lecture 3.11.2011

we had in the last week:

- preparation of atomic beams II
- selected example with supersonic beams

today:
- selected example with supersonic beams
- atom beam diffraction
- ultracold He atom beam scattering from surfaces

atom beam application for fundamental questions

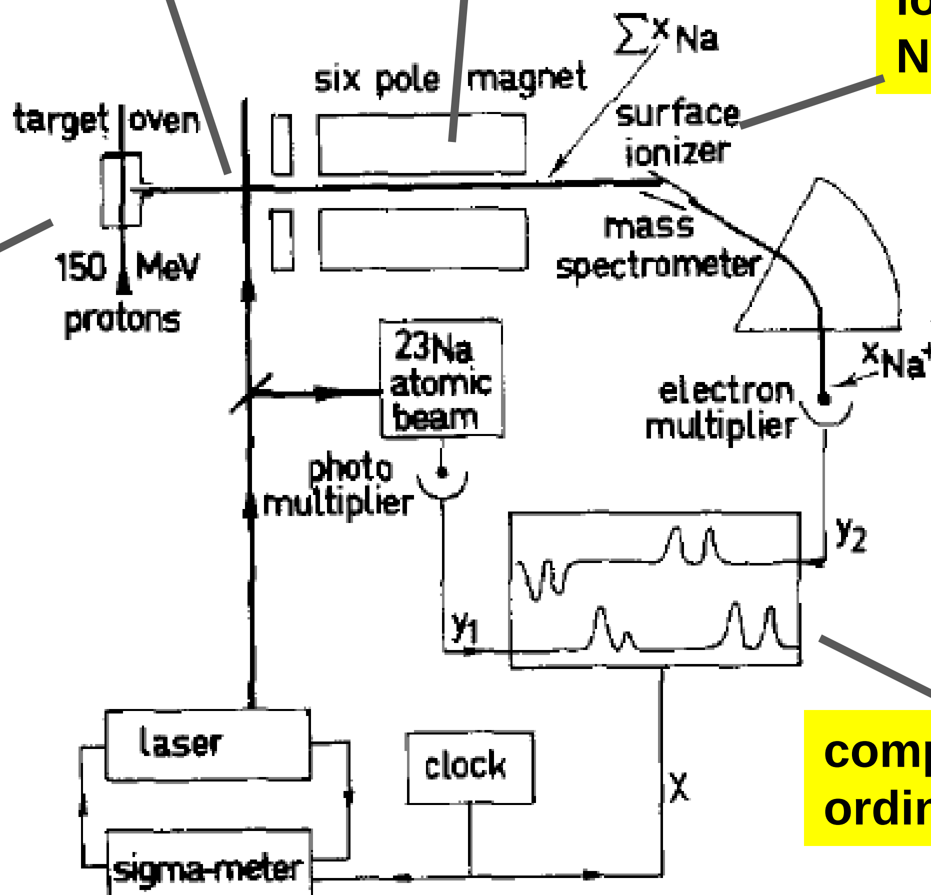
example: hyperfine spectroscopy

all Na isotopes laser excitation

selecting a hyperfine m_J state by focusing the neutral beam

ionize the focused Na atoms

creating Na isotopes by ^{27}Al spallation



select and detect the isotope

compare with the ordinary ^{23}Na spectrum

M_J state focusing of an atom

consider an atom in a **magnetic field**: Zeeman interaction Hamiltonian H'

$$\hat{H}' = -\mu_J \cdot \mathrm{B} \qquad\qquad \mu_J = -g_J \frac{\mu_B}{\hbar}\mathbf{J}$$

where μ_J is the magnetic moment with the total angular momentum J, g_J is the g-factor for the state with J, and μ_B the Bohr magnetron. Pertubation theory:

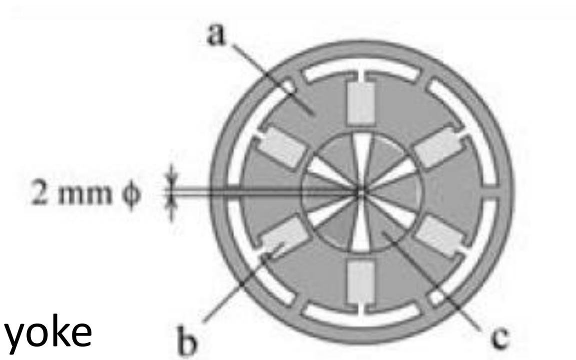
$$W_{Zeeman} = \langle J M_J | \hat{H}' | J M_J \rangle = g_J \mu_B M_J B$$

with M_J the magnetic quantum number of J. For L-S coupling:

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

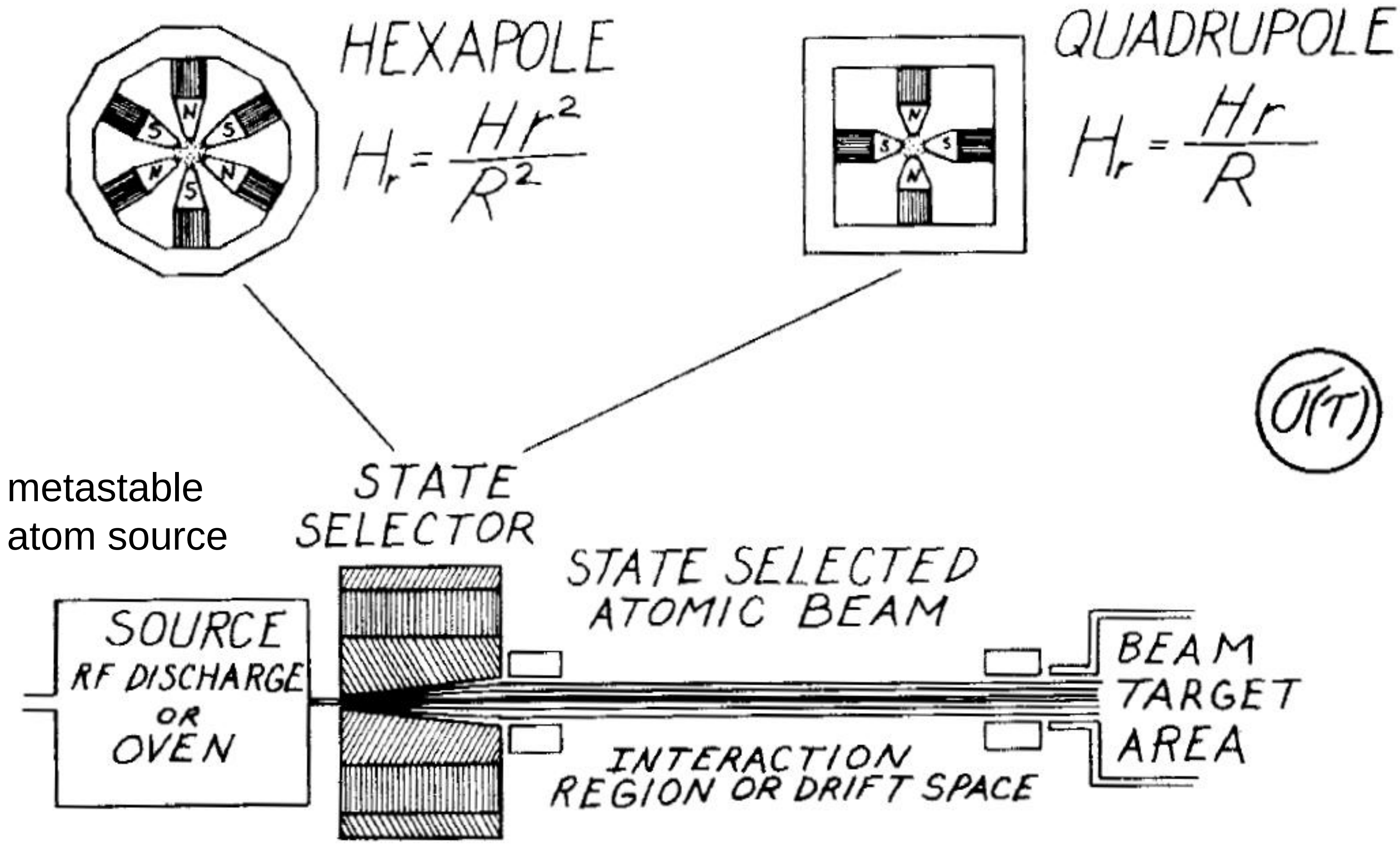
In an inhomogeneous magnetic hexapole field a radial force is experienced by the atoms:

$$\boxed{\begin{aligned} Fr &= -\frac{\partial W_{Zeeman}}{\partial r} = -g_J \mu_B M_J \frac{\partial B(r)}{\partial r} \\ B(r) &= \frac{H_R}{R^2} r^2 \end{aligned}}$$



a: mild steel yoke
b: permanent magnet
c: pole piece

magnetic state selection is an important tool in atomic frequency and time standards (atomic clocks)

