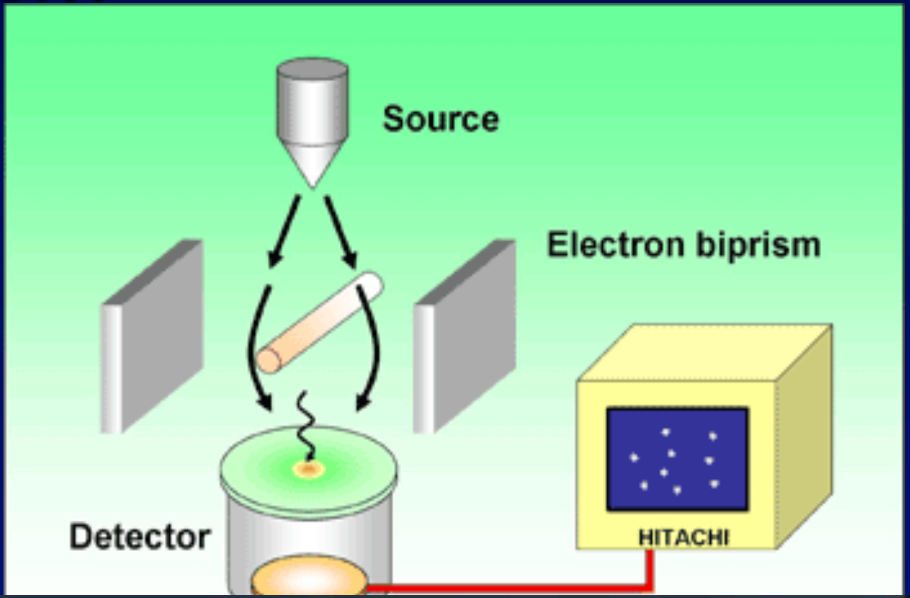
R. P. Feynman:
Interference is … “the heart of QM.
In reality it contains the *only* mystery.
We cannot make the mystery go away
by ‘explaining’ how it works.”

"Double-slit" Experiment for Electrons

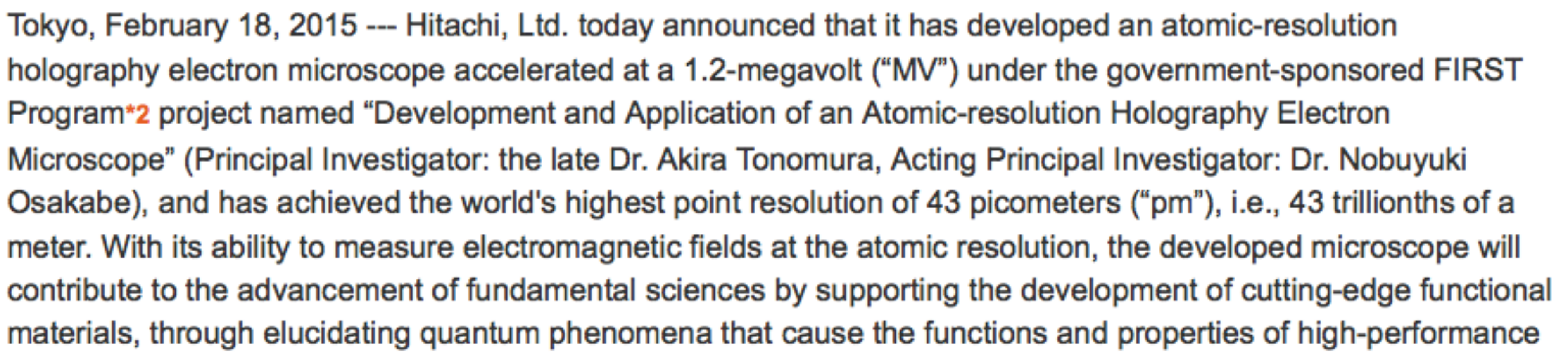
- Electrons are accelerated to 50 keV → λ = 0.0055 nm
- Central wire is positively charged → bends electron paths so they overlap
- A position-sensitive detector records where they appear.
- << 1 electron in system at any time

[A. TONOMURA (Hitachi) -- pioneered electron holography]



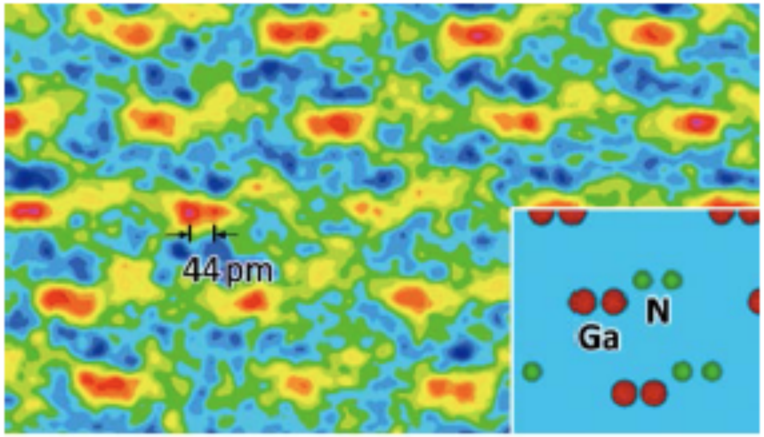
Application: Electron Holography

Development of an Atomic-Resolution Holography Electron Microscope*1 with the World's Highest Point Resolution (43 picometers)



Tokyo, February 18, 2015 --- Hitachi, Ltd. today announced that it has developed an atomic-resolution holography electron microscope accelerated at a 1.2-megavolt ("MV") under the government-sponsored FIRST Program*2 project named "Development and Application of an Atomic-resolution Holography Electron Microscope" (Principal Investigator: the late Dr. Akira Tonomura, Acting Principal Investigator: Dr. Nobuyuki Osakabe), and has achieved the world's highest point resolution of 43 picometers ("pm"), i.e., 43 trillionths of a meter. With its ability to measure electromagnetic fields at the atomic resolution, the developed microscope will contribute to the advancement of fundamental sciences by supporting the development of cutting-edge functional materials, through elucidating quantum phenomena that cause the functions and properties of high-performance materials, such as magnets, batteries, and superconductors.

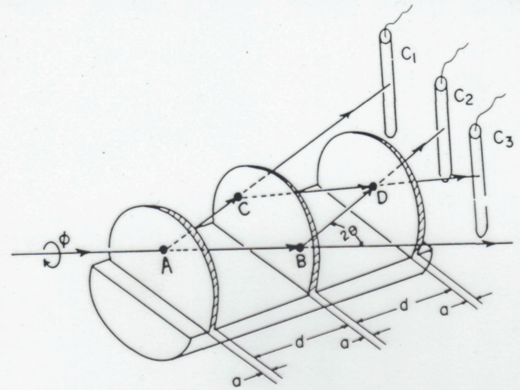
"Aberration corrected 1.2-MV cold field-emission transmission electron microscope with a sub-50-pm resolution."
Akashi et al., Appl. Phys. Lett. 106, 074101 (2015)



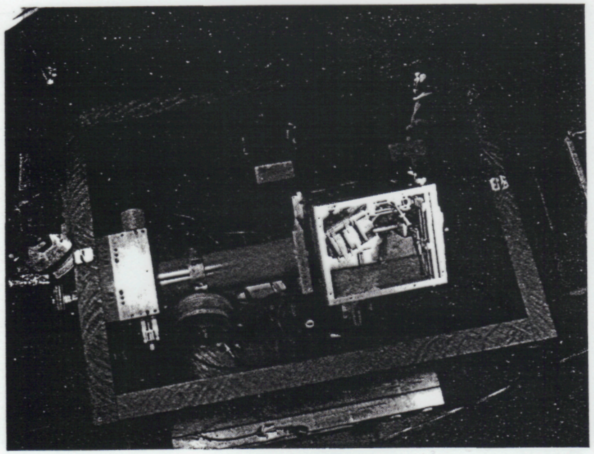
Low-pass filtered image Atomic positions

