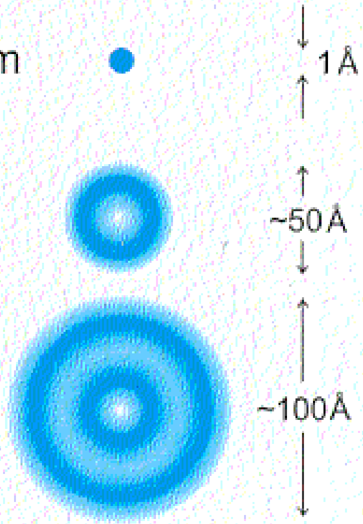
Marvelous Mysteriously Magic Helium
(an enigmatic element)

Most inert and smallest atom

He_2 : largest ground state diatomic molecule

He_3 : Efimov excited state? (only candidate)



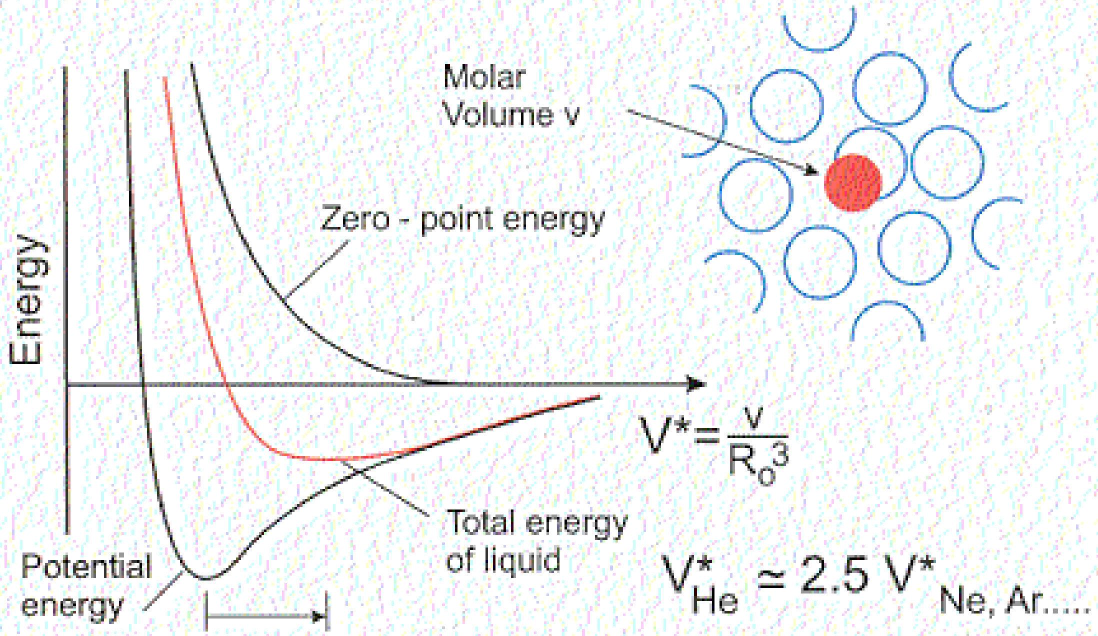
only substance which is liquid at 0K
high vapor pres.: 0.05 bar at 2.2 K

Boson (^4He) and Fermion (^3He)

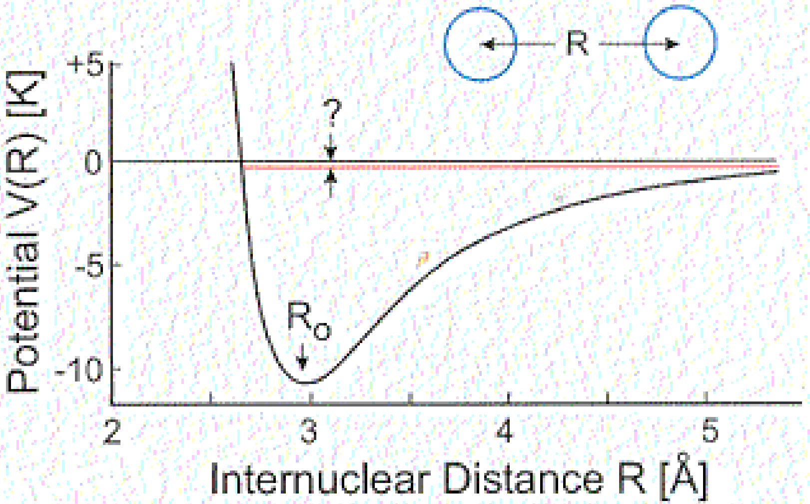
only naturally occuring superfluids

^4He: $T_c = 2.2$ K $\quad$ ^3He: $T_c \approx 3 \cdot 10^{-3}$ K

Its Large Zero Point Energy Makes Helium the Most Tenuous of all Liquids

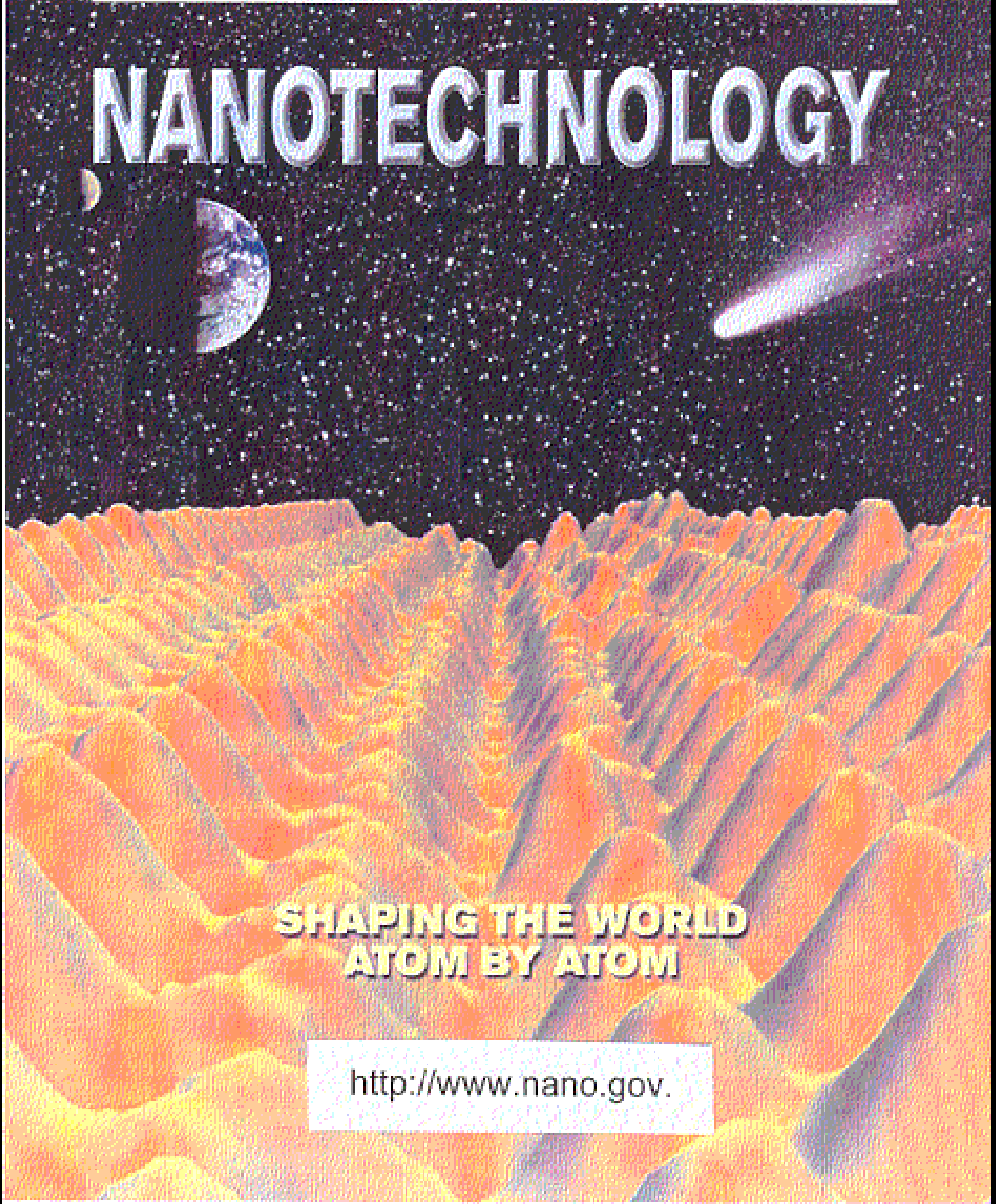


and the Most Weakly Bound Ground State Dimer



The U.S. National Nanotechnology Initiative
(Supplement to Presidents FY 2001 Budget)

NANOTECHNOLOGY

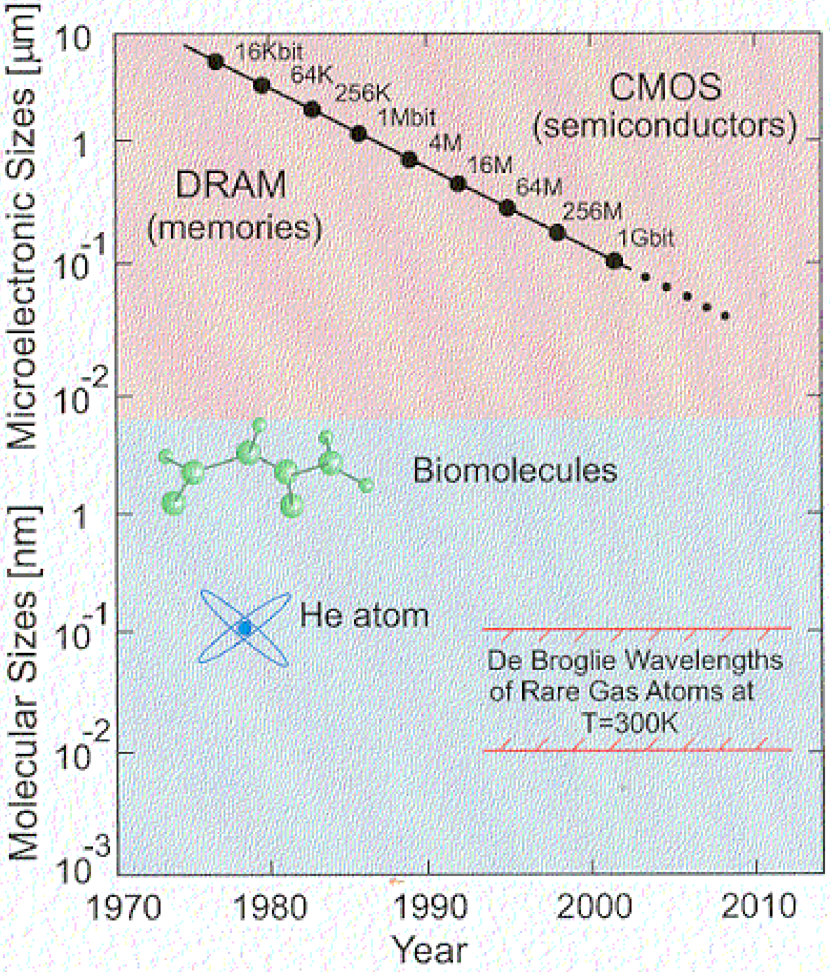


SHAPING THE WORLD ATOM BY ATOM

http://www.nano.gov.

Microelectronic vs Moleculares Sizes

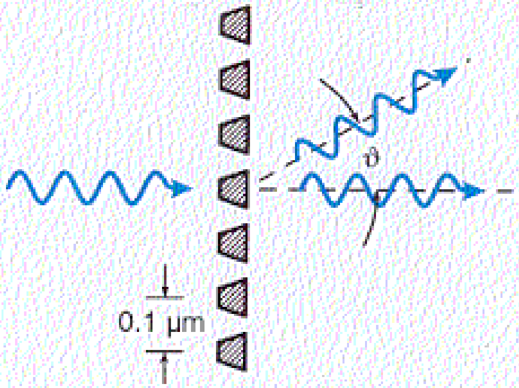
Moore: (1965) The number of transistors on a chip should double every 18 months



Feynmann: (1960) “There’s plenty of room at the bottom”

2002-02-26-T2-Ka

Manipulating Matterwaves via Diffraction from Nanostructures



de Broglie wavelength

$$\lambda = \frac{h}{m \cdot v} \quad , \; \lambda\,(\mathrm{He},\, 300\ \mathrm{K}) = 0.6\ \text{Å}$$

Bragg diffraction

$$\vartheta = \frac{n\,\lambda}{d} \quad , \; n = 0, 1, 2, \ldots$$

$$\frac{0.6\ \text{Å}}{0.1\ \mu\mathrm{m}} = 0.6 \cdot 10^{-3}\ \mathrm{radian}$$

Via diffraction can manipulate phases of transmitted de Broglie Waves

Phases of Q.M. Waves

Simple Wave Function

$$\Psi_i = \underbrace{|A| \exp(i\eta)}_{= f_i} \exp(ikz)$$

Microscopic Physics (e.g. atomic scattering)

$$|\Psi|^2 = |\Sigma f_i|^2$$

Macroscopic Physics

$$|\Psi|^2 = \Sigma |f_i|^2$$

with nanostructures can access phase information

otherwise only of significance in scattering

Brloni250802

Diffraction of Matter Waves from Nanostructures: New Physics and Novel Applications

J. Peter Toennies
Max-Planck-Institut für Strömungsforschung, 37073 Göttingen
jtoenni@gwdg.de

I. Diffraction from transmission gratings
   - a non-perturbing „mass spectrometer“
   - measurements of particle-wall forces
   - measurements of particle sizes.

