FOUNDATIONAL EXPERIMENTS IN QUANTUM MECHANICS

Matter Optics and Shelving Effect

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Order of magnitudes

	$m(\mathrm{g})$	$\lambda_{\mathrm{dB}}(\mathrm{pm})$	$v(\mathrm{m/s})$	realization
electrons	10^{-27}	$4-6$	$0,5X10^8$	$'80$
neutrons	10^{-24}	$200-2000$	$200-2000$	$'70-'90$
atoms	10^{-23}	$10-20$	$800-1000$	$'80-'90$
molecules	10^{-21}	$2-5$	$100-250$	$'90-'00$

Bohr radius: $a_0 \approx$0,5 Å

1 Å= 100 pm=10^{-10}m

visible light: $\lambda \approx$0,5 μm

1 μm=10^4Å=10^{-6}m

X rays: $\lambda \leq$ 1Å

Traditional axiomatic of quantum mechanics

One particle system:

ψ normalized vector in a Hilbert space $\mathcal{H}$

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Statistical interpretation:

e event associated to a subspace $\mathcal{S}_e \subset \mathcal{H}$

$$p_e = \|\hat{P}_e \psi\|^2 = \langle \psi | \hat{P}_e \psi \rangle$$

e_t time translated event

$$p_e(t) = \|\hat{P}_e(t)\psi\|^2 = \langle \psi_t | \hat{P}_e \psi_t \rangle \qquad \psi_t = e^{-\frac{i}{\hbar}\hat{H}t}\psi$$

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Observable quantity:

$\hat{A}$ self-adjoint operator in $\mathcal{H}$

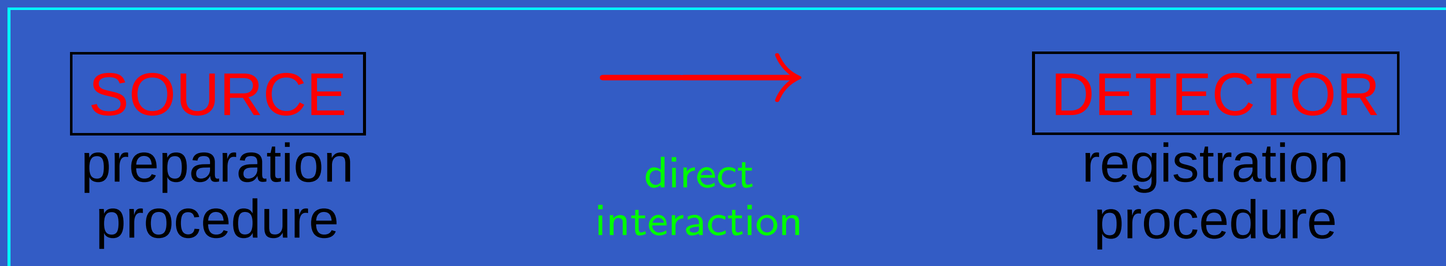
$$\hat{A} = \sum_n a_n \hat{P}_n \qquad \langle \hat{A} \rangle_t = \sum_n a_n p_{e_n}(t) = \sum_n a_n \|\hat{P}_{e_n}(t)\psi\|^2$$

family of events e_n corresponding to the property:

the quantity A has the value a_n

Statistical nature of experiments

General Scheme of single particle experiment:



Statistical nature of experiments

General Scheme of single particle experiment:

SOURCE → **DETECTOR**

SOURCE: preparation procedure

direct interaction

DETECTOR: registration procedure

Available data:

description of source and detector, relative frequencies (reproducible)

Statistical nature of experiments

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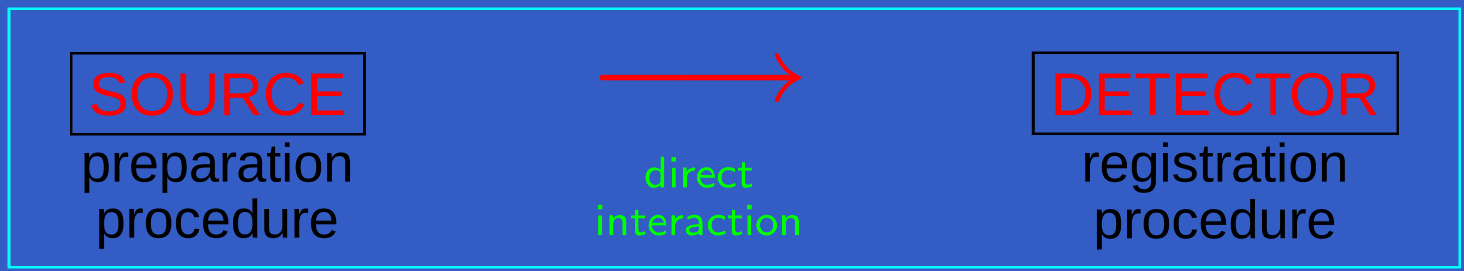