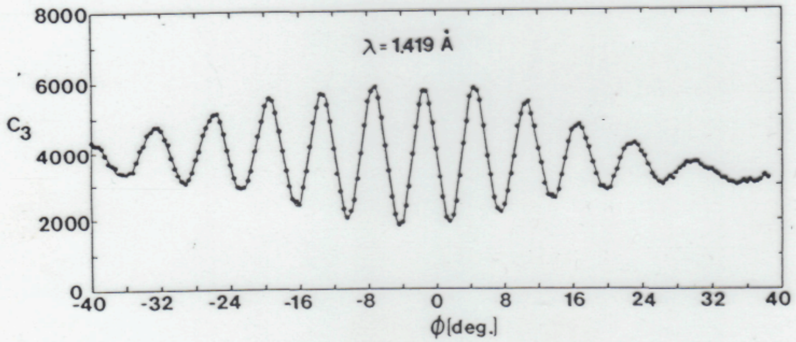
Fig.2 Observation case of GaN crystal

Neutron interference



Path lengths are fixed. As entire interferometer is rotated, the paths are at different heights → different gravitational potential energies → different speeds → different phases
→ fringes





COW experiment:
Colella, Overhuaser and Werner
PRL **34**, 1472 (1975)

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Optics and Interferometry with Na_2 Molecules

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Stefan Wehinger,[1,2] and David E. Pritchard[1]
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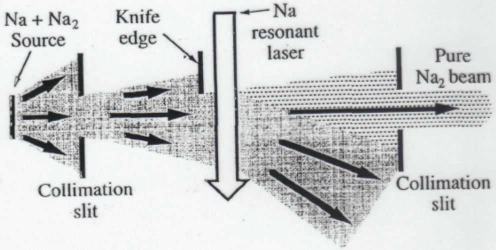
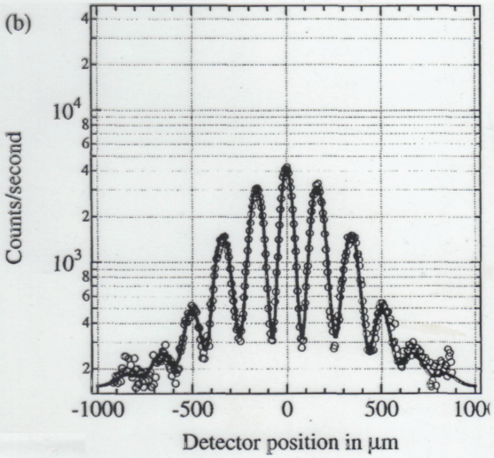
(Received 20 January 1995)

We have produced an intense, pure beam of sodium molecules (Na_2) by using light forces to separate the atomic and molecular species in a seeded supersonic beam. We used diffraction from a microfabricated grating to study the atomic and molecular sodium in the beam. Using three of these gratings, we constructed a molecule interferometer with fully separated beams and high contrast fringes. We measured both the real and imaginary parts of the index of refraction of neon gas for Na_2 molecule de Broglie waves by inserting a gas cell in one arm of the interferometer.





$\lambda_{dB}(Na_2) = 0.11$ Å

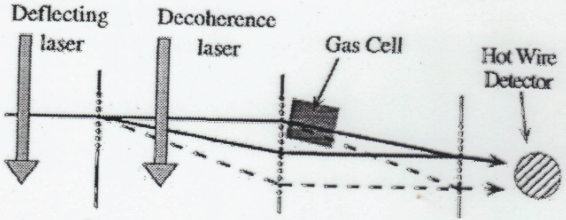


FIG. 3. Schematic of our interferometer showing the paths of Na (dashed line) and Na_2 (solid line). G1, G2, and G3 indicate the three diffraction gratings.

ICTP Triest, 8.11. 2004

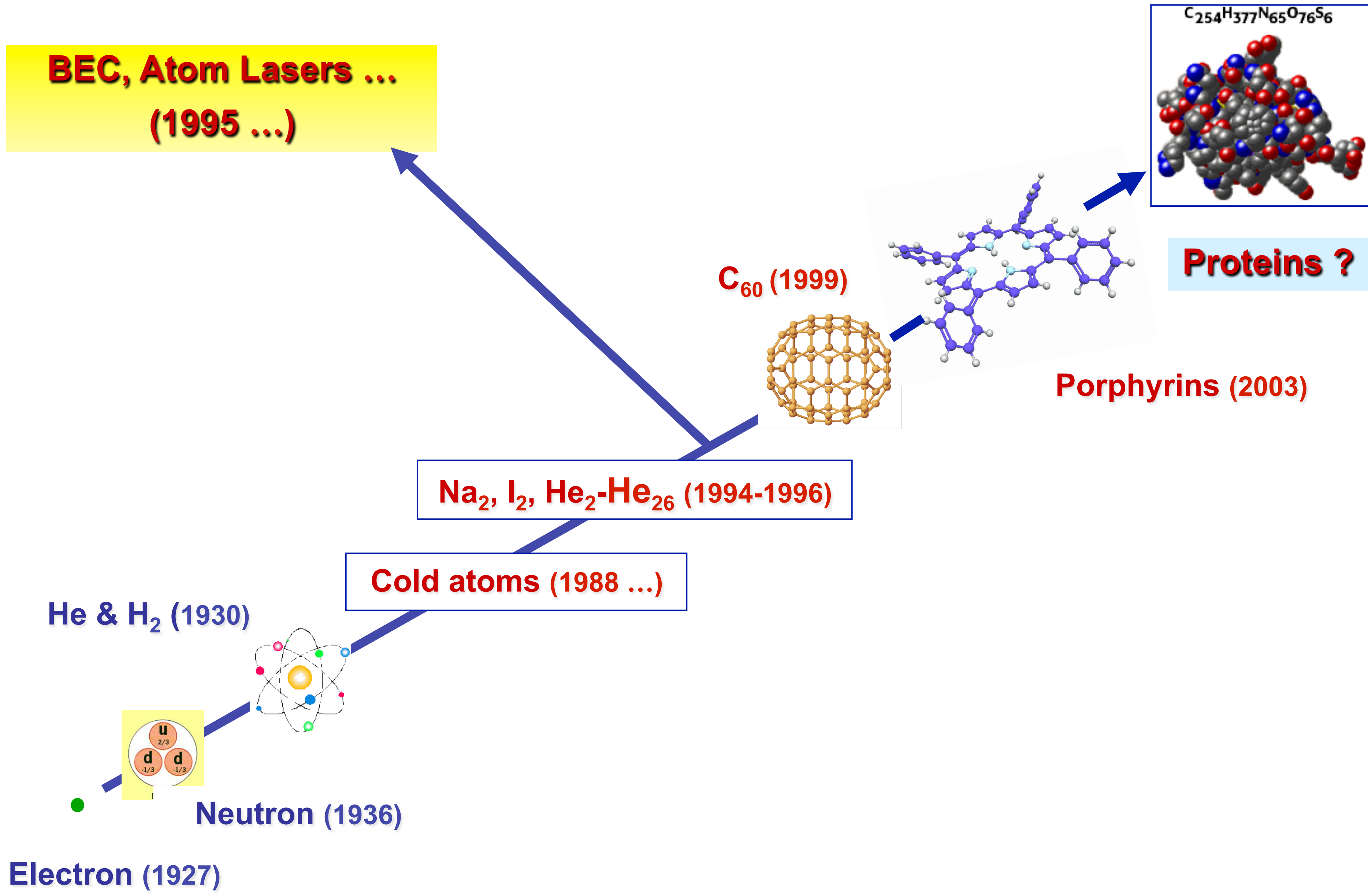
Which-Path Information, Decoherence & Dephasing

in Macromolecule Interferometry

Markus Arndt

Institut für Experimentalphysik, Universität Wien

Part A: Matter wave experiments



BEC, Atom Lasers …
(1995 …)

Proteins ?