II. A new universal matter-wave interferometer.

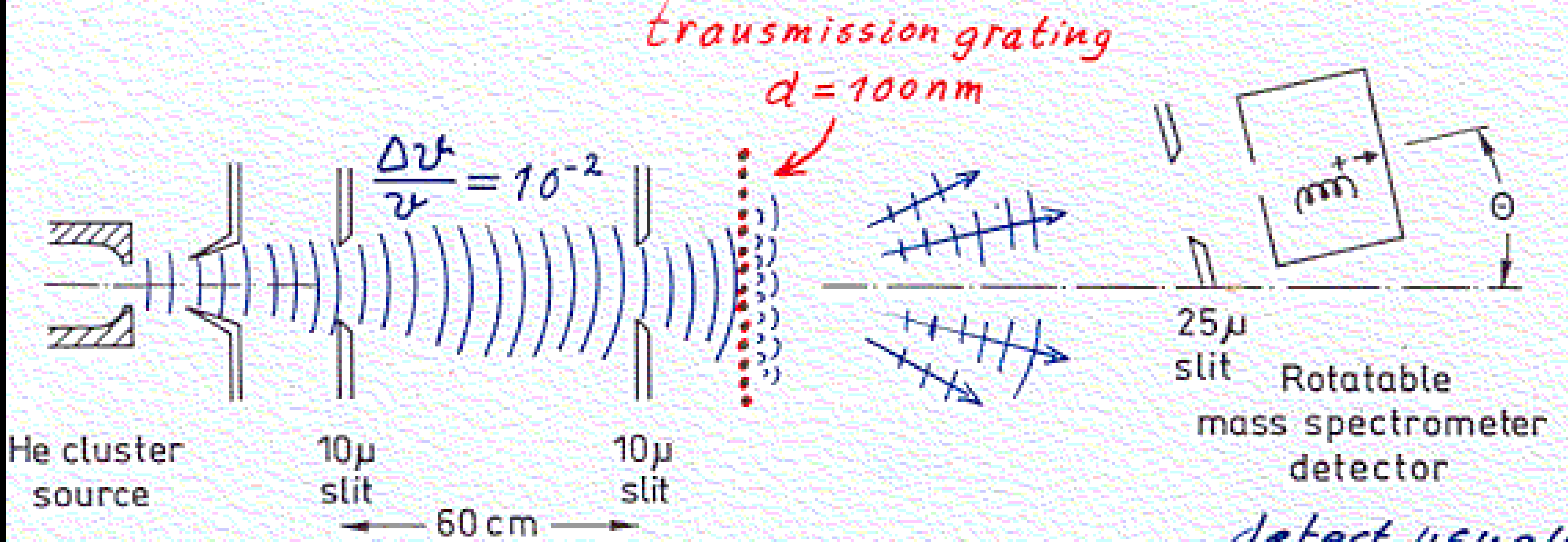
III. Focussing atom beams.

Collaborators

Experiments	Theory
Wieland Schöllkopf	Gerhard Hegerfeldt
Robert Grisenti	Thorsten Köhler
Oleg Kornilov	Martin Stoll
Rüdiger Brühl	Christian Walter

A Nearly Non-destructive Diffraction Grating Mass Spectrometer

Previous: Pritchard et al, 1988; Mlynek et al, 1991



detect usually at mass 4 (He^+) or mass 8 (He_2^+)

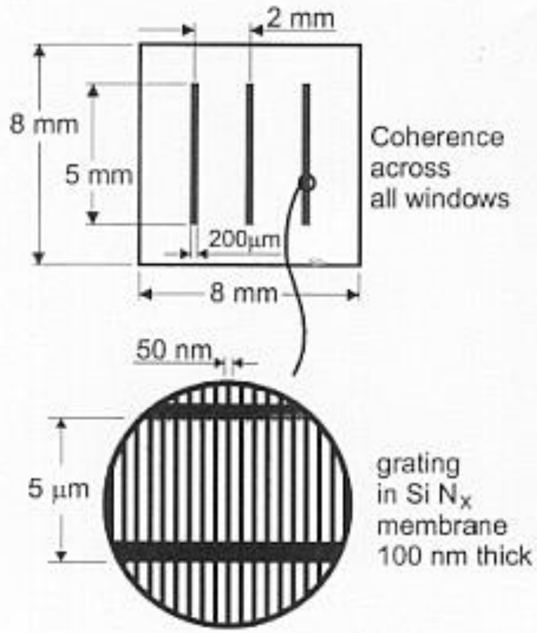
de Broglie: $\lambda = \frac{h}{N \cdot m_{He} \cdot v}$

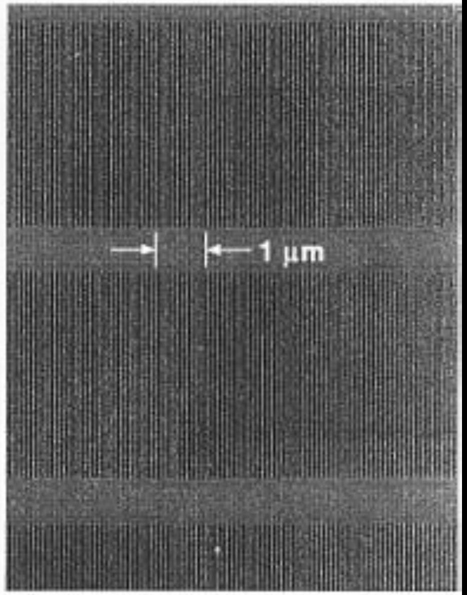
$$\sin \vartheta \cong n \frac{\lambda}{d}$$

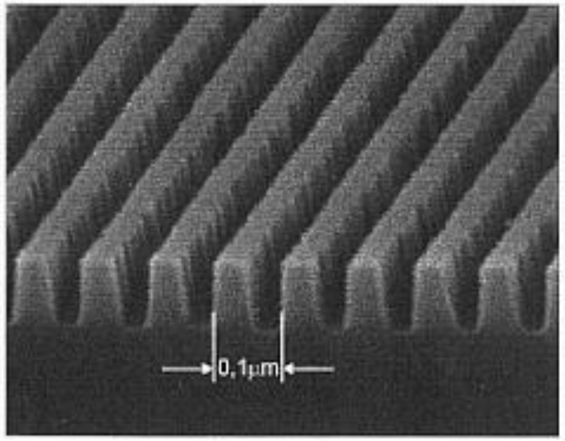
$$\cong n \frac{h}{\underline{N} \cdot m_{He} \cdot v \cdot d}$$

e.g. $\lambda = 0.1\,nm$, $d = 100\,nm$ $\qquad \vartheta \approx 10^{-3}\,rad$ $(n = 1)$

Electron Microscope Pictures of the Si N_x Transmission Gratings

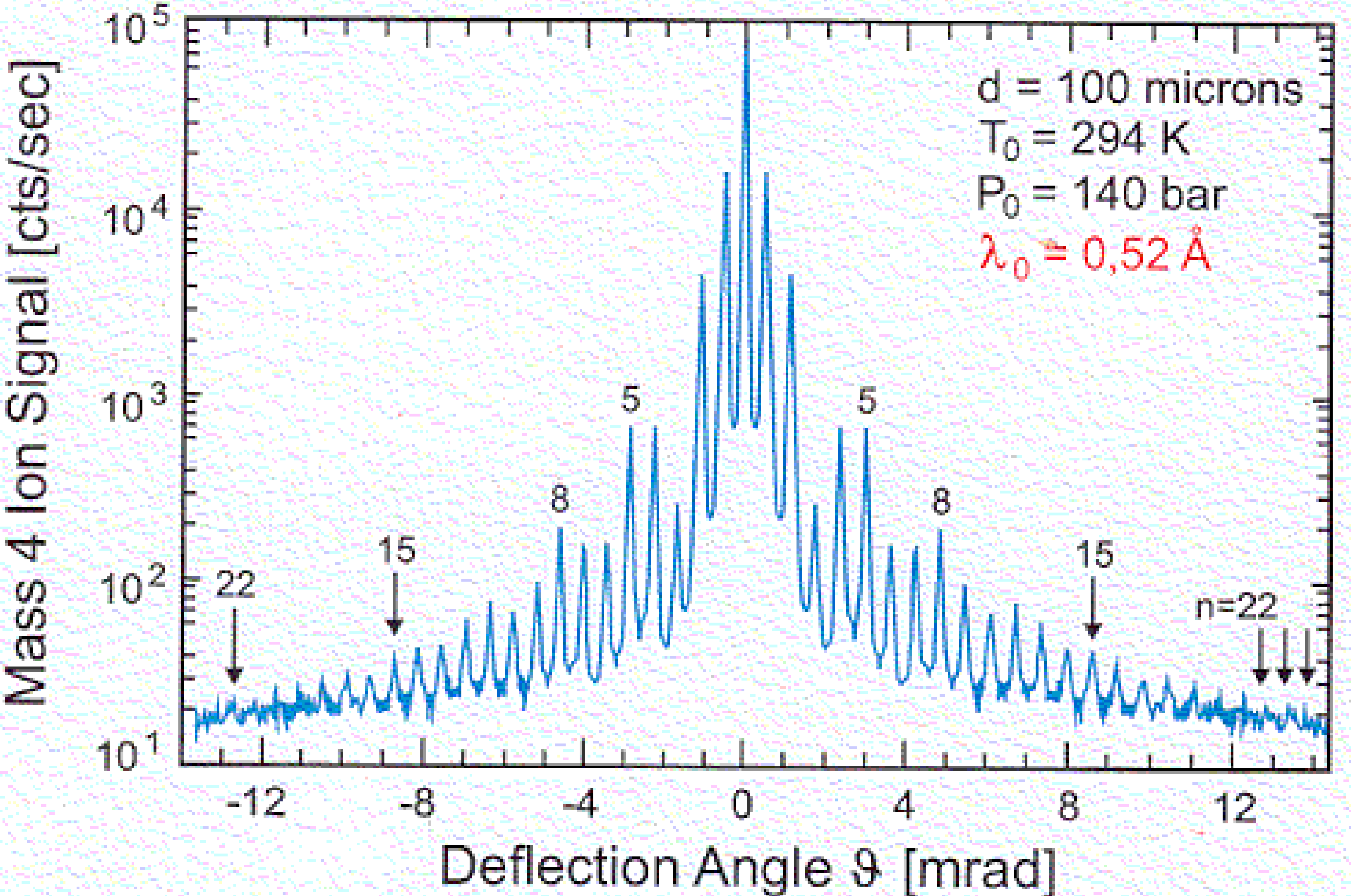




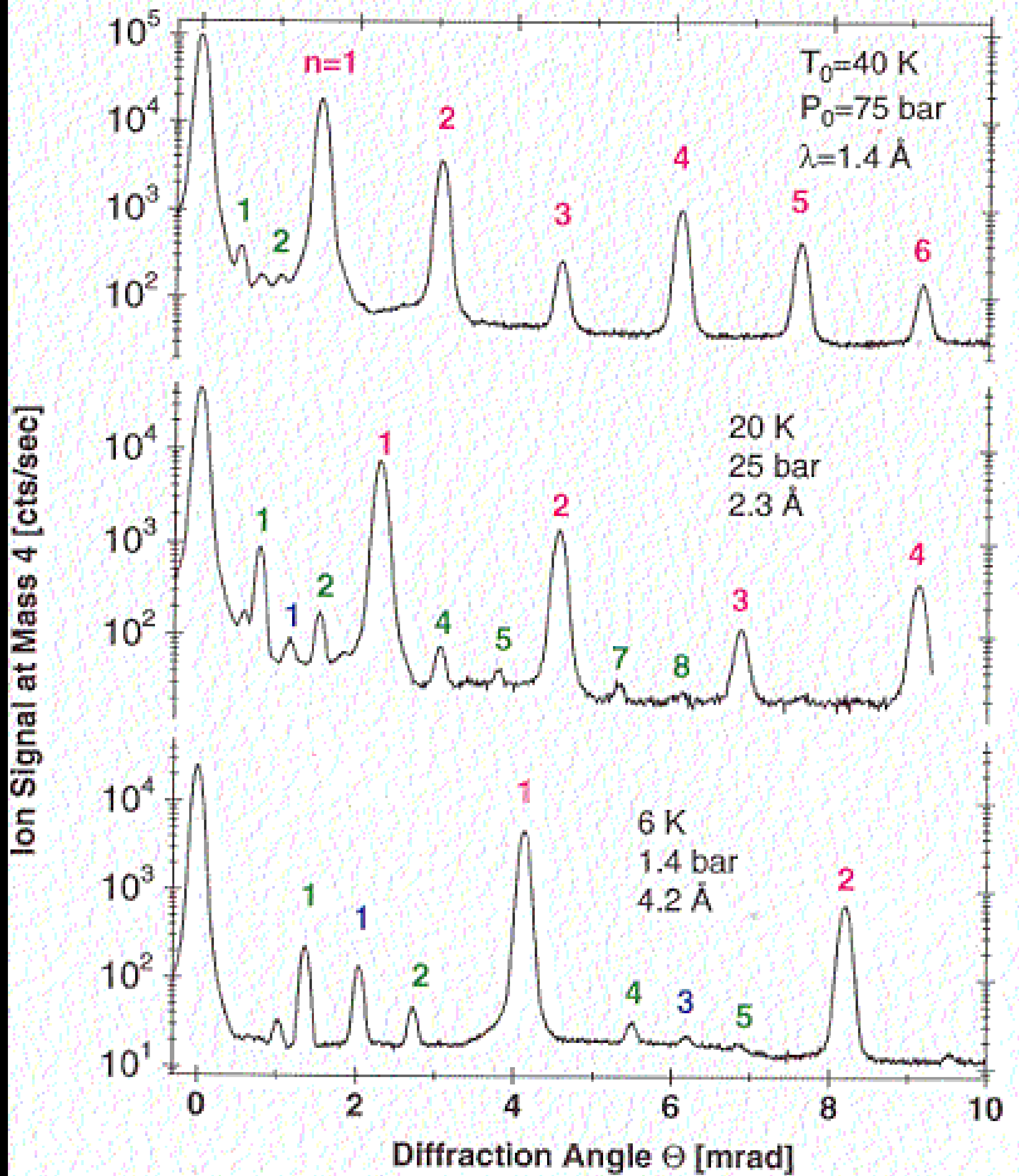


Courtesy of Hank Smith and Tim Savas, M I T

He Atom Diffraction Pattern for 300 K Beam

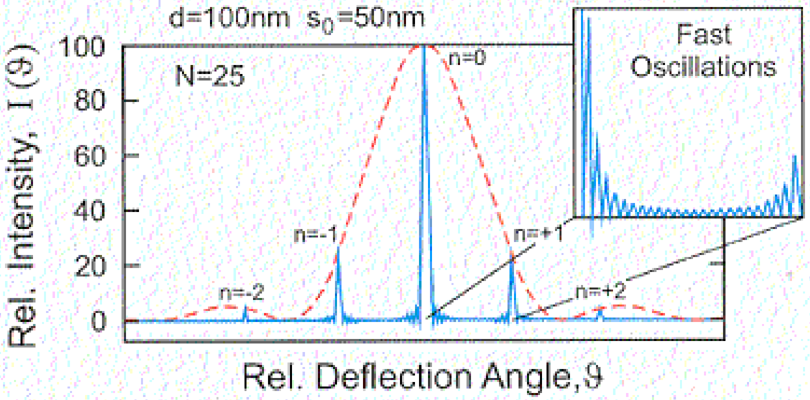


Diffraction of He-Atoms, He_2 and He_3 Clusters for Different Source Temperatures T_0

