennies, Chemical Reviews 96, 1996, 1307

scattered Helium atom angular distribution



a)

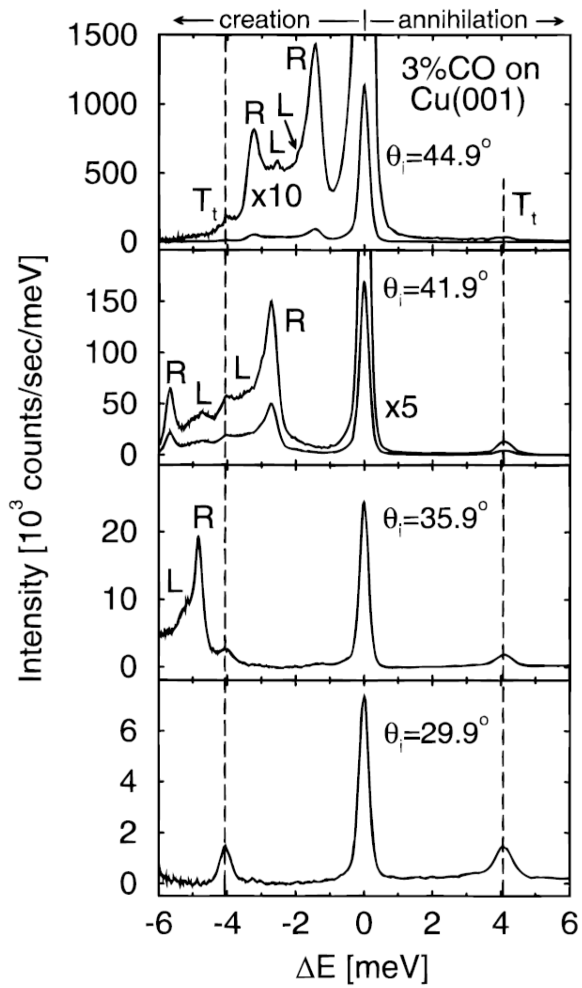
main feature from copper, tiny side wings from CO

zero point corresponds to specular reflection

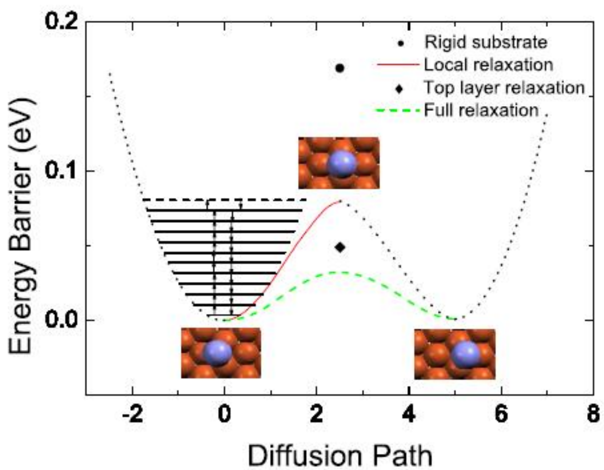
Helium atom scattering with pulsed beam

$$\hbar\omega = \frac{\hbar^2}{2m}(k_i^{\,2} - k_f^{\,2})$$

$$\Delta \mathbf{K} = k_f \sin\theta_f - k_i \sin\theta_i$$



with k_i and k_f initial and final wave vectors,
m probe mass
Θ_i and Θ_f inc. and final scattering angles

