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

"Aberration corrected 1.2-MV cold field-emission transmission electron microscope with a sub-50-pm resolution."

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)
Optics and Interferometry with Na₂ Molecules

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We have produced an intense, pure beam of sodium molecules (Na₂) 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 Na₂ molecule de Broglie waves by inserting a gas cell in one arm of the interferometer.

\[ \lambda_{d} (\text{Na}_2) = 0.11 \text{ Å} \]

FIG. 3. Schematic of our interferometer showing the paths of Na (dashed line) and Na₂ (solid line). G1, G2, and G3 indicate the three diffraction gratings.
Which-Path Information, Decoherence & Dephasing in Macromolecule Interferometry

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Part A: Matter wave experiments

BEC, Atom Lasers ... (1995 ...)

He & H₂ (1930)

Neutron (1936)

Electron (1927)

Cold atoms (1988 ...)

Na₂, I₂, He₂-He₂₆ (1994-1996)

C₆₀ (1999)


C₂₅₄H₃₇₇N₆₅O₇₆S₆
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\textsubscript{60}, a.k.a. “fullerenes”.

\[ \langle p^2 \rangle = \frac{K.E.}{2m} \approx \frac{3}{2} kT \Rightarrow \langle p \rangle = \sqrt{3kTm} = 2.1 \times 10^{-22} \text{ kg m/s} \]

\[ \lambda = \frac{h}{p} = 2.5 \text{ pm} \quad \text{(c.f. C\textsubscript{60} is \sim 1 nm across!)} \]

\[ \text{Mass} = (60 \text{ C})(12 \text{ g/mole}) = 1.2 \times 10^{-24} \text{ kg} \]

[A. Zeilinger (U. Vienna), 1999]
Short reminder: Far-Field Diffraction at a nanograting

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 interferometry
Talbot-Lau Interferometer

Gratings: Heidenhain, Traunreut, AXAF/CHANDRA

Visibility:

\[ V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]
Exploring higher mass & complexity

- $\text{C}_{60}\text{F}_{48}$
- 1632 amu!
- 108 atoms in a *single object*!
- Several isomers with different symmetries

Low velocity $\rightarrow$ Vibrational Dephasing!!
Question: Will high interference visibility vanish with reduced symmetry of the quantum object?
Various gases can be added with a well controlled pressure
Collision generates **entanglement**

\[
|\psi\rangle = \frac{1}{\sqrt{2}} \left[ |C_{70}^{\text{left}}\rangle + |C_{70}^{\text{right}}\rangle \right] \otimes |g\rangle \xrightarrow{\text{coll.}} \frac{1}{\sqrt{2}} \left[ |C_{70}^{\text{left}}\rangle |g_{\text{scat}}^{\text{left}}\rangle + |C_{70}^{\text{right}}\rangle |g_{\text{scat}}^{\text{right}}\rangle \right]
\]
Fringe visibility:
Exponential pressure dependence

\[ V(p) = 2 \frac{|T_1|}{T_0} \exp \left( -\frac{2 L \sigma_{\text{eff}}}{k_B T} p \right) =: V_0 e^{-p/p_0} \]
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? 

\[ M = 5 \times 10^7 \text{ amu} \]
\[ v_m = 10 \text{ m/s} \]
\[ L = 1 \text{ m} \]

\[ p \approx 3 \times 10^{-10} \text{ mbar} \]

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

Heating of C\textsubscript{70} before it enters the interferometer (up to \(\sim 3000\) K).

Hot fullerenes emit visible light (see Mitzner & Campbell)

The interference contrast decreases, with increasing temperature

Interference patterns for Increasing heating laser power
Interference of heated molecules

increasing temperature
vanishing quantum interference

Molecule fragments or ionizes (misses detector altogether)
(Semi-)classically

\[ p \propto I \propto \langle E^2 \rangle \]

Classically, \( E \) is real, but we can write

\[
\begin{align*}
\tilde{E}(\vec{r},t) &= \int_{-\infty}^{+\infty} d\omega \ \tilde{E}(\vec{r},\omega) \ e^{-i\omega t} \\
&= \int_{-\infty}^{0} d\omega \ \tilde{E}(\vec{r},\omega) \ e^{-i\omega t} + \int_{0}^{+\infty} d\omega \ \tilde{E}(\vec{r},\omega) \ e^{-i\omega t} \\
&\equiv \int_{-\infty}^{0} d\omega \ \tilde{E}^{(-)}(\vec{r},\omega) + \int_{0}^{+\infty} d\omega \ \tilde{E}^{(+)}(\vec{r},\omega)
\end{align*}
\]

QM

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

\[ \hat{E} \propto (\hat{a} - \hat{a}^{\dagger}) \]
Typical detector has atom size \( \ll \lambda \)

\( \rightarrow \) electric dipole approximation:

\[ H = -e \vec{d} \cdot \vec{E} \]

Photodetection \( \sim \) photoabsorption

Matrix element

\[ \langle f | \hat{E}^\oplus (\vec{r},t) | i \rangle \]

\( W_{i \rightarrow f} = \frac{\text{prob}}{\text{unit time}} \) for a photon to be absorbed at \( \vec{r},t \)

\[ = \sum_f \left| \langle f | \hat{E}^\oplus (\vec{r},t) | i \rangle \right|^2 = \sum_f \langle i | \hat{E}^\ominus (\vec{r},t) | f \rangle \langle f | \hat{E}^\oplus (\vec{r},t) | i \rangle \]

sum over final states of atom

Define “1\textsuperscript{st}-order” correlation function

\[ G^{(1)}(\vec{r}_1,t_1;\vec{r}_2,t_2) \equiv \langle \hat{E}^\ominus (\vec{r}_1,t_1) \hat{E}^\oplus (\vec{r}_2,t_2) \rangle \]

‘Ergodic’ fields: ensemble average = time average
$G^{(1)}$ measures field-field correlations

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

$$p(t) = G^{(1)}(\vec{r}_1,t;\vec{r}_2,t) \propto \langle \hat{a}^\dagger \hat{a} \rangle = \langle \hat{n} \rangle$$

Prob detection per unit time

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

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