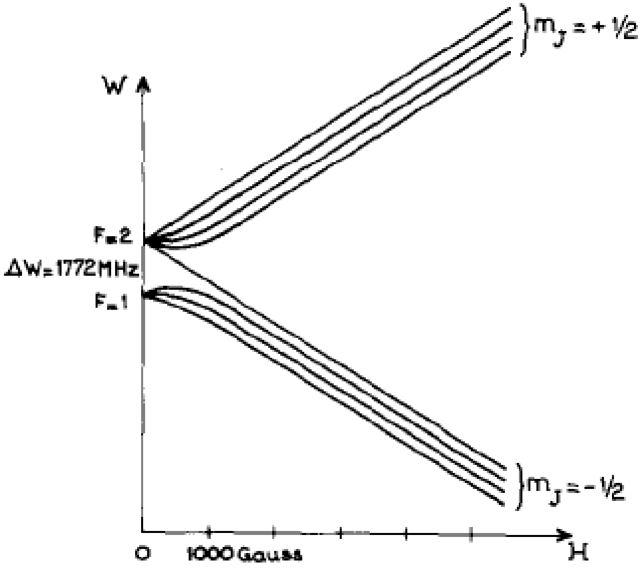


old and now published report of the Sigma Tau Standards Corporation, Alabama

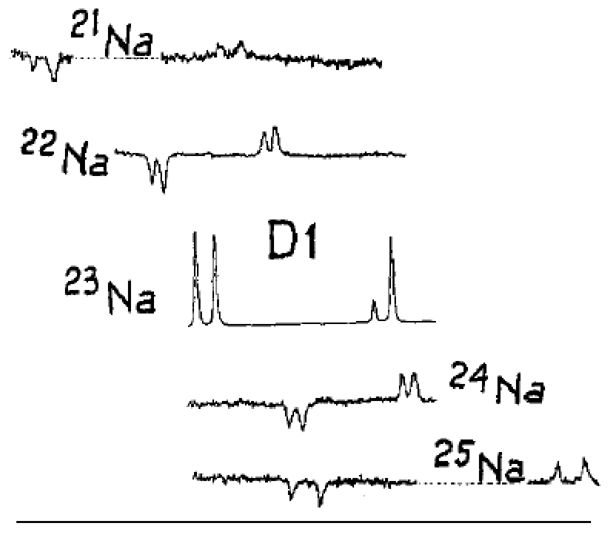
coming back to our experiment: selecting a single HFS state
with an electrostatic six-pole magnet

a magnetic 6-pole focuses atoms in the sublevel m_J = +1/2 of the ground state, it defocuses atoms in the sublevel m_J = -1/2

thus the HFS level with m_J = +1/2 can selectively be monitored



HFS transitions for Na d-lines



scale 10^{-3} cm^{-1}

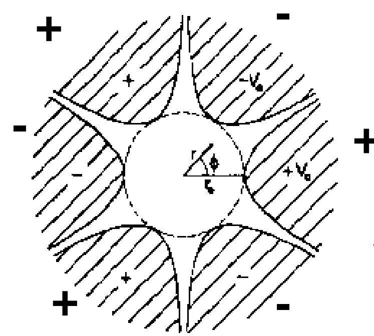
Duong et al., in *Laser Spectroscopy* II, Springer lecture notes 43 (1975)

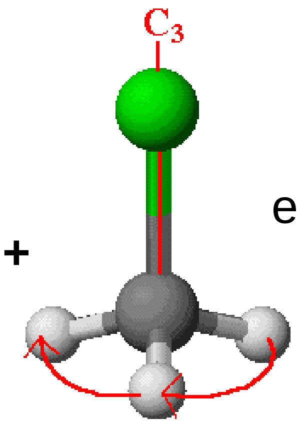
Hexapole state selection and focusing of neutral beam molecules

as side remark

In an **electrostatic hexapole field**, generated by six alternately charged parallel rods in a hexagonal configuration, molecules experience a radial force, which is in a first approximation determined by the first-order Stark effect

$$E_{\mathrm{Stark}} = -\boldsymbol{\mu} \cdot \mathscr{E} \frac{KM}{J(J+1)}$$





e.g. CH_3F

where **μ is the molecular dipole** moment and E is the electric field strength.

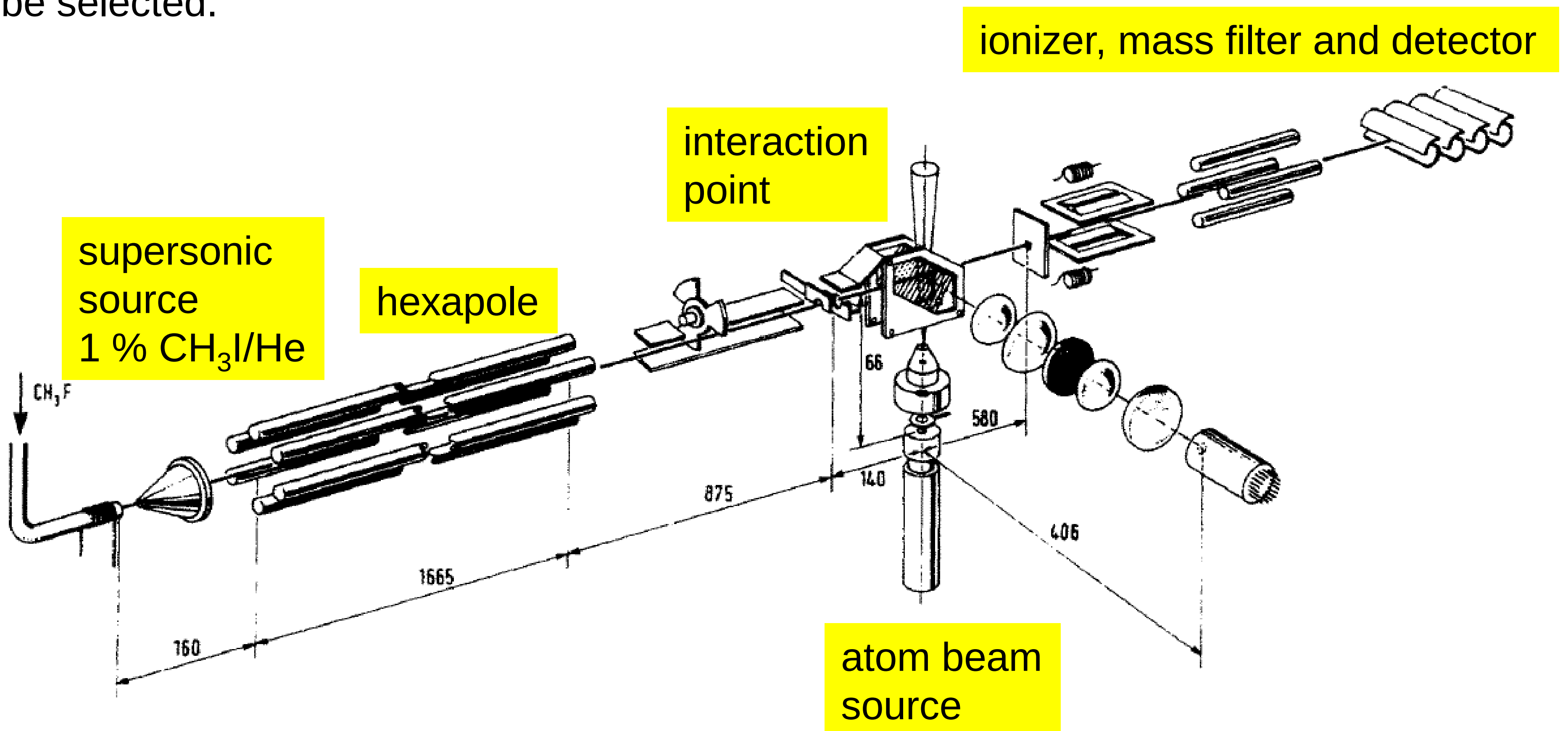
The molecular z-axis is chosen in the direction of the dipole moment. The radial force exerted on molecules travelling along the hexapole axis is, to first order, given by

$$F_r = \frac{6\mu V_0}{r_0^3} \frac{KM}{J(J+1)} r$$

eqn. 2

Here, r_o is the distance from the hexapole axis to the rods, r is the radial distance from the axis, and V_0 is the voltage applied to the hexapole rods. Molecules that are off-axis are pushed towards the axis if the product KM is negative; they are pulled away from the axis, and removed, if KM is positive.

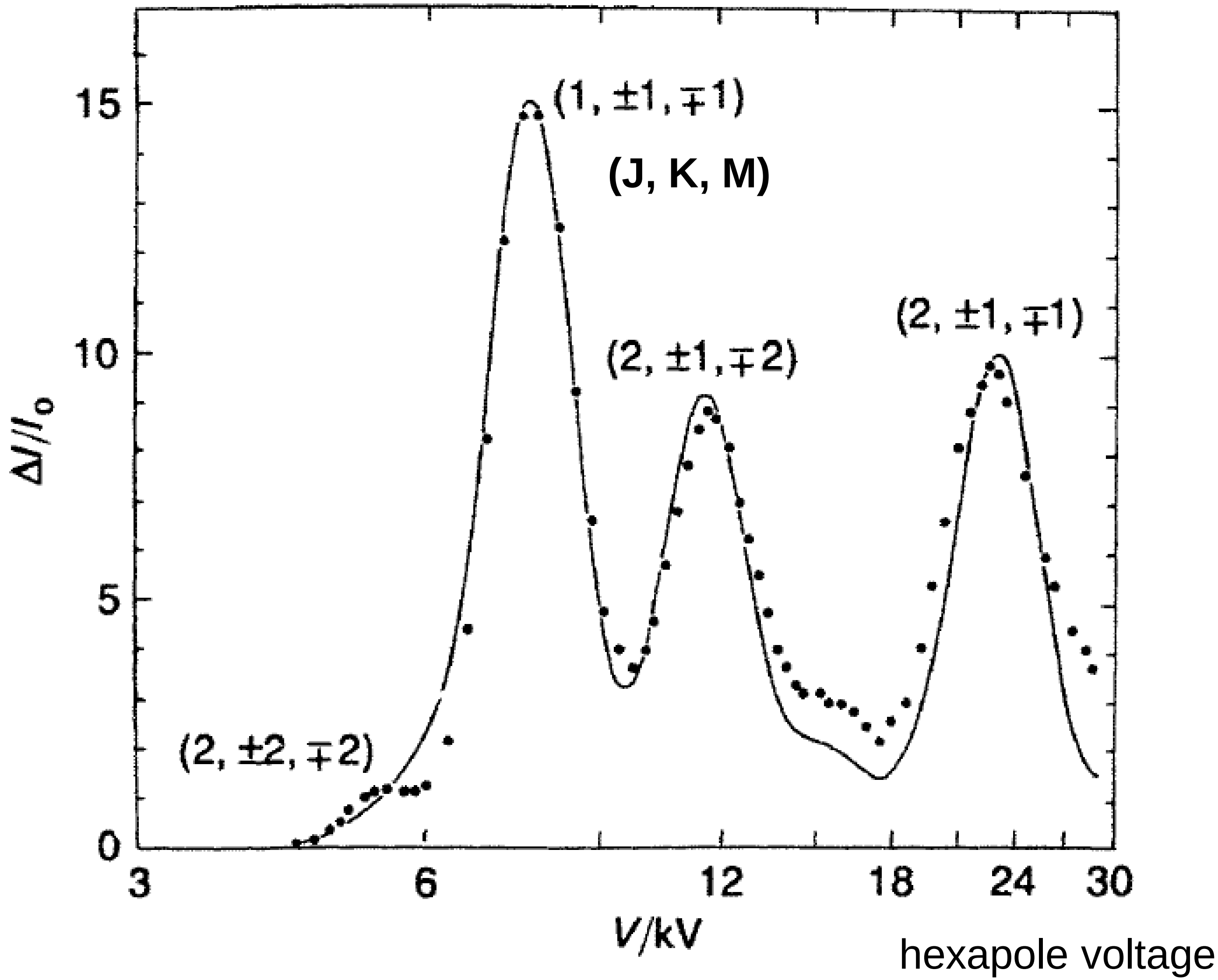
As a consequence of eqn. (2) and our convention, molecules in states with KM < 0, will be focused onto a small spot on the axis, **provided their velocity distribution is very narrow**. Clearly, states with either K or M = 0, or KM > 0 cannot be selected.