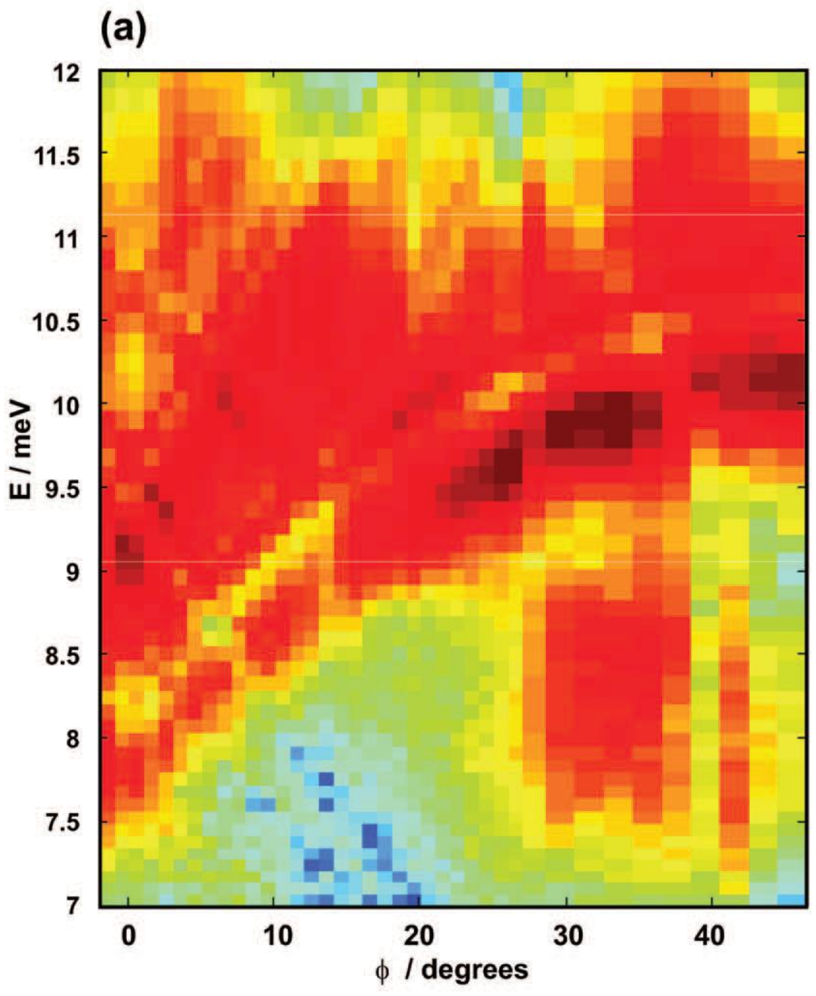


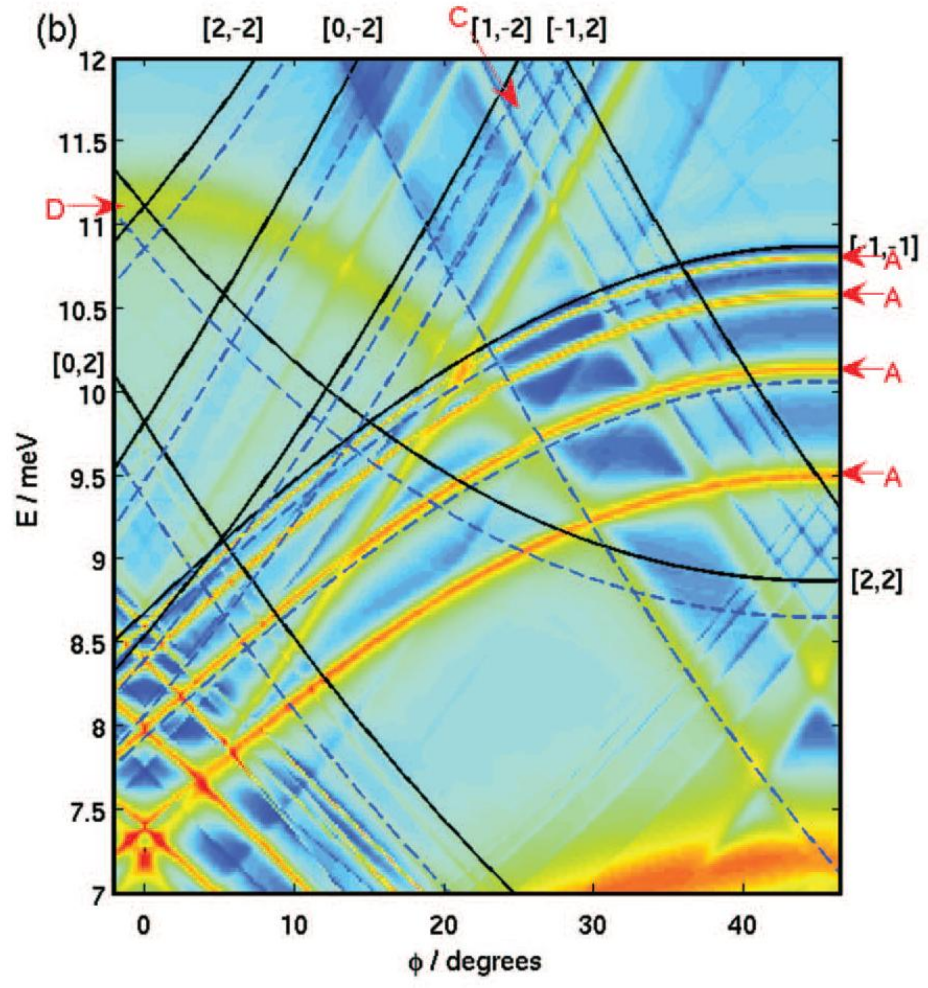
creation ***annihilation***
of a vibrational quantum (R,L: phonons)
from the time-of-flight measurement

T_i: T mode, resonant hopping

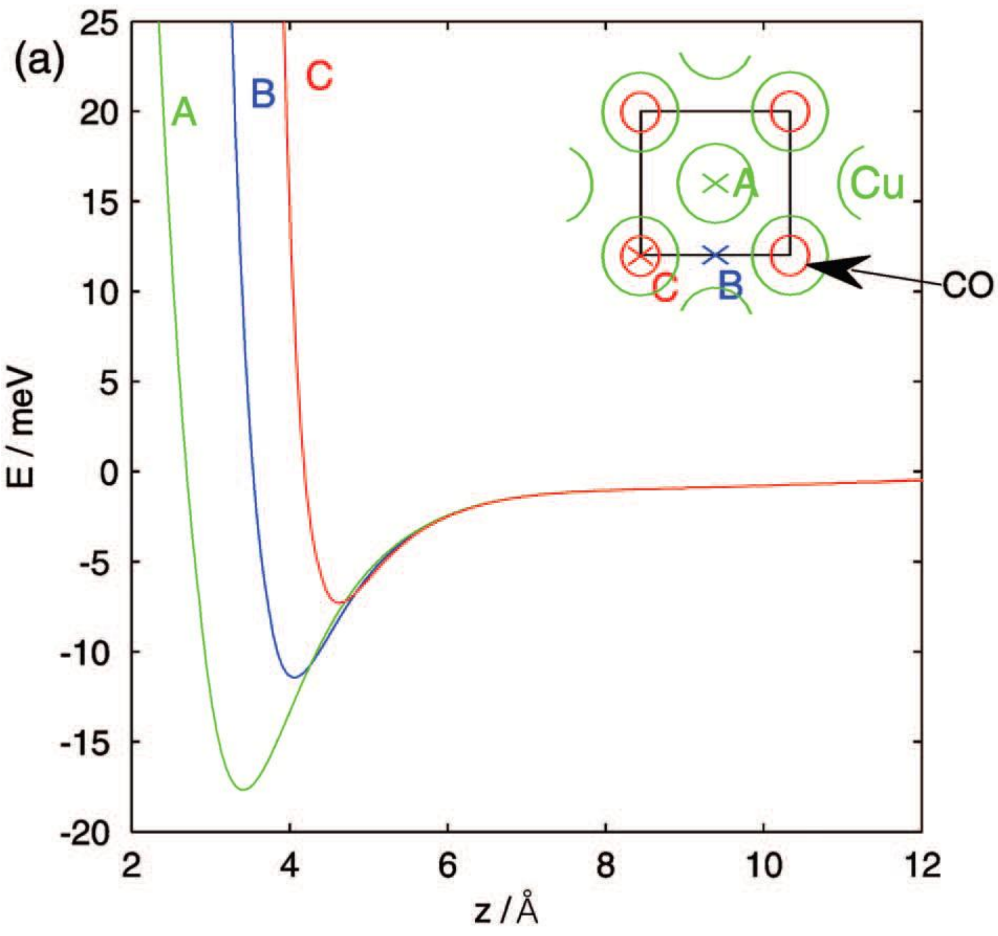
full energy - angular distribution landscape

Cu(001) - CO Helium atom scattering. a) measured, b) calculated





deduced interaction potentials Helium - CO/Cu(001)