C_{60} (1999)

Porphyrins (2003)

Na_2, I_2, He_2-He_{26} (1994-1996)

Cold atoms (1988 …)

He & H_2 (1930)

Neutron (1936)

Electron (1927)

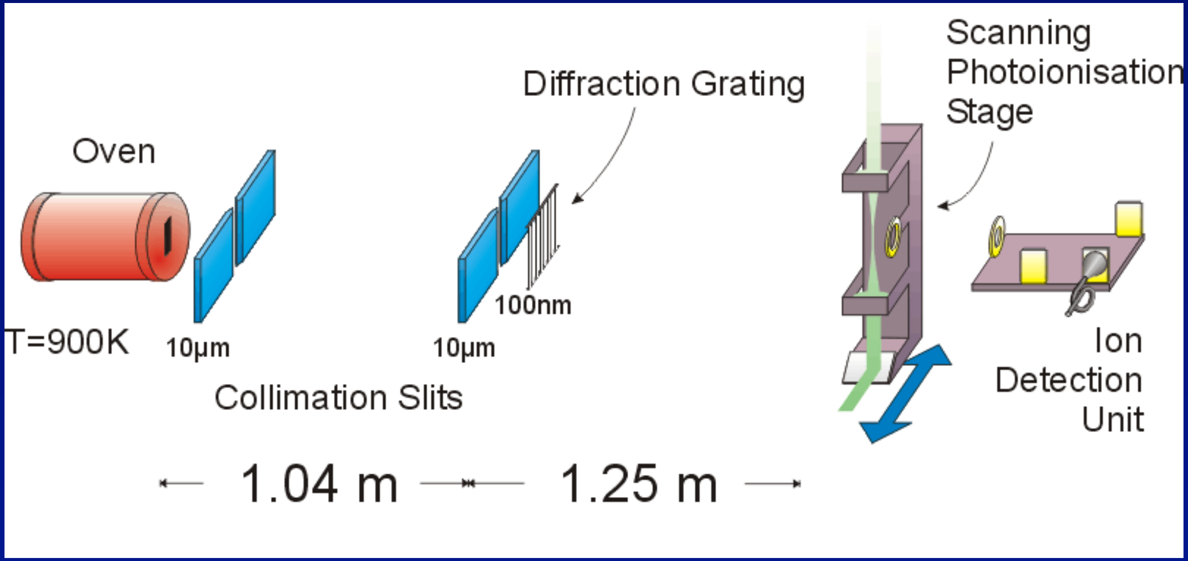
Interference of larger particles

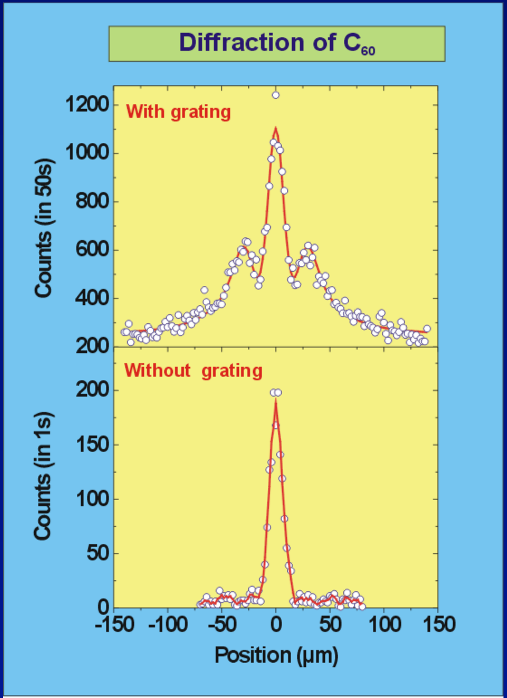
- Matter-wave interference has now been demonstrated with electrons, neutrons, atoms, small molecules, BIG molecules, & biological molecules
- Recent Example: Interference of C_{60}, a.k.a. “fullerenes”,

Mass = (60 C)(12 g/mole) = 1.2×10^{-24} kg

$$\frac{\langle p^2 \rangle}{2m} = K.E. \approx \frac{3}{2}kT \quad \Rightarrow \quad \langle p \rangle = \sqrt{3kTm} = 2.1\times10^{-22}\, kg\, m/s$$

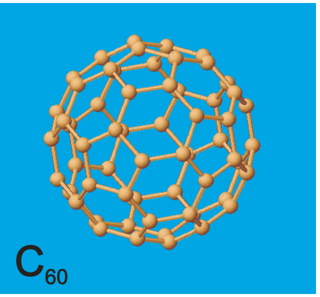
$\lambda = h/p = 2.5$ pm (c.f. C_{60} is ~ 1 nm across!)