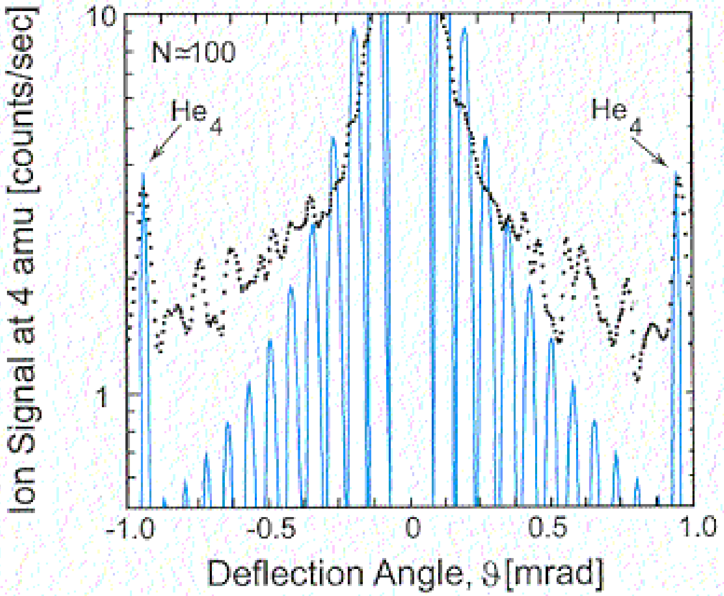


Brühl, Kalinine, Kornilov and Toennies

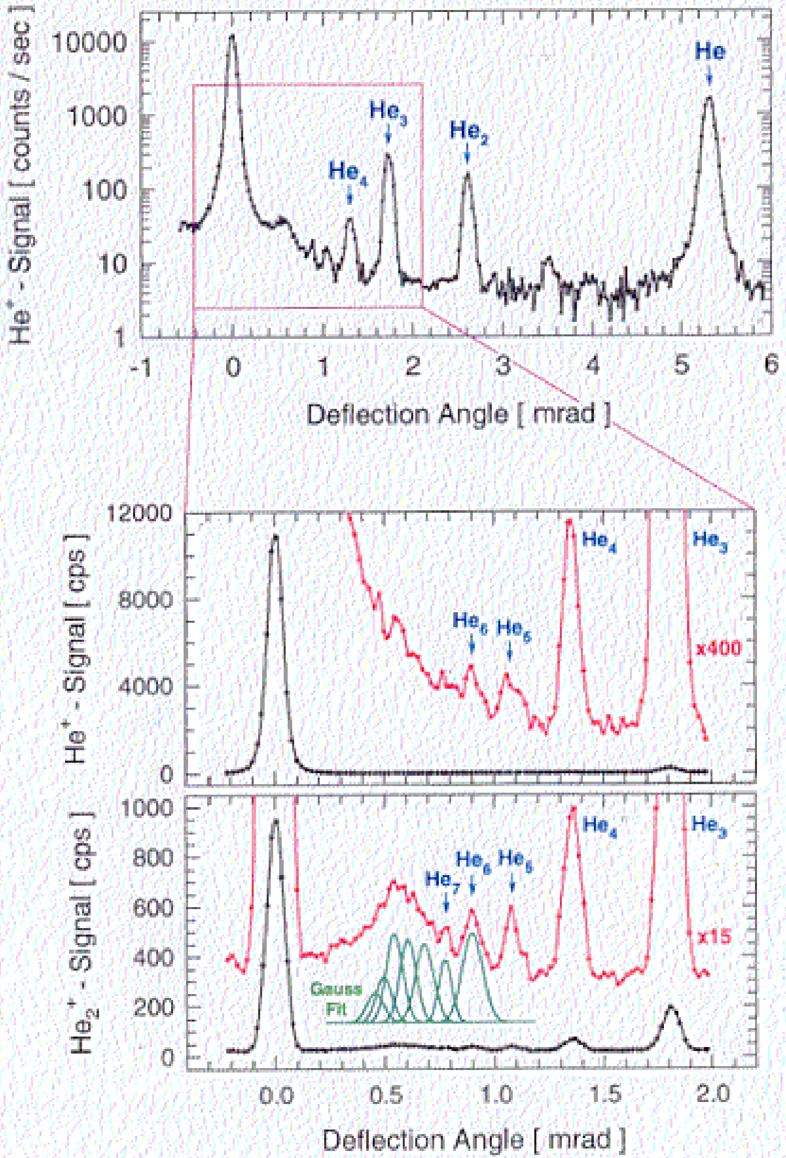
“Fast” Oscillations from Collimating Slits Limit Sensitivity at Small Angles



Experimental Observation near $\vartheta \approx 0$

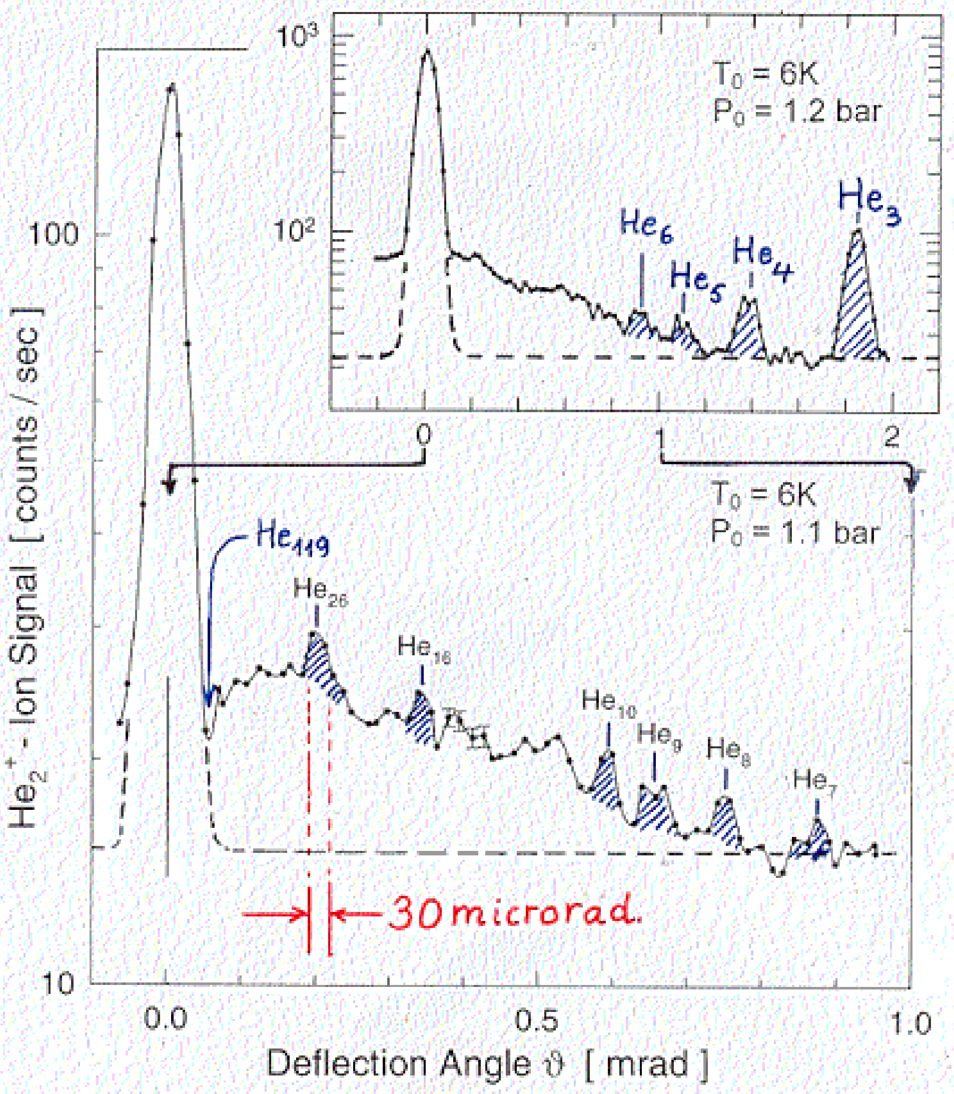


Mass Analysis of ^4He Cluster Beam at $T_0 = 6$ K, $P_0 = 1$ bar
Detected with $^4He^+$ and $^4He_2^+$ - Ion



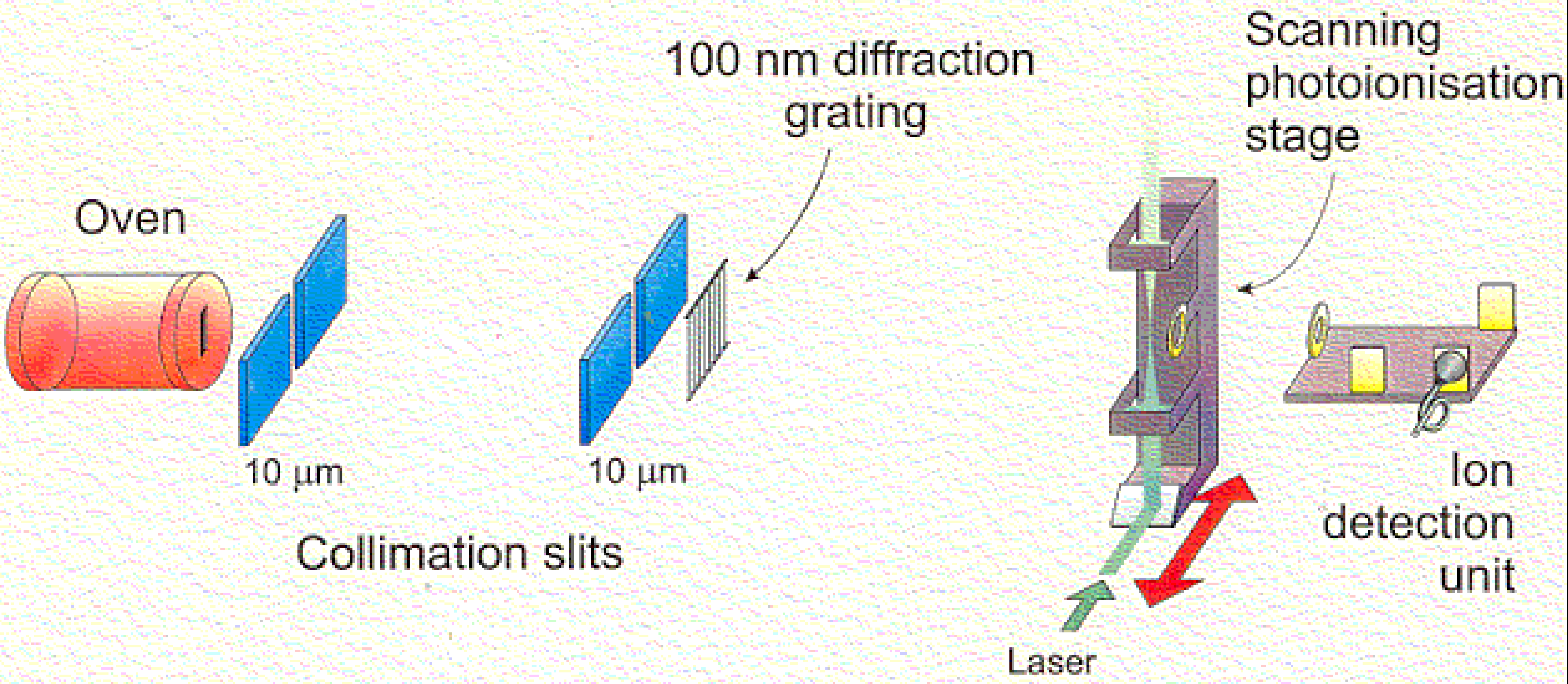
W. Schöllkopf and J. P. Toennies, to be published.