hexapole focusing machine, used for studying collision processes between state-selected, oriented molecules and atoms

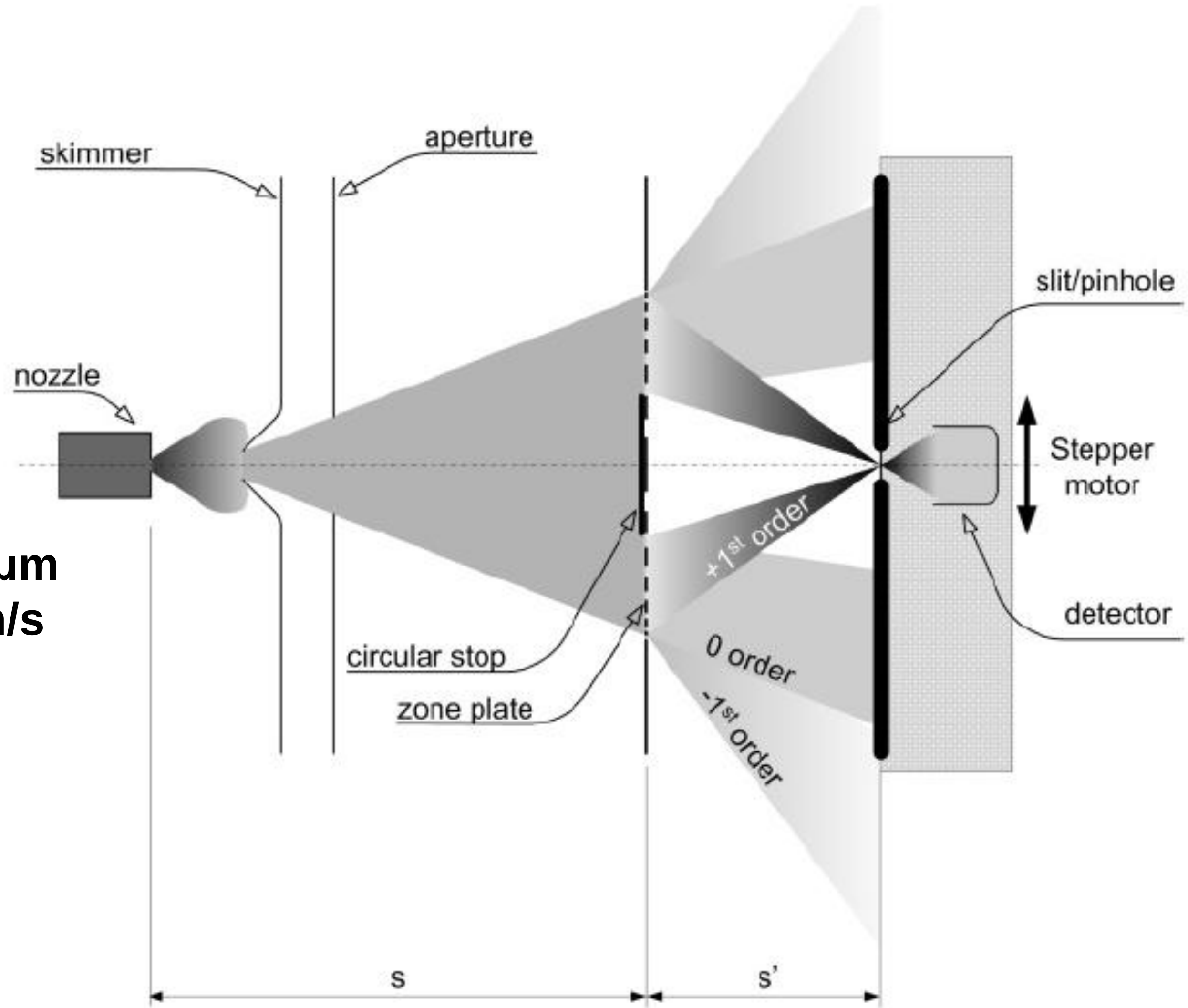
S. Stolte et al., J. Chem. Soc. Faraday Trans., 1995, 91, 205

Focusing curve for a He-seeded beam of CH_3I



e.g., at 9 kV molecules in the (1,+-1,+-1) stated will be focussed

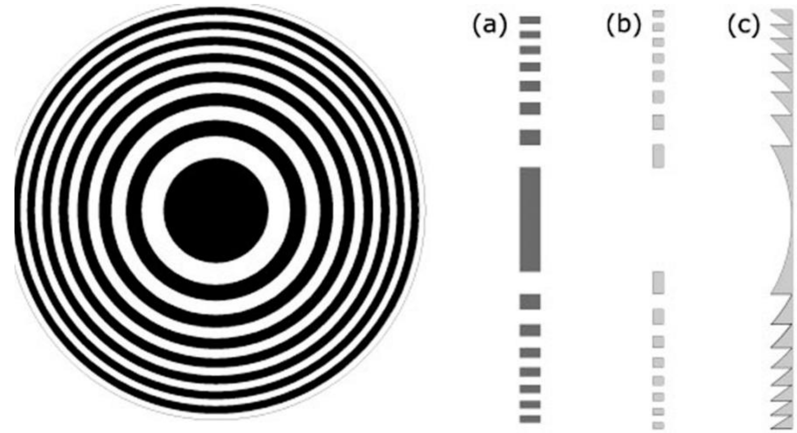
doing optics with an ultracold atom beam
focussing of a neutral He beam by diffraction