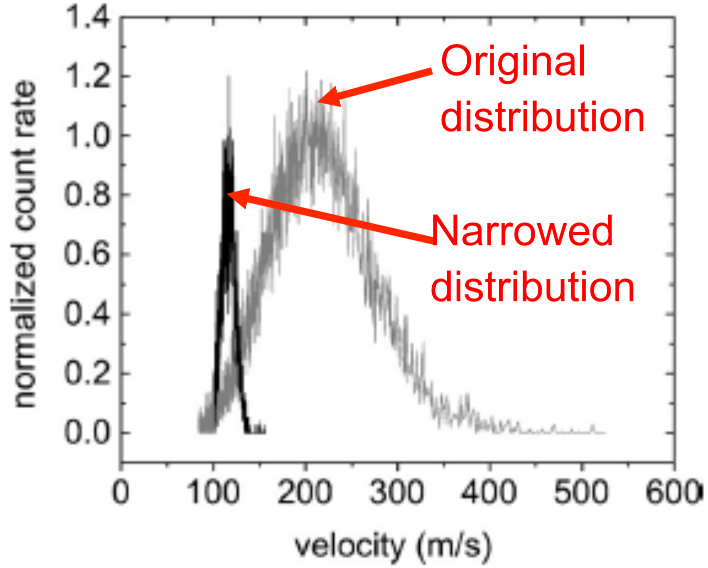


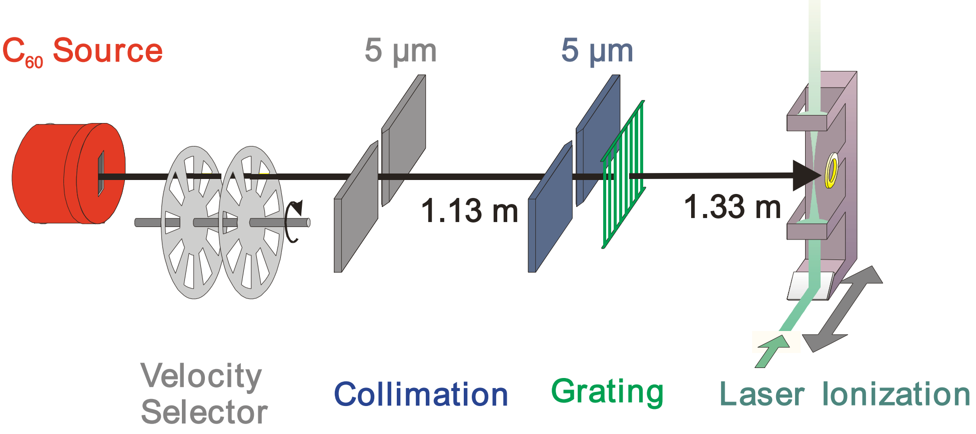


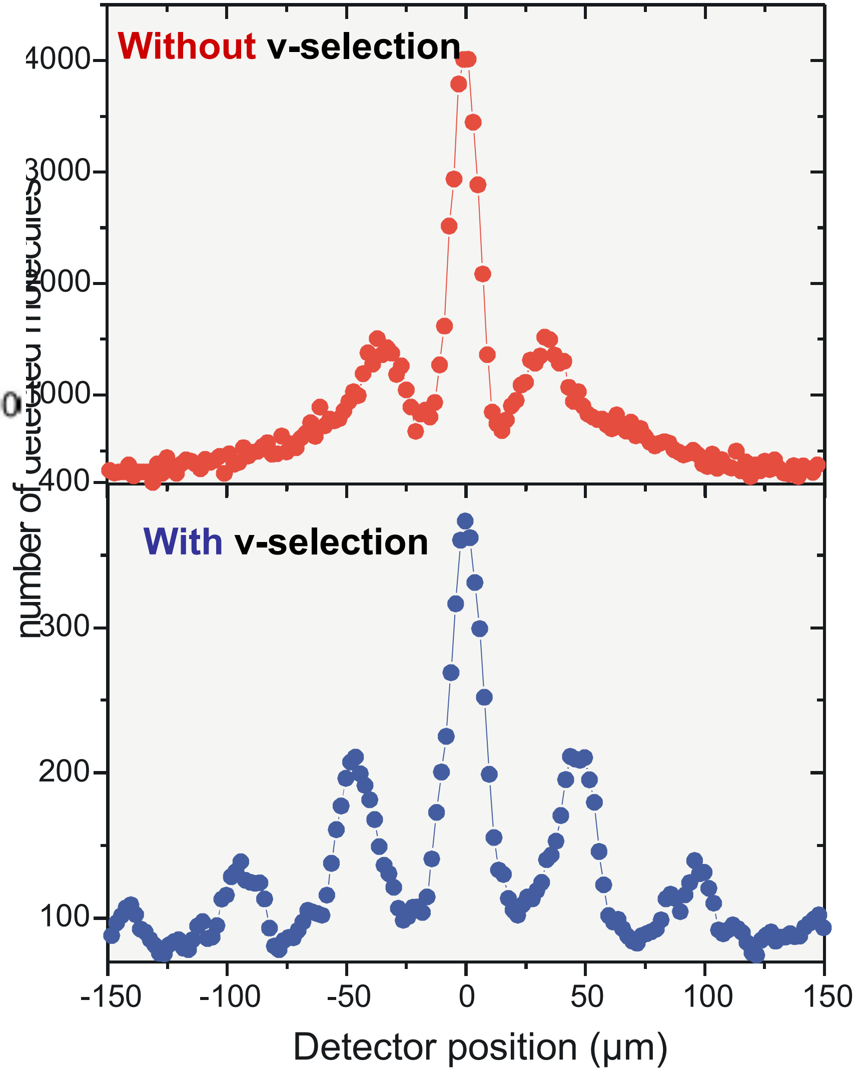
[A. Zeilinger (U. Vienna), 1999]

Short reminder: Far-Field Diffraction at a nanograting









M. Arndt et al., Nature 401, 680 (1999).

O. Nairz, M. Arndt, A. Zeilinger, AJP 71, 319 (2003).

Matter waves of very massive objects ?

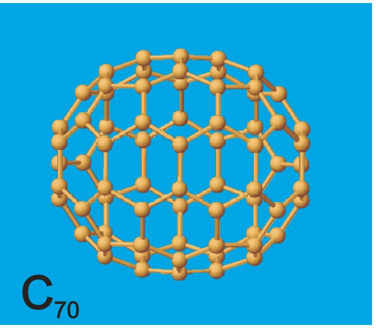
Challenges for very massive objects:

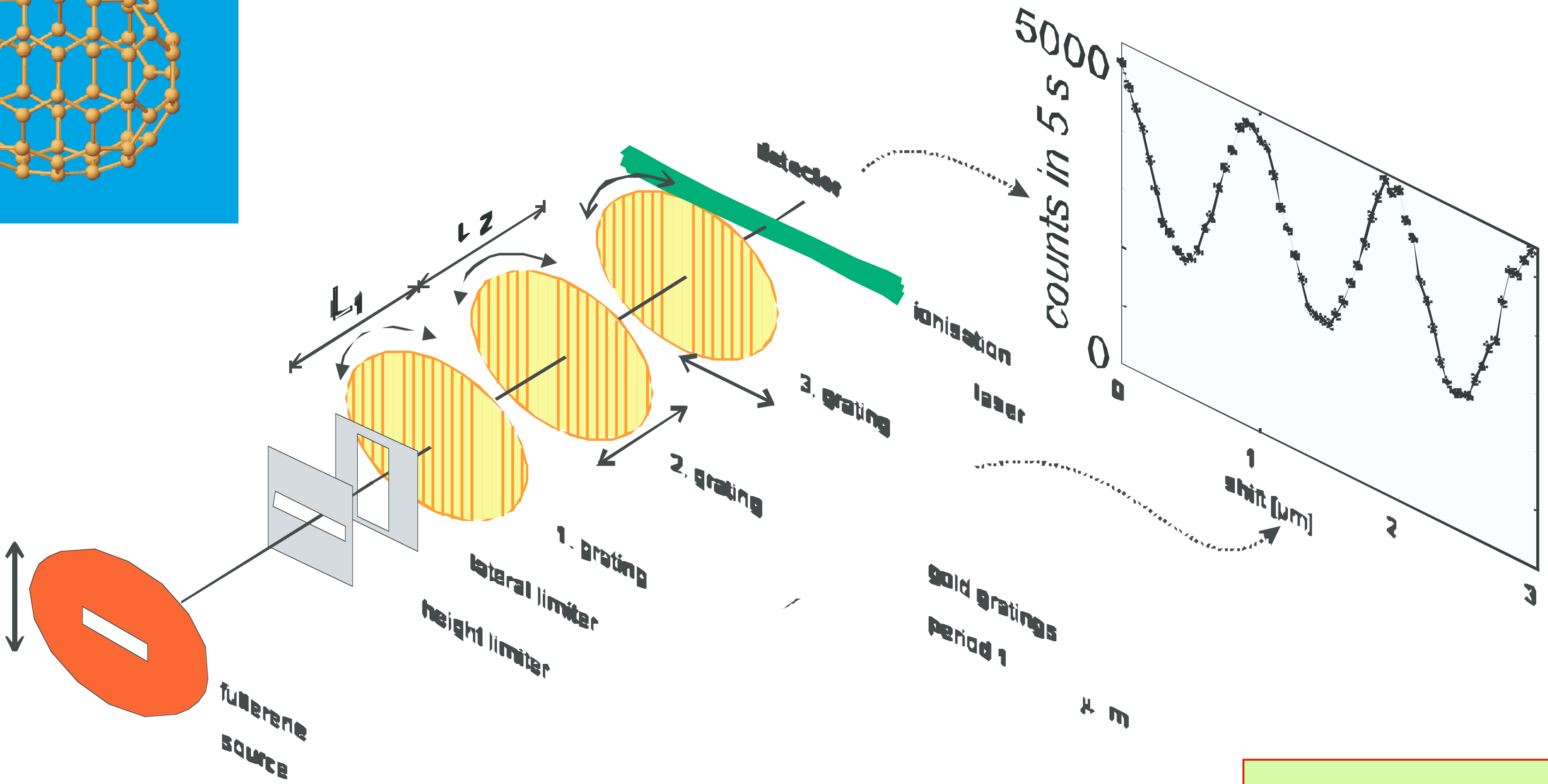
- smaller de Broglie wavelength
- tighter collimation
- smaller count rate
- high-resolution detector required, …

Solutions:

1. Slowing and Cooling: still open field of research
2. Near-field interferometery

Talbot-Lau Interferometer





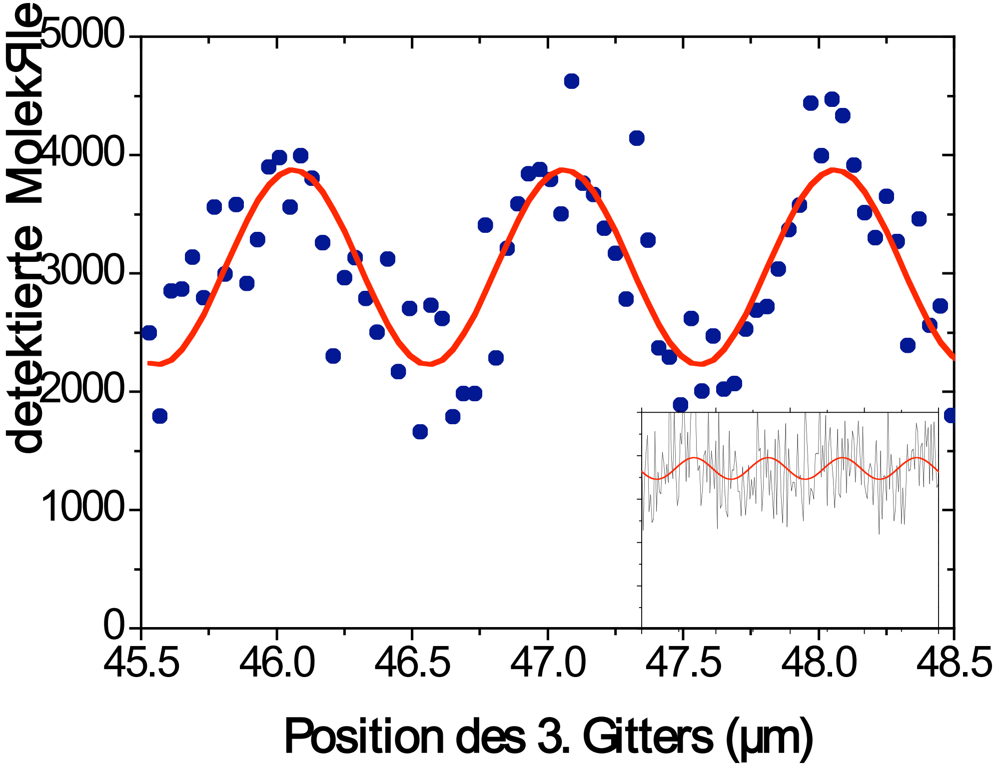
Visibility:

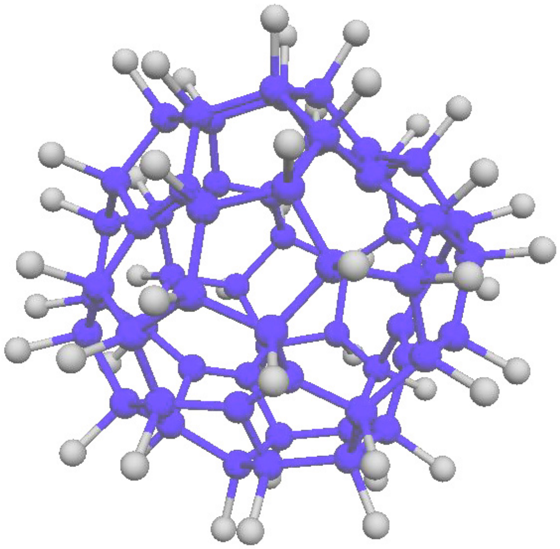
$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Gratings: Heidenhain, Traunreut, AXAF/CHANDRA

Exploring higher mass & complexity

- $C_{60} F_{48}$
- **1632 amu !**
- **108 atoms in a *single object* !**
- **Several isomers with different symmetries**



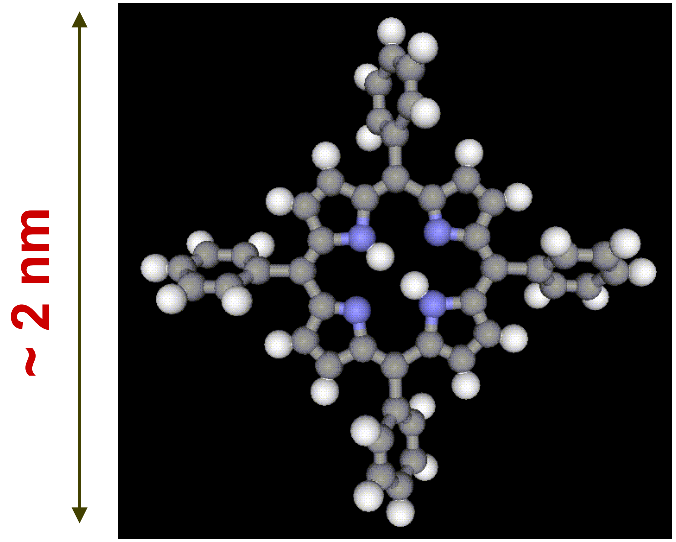


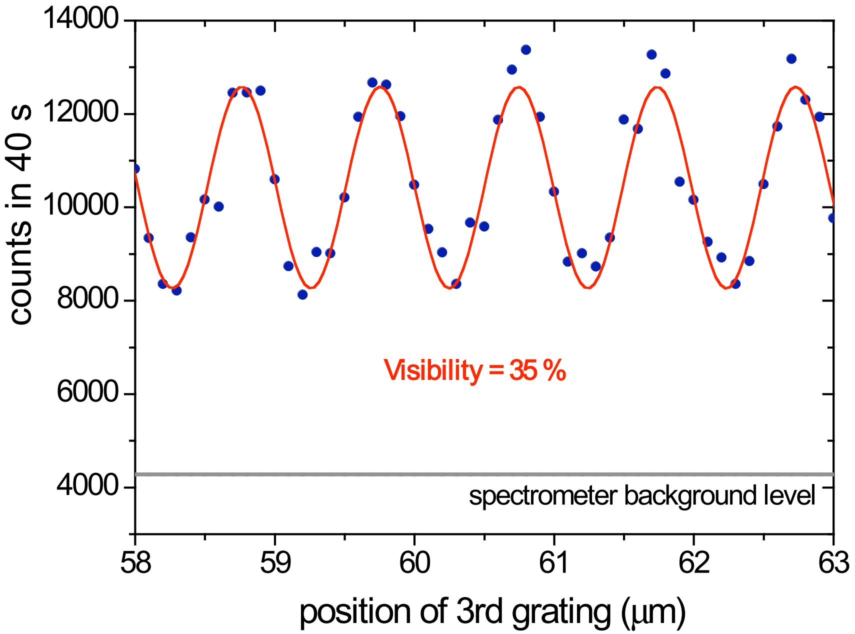
**Low velocity →
Vibrational Dephasing !!**

Interferometry with Porphyrins: $C_{44}H_{30}N_4$ (TPP)

Question:

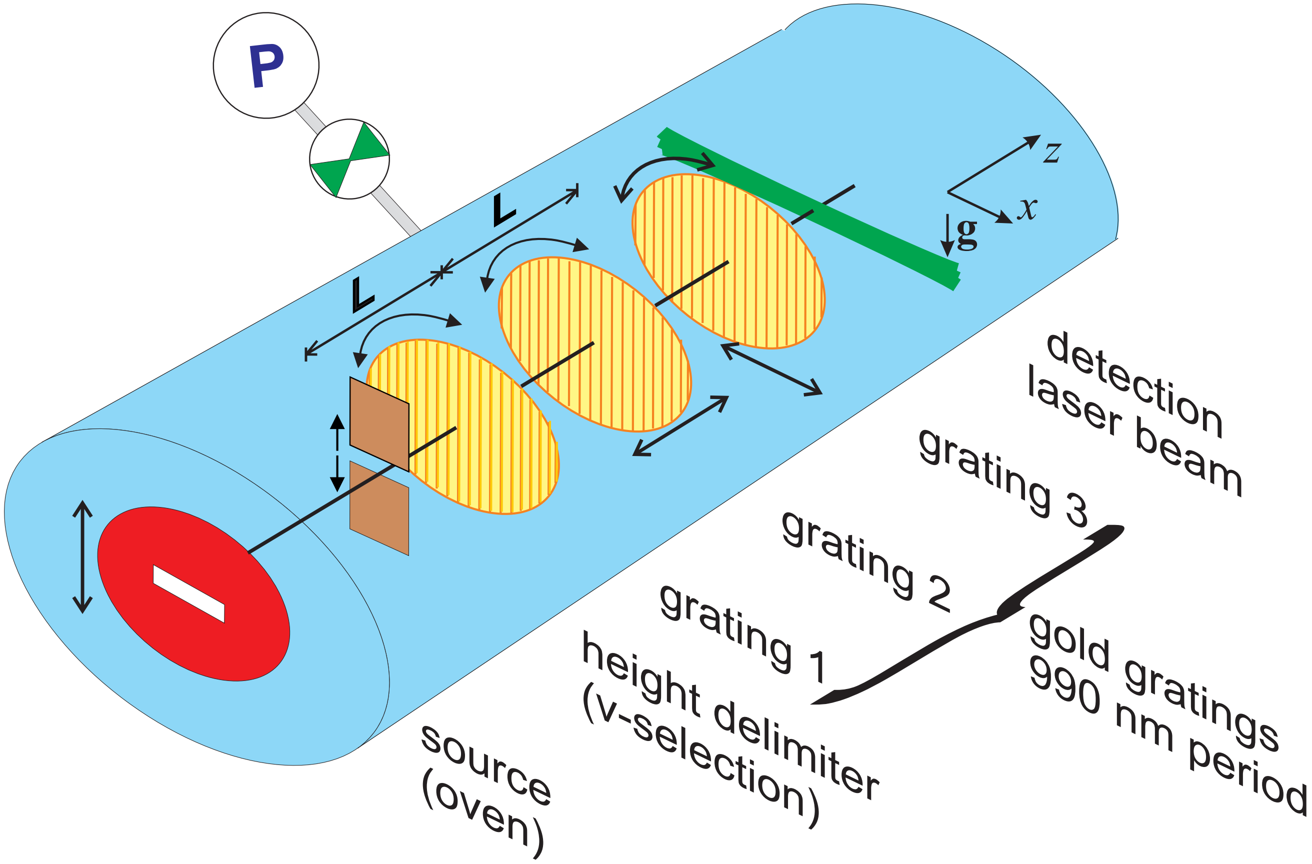
Will high interference visibility vanish with reduced symmetry of the quantum object ?



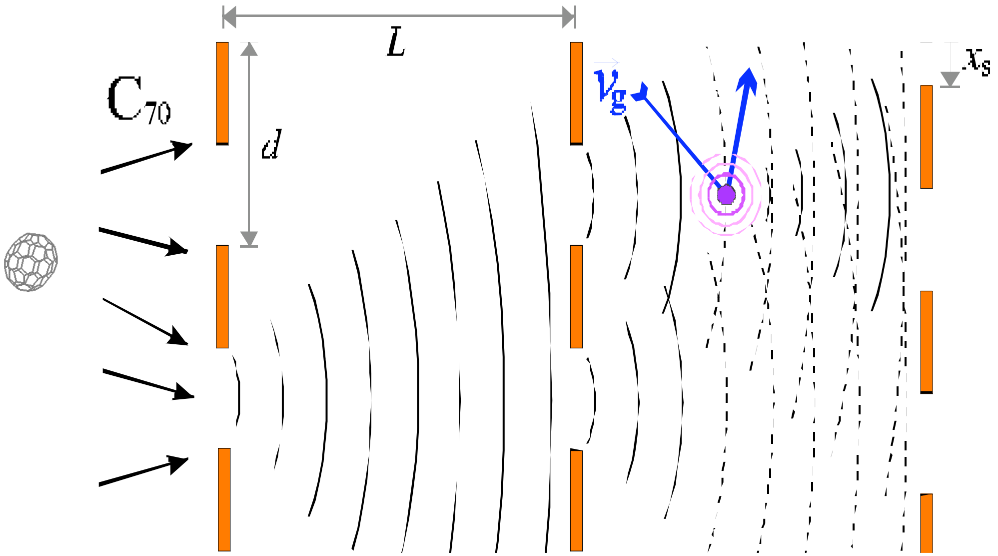


Decoherence by collisions: Realization

Various gases can be added with a well controlled pressure



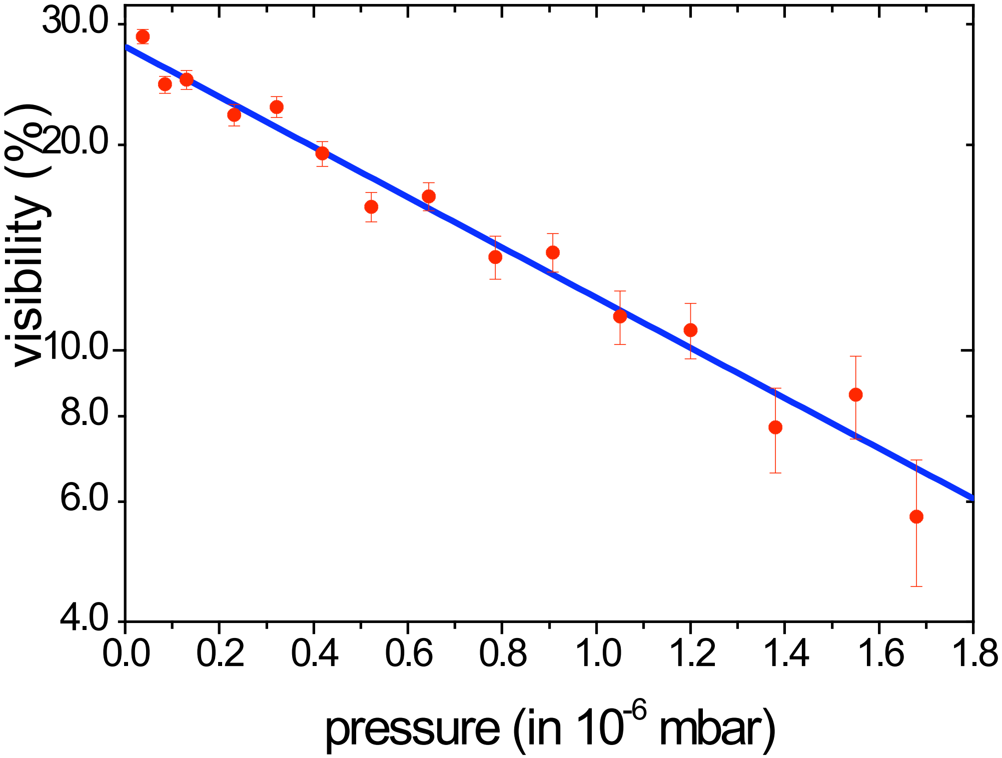
Decoherence by collisions: The Idea



- **Collision generates entanglement**

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left[|C_{70}^{\mathrm{left}}\rangle + |C_{70}^{\mathrm{right}}\rangle\right] \otimes |\mathrm{g}\rangle \xrightarrow{\mathrm{coll.}} \frac{1}{\sqrt{2}}\left[|\mathrm{C}_{70}^{\mathrm{left}}\rangle|\mathrm{g}_{\mathrm{scat}}^{\mathrm{left}}\rangle + |\mathrm{C}_{70}^{\mathrm{right}}\rangle|\mathrm{g}_{\mathrm{scat}}^{\mathrm{right}}\rangle\right]$$

Fringe visibility:
Exponential pressure dependence



$$V(p) = 2\frac{|T_1|}{T_0}\exp\left(-\frac{2L\sigma_{\text{eff}}}{k_{\text{B}}T}p\right) =: V_0\,\mathrm{e}^{-p/p_0}$$

Three models lead to the same predictions *for pure de Broglie experiments*

Bohr: Complementarity

Which-path information and interference contrast are complementary

Heisenberg: „microscope“ argument

Random recoils wash out the interference pattern

Modern language: „Entanglement“ with the environment

Leads to an uncontrolled extension of the quantum system.

May be regarded as a mathematical formulation of Bohr‘s view.

Can collisions limit matter interferometry ?