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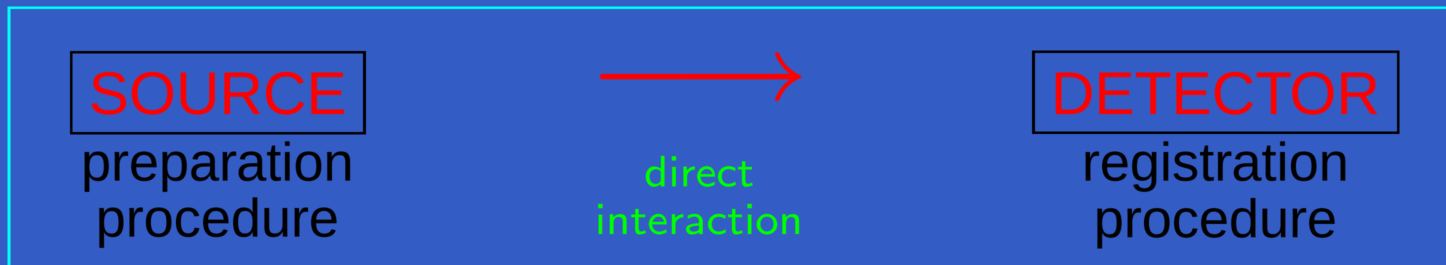

Available data:

description of source and detector, relative frequencies (reproducible)

Preparation of the system:

ψ normalized vector in a Hilbert space $\mathcal{H}$

Observed data:

probability that the quantity A
associated to the self-adjoint operator $\hat{A}$ in $\mathcal{H}$

takes values in a given interval M of the real line

Matter optics □

Linearity of the Schrödinger equation:

$i\hbar \frac{d}{dt}|\psi_t\rangle = \hat{H}|\psi_t\rangle$

$\psi_{1t} = e^{i\phi t}|\psi_{1t}|, \quad \psi_{2t} = e^{i\chi t}|\psi_{2t}|$ stationary solutions

$\Rightarrow \psi_{1t} + \psi_{2t}$ solution

$|\psi_{1t} + \psi_{2t}|^2 = |\psi_{1t}|^2 + |\psi_{2t}|^2 + 2|\psi_{1t}||\psi_{2t}| \cos[(\phi - \chi)t]$

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Equation for the stationary states:

$\hat{H}|\psi\rangle = E|\psi\rangle$

$\nabla\psi(\mathbf{x}) + \frac{2m}{\hbar^2}[E - V(\mathbf{x})]\psi(\mathbf{x}) = 0$

$V(\mathbf{x})$ optical potential (also complex, macroscopic quantity)

$\mathbf{k}(\mathbf{x}) = \frac{1}{\hbar}\sqrt{\frac{2m}{\hbar^2}[E - V(\mathbf{x})]\hat{\mathrm{e}}} \qquad n(\mathbf{x}) = \frac{k(\mathbf{x})}{k_0} = \sqrt{1 - \frac{V(\mathbf{x})}{E}}$

wave vector and refraction index

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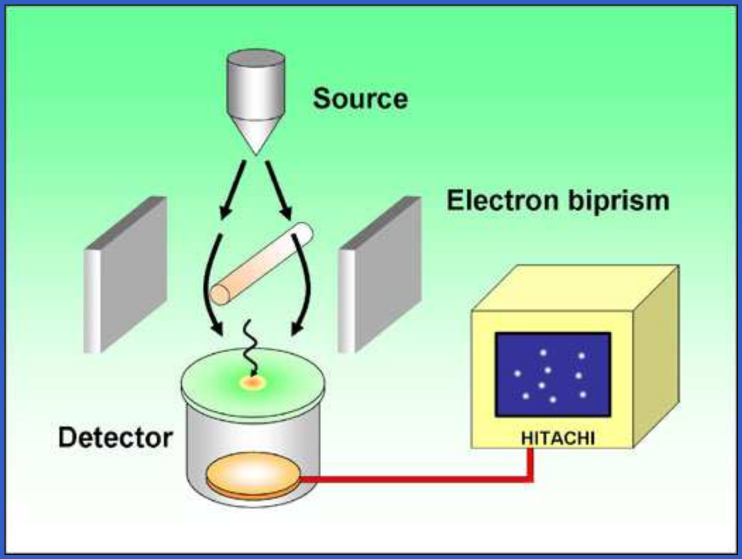
wave vector and refraction index