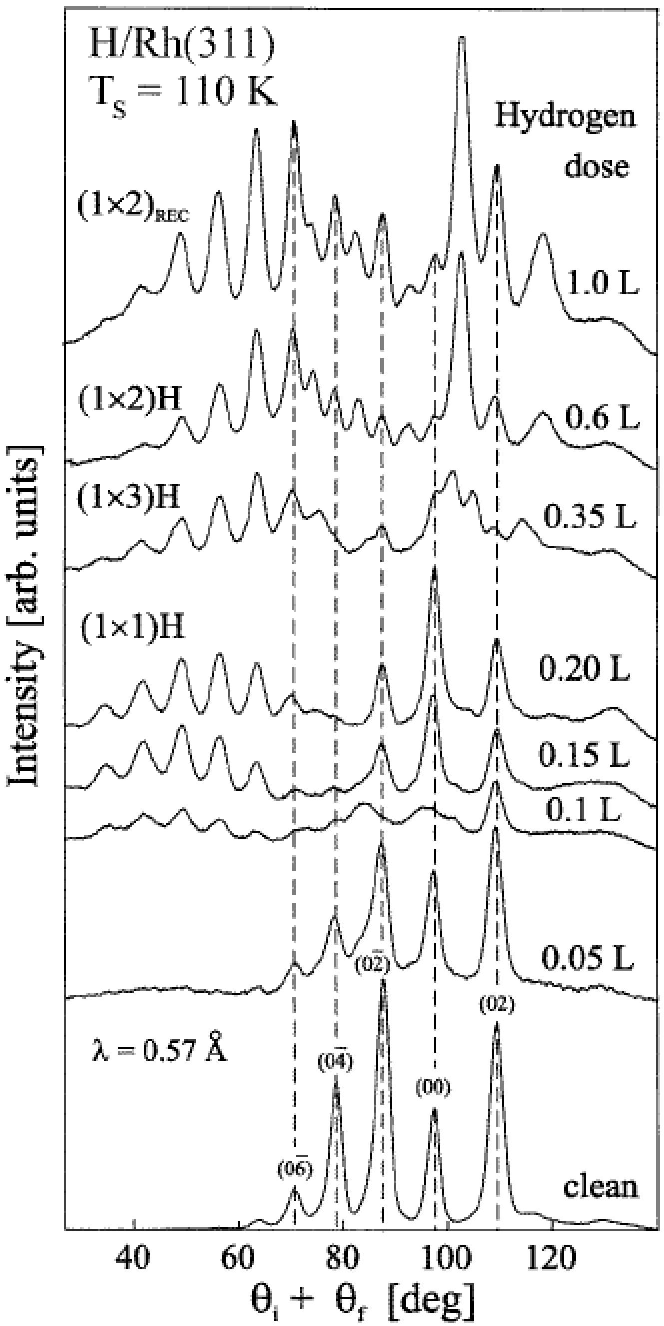


hollow site A,
bridge site B
and top site C

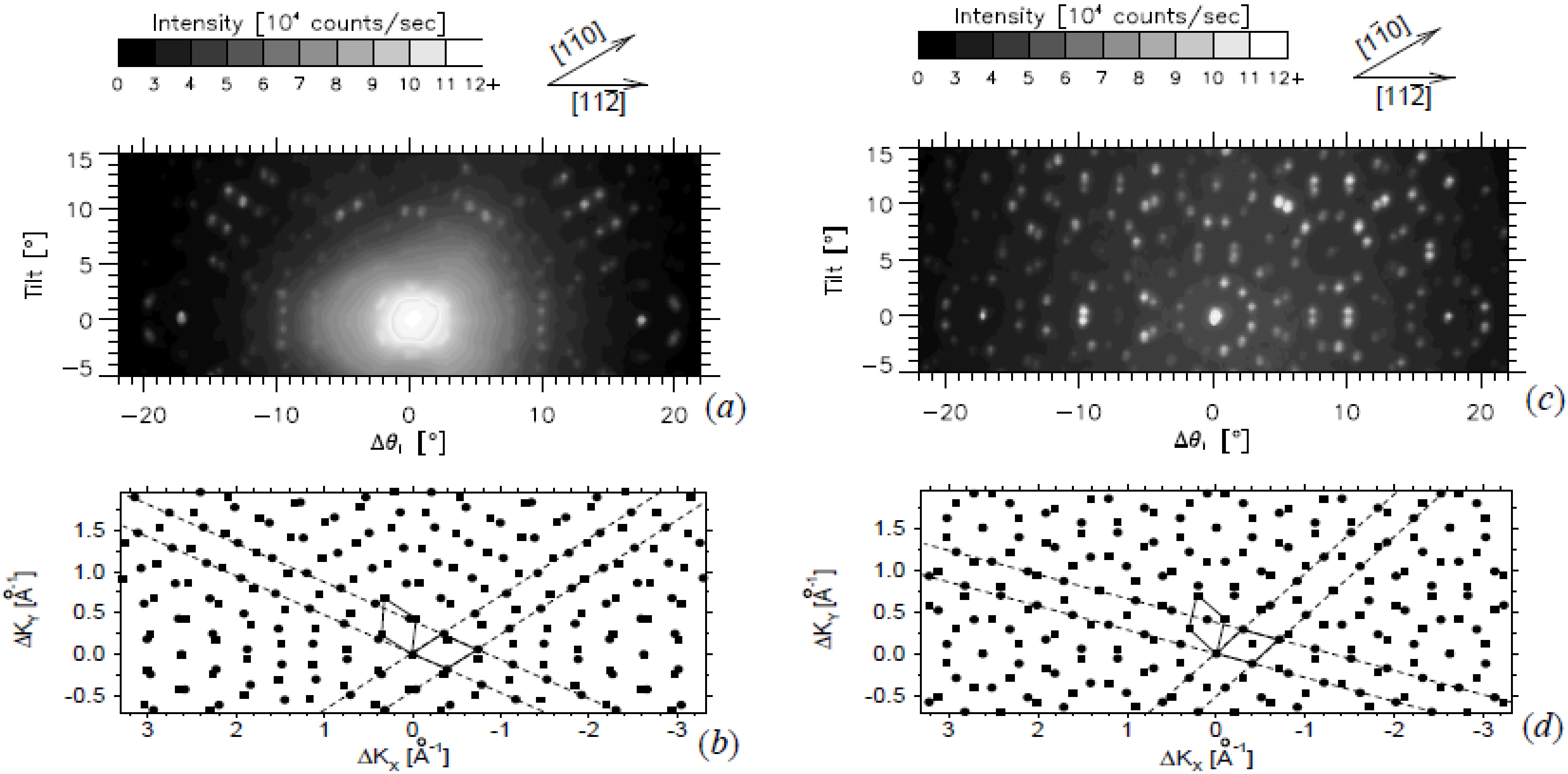
J. Chem. Phys. 128, 154712 2008

last example:

development of the hydrogen phases on Rh(311) surfaces with increasing exposure at 110 K as observed with He diffraction



two-dimensional helium diffraction pattern for an 80% coverage of the Pt(111) surface with D2O islands (a) and for a complete bilayer (c)



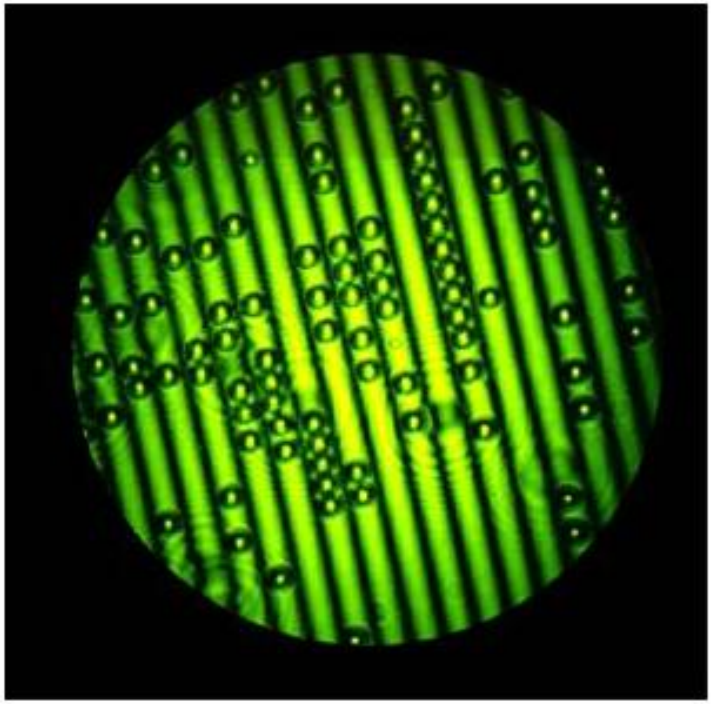
The incident helium energy is 22 meV and the surface temperature 130 K