He_{26} is the Largest Helium Cluster Resolved so Far



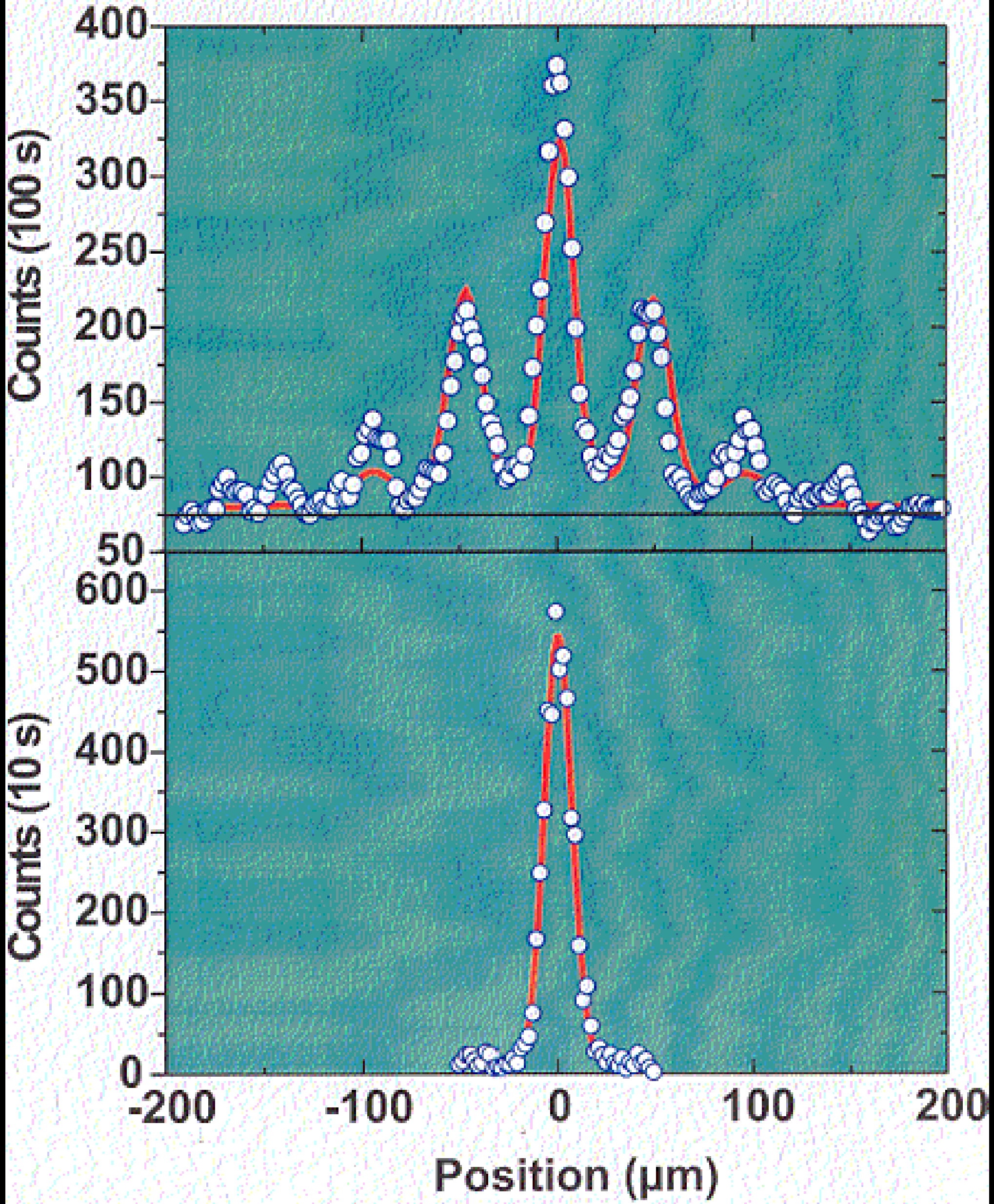
L. Bruch, W. Schöllkopf and J.P. Toennies, in preparation

Setup for Quantum Interference of Fullerenes



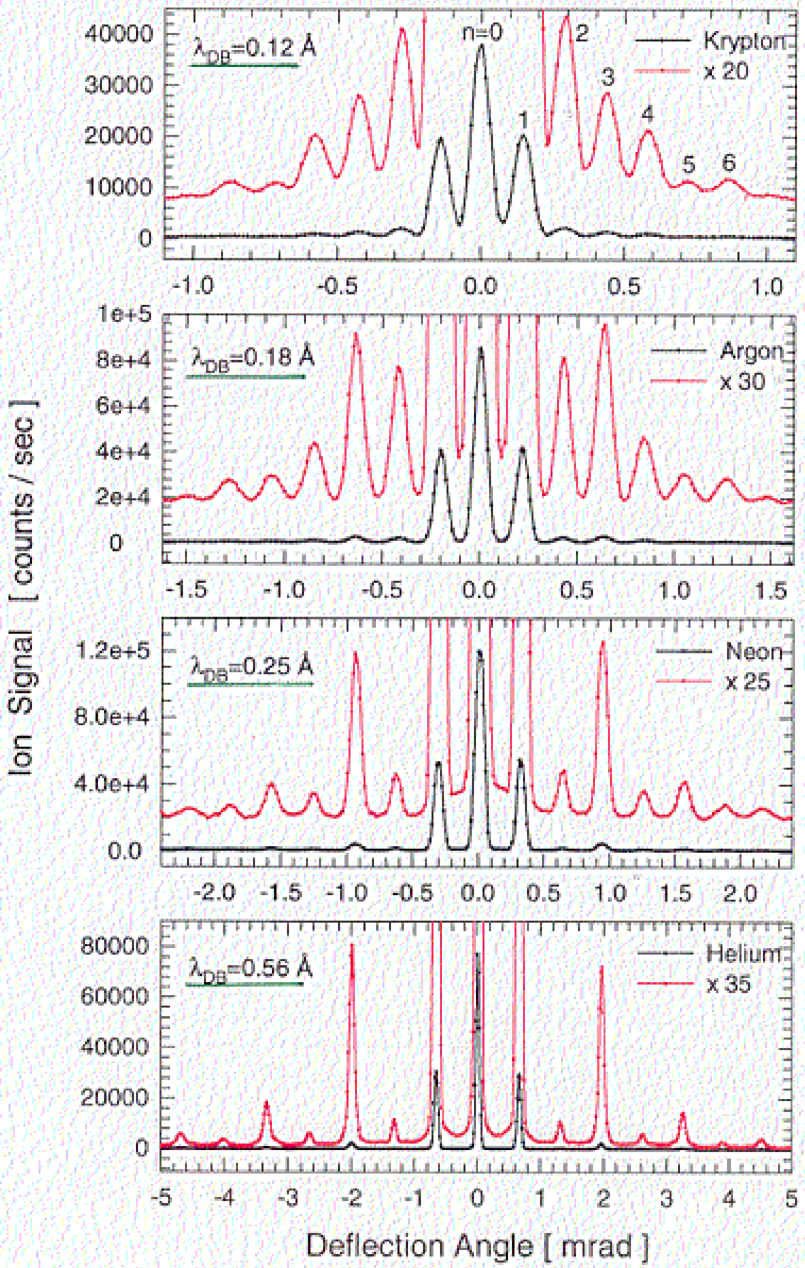
Zeilinger group, Vienna University

velocity selected C_{60}



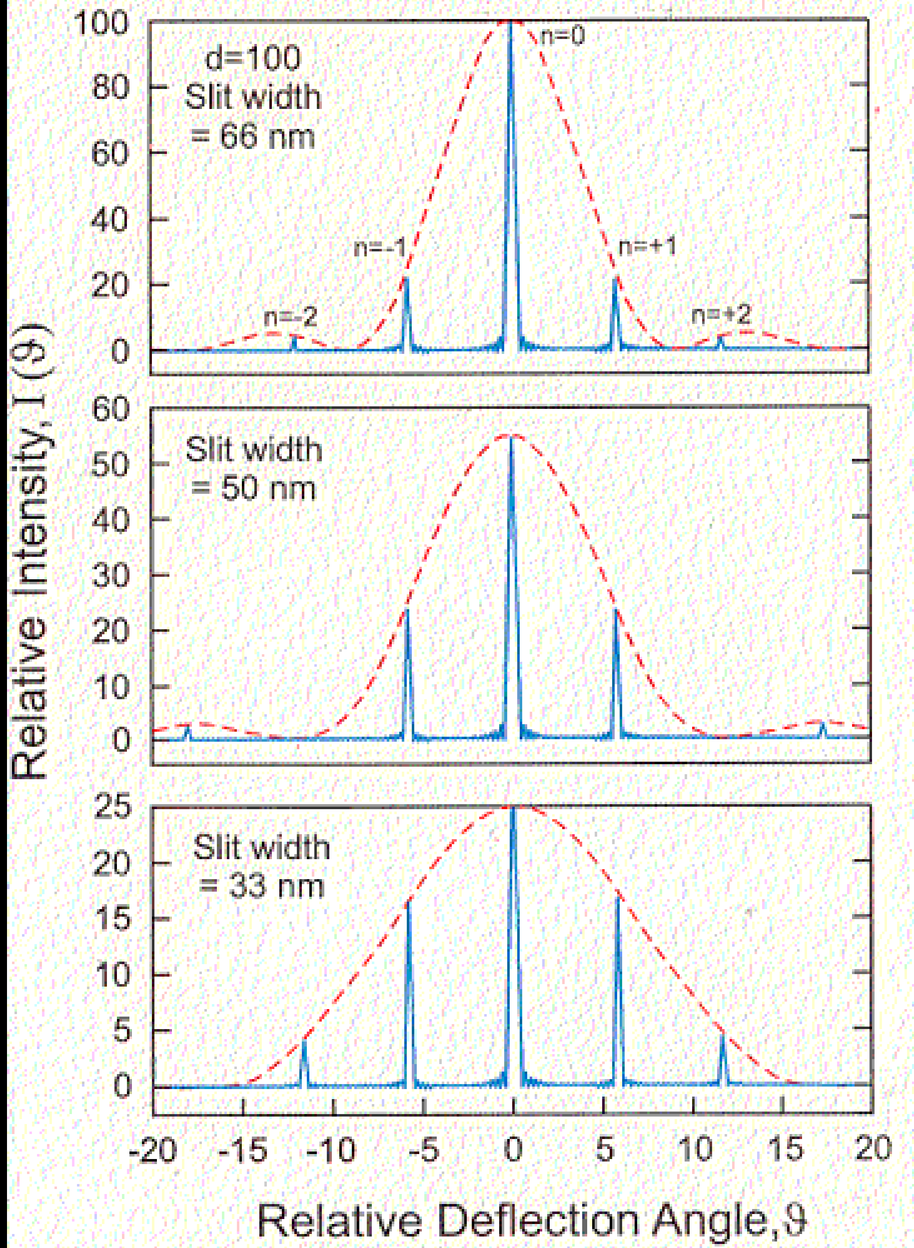
Nairz, Arndt, Zeilinger: unpublished

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

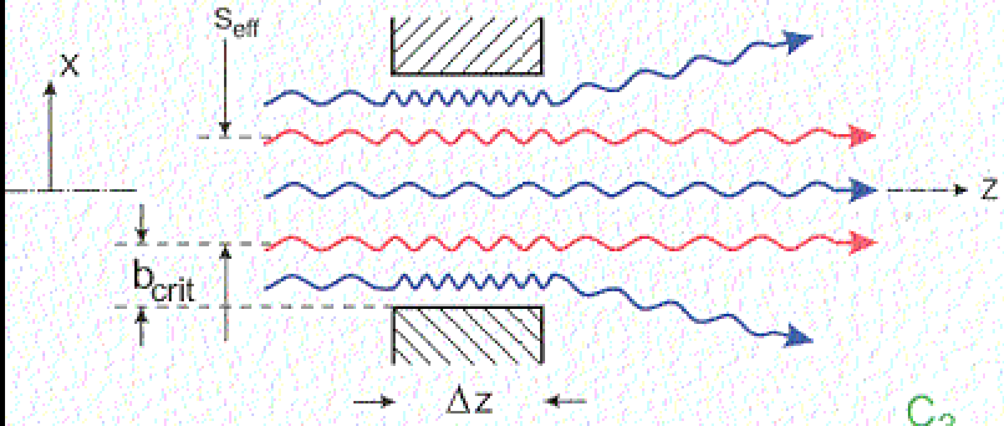


The Relative Diffraction Peak Intensities Depend on the Effective Slit Width

$$I(\vartheta) = i_{slit}(\vartheta) \cdot S(\vartheta)$$



Reduction in Effective Slit Width due to Atom - Wall Potential and Size of Cluster (primitive theory)



$$V(x) = -\frac{C_3}{x^3}$$

Estimate b from Eikonal theory:

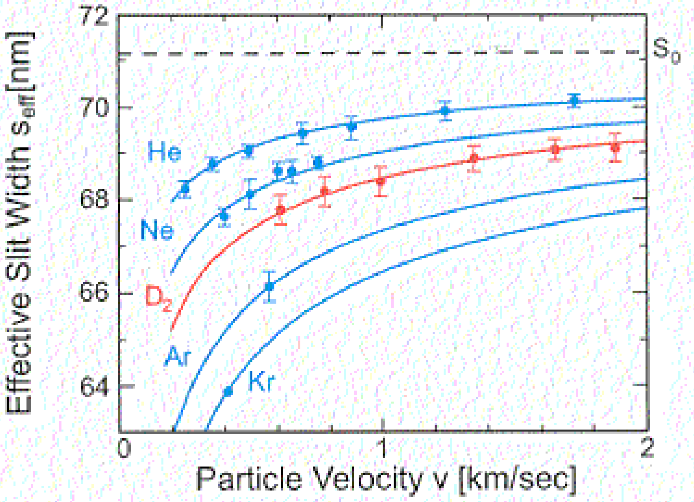
Phase difference $\phi \cong \pi = k_0 \left[\int \left(1 - \frac{V}{E}\right) dz - \int dz \right]$

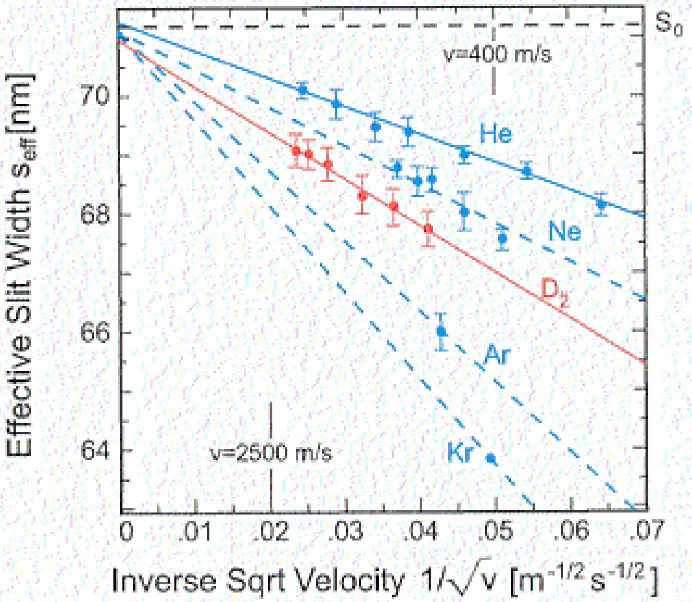
$$b_{crit} = \left(\frac{C_3}{\pi \hbar v} \Delta z \right)^{1/3}$$

For a compact particle the effective slit width s_{eff} is less than the geometrical s_0