Helmholtz equation:

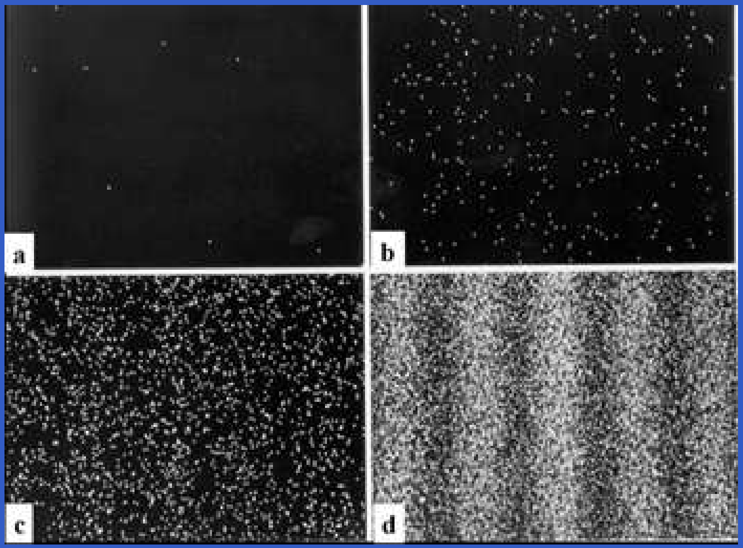
$[\nabla + k^2(\mathbf{x})]\psi(\mathbf{x}) = 0$

Electron optics



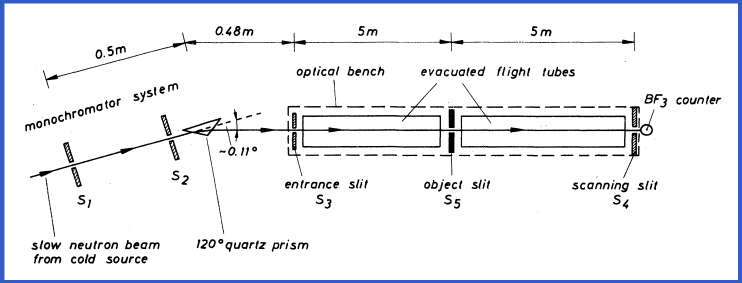
- Biprism
- Source: electron gun
- Phase: interaction with electrostatic field
- Values: $m \approx 10^{-27}\text{g} \quad \lambda_{\text{dB}} \approx 5\text{pm}$
- Single particle experiment

Experimental results



- Difficulties in producing a sufficiently coherent beam (monochromatic and well collimated)
- Developments in electronic microscopy
- Detection efficiency close to one
- Experiments last approximately 30 minutes

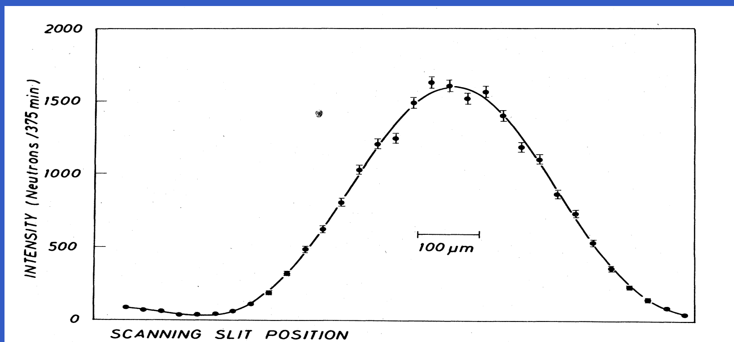
Neutron optics I



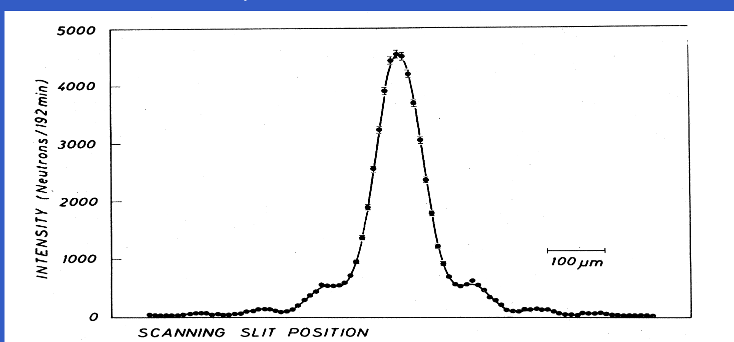
- Single and double slit
- Source: nuclear reactor
- Values: $m \approx 10^{-24}\mathrm{g} \quad \lambda_{\mathrm{dB}} \approx 2000\mathrm{pm}$
- Single particle experiment