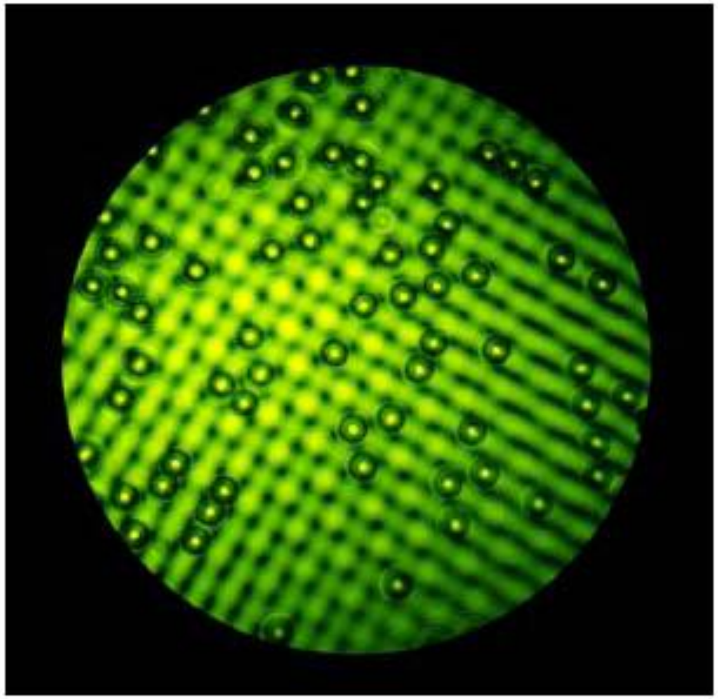
for a review see: Farias and Rieder, Rep. Prog. Phys. 61 (1998) 1575 end of atomic beam physics


radiation pressure
useful for atom cooling
Komet Hale-Bopp
Strahlungsdruck

optical gratings generated by interfering laser beams

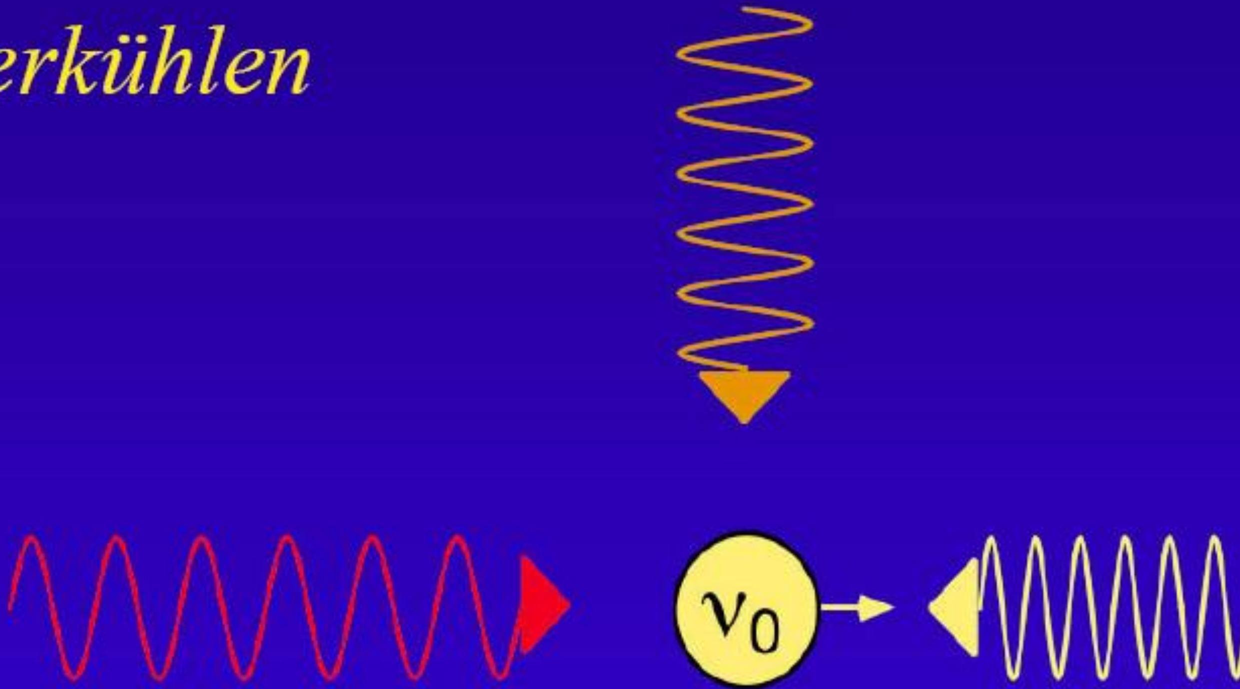
4 µm polysterene spheres soluted in water