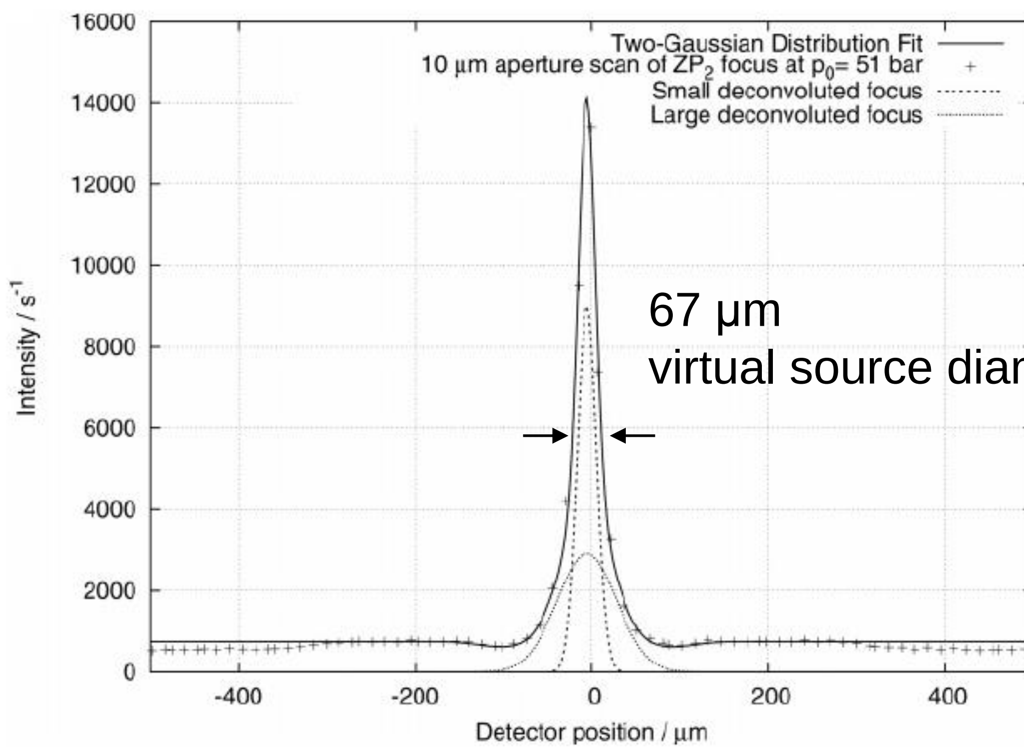


nozzle 10 μm
v = 1865 m/s
λ = 0.5 Å

focussing of a neutral He beam by diffraction
Fresnel zone plate

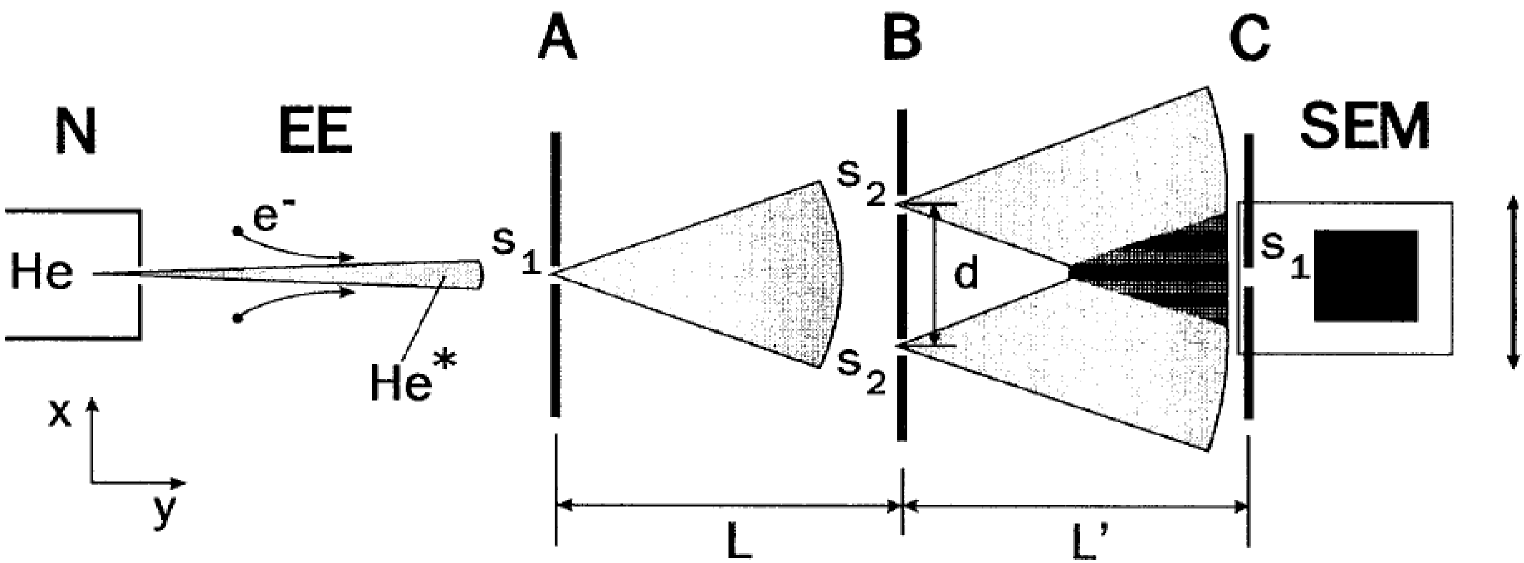
Nickel zone plate
540 µm diameter
2700 free standing zones
center blocked to supress 0^{th} order

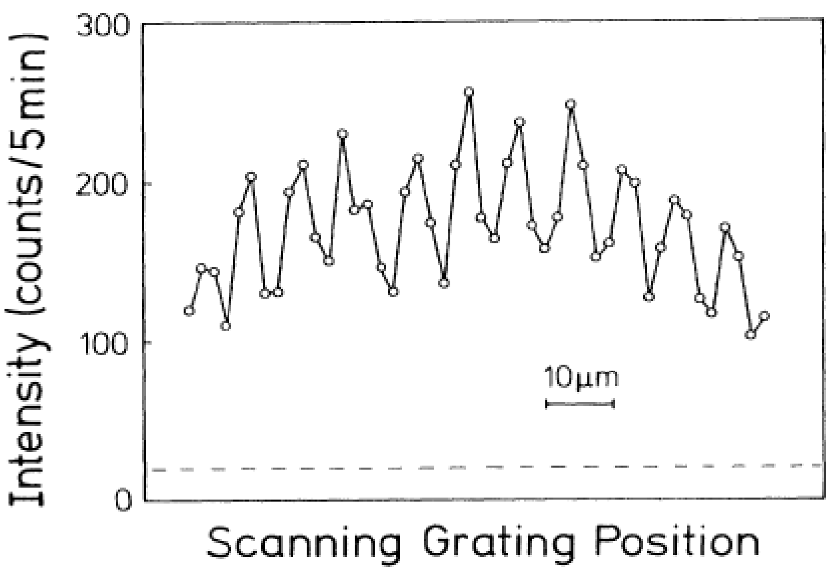




Reisinger et al.,
J. Phys. Chem. A 111,
2007, 12620

Young double-slit experiment with Helium atoms





λ_{dB} = 1.03 Å tuned by oven temperature set to 83 K

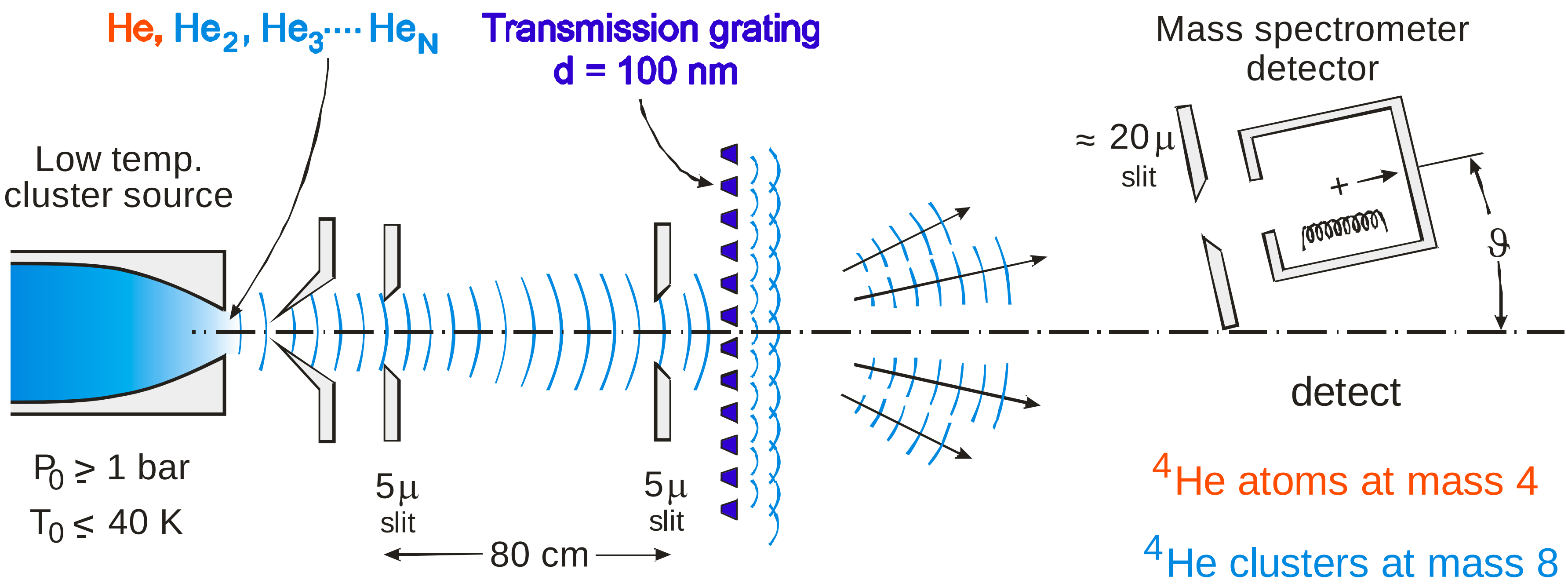
thermal de Broglie wavelength

$$\lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}}$$

Carnal and Mlynek, Phys. Rev. Lett. 21, 2689 (1991)

Non - destructive Diffraction Grating "Mass Spectrometer"

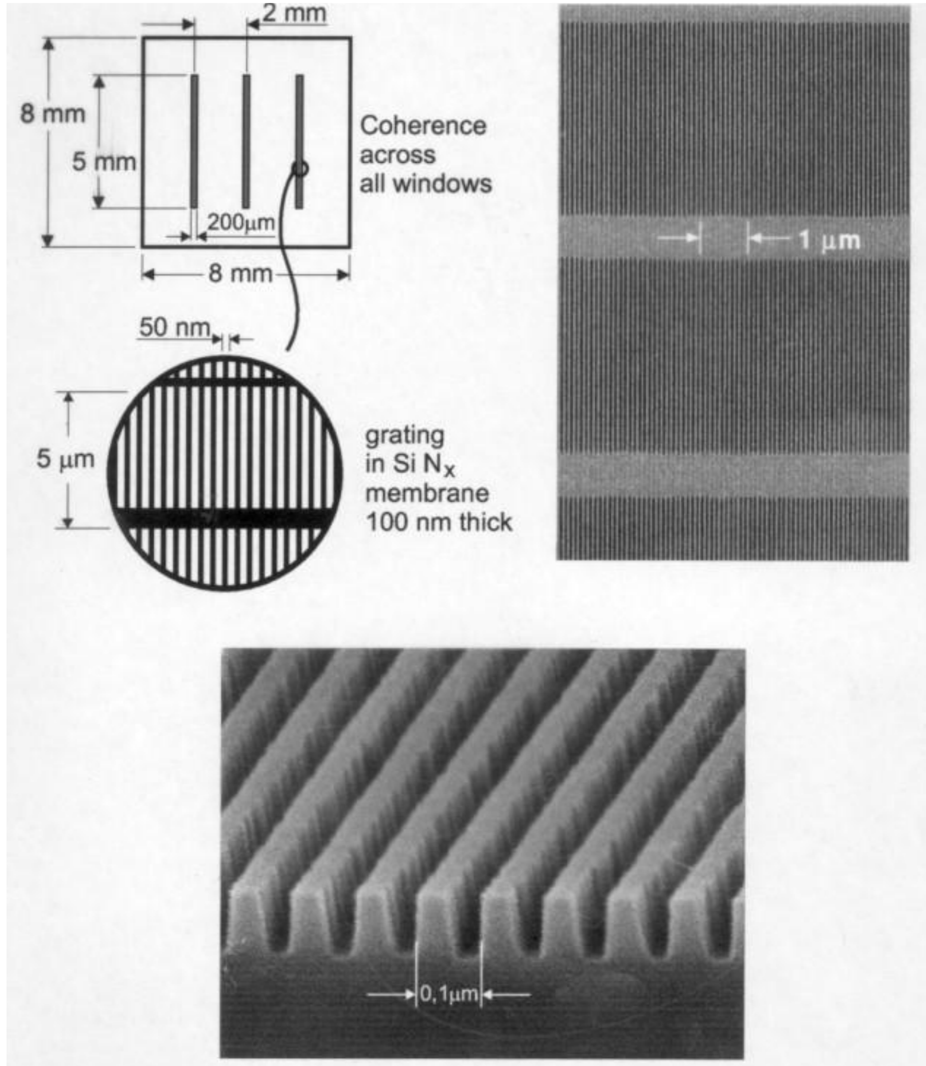
Previous: Na atoms, Pritchard et al (1988); He*, Mlynek et al (1991)