Experimental results

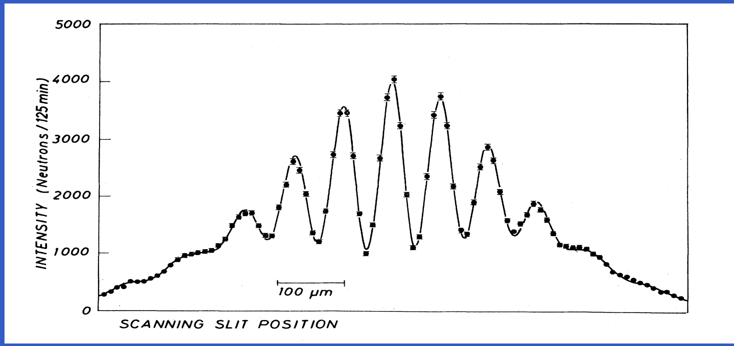
Slit width 90μm



Slit width 23μm

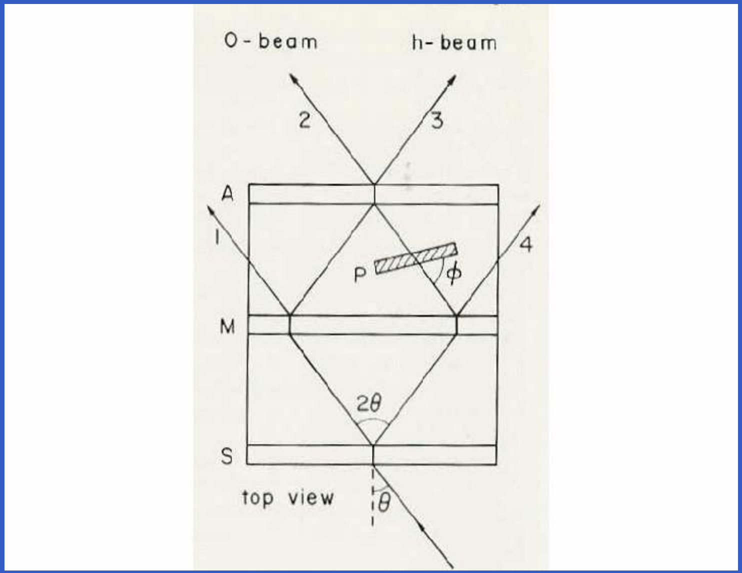


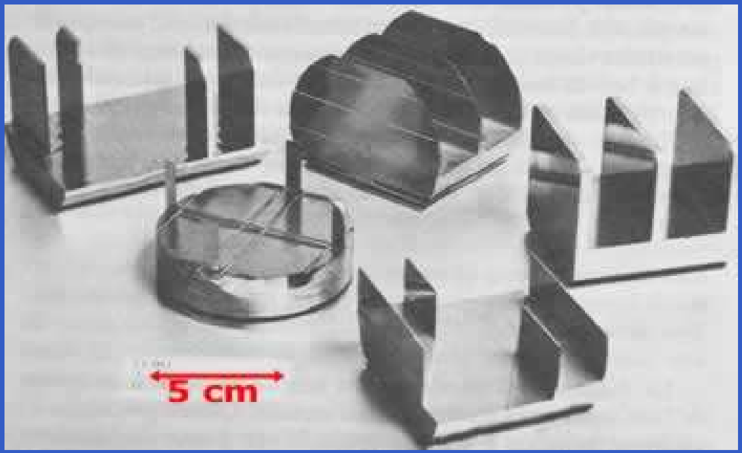
Double slit



- Single slit obtained through glass plates coated with strong absorbers (gadolinium, borum)
- Double slit obtained inserting in the middle a thin line of borum
- Experiments last approximately 300 hours