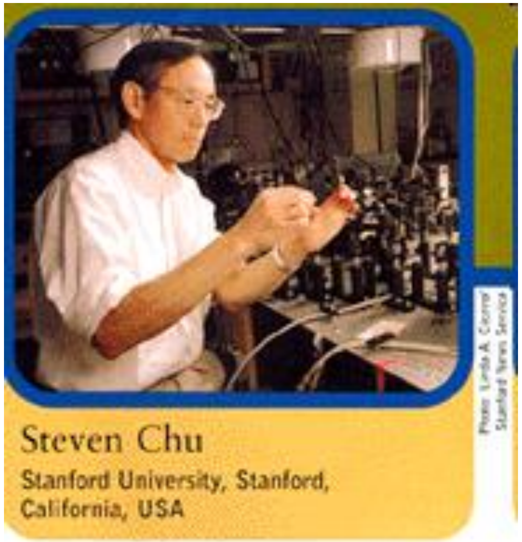
optical forces confine the particles

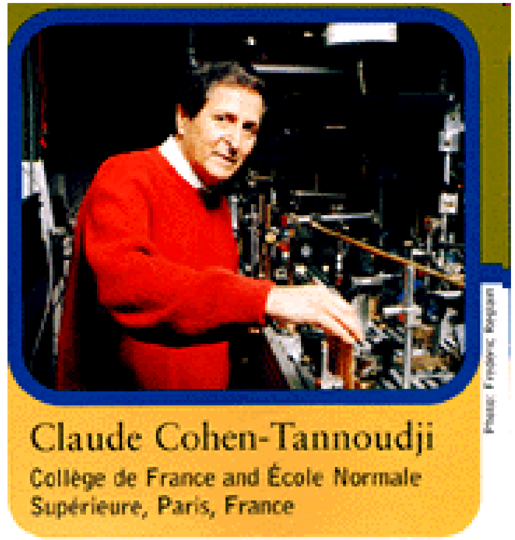
Laserkühlen

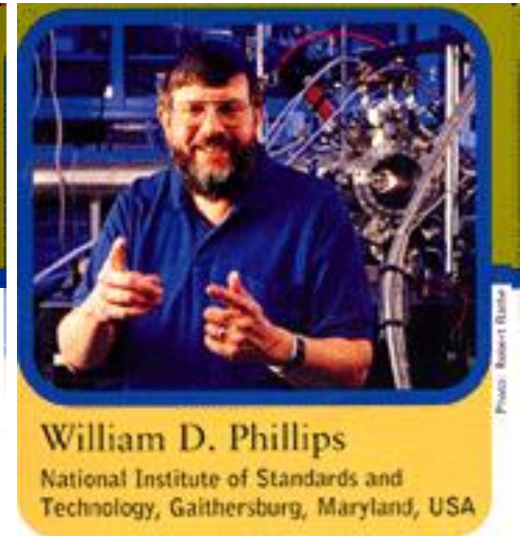


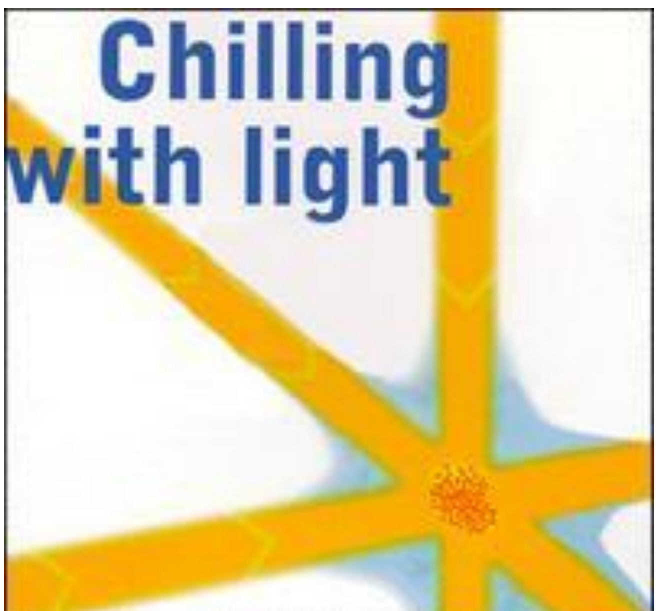
T.W. Hänsch and A.L. Schawlow, Opt. Comm. 13, 68 (1975)

Nobel price in physics 1997









This year's Nobel laureates in physics have developed methods of cooling and trapping atoms by using laser light. Their research is helping us to study fundamental phenomena and measure important physical quantities with unprecedented precision.

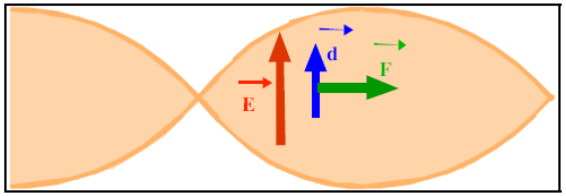
from the Nobel homepage

Light forces
<u>classically</u>:

force is gradient of the potential energy U

$$\vec{F} = - \vec{\nabla} U = \vec{\nabla} (\vec{E} \cdot \vec{d})$$

Though atoms have no permanent dipole moment, one can be induced by the radiation. The scalar product may become non-zero. A fast variing gradient and by this large force appears in an inhomogeneous laser beam, i.e. in the focus or a standing wave:



In a plane wave the transverse derivatives disappear, so a force would act in the propagation direction of the light. However if the force is periodic with the light frequency there is no net force.
In the case of absorption, e.g. by an atom, the force behind the atom is smaller than before. The gradient will be non-zero on average, leading to a finite force on the particle. This force will increase with increasing absorption rate.

First experimental proof of light forces with an atomic beam in 1933 by Frisch.

first demonstration of Na atom beam deflection

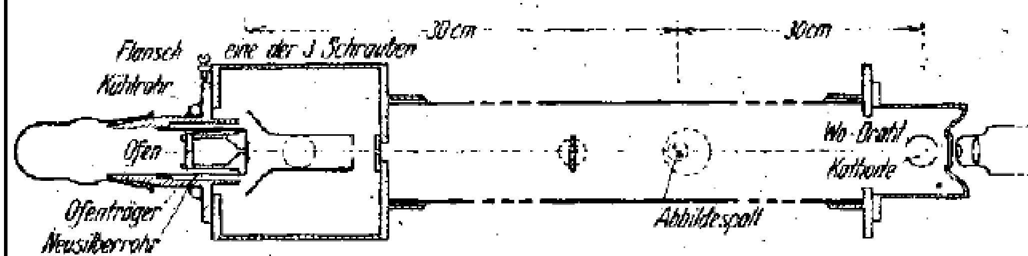
R. Frisch, Z. Phys. 86, 42-48 (1933).

(Untersuchungen zur Molekularstrahlmethode aus dem Institut für physikalische Chemie der Hamburgischen Universität. Nr. 30.)

Experimenteller Nachweis des Einsteinschen Strahlungsrückstoßes.

Von R. Frisch in Hamburg.

Mit 6 Abbildungen. (Eingegangen am 22. August 1933.)



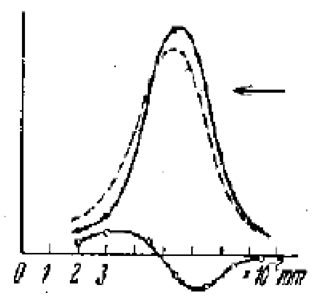


Fig. 5. Versuch mit seitlicher Beleuchtung.
Abszisse: Stellung des Auffängers.
Ordinate: Elektrometerausschlag.
—●— Intensität ohne Beleuchtung.
—○— Wirkung der Beleuchtung.
- - - - Summe dieser beiden, also Intensität mit Beleuchtung.
Der Pfeil deutet die Richtung des Lichteinfalls an.