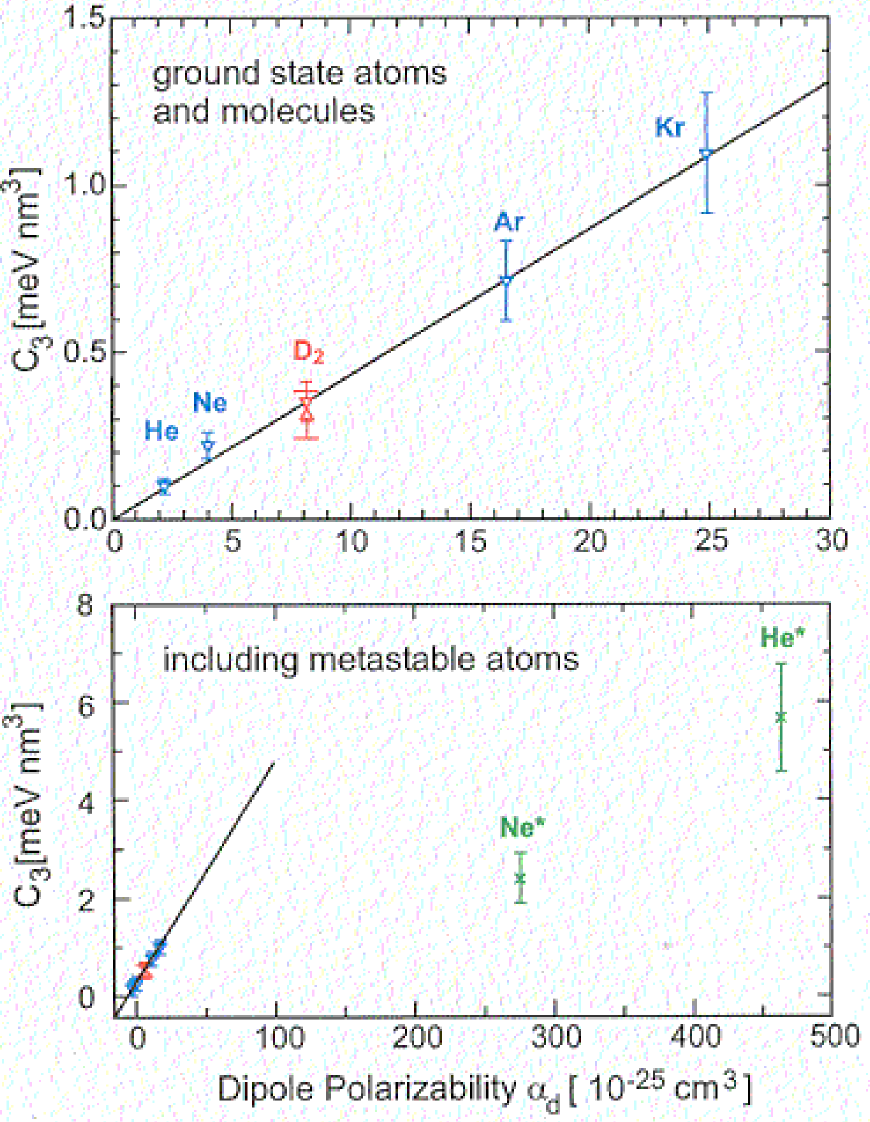
$$s_{eff} = s_0 - 2b$$

Determination of Potential Strength C_3 from Effective Slit Widths





C_3 Constants vs. Dipole Polarizability α_d

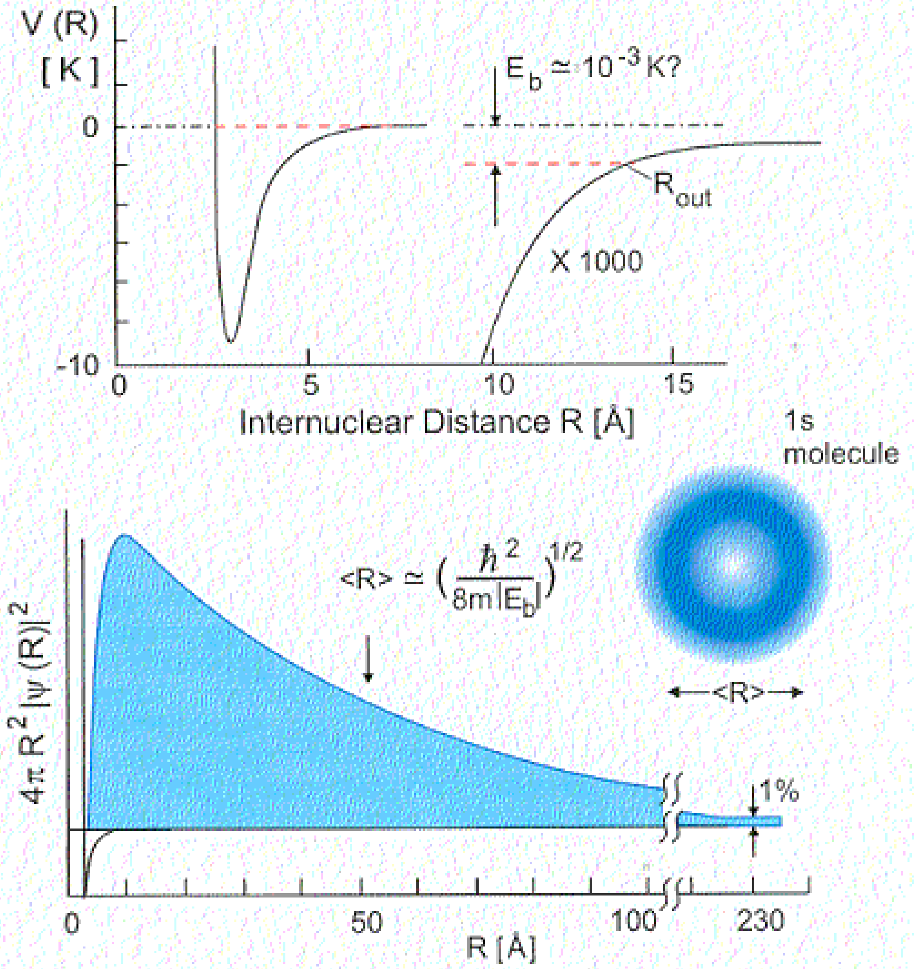


Theory:

$$C_3 = \frac{1}{4\pi} \int_0^{\infty} \alpha\,(i\,E)\;\frac{\varepsilon\,(i\,E) - 1}{\varepsilon\,(i\,E) + 1}\; d\,E$$

Lifschitz, 1956

The Unique He - He van der Waals Potentials



The ^{4}He-Dimer is the world`s weakest bound and largest molecule and the only known "Halo" molecule

The Effect of Retardation on He - Dimer Potential

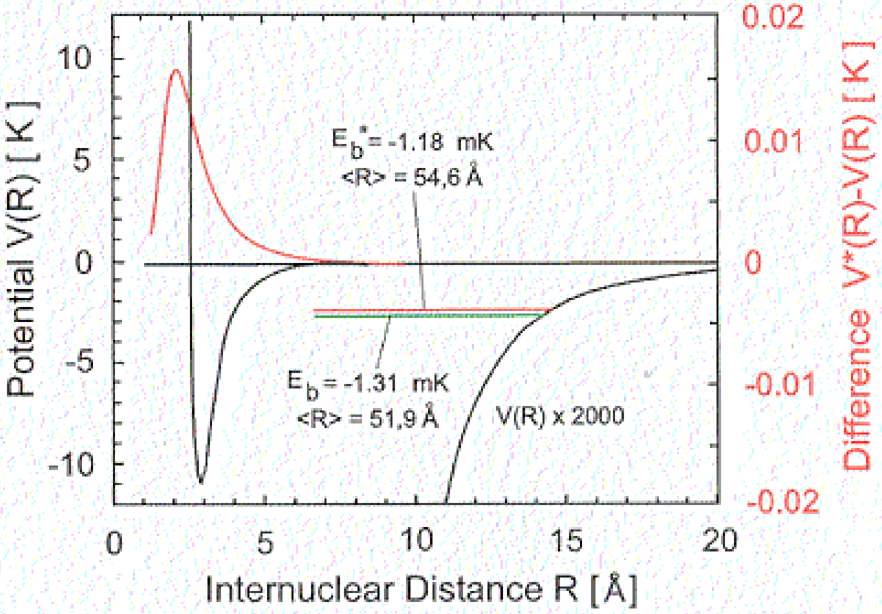
Retardation affects potential when
photon transfer time $t = \frac{R^*}{c}$ is greater than photon period $\tau = \frac{1}{\nu_O}$

$$\frac{R^*}{c} \gtrsim \frac{1}{\nu_O} \quad \Longrightarrow \quad R^* \geq \frac{c}{\nu_O} \approx 10^3 \text{ Å}$$

Its effect is especially large in the He dimer:

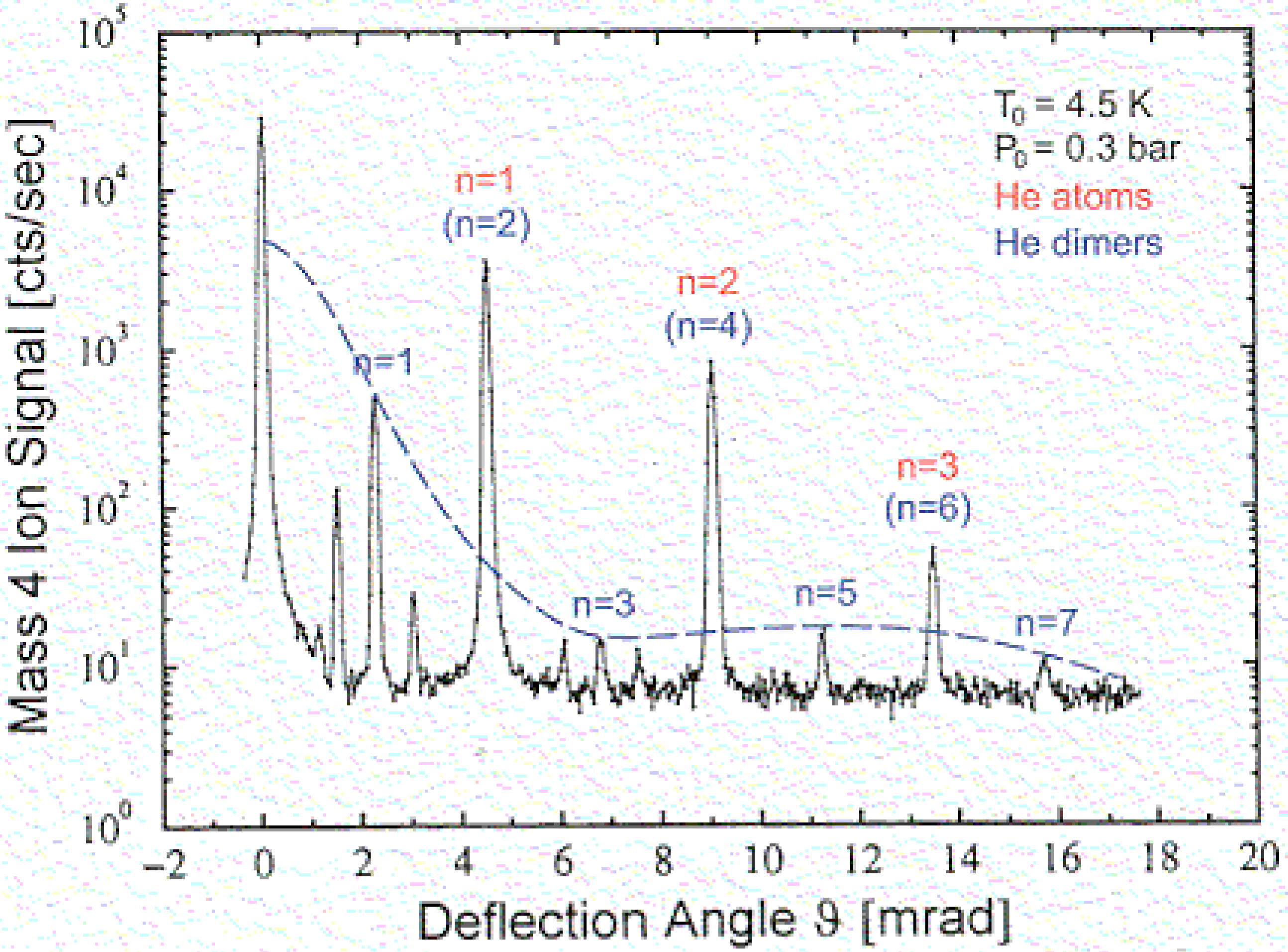
1. Large internuclear separation
2. ν_O is large ($h\nu_O \simeq 20$eV): $R^* \approx 600$ Å
3. Effect is large in relation to weak bond

Calculated Effect on Potential and Binding Energy E_b

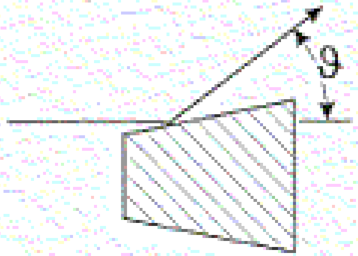


Luo, Kim, McBane, Giese and Gentry, J. Chem Phys. 98 9687 (1993)