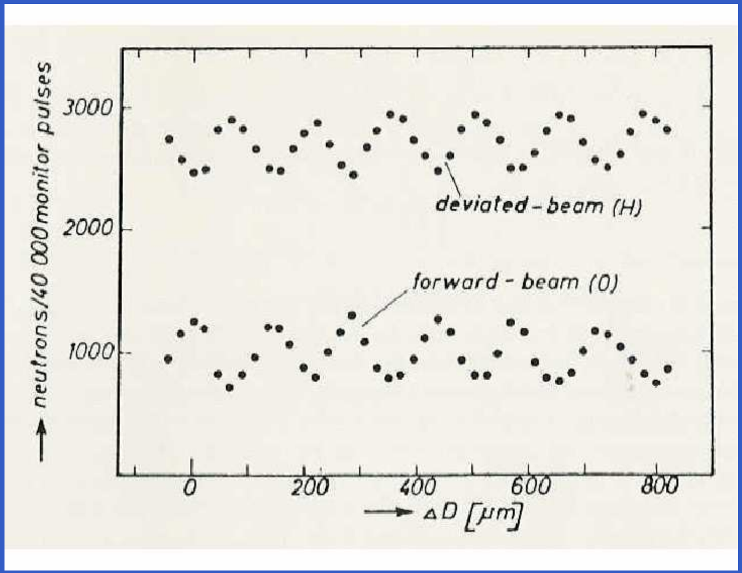
Neutron optics II





- Mach-Zender interferometer (Bragg reflection from a monolithic silicon crystal)
- Source: nuclear reactor
- Phase: interaction with a sample of homogeneous material (Al)
- Values: $m \approx 10^{-24}\text{g} \quad \lambda_{\text{dB}} \approx 200\text{pm}$
- Single particle experiment

Experimental results □



- Optic potential $V = \frac{2\pi\hbar^2}{m}\rho b$
  ρ sample density
- Refractive index $n = 1 - \frac{2\pi\hbar^2}{p^2}\rho b$
  $e^{\frac{i}{\hbar}\mathbf{p}\cdot\mathbf{x}} \longrightarrow e^{\frac{i}{\hbar}\mathbf{p}\cdot(\mathbf{x}-\mathbf{\Delta})}$ $\quad\quad$ $\mathbf{\Delta} = \frac{2\pi\hbar^2}{p^2}\rho b \mathbf{l}_{\mathrm{Al}}$
- Good visibility also at high interference order
- Macroscopic dimensions of apparatus (centimeters)
  and related possibility to interact with the beam

Interference of Gaussian wave-packets

Preparation given by a Gaussian minimum uncertainty wave-packet:

$$\psi_{\text{in}}(\mathbf{x}) = \left(\frac{1}{2\pi\sigma_x^2}\right)^{3/4} \exp\left(-\frac{1}{4\sigma_x^2}\mathbf{x}^2 + \frac{i}{\hbar}\mathbf{p}_0 \cdot \mathbf{x}\right)$$

$$\widetilde{\psi}_{\text{in}}(\mathbf{p}) = \left(\frac{1}{2\pi\sigma_p^2}\right)^{3/4} \exp\left(-\frac{1}{4\sigma_p^2}(\mathbf{p} - \mathbf{p}_0)^2\right)$$

$$\sigma_x\sigma_p = \frac{\hbar}{2}$$

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$$\sigma_x\sigma_p = \frac{\hbar}{2}$$

Output state:

$$\psi_{\rm out}(\mathbf{x}) = \frac{1}{2}\frac{1}{\sqrt{2}}\left[\psi_{\rm in}(\mathbf{x}) + \psi_{\rm in}(\mathbf{x}-\mathbf{\Delta})\right]$$

$$\widetilde{\psi}_{\rm out}(\mathbf{p}) = \frac{1}{2}\frac{1}{\sqrt{2}}\left[\widetilde{\psi}_{\rm in}(\mathbf{p}) + \widetilde{\psi}_{\rm in}(\mathbf{p})e^{-\frac{i}{\hbar}\mathbf{p}\cdot\mathbf{\Delta}}\right]$$

$\mathbf{\Delta}$ relative phase due to interaction with the aluminum sample in one of the two paths of the interferometer

The free evolution does not influence the interference pattern

Related probability distributions □

Position and momentum probability distributions:

$$I(\mathbf{x}) = |\psi_{\rm out}(\mathbf{x})|^2$$

$$= \frac{1}{8}\left(\frac{1}{2\pi\sigma_x^2}\right)^{3/2}\left[e^{-\frac{1}{2\sigma_x^2}\mathbf{x}^2} + e^{-\frac{1}{2\sigma_x^2}(\mathbf{x}-\mathbf{\Delta})^2} + 2e^{-\frac{\Delta^2\sigma_p^2}{2\hbar^2}}\cos\left(\frac{\mathbf{p}_0\cdot\mathbf{\Delta}}{\hbar}\right)e^{-\frac{1}{2\sigma_x^2}(\mathbf{x}-\frac{\mathbf{\Delta}}{2})^2}\right]$$

$$I(\mathbf{p}) = |\widetilde{\psi}_{\rm out}(\mathbf{p})|^2$$

$$= \frac{1}{4}\left(\frac{1}{2\pi\sigma_p^2}\right)^{3/2} e^{-\frac{1}{\sigma_p^2}(\mathbf{p}-\mathbf{p}_0)^2}\left[1+\cos\left(\frac{\mathbf{p}\cdot\mathbf{\Delta}}{\hbar}\right)\right]$$