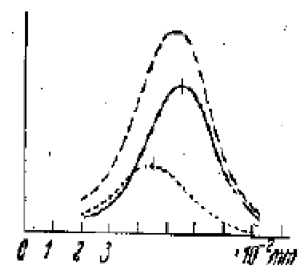
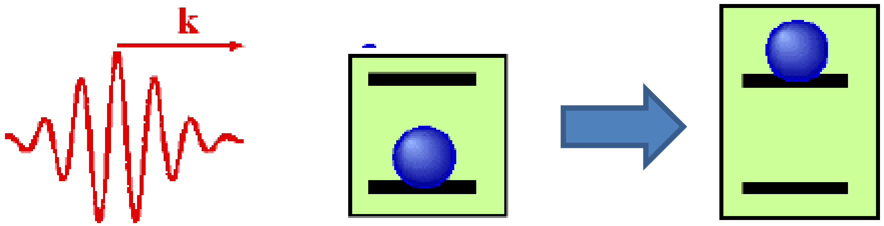


Fig. 6.
- - - - Strahl mit Beleuchtung.
—— $^2/_3$ vom Strahl ohne Beleuchtung.
······ Differenz dieser beiden, also Verteilung der abgelenkten Atome.

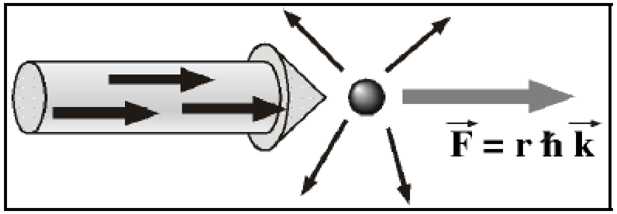
Light forces

quantum mechanically: transfer of momentum and energy of the photon

$E = \hbar\omega$, $p = \hbar k$

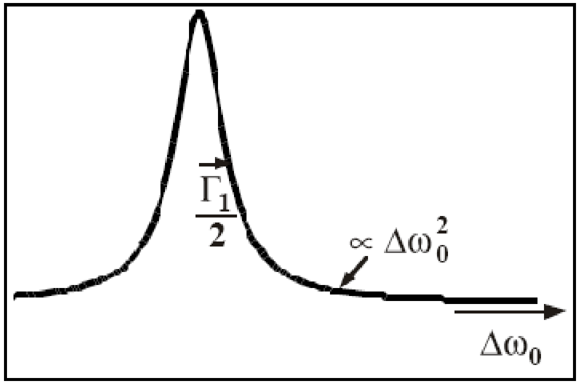


absorption is directed, emission isotropic.
So the emission leads to no net force and thus can be neglected in a theoretical description.



$F = r\,\hbar K$, with r: the absorption rate

$$r = \Gamma_1\, \omega_x^2/(\Gamma_1^2 + 4\,\Delta\omega^2)$$



ω_x^2 proportional to laser intensity

Γ: inverse life time

$\Delta\,\omega$: $\omega_{laser} - \omega_0$, i.e. the laser detuning from the atomic resonance ω_0.

You know the Lorentzian absorption curve from the theoretical lessons.

influence of the Doppler effect

for an atom moving with velocity **v**: $\Delta\omega \rightarrow \Delta\omega + \mathbf{kv}$, with **k**: wave vector
thus the rate r changes to

$$r = \Gamma_1 \frac{\omega_x^2}{\Gamma_1^2 + 4(\Delta\omega_0 + kv)^2}$$

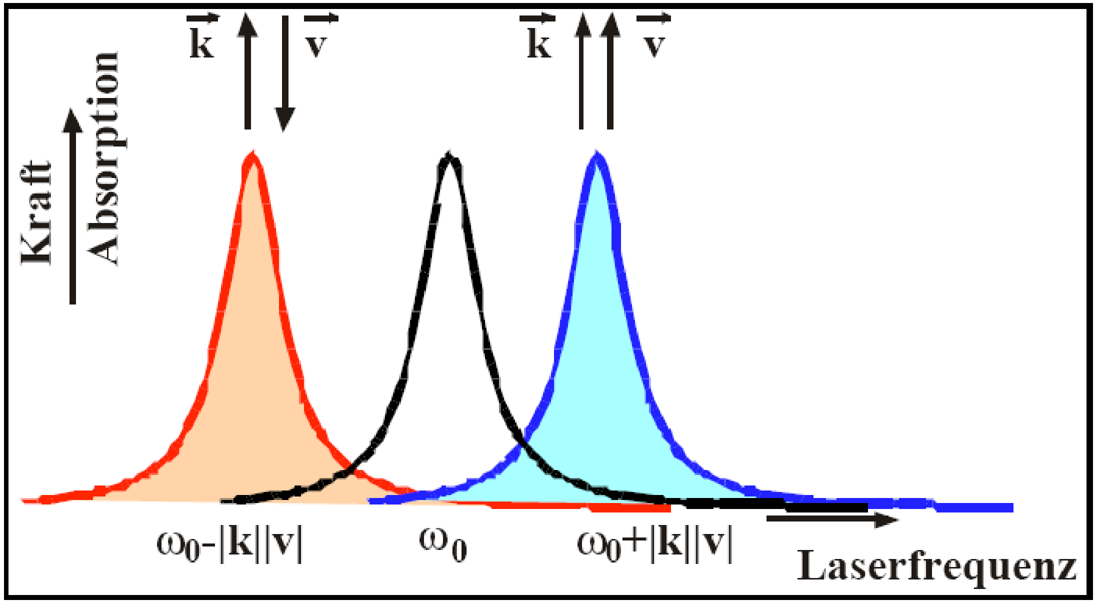
Force F = r ЋK

$$F = \hbar k \Gamma_1 \frac{\omega_x^2}{\Gamma_1^2 + 4(\Delta\omega_0 + kv)^2}$$

has maximum if $v = -\Delta\omega_0/k$

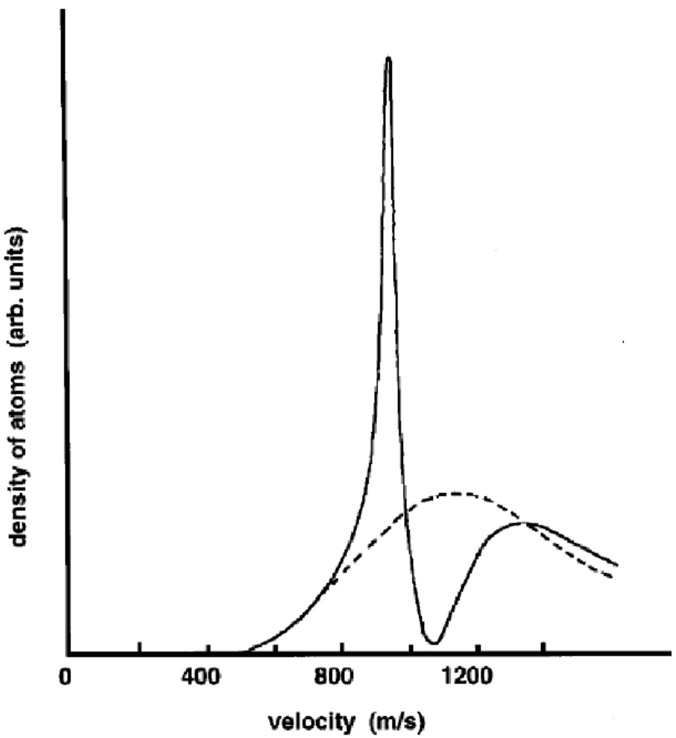
this means the Doppler shift drives the spectrum into resonance.