The He Dimer Diffraction Pattern and Slit Function



Energy Transfer:



$$\Delta E = \frac{(\Delta k_\perp)^2}{2m} \propto E_i\,\vartheta^2$$

$E_i \simeq 5K$

$\vartheta \simeq 10$ mrad

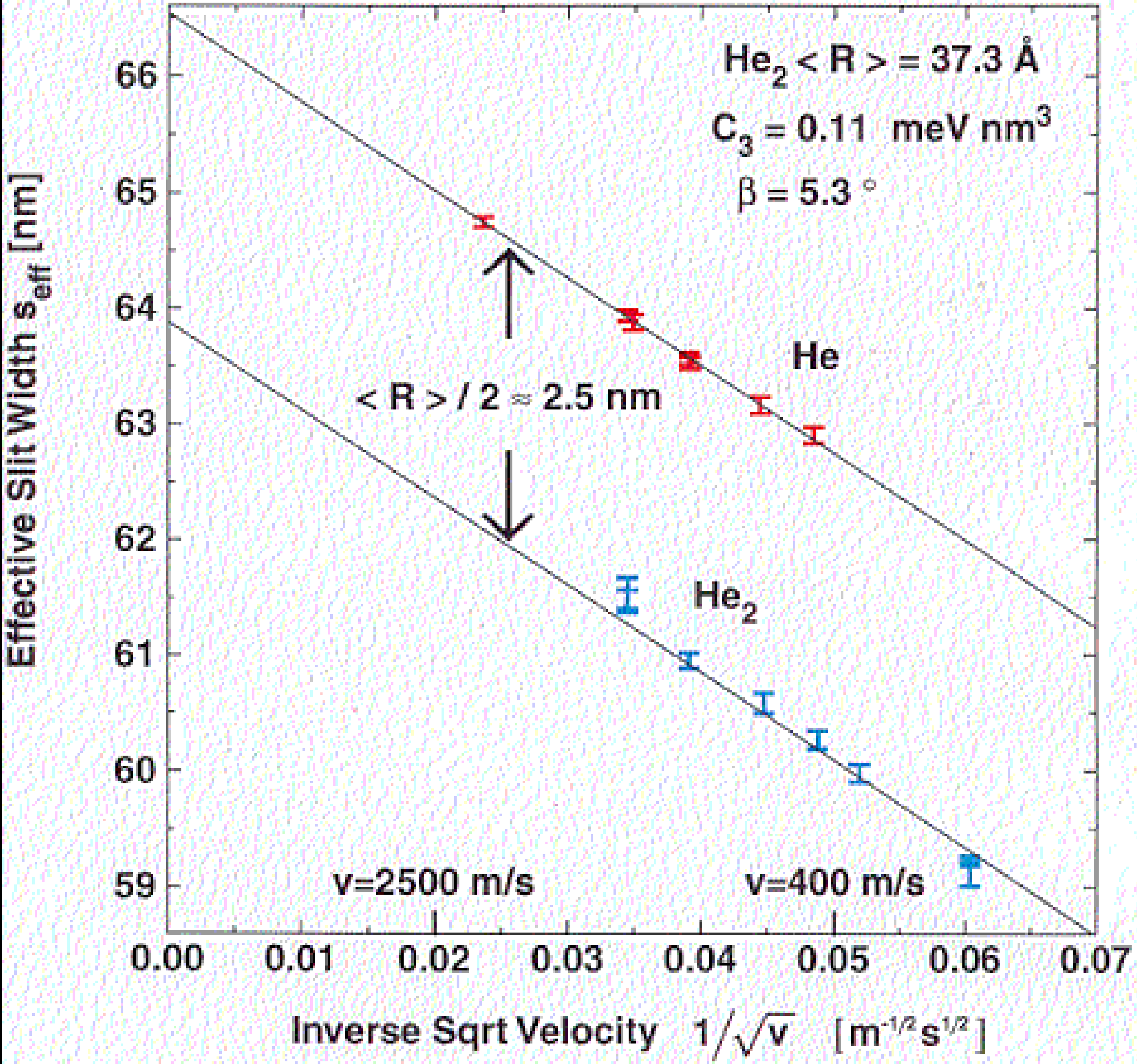
$\Delta E \simeq 5 \cdot 10^{-4} K < E_b$!

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

2002-07-08-T1-Ka

Effective Slit Width vs Inverse Sqrt Velocity

Grating 8.1.1, 09.03.2002



Brühl, Kalinine, Kornilov, Stoll and Toennies

Physical Review Focus

Determination of the Bond Length and Binding Energy of the Helium Dimer by Diffraction from a Transmission Grating
R. E. Grisenti, W. Schöllkopf, J. P. Toennies, G. C. Hegerfeldt, T. Köhler, and M. Stoll
Phys. Rev. Lett. 85, 2284 (11 September 2000)
[Free abstract available 8 September.]

Measuring a Fragile Molecule

6 September 2000

$\langle R \rangle = 52 \pm 4$

Mark Sincell

Although theory has long predicted that two helium atoms can form a diatomic molecule, or dimer, experimental evidence was elusive. Traditional probes of atomic structure don't work for helium because they tear apart the fragile molecule like a butterfly blasted with a shotgun. Now, in the 11 September *PRL*, researchers describe a non-destructive technique that confirms that the atoms in a helium dimer form the longest and weakest chemical bond known, and the largest two-atom molecule.

Butterfly of molecules. Like catching a butterfly, measuring the delicate molecule formed by two helium atoms requires a light touch. The helium dimer is the largest

Helium is only one step in the periodic table away from hydrogen, which forms nature's most common dimer. "Helium is a very fundamental atom," says Harvard University's Isaac Silvera, "so we can make very accurate calculations of its bound states." Those calculations showed that the helium-helium attractive force should create a dimer state with a tiny binding energy of about 10^{-7} eV, compared with 5 eV for diatomic hydrogen.

Present Status: He_2
Bond Length <R> and Binding Energies E_b

CALCULATIONS (>28 since 1989):

Potential	<R>[Å]	E_b[mk]	Authors
(r_{12})MR-CI	50.5 ± 13	2.24 ± 0.99	Gdanitz 1999
FCI-CBS	46.3	1.67	Van Mourik + Dunning 1999
(r_{12})MR-CI	46.4 ±1.4	1.67 ± 0.11	Gdanitz 2001

corrections for retardation and non-adiabatic terms in progress

EXPERIMENTS:

Transmission	62 ±10	0.95 ± 0.3	Luo et al. 1996
Diffraction (cold grating)	52 ± 4	1.1 ± 0.25	Grisenti et al. 2000
Diffraction (7.2.02) (hot grating)	37.3 ± 1	1.46 ± 0.10	Brühl et al. 7. Feb. 2002
Diffraction (9.3.02) (hot grating)	40.0 ± 1	1.35 ± 0.10	Brühl et al. 9. March 2002

corrections for roughness in progress

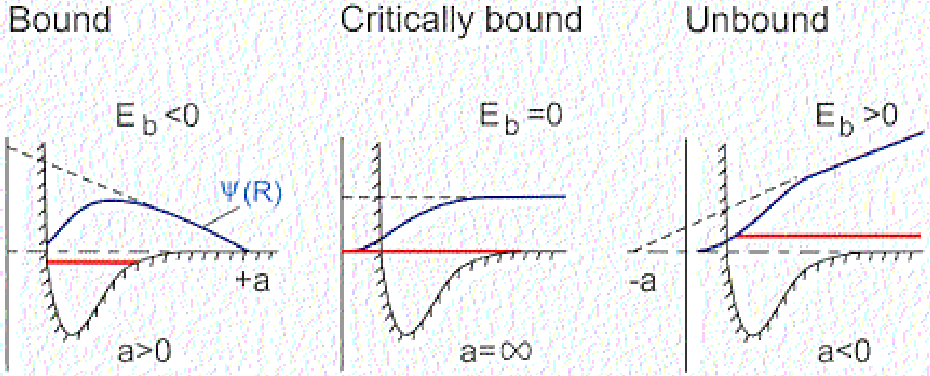
Efimov Effect

The Efimov effect is one of the most interesting of the unexpected phenomena to turn up in the quantum three-body problem. It was first pointed out by Efimov in 1970 that a three-body system can have an infinite number of bound states if some of the two-body interactions have zero-energy bound states. The infinite number of three-body-states represents an example of how long-range effects can arise in the three-body problem in a manner unanticipated by two-body intuition.

Taken from A.C. Foncseca, E.F. Redish and P.E. Stanley, Nuclear Physics A320, 273 (1979)

The Efimov Effect

Efimov (1970): If between 2 of 3 identical Bosons the bond is critical ($a=\infty$) then there are an infinite no.of three particle bound states



For $a \gtrsim \infty$

No. of Efimov states: $N_{Ef} \simeq \frac{1}{\pi} \ln \frac{|a|}{r_0}$

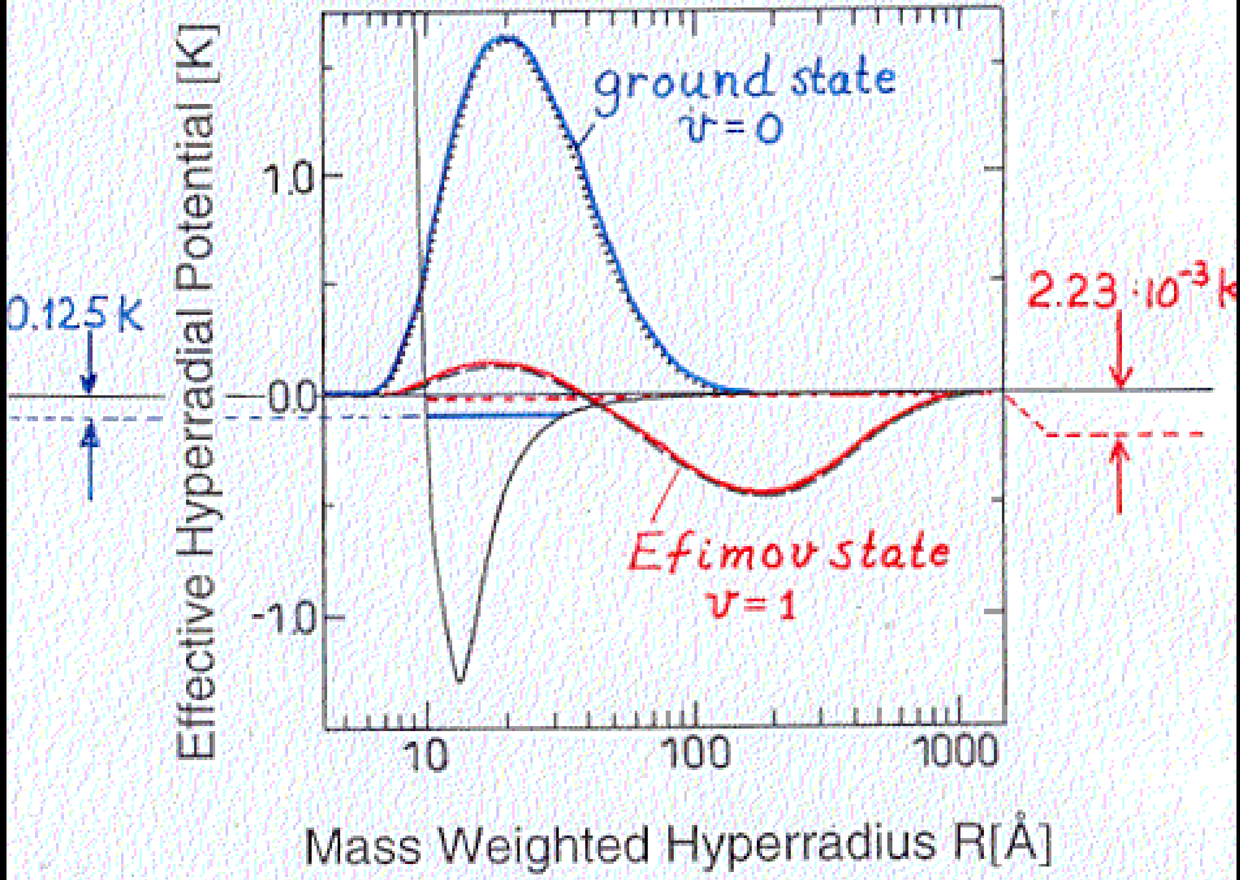
For He_3 $N_{Ef} \simeq 0{,}83$

Note: As $|E_b|$ increases $|a|$ decreases and $N_{Ef} \longrightarrow 0$

V. Efimov, Phys. Lett. B33 563 (1970)

Effective Adiabatic Hyperspherical Potentials and Wave Functions of He_3

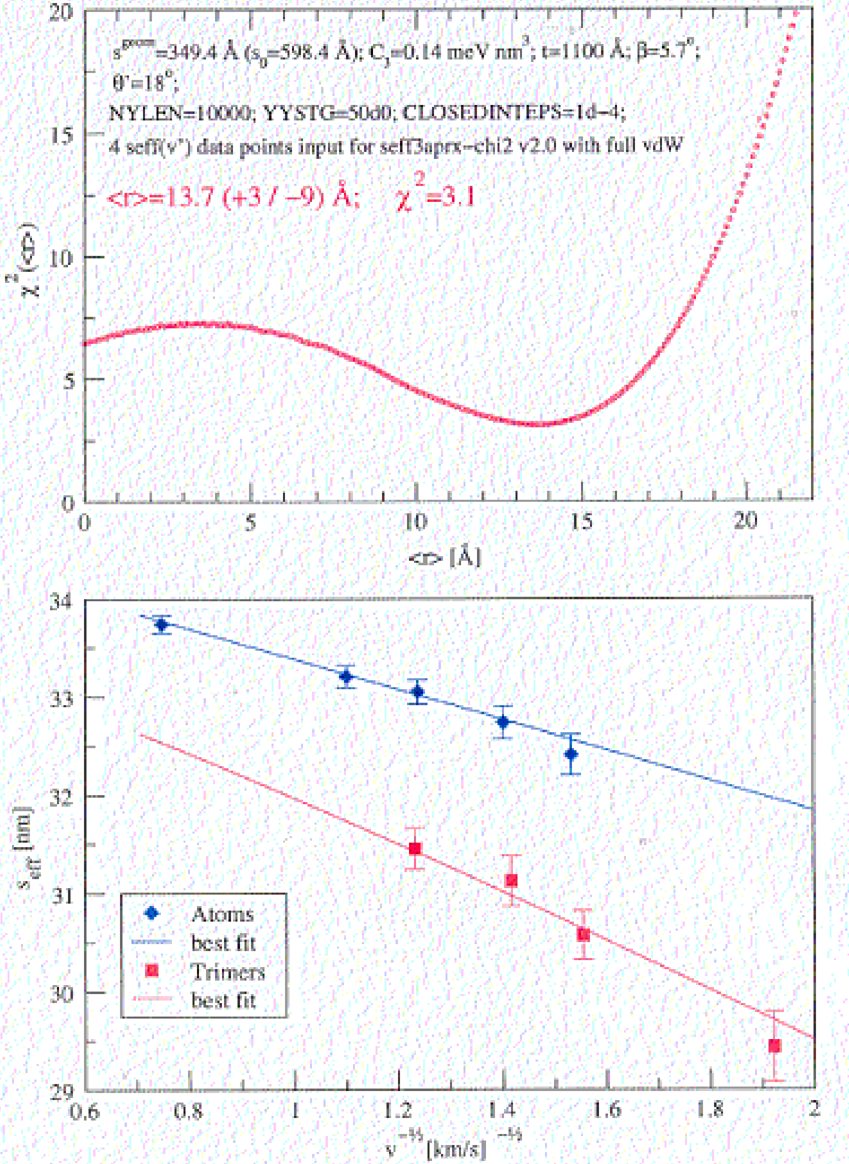
$$H = -\frac{1}{2\mu}\frac{\partial^2}{\partial R^2} + \frac{15}{8\mu R^2} + \frac{\Lambda^2}{2\mu R^2} + \sum_{i<j} V_{\mathrm{pair}}(r_{ij}).$$