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$$I(\mathbf{p}) = |\widetilde{\psi}_{\rm out}(\mathbf{p})|^2$$

$$= \frac{1}{4}\left(\frac{1}{2\pi\sigma_p^2}\right)^{3/2} e^{-\frac{1}{\sigma_p^2}(\mathbf{p}-\mathbf{p}_0)^2}\left[1 + \cos\left(\frac{\mathbf{p}\cdot\boldsymbol{\Delta}}{\hbar}\right)\right]$$

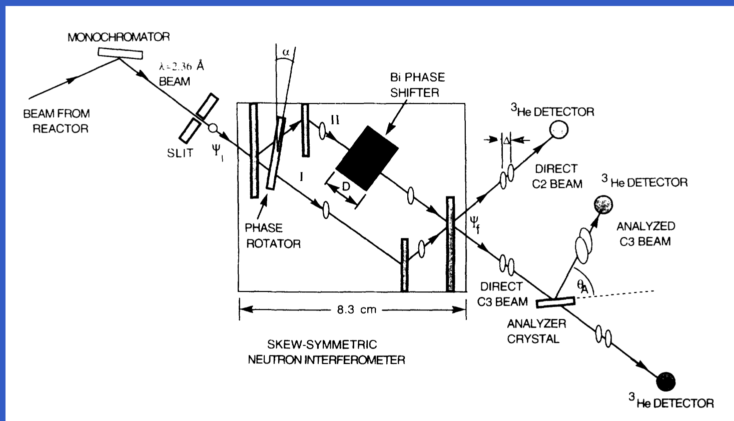
Total fraction of outgoing neutrons:

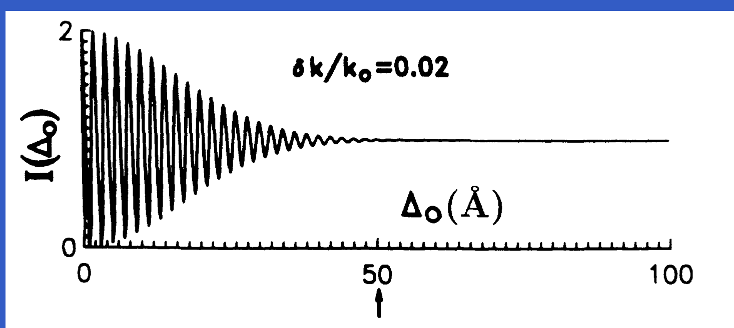
$$I = \int_{\mathbb{R}^3} d^3x\,|\psi_{\rm out}(\mathbf{x})|^2 = \int_{\mathbb{R}^3} d^3p\,|\widetilde{\psi}_{\rm out}(\mathbf{p})|^2 = \frac{1}{4}\left[1 + e^{-\frac{\Delta^2\sigma_p^2}{2\hbar^2}}\cos\left(\frac{\mathbf{p}_0\cdot\boldsymbol{\Delta}}{\hbar}\right)\right]$$

I measured quantity as a function of $\boldsymbol{\Delta}$

Interference pattern lost if $\frac{\Delta^2\sigma_p^2}{2\hbar^2} \gg 1 \Leftrightarrow \frac{\Delta^2}{\sigma_x^2} \gg 1$