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

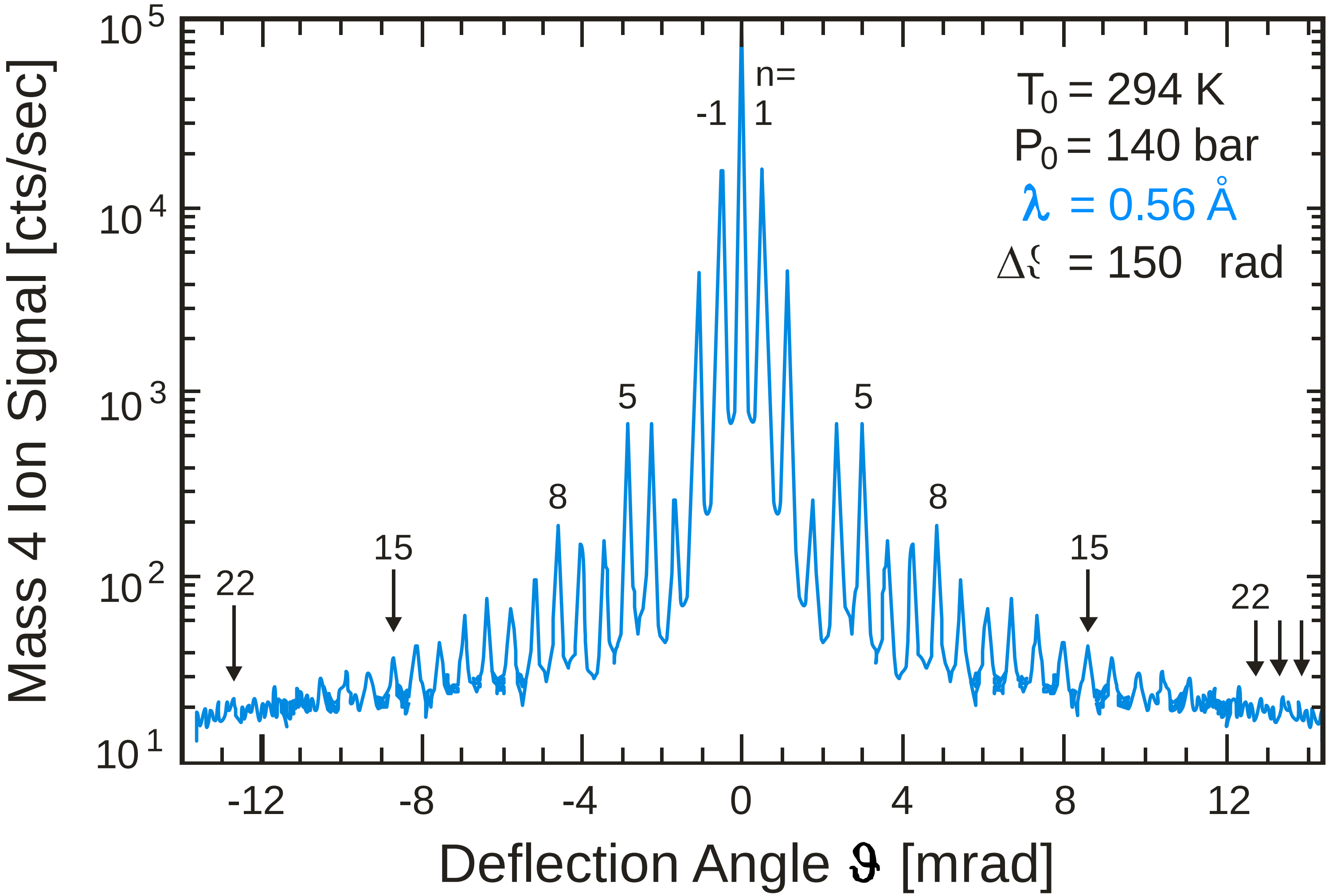
from J. P. Toennies

electron microscope pictures of SiN_x transmission gratings



Courtesy of Prof. H. Smith and Dr. Tim Savas, M. I. T.

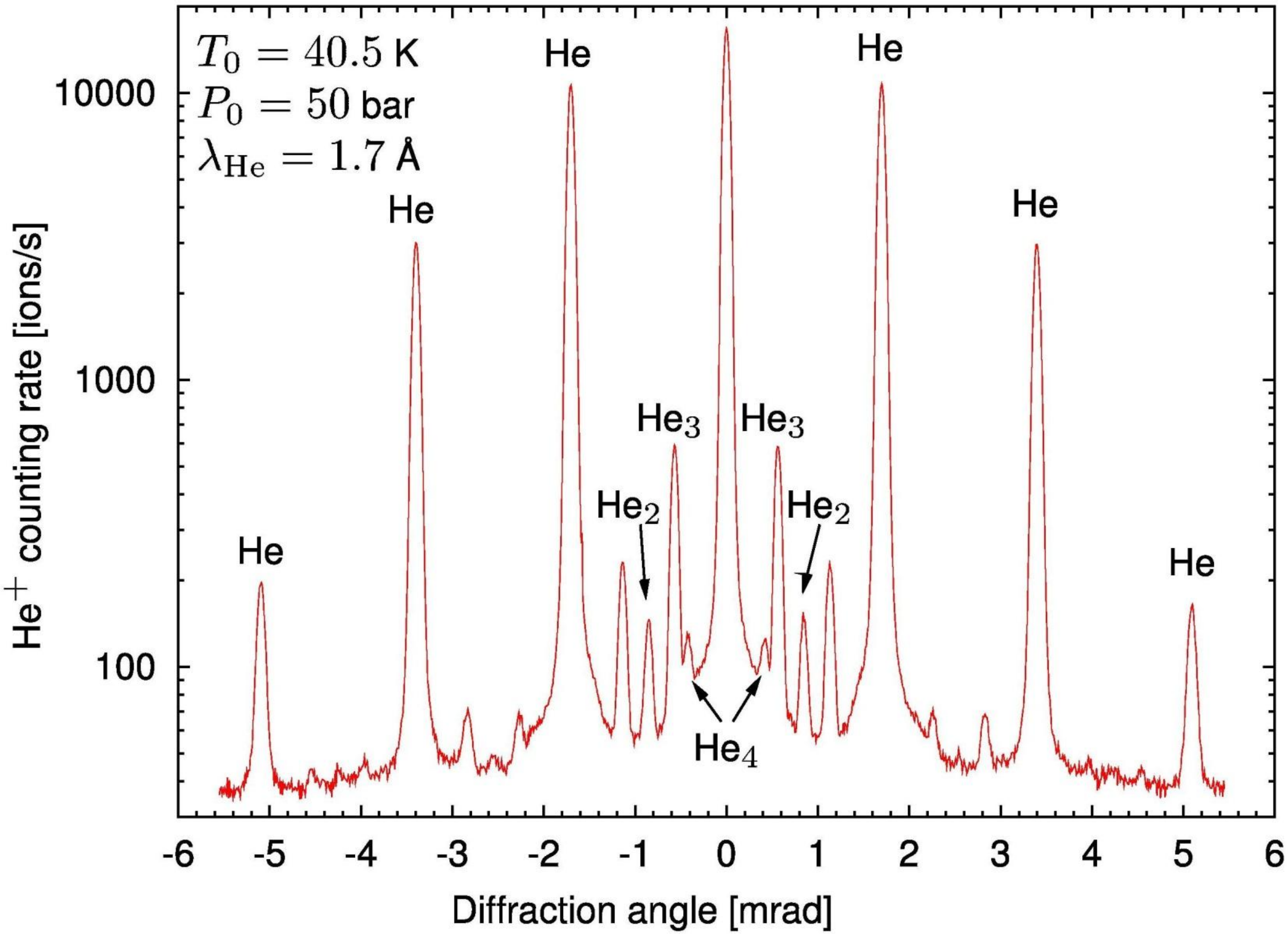
He Atom Diffraction Pattern for 300 K Beam



$$\text{Bragg: } \vartheta \simeq \frac{n\,\lambda}{d} = \frac{0.56\ \text{Å}}{1000\ \text{Å}}\ (n=1) = 0.56 \cdot 10^{-3}\ \text{rad.}$$

from J. P. Toennies

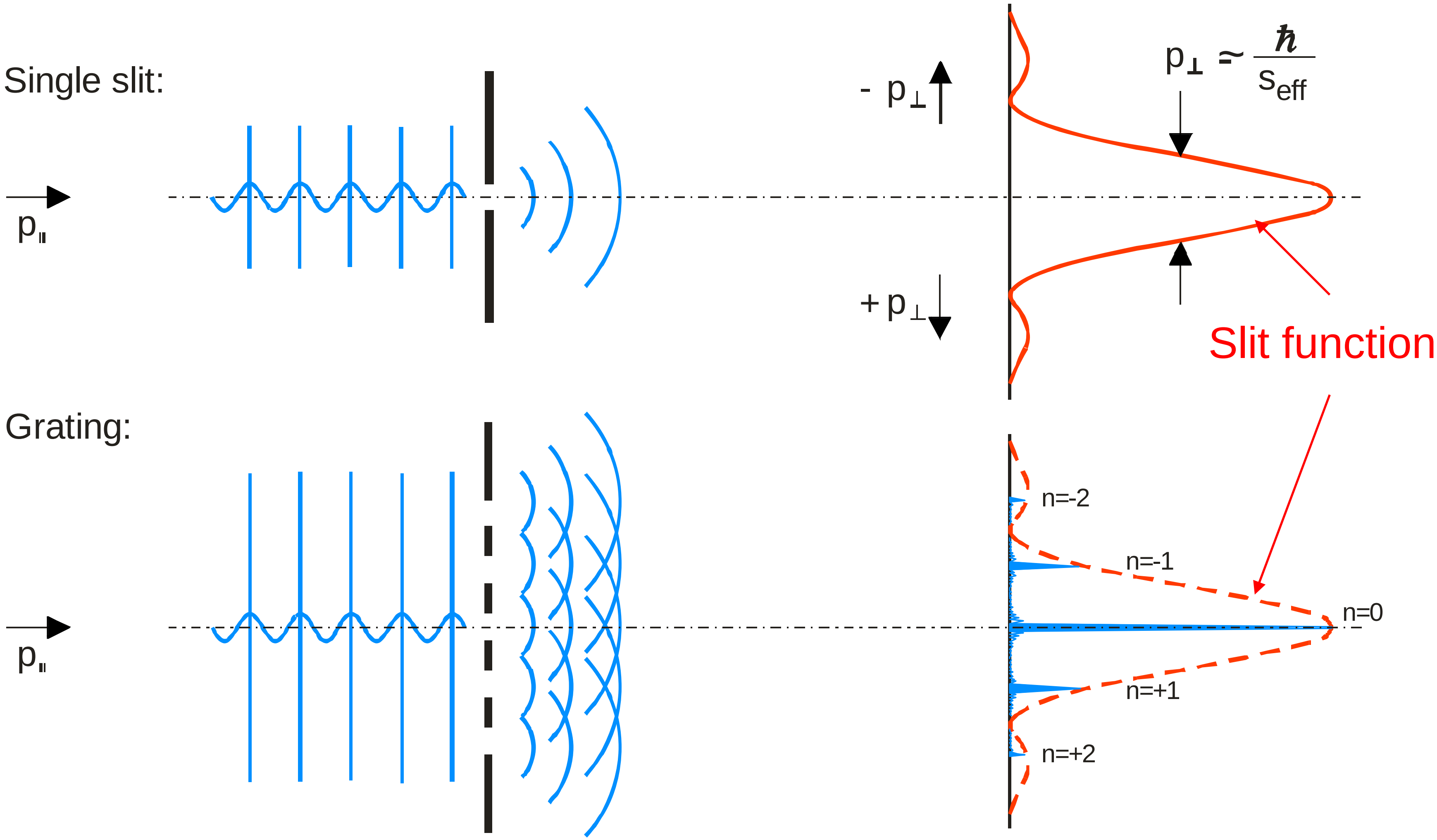
at low source temperatures new diffraction peaks appear