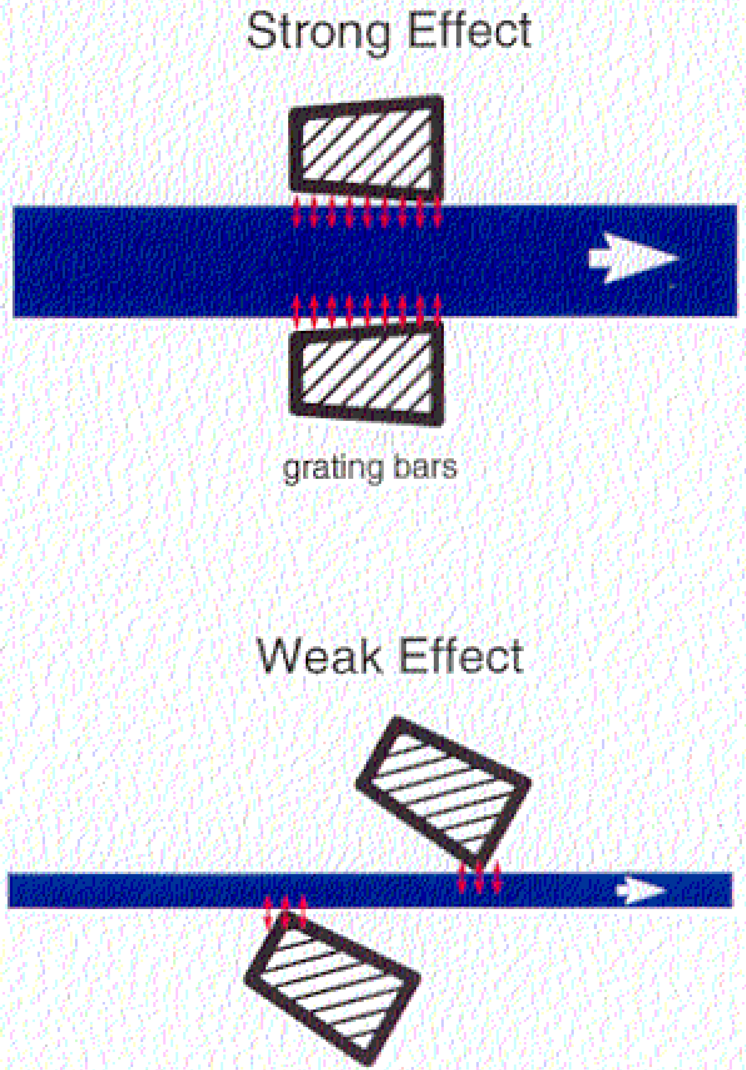
Esry, Lin and Greene, Phys. Rev. A54, 394 (1996)
Blume, Greene and Esry, J. Chem. Phys. 113, 2145 (2000)

χ^2 for the Pair Distance in the Helium Trimer

August 2002; Grating 9.2.2; file=~/prog/He3−Experiment/2002−IV/seff_He3−th18.0.txt

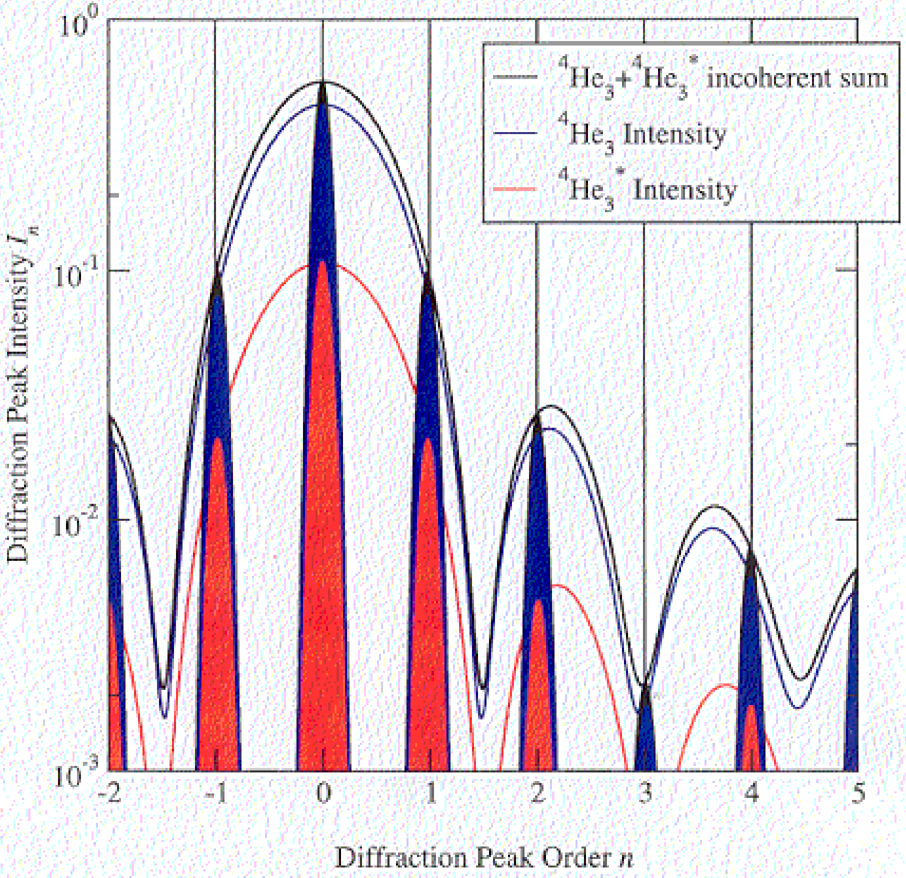


Minimizing the van der Waals Interaction between the Helium Beam and the Grating



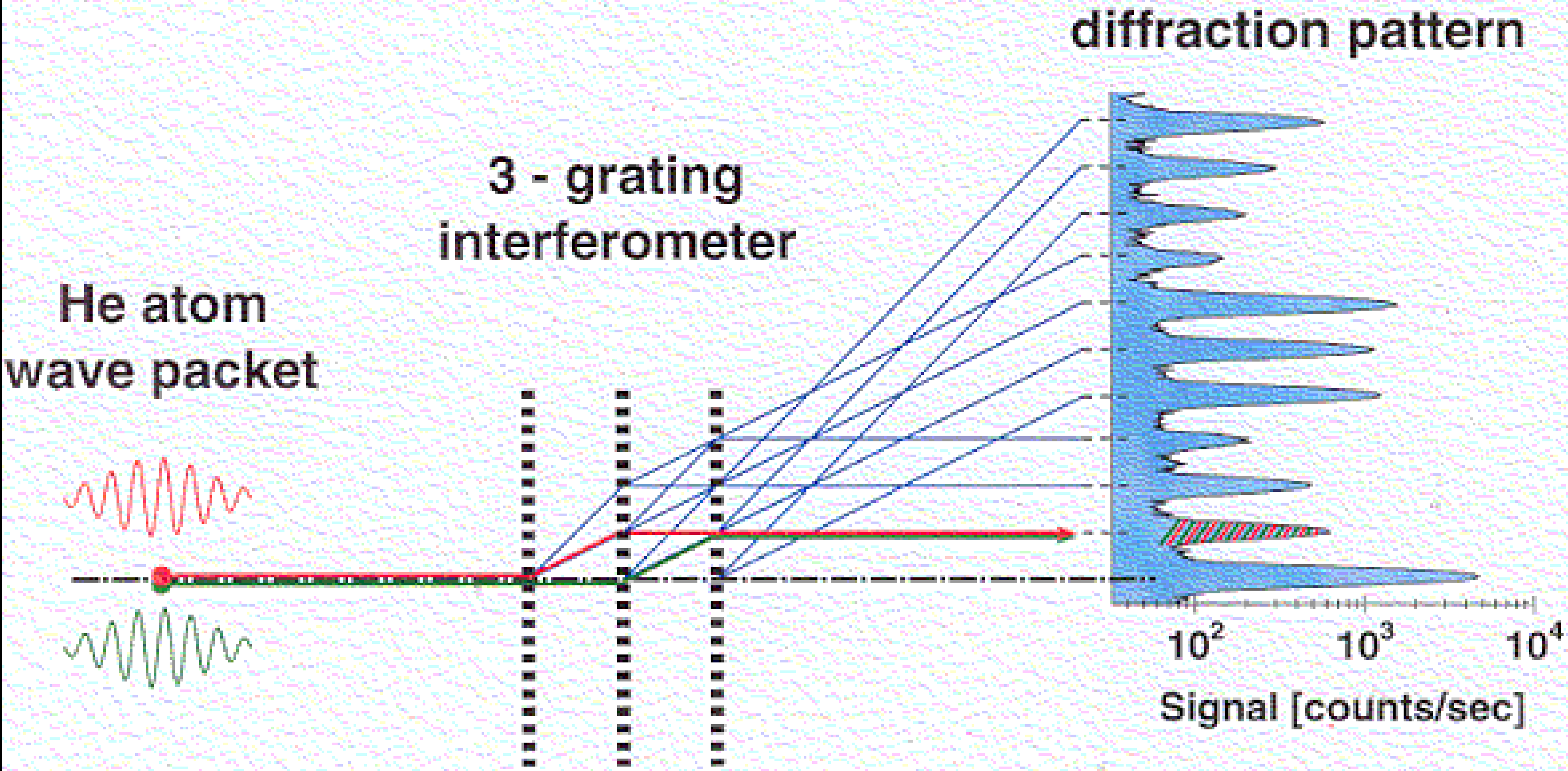
The Mixed Beam Trimer Diffraction Experiment

<u>Problem:</u> The $^4He_3$ and $^4He_3{}^*$ diffraction peaks are spatially superposed. The number ratio η is unknown.



An incoherent sum $I_n^{\mathrm{tot}} = I_n^G + \eta\, I_n^E$ with parameters $s_{\mathrm{eff}}^{B,G}$ and $s_{\mathrm{eff}}^{B,E}$, respectively, is required for the evaluation.

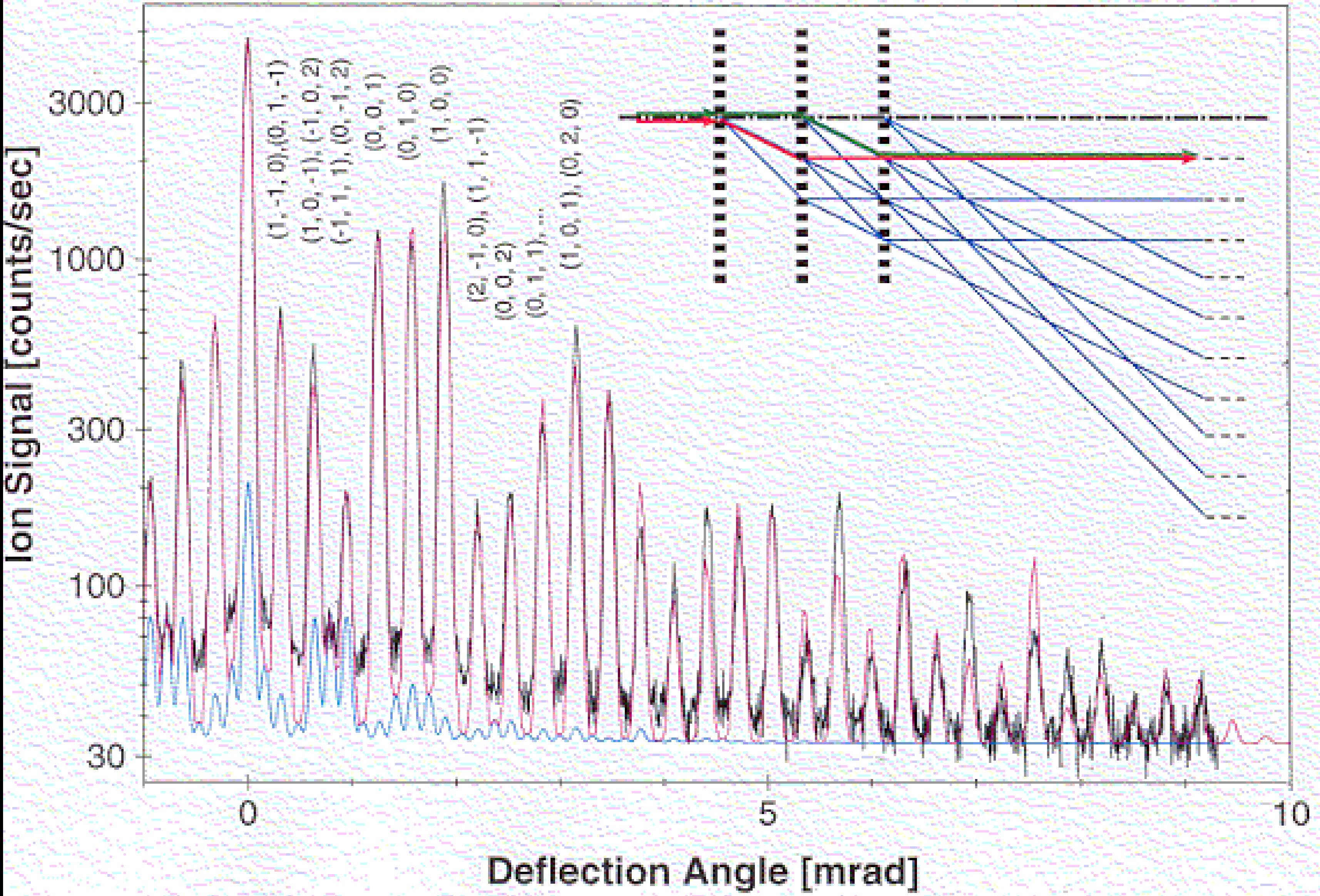
Mach-Zehnder Matter Wave Interferometer: Diffraction Pattern