Loss of interference pattern

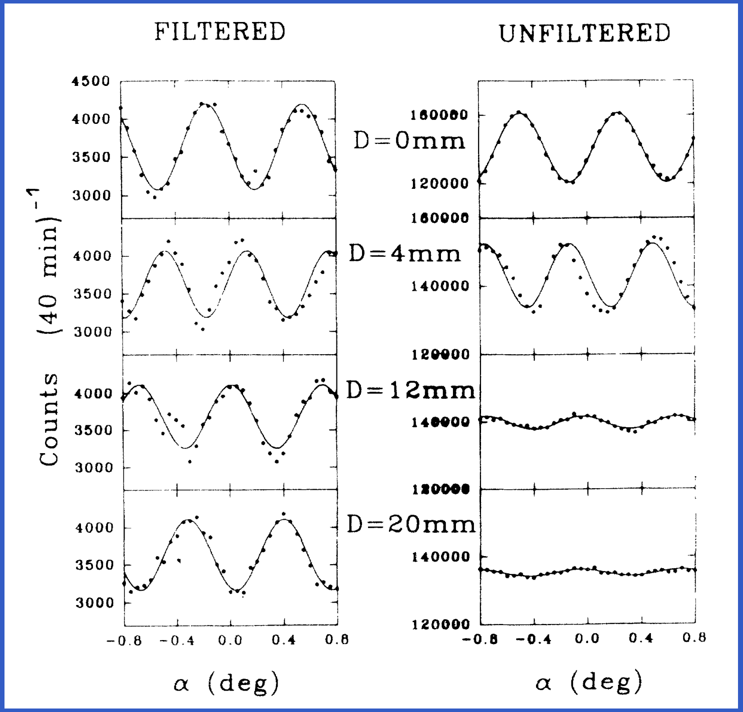




- With increasing relative phase the interference pattern is more and more suppressed

- $$I_{\rm osc} \propto e^{-\frac{\Delta^2 \sigma_p^2}{2\hbar^2}} \cos\left(\frac{\mathbf{p}_0 \cdot \mathbf{\Delta}}{\hbar}\right)$$

Recover of interference pattern



- $I_{\text{osc}} \propto e^{-\frac{\Delta^2 \sigma_p^2}{2\hbar^2}} \cos\left(\frac{\mathbf{p}_0 \cdot \boldsymbol{\Delta}}{\hbar}\right)$
- By momentum selection σ_p is decreased and the interference pattern is recovered
- Obvious reduction of average countings

Interference: x versus p □

- $I_{\rm osc} \propto e^{-\frac{1}{8}\frac{\Delta^2}{\sigma_x^2}} \cos\left(\frac{\mathbf{p}_0\cdot\boldsymbol{\Delta}}{\hbar}\right)$
  versus
  $I_{\rm osc}(\mathbf{p}) \propto e^{-\frac{1}{2\sigma_p^2}(\mathbf{p}-\mathbf{p}_0)^2} \cos\left(\frac{\mathbf{p}\cdot\boldsymbol{\Delta}}{\hbar}\right)$

- setting $\chi = \frac{\Delta}{\hbar} = \frac{2\pi\hbar^2}{p_0^2}\rho b \mathbf{l}_{\rm Al}$
  one has
  $I_{\rm osc} \propto e^{-\frac{1}{8}\frac{\Delta^2}{\sigma_x^2}} \cos\left(\chi p_0\right)$
  versus
  $I_{\rm osc}(\mathbf{p}) \propto e^{-\frac{1}{2\sigma_p^2}(\mathbf{p}-\mathbf{p}_0)^2} \cos\left(\chi p_0 \frac{p_0}{p}\right)$

- The spectrum of outgoing neutrons is measured

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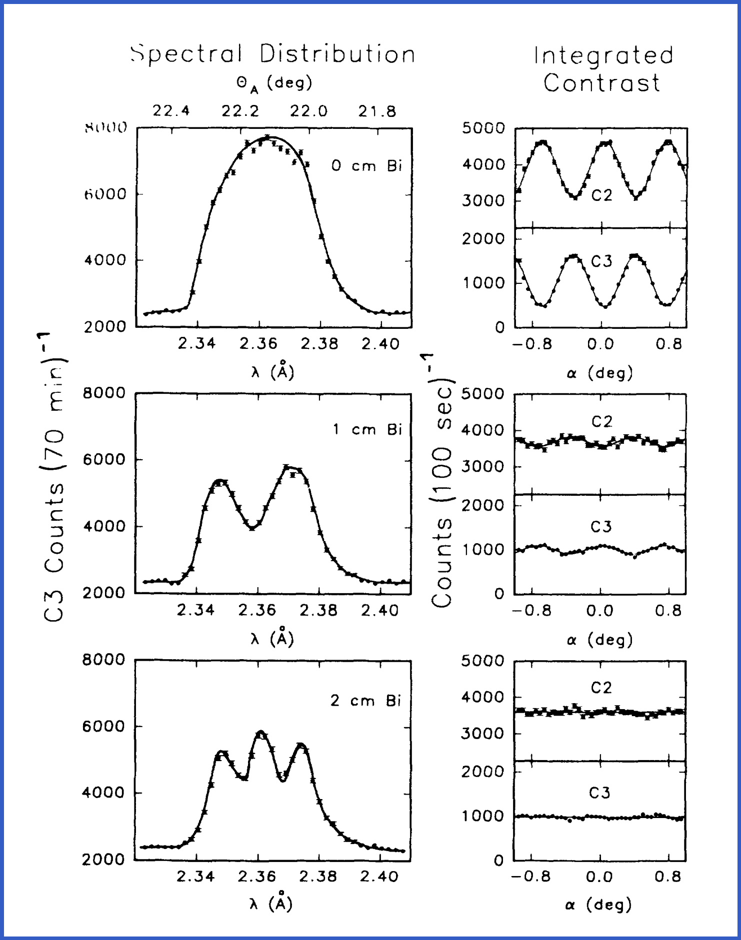