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

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

Single Slit Diffraction is Envelope of Grating Diffraction

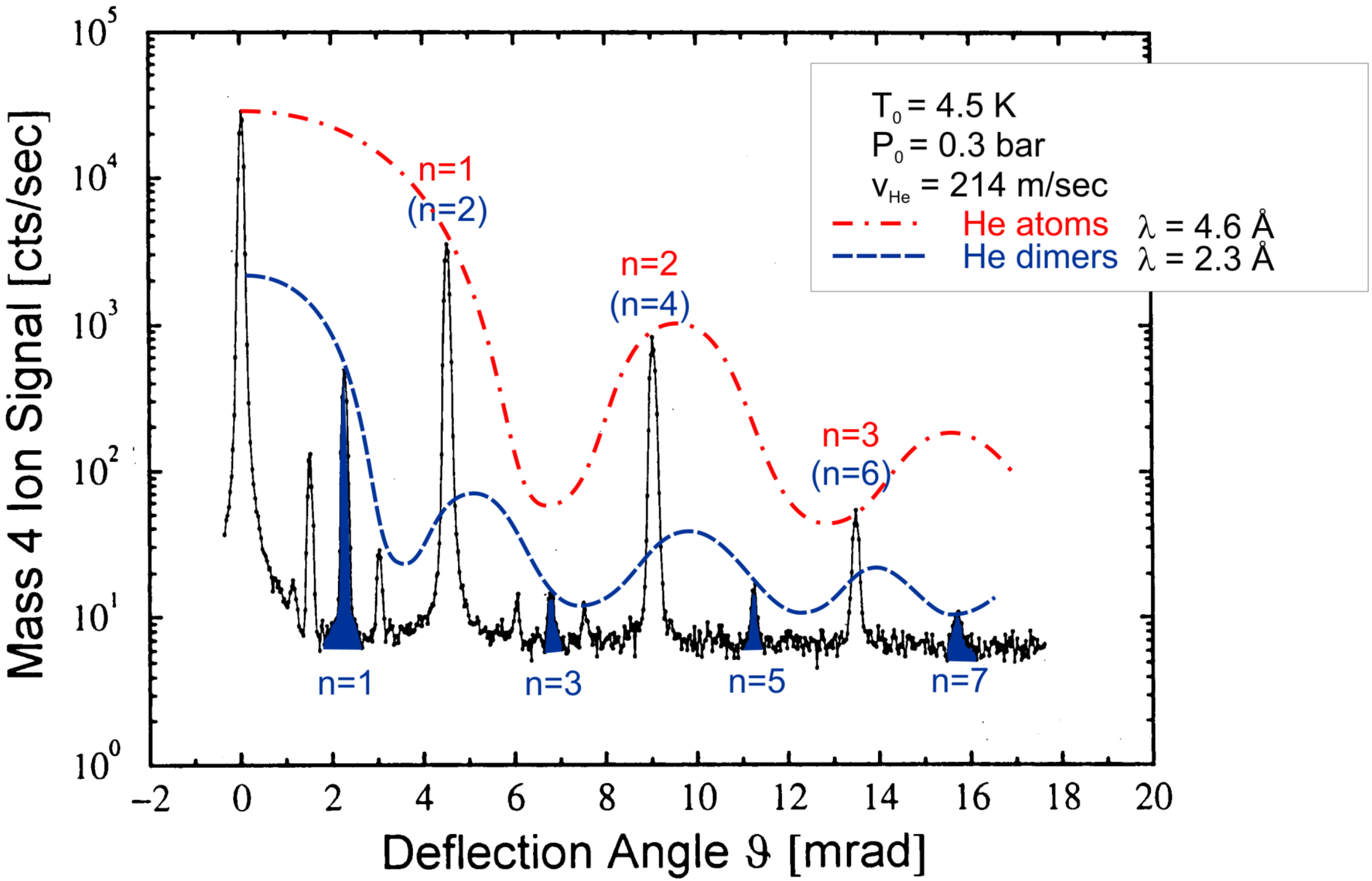


2003-07-17-T1-Schr.

Matter Waves: Feynmann: Lecture Notes in Physics

from J. P. Toennies

The He Dimer Diffraction Pattern and Slit Function



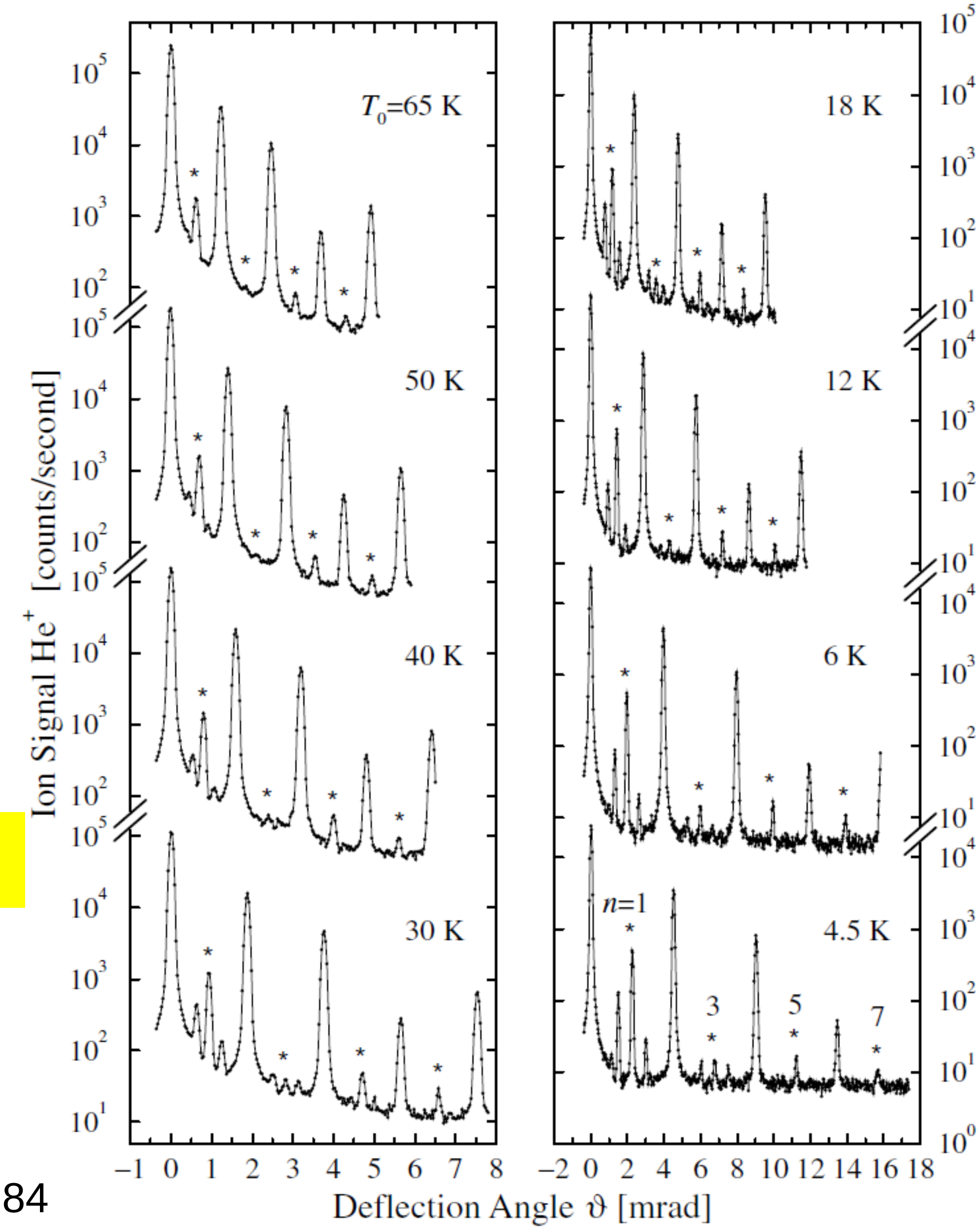
Grisenti, Schöllkopf, Toennies, Hegerfeld, Köhler and Stoll, Phys. Rev. Lett. 85, 2284 (2000)

2003-07-14-T1-Ba

Determination of the bond length and binding energy of the Helium dimer by diffraction from a transmission grating

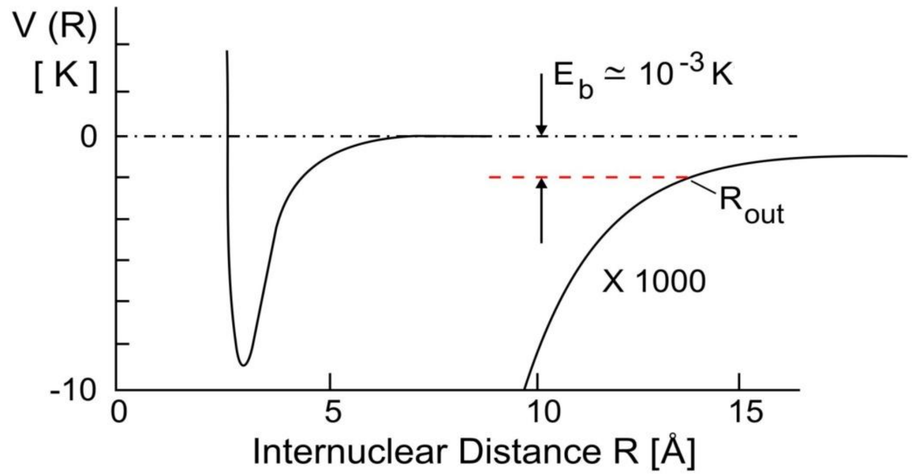
Patterns of ^4He cluster beams diffracted from a 100 nm period transmission diffraction grating with different nozzle temperatures. The odd order dimer diffraction peaks are marked by an asterisk.