Is a virus interferometer conceivable?

$$M = 5 \times 10^{7}\,\mathrm{amu}$$

$$v_{\mathrm{m}} = 10\,\mathrm{m/s}$$

$$L = 1\,\mathrm{m}$$

$$\longrightarrow \quad \boxed{p \simeq 3 \times 10^{-10}\,\mathrm{mbar}}$$

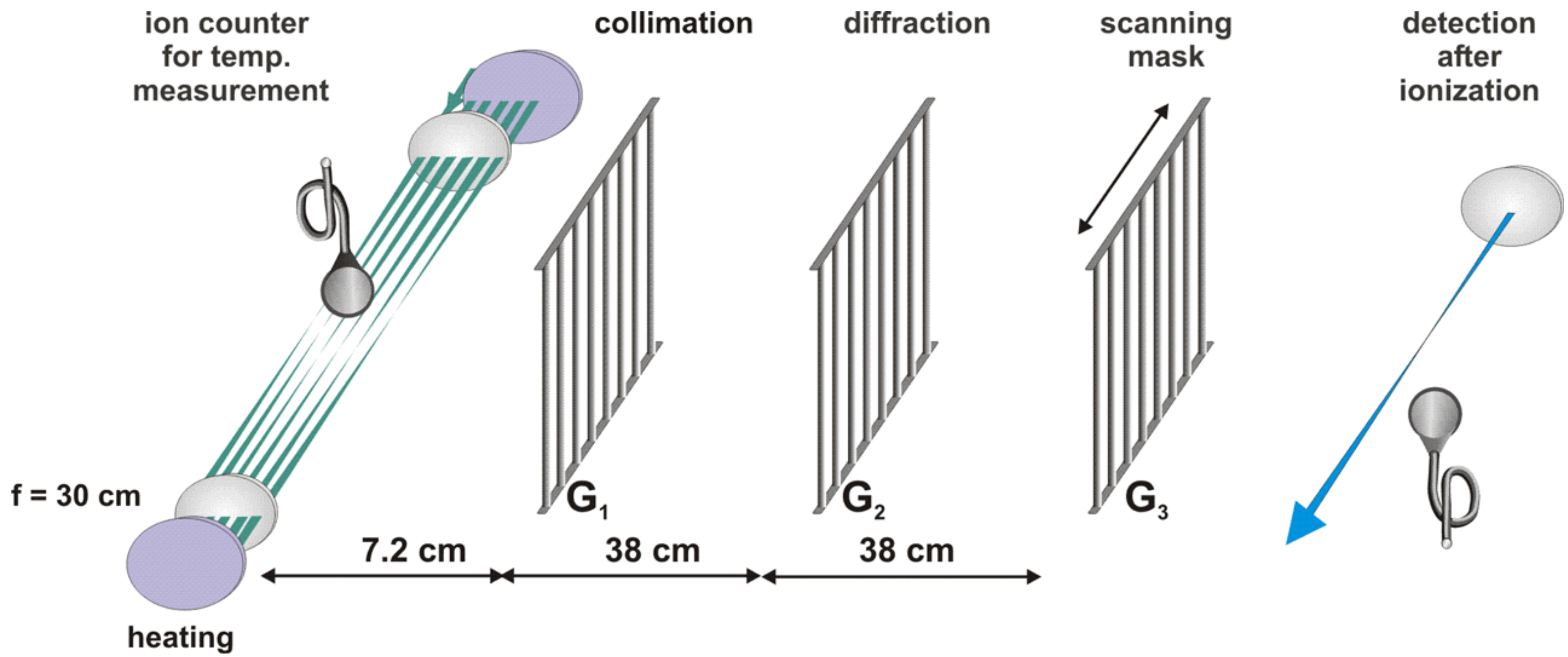
A „Virus Interferometer“ would not yet be limited by collisions

Loss of interference due to Thermal Radiation

Idea:

- Warm bodies emit light
- A single photon suffices to localize the emitter to within the photon‘s wavelength

“Self-Localization“ due to thermal radiation

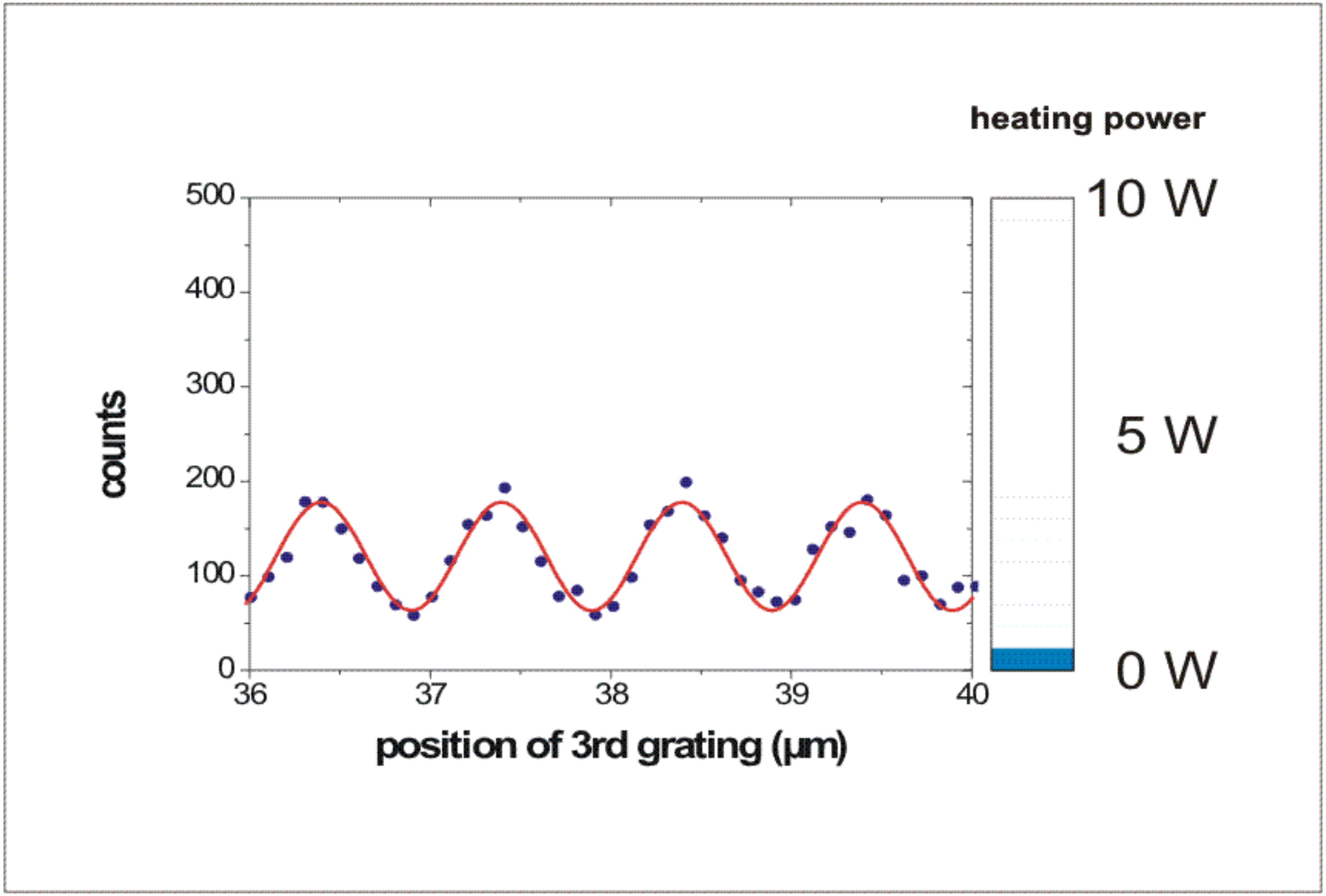


Now 1-µm slit spacing

- Heating of C_{70} before it enters the interferometer (up to ~ 3000 K).
- Hot fullerenes emit visible light (see Mitzner& Campbell)
- The interference contrast decreases, with increasing temperature