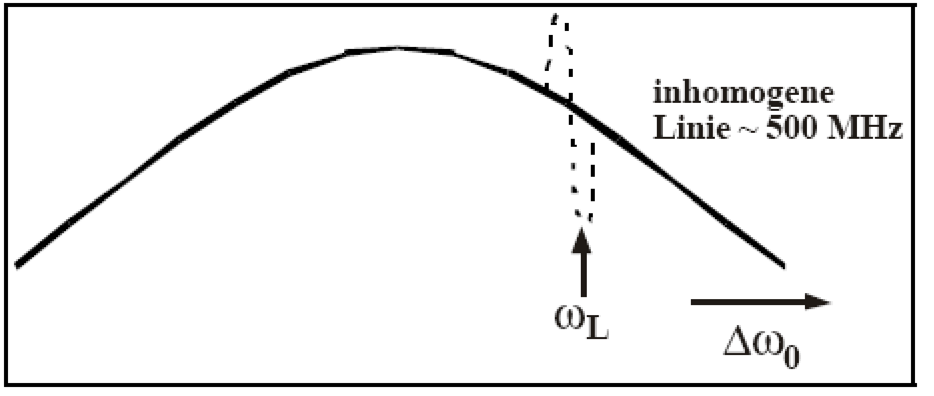
force



→ slowing down is possible!

velocity distribution after irradiation with fixed frequency



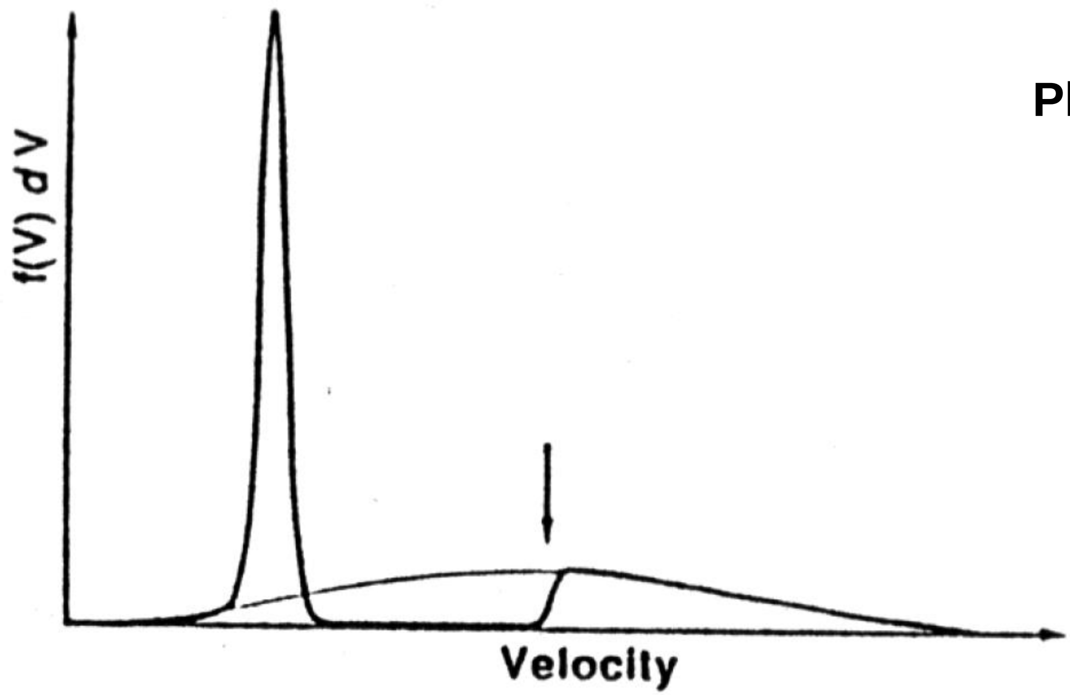


problem with fixed frequency: a hole is burned into the velocity distribution

Phillips RMP 1998

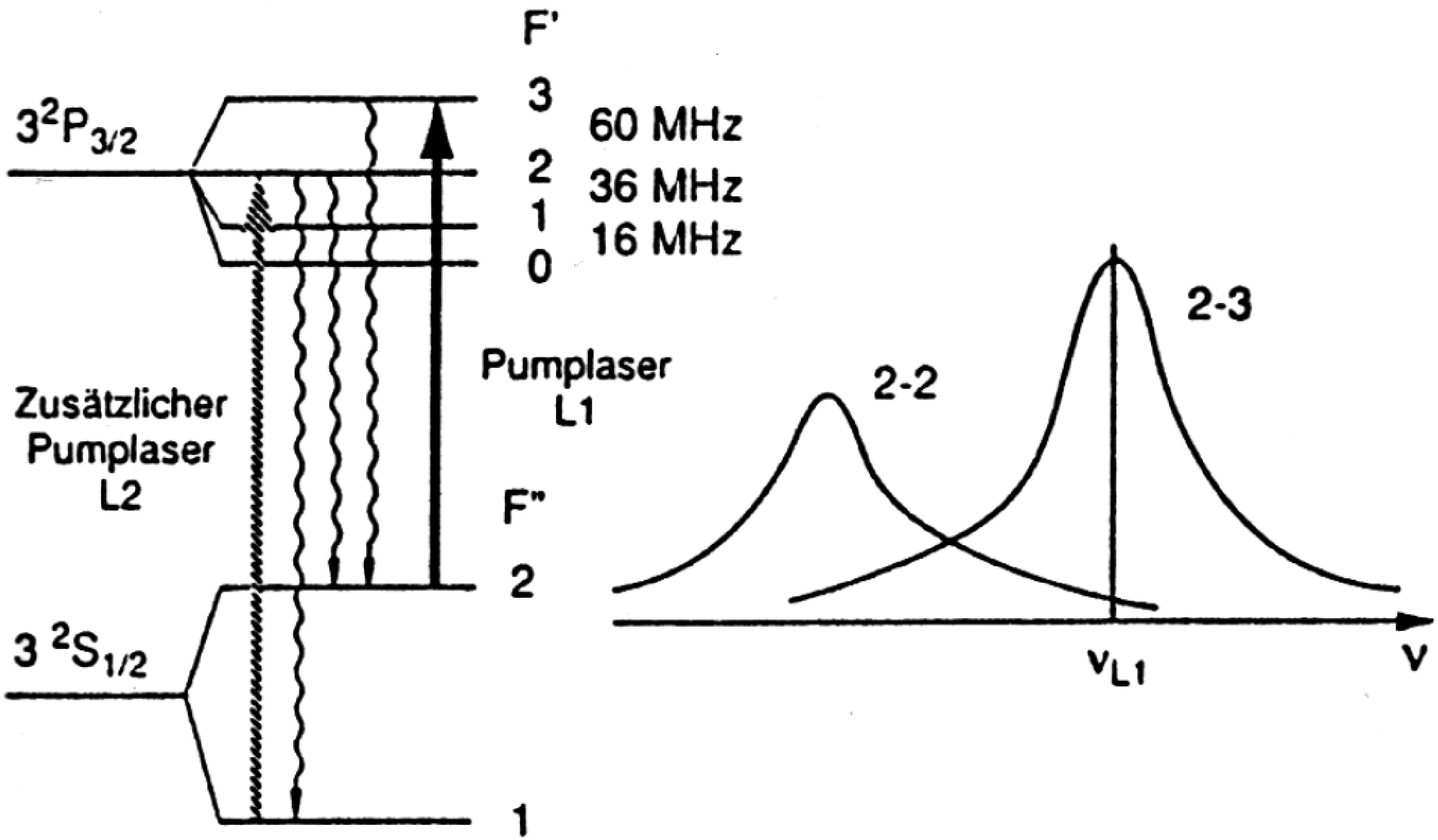
velocity distribution after irradiation with chirped frequency