Result: d (He_2) = 5.2 nm !!

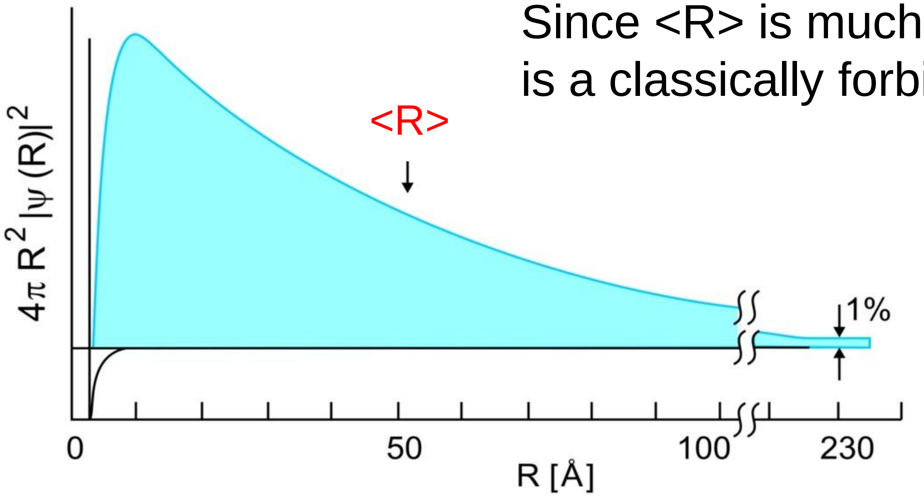


Grisenti, Toennies et al., PRL 85, 2000, 2284

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



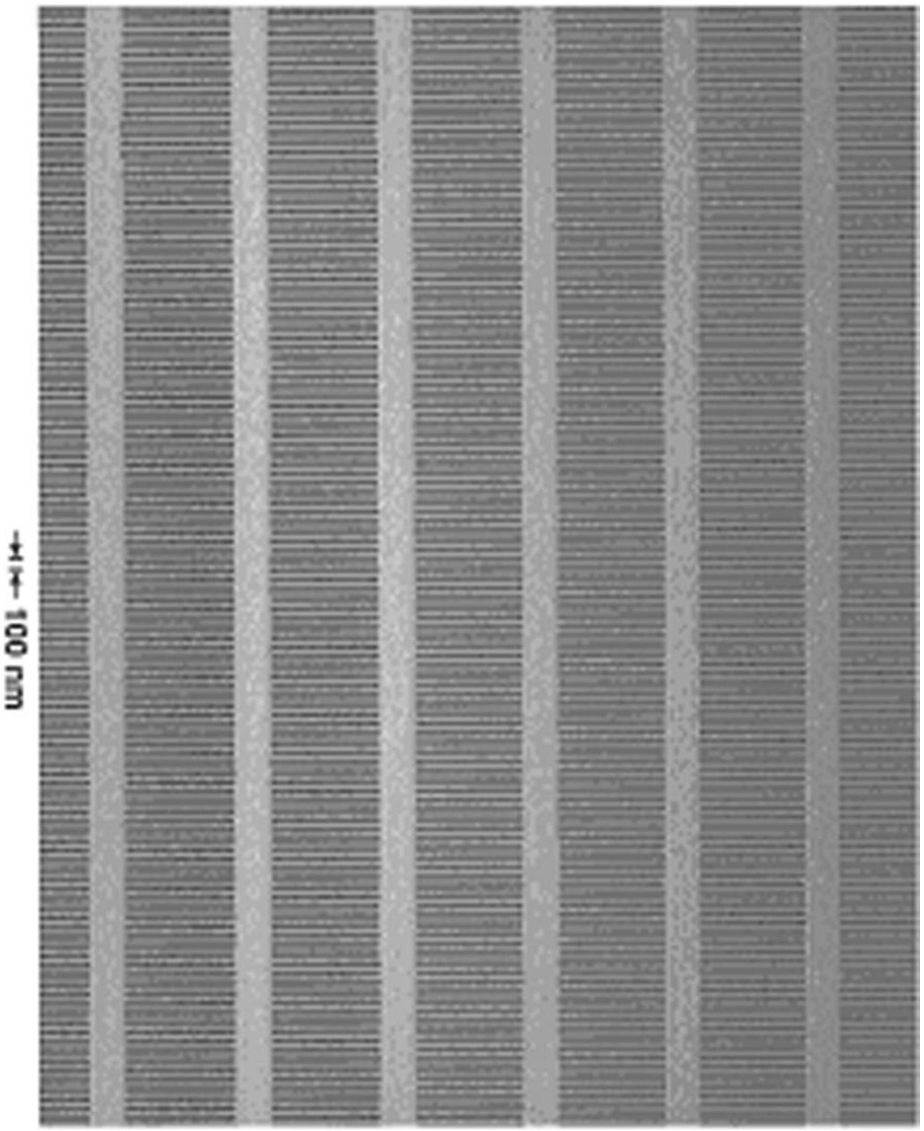
Scattering length: $a \simeq 2 \langle R \rangle \approx 100$ Å

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

A frail GIANT!

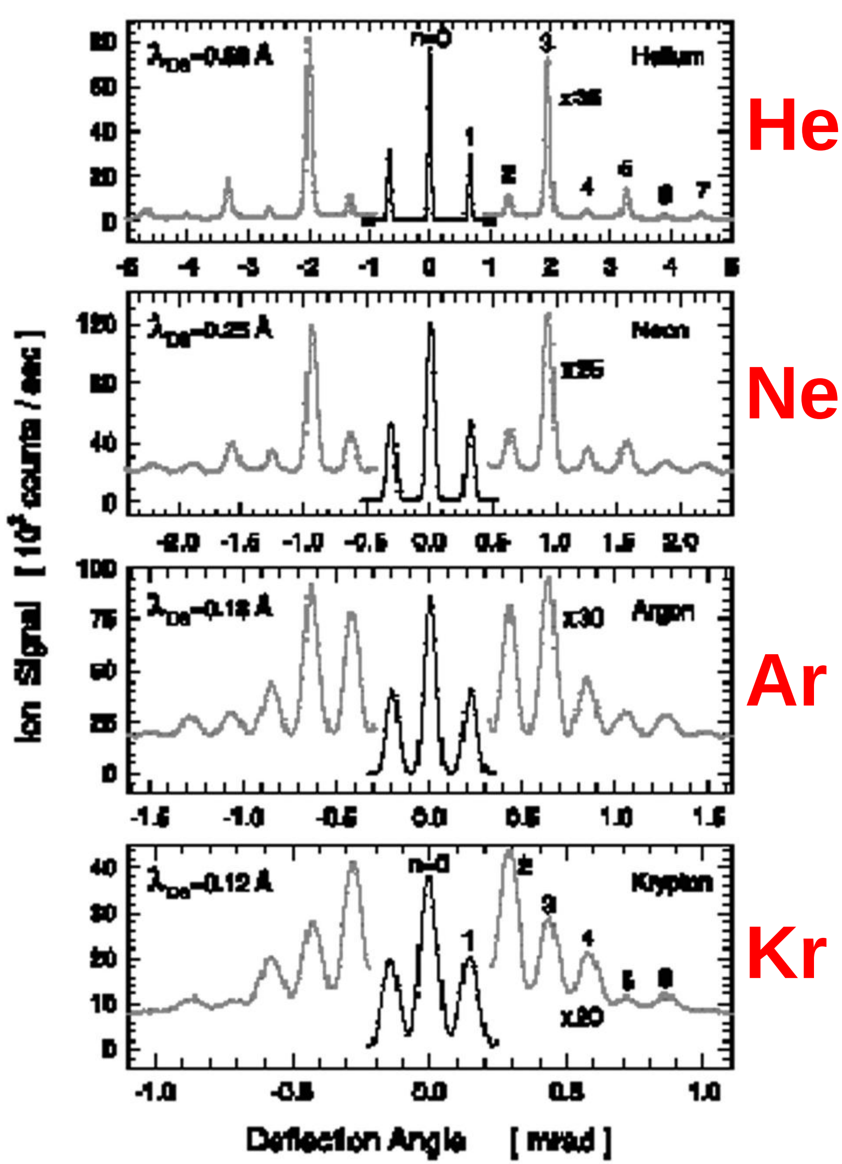
from J. P. Toennies

new 50 nm-wide bar grating



2003

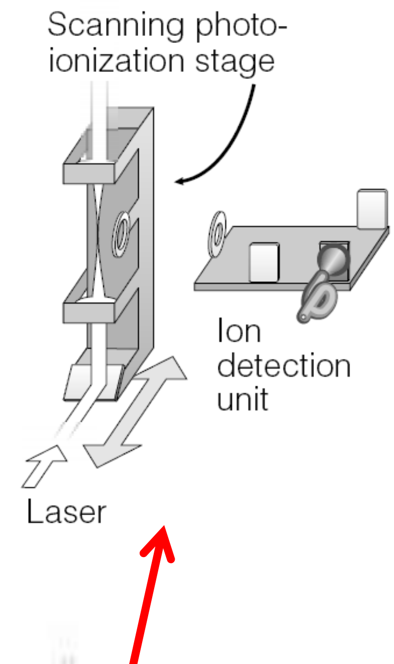
Rare Gas Atomic Beam Diffraction Patterns at 300 K for Normal Incidence