L. Hackermüller, K. Hornberger, B. Brezger, A. Zeilinger & M. Arndt, Nature **427**, 711(2004)

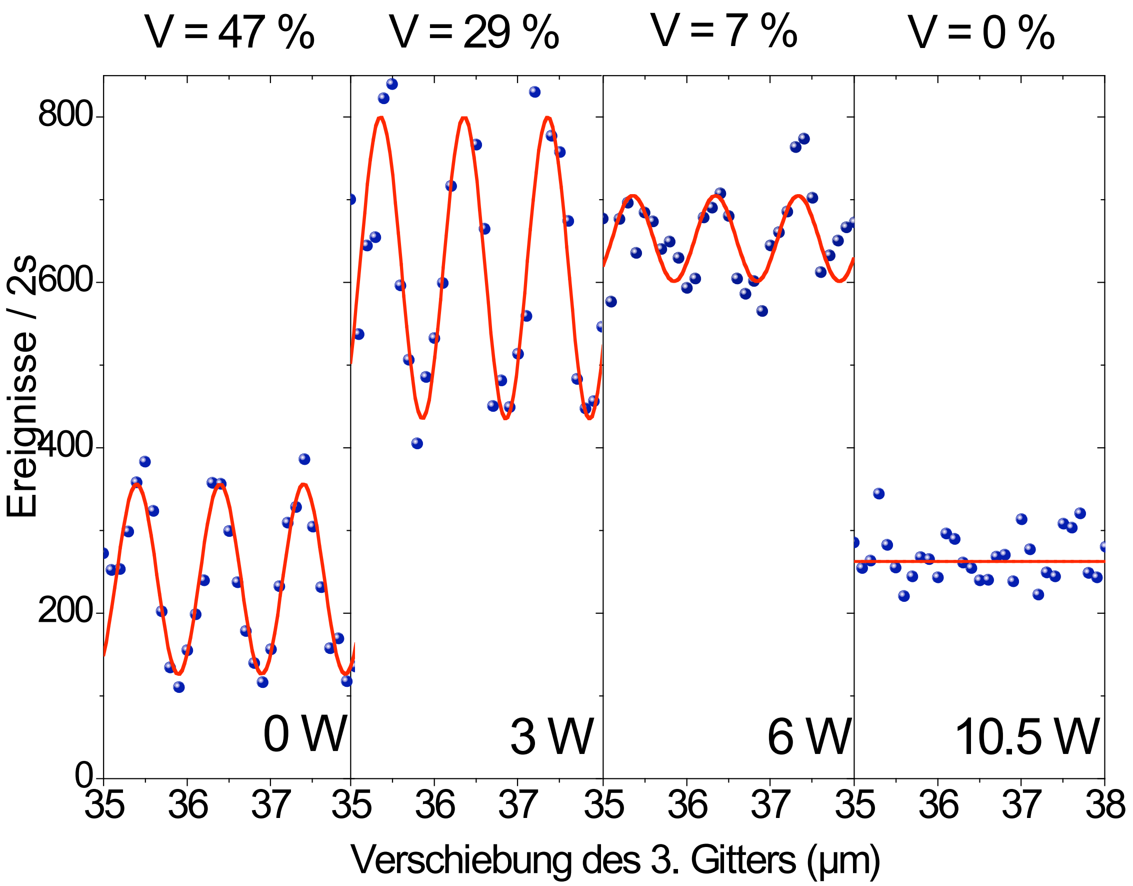
Interference patterns for Increasing heating laser power



Interference of heated molecules

increasing temperature

vanishing quantum interference



Molecule fragments or ionizes (misses detector altogether)

Roy Glauber   Nobel 2005
Quantum Theory of Optical Coherence & Photodetection

(Semi-)classically

September 1, 1925 –
December 26, 2018

$$p \propto I \propto \left\langle E^2 \right\rangle \qquad\qquad p(\Delta T) = \int_{-\Delta T/2}^{+\Delta T/2} I(t)\,dt$$

Classically, E is real, but we can write

$$\vec{E}(\vec{r},t) = \int_{-\infty}^{+\infty} d\omega\, \vec{E}(\vec{r},\omega)\, e^{-i\omega t}$$

$$= \int_{-\infty}^{0} d\omega\, \vec{E}(\vec{r},\omega)\, e^{-i\omega t} + \int_{0}^{+\infty} d\omega\, \vec{E}(\vec{r},\omega)\, e^{-i\omega t}$$

$$\equiv \int_{-\infty}^{0} d\omega\, \vec{E}^{(-)}(\vec{r},\omega) + \int_{0}^{+\infty} d\omega\, \vec{E}^{(+)}(\vec{r},\omega)$$

QM

$$\hat{E} = \hat{E}^{(+)} + \hat{E}^{(-)} \qquad \hat{E}^{(+)} = \hat{E}^{(-)\dagger}$$

$$\hat{E}^{(+)}(\vec{r},t) = i \sum_{k,\sigma} \sqrt{\frac{\hbar\omega_k}{2\varepsilon_0 V}}\, \vec{u}_{k,\sigma}(\vec{r})\, e^{-i\omega t}\ \hat{a}_{k,\sigma}$$

photon
absorption

$$\hat{E}^{(-)}(\vec{r},t) = -i \sum_{k,\sigma} \sqrt{\frac{\hbar\omega_k}{2\varepsilon_0 V}}\, \vec{u}^{*}_{k,\sigma}(\vec{r})\, e^{+i\omega t}\ \hat{a}^{\dagger}_{k,\sigma}$$

photon
creation

$$\hat{E} \propto (\hat{a} - \hat{a}^{\dagger})$$

Typical detector has atom size << λ

→ electric dipole approximation: $H = -e\vec{d} \bullet \vec{E}$

Photodetection ~ photoabsorption

Matrix element

$$\left\langle f \middle| \hat{\vec{E}}^{(+)}(\vec{r},t) \middle| i \right\rangle$$

light + atom (assume initially in ground state, ready to count)

$$w_{i\to f} = \frac{\text{prob}}{\text{unit time}} \text{ for a photon to be absorbed at } \vec{r},t$$

$$= \sum_f \left| \left\langle f \middle| \hat{\vec{E}}^{(+)}(\vec{r},t) \middle| i \right\rangle \right|^2 = \sum_f \left\langle i \middle| \hat{E}^{(-)}(\vec{r},t) \middle| f \right\rangle \left\langle f \middle| \hat{E}^{(+)}(\vec{r},t) \middle| i \right\rangle$$

sum over final states of atom

$$= \left\langle i \middle| \hat{E}^{(-)}(\vec{r},t) \hat{E}^{(+)}(\vec{r},t) \middle| i \right\rangle$$

Define "1st-order" correlation function

$$G^{(1)}(\vec{r}_1,t_1;\vec{r}_2,t_2) \equiv \left\langle \hat{E}^{(-)}(\vec{r}_1,t_1) \hat{E}^{(+)}(\vec{r}_2,t_2) \right\rangle$$

'Ergodic' fields: ensemble average = time average

$G^{(1)}$ measures field-field correlations

For stationary fields: $G(t_1,t_2) = G(\tau = t_2 - t_1)$

$$p(t) = G^{(1)}(\vec{r},t;\vec{r},t) \propto \langle \hat{a}^\dagger \hat{a} \rangle = \langle \hat{n} \rangle$$

Prob detection per unit time

assume detector is localized at one place, and very fast

evaluated over the initial state of the light field

E.g., $|\psi\rangle = |1\rangle_\omega$ monochromatic field

or $|\psi\rangle = \int d\omega\, \phi(\omega)\, e^{i\omega t} |1\rangle_\omega$ single-photon wavepacket

or $\rho = \sum_i p_i |i\rangle\langle i|$ mixed state

$$\langle i|\hat{E}^{(-)}\hat{E}^{(+)}|i\rangle \Rightarrow \sum_i p_i \langle i|\hat{E}^{(-)}\hat{E}^{(+)}|i\rangle \equiv Tr(\rho\, \hat{E}^{(-)}\hat{E}^{(+)})$$