Brühl and Toennies, to be published

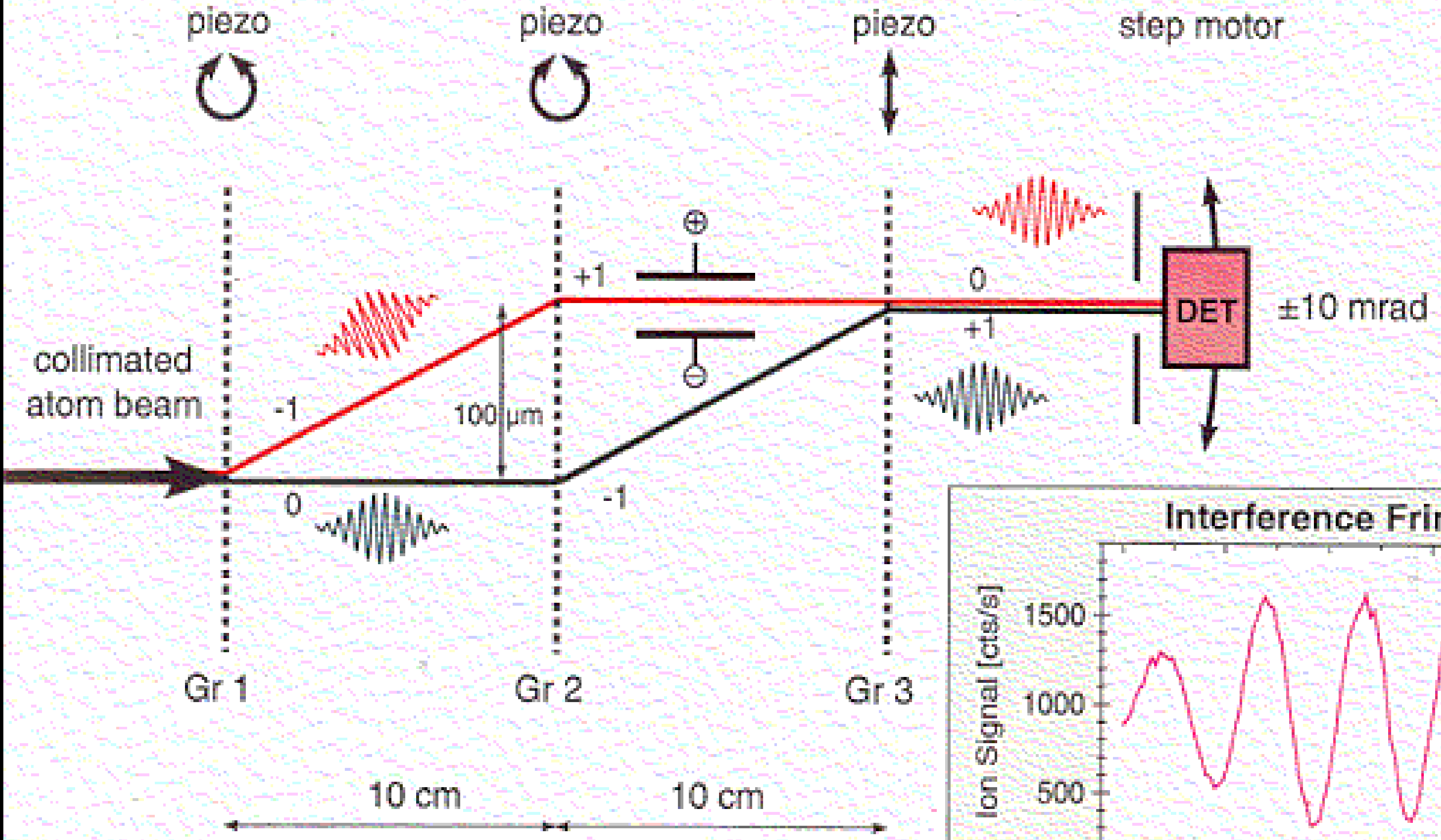
Interferometer Diffraction Pattern

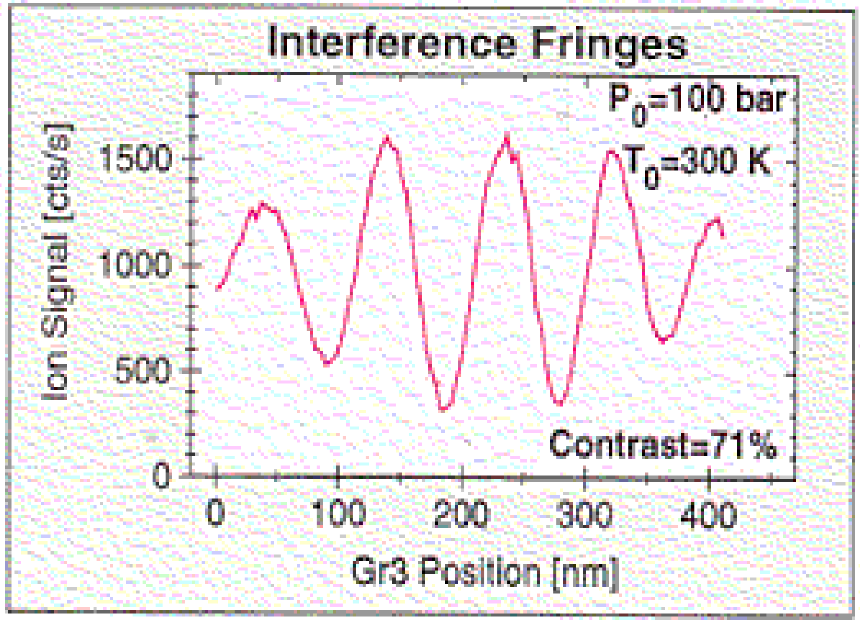
P_0=17 bar, T_0=49 K



The Göttingen Universal Matter Wave Interferometer

Polarizability Measurement





Brühl, Kornilov and Toennies in preparation

Wave - Particle Dualism

Classical Particles

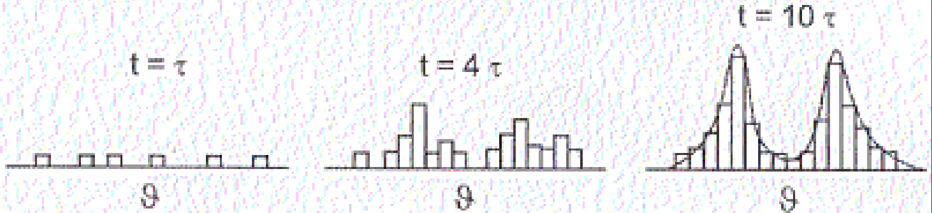
can go only either right or left !

Quantum waves

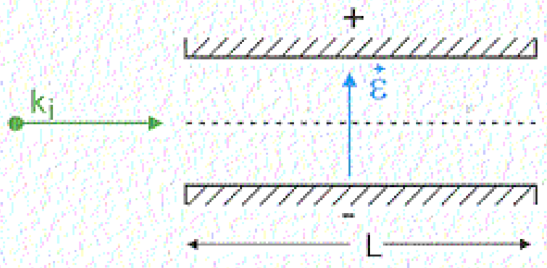
can go both ways (see skier)

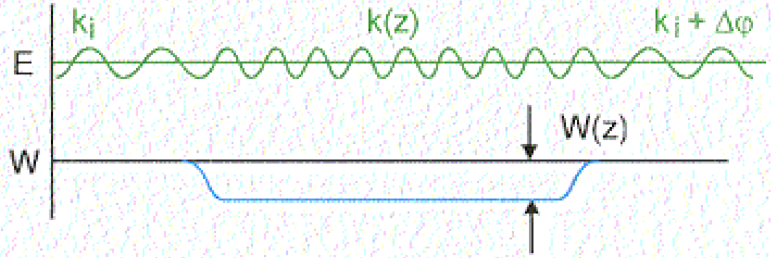
Dirac: "Each photon (atom) interferes only with itself"

Time evolution of diffraction pattern:



Measuring Atom Polarizabilities





Stark effect: $W(z) = -\frac{1}{2}\,\alpha\,\varepsilon^2$

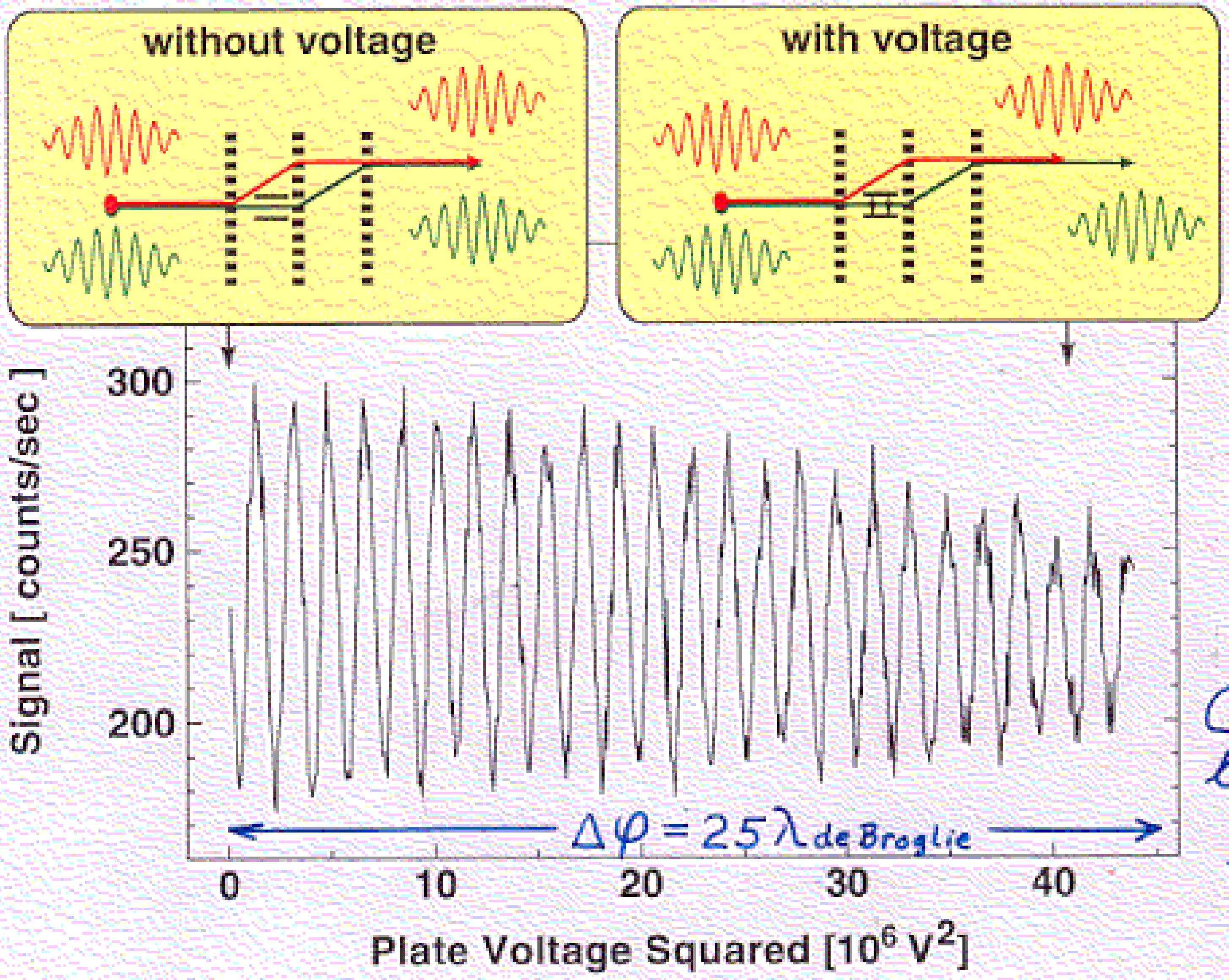
$$\Delta\varphi = \int_0^L (k(z) - k_i)\,dz$$

where $k(z) = \sqrt{2m\,(E_i - W(z))}$

$$\Delta\varphi \simeq \frac{\alpha}{2\hbar v}\,\varepsilon^2 L_{eff}$$

He Atom Stark Effect Interferogram

$T_0 = 6K$



Coherence length L

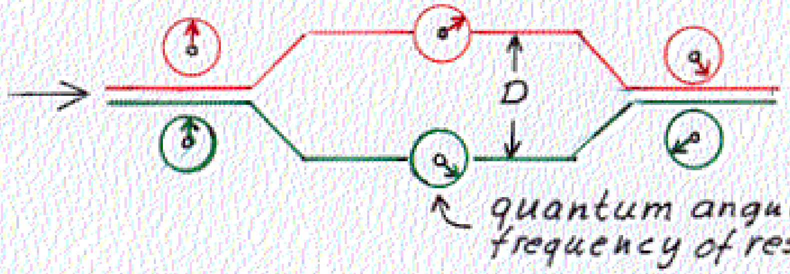
$L > 25 \cdot 4{,}2\ \text{Å}$

$> 105\ \text{Å}$

Brühl and Toennies, to be published

Decoherence due to Gravity Fluctuations

Ian Percival: "Quantum State Diffusion", 1998



Phase change in earth gravity field:

$$\eta = \frac{mc^2}{\hbar} t \quad t = \text{drift time} \approx 10^{-2}\,\text{sec}$$

$$\simeq 10^{24}\ \text{radians}$$

Fluctating phase change:

$$\delta\eta \simeq \left(\frac{\tau_0}{t}\right)^{1/2} \eta \quad \tau_0 = \text{Planck's time} = 5 \cdot 10^{-44}\,\text{sec.}$$

$$\approx 10^{3}\ \text{radians}$$

Expt'l resolution is < 0.1 radian

Spontaneous decoherence so far not seen!

D too small?

Penrose: Time for quantum state reduction

proton: $T \approx 10^{6}$ years

H_2O drop 10^{-3} cm: $T \simeq$ hours

H_2O drop 1000 Å: $T \simeq 10^{-6}$ sec