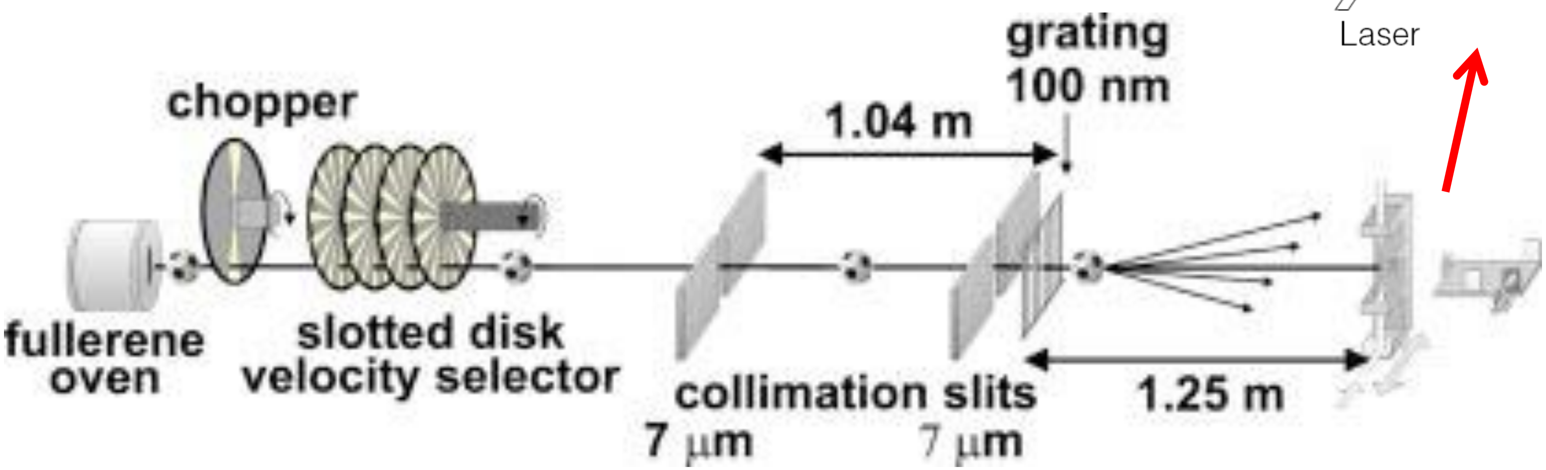


where is the end of the scale?

the fullerene molecule C_{60}

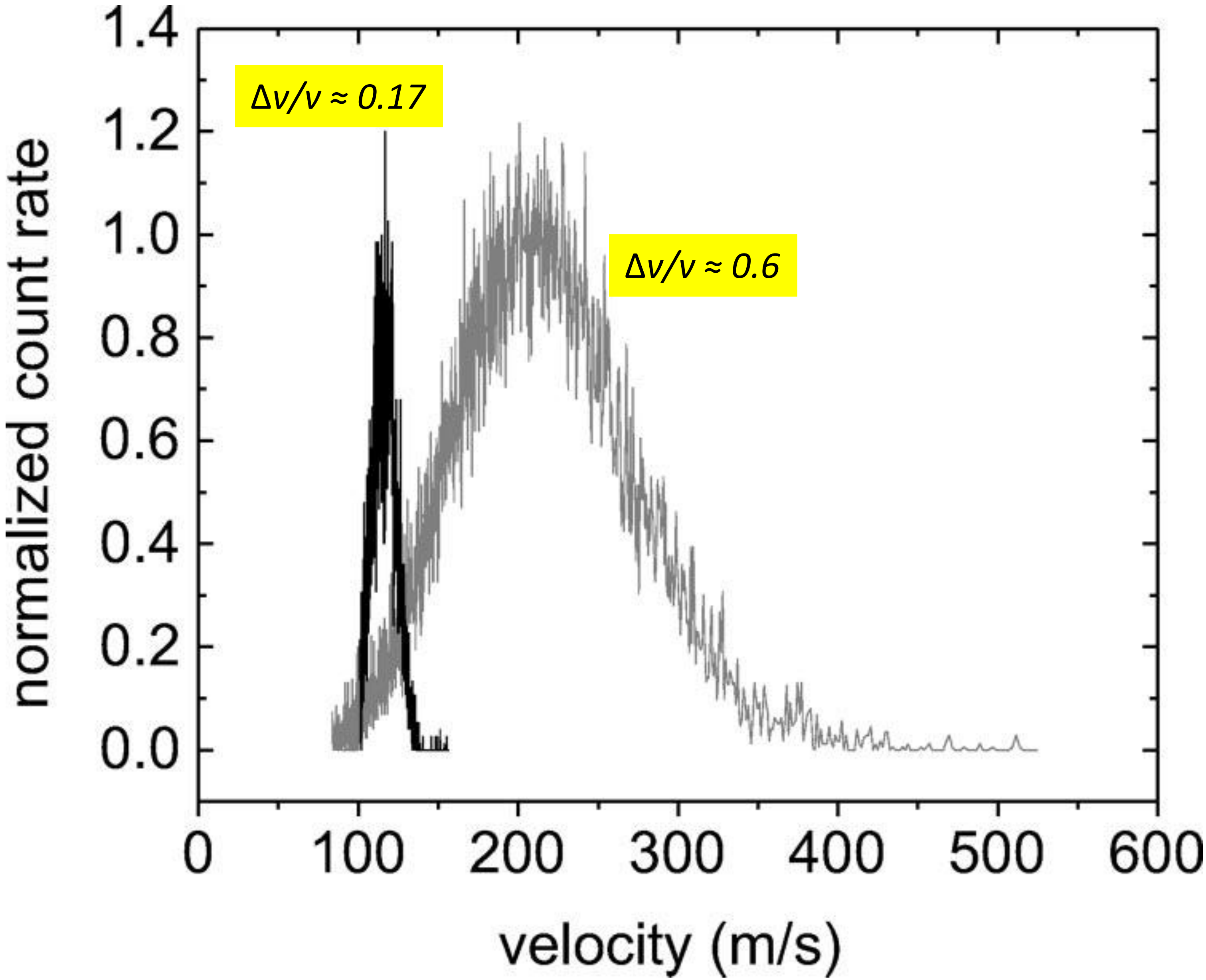
60 carbon atoms arranged in a truncated icosahedral shape





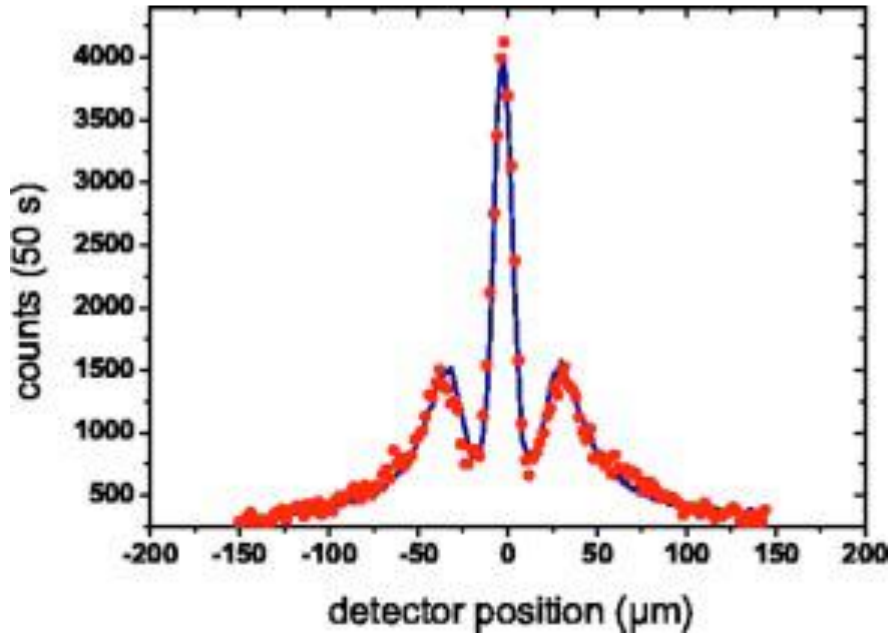
Nairz, Arndt, Zeilinger, Am. J. Phys. 71, 319, 2003

effect of velocity selection of C_{60}

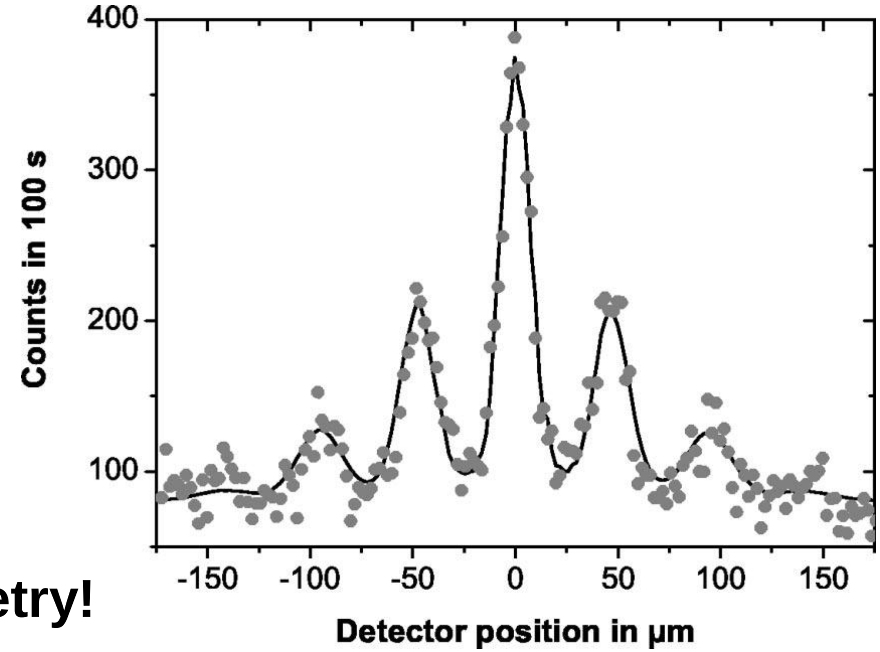


C_{60} diffraction pattern with

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