Phillips RMP 1998



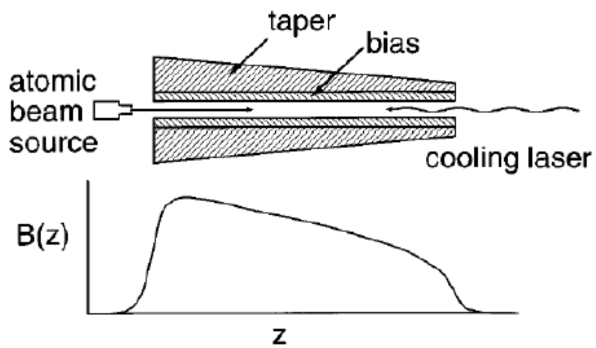
a chirped, i.e. temporally tuned frequency can shift a significant part of the velocity distribution and thus cool the atom ensemble.
Problem: it is difficult to create such chirped laser radiation.
Solution: we do not tune the laser but the atomic resonance

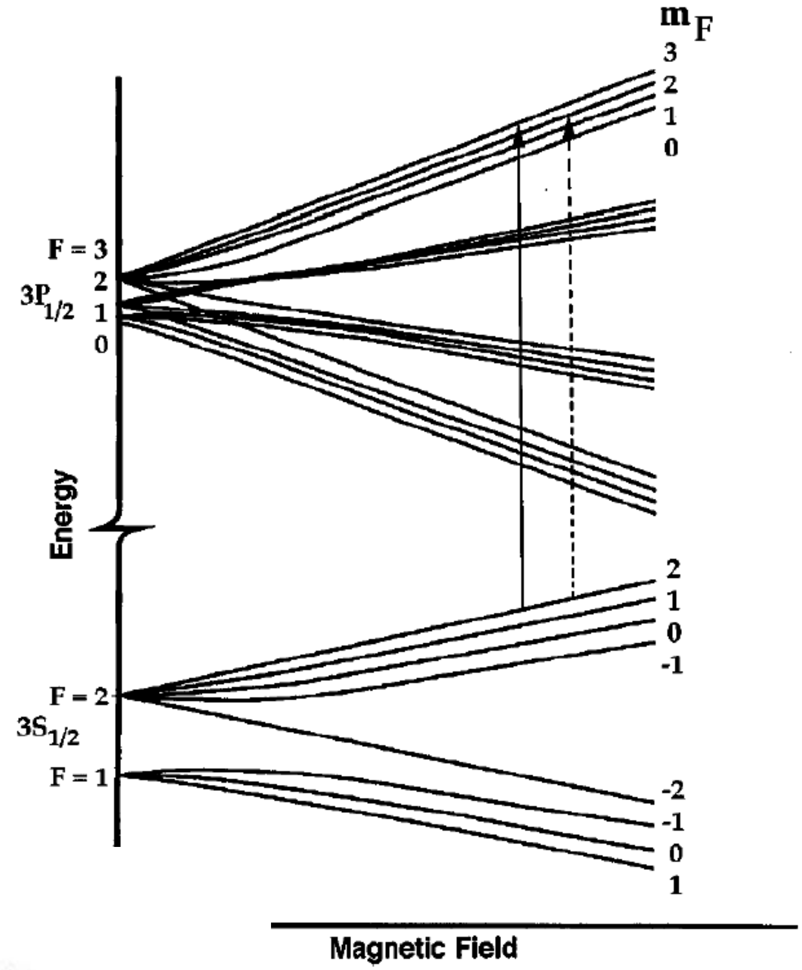
so far: idealized two-level system
in reality: HFS levels involved, e.g. Na $3^2S_{1/2}$ - $3^2P_{3/2}$



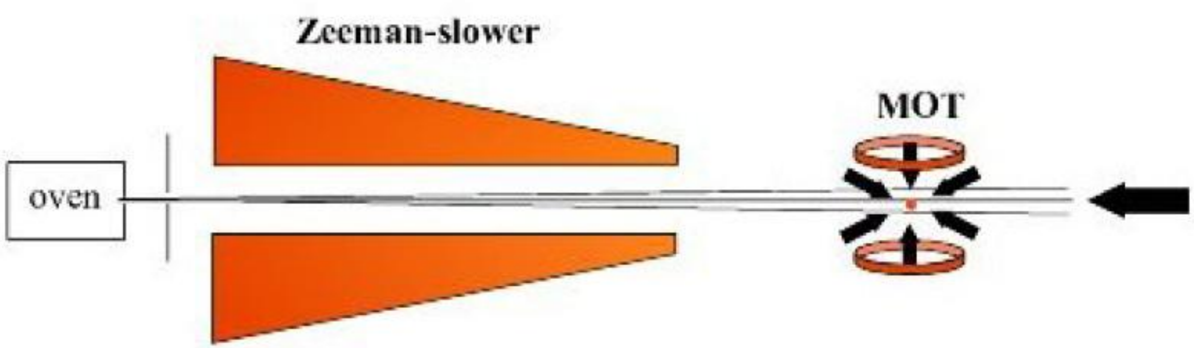
magnetic field helps to separate and to shift the levels

Zeeman cooler: deceleration to identical v possible





- Zirkular polarisiertes Licht σ^+
- Übergang:
  $3S_{1/2}(m_F = 2) \leftrightarrow 3P_{3/2}(m_F = 3)$
- Wahrscheinlichkeit für falschen Übergang extrem gering



Phillips RMP 1998