Absorption in one path: *amplitude* versus *probability*

Sample of absorbing material in one path:

$$\psi_{\rm out}(\mathbf{x}) = \frac{1}{2}\frac{1}{\sqrt{2}}\left[\psi_{\rm in}(\mathbf{x}) + \sqrt{a}\psi_{\rm in}(\mathbf{x} - \boldsymbol{\Delta})\right]$$

a transmission probability, $a = |e^{-\sigma_{\rm abs} n l}|^2$, $0 \leq a \leq 1$

$$I = \frac{1}{8}\left[1 + a + 2\sqrt{a}e^{-\frac{\Delta^2 \sigma_p^2}{2\hbar^2}} \cos\left(\frac{\mathbf{p}_0 \cdot \boldsymbol{\Delta}}{\hbar}\right)\right]$$

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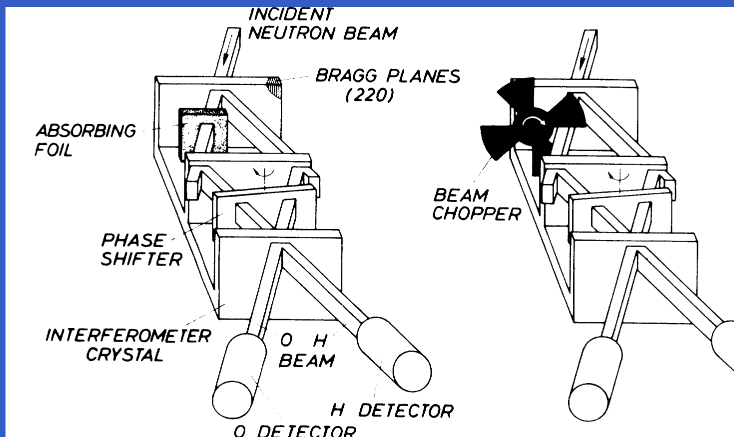
Turning sawtooth wheel of absorbing material in one path:

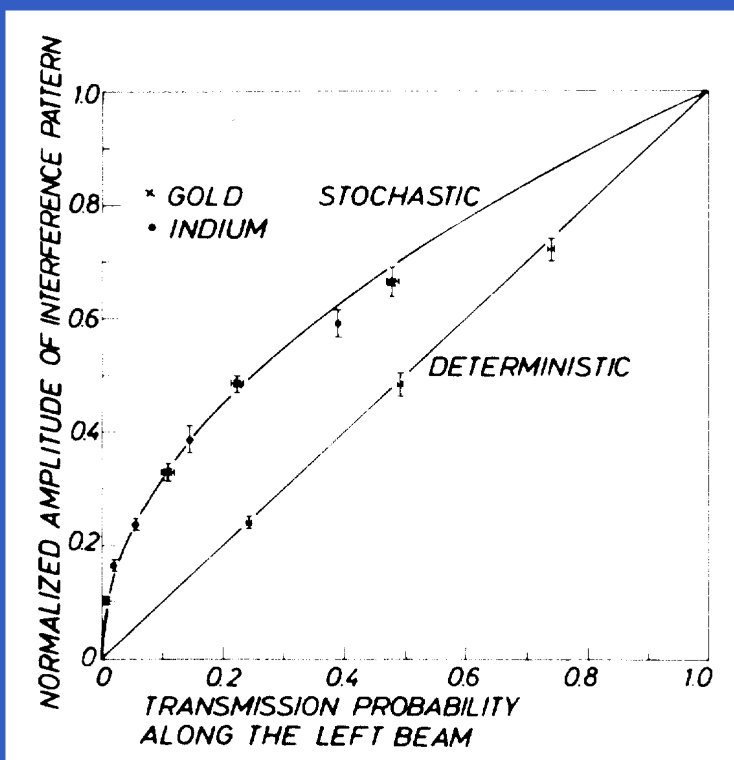
a transmission probability, $a = \frac{t_{\rm open}}{t_{\rm open}+t_{\rm close}}$, $0 \le a \le 1$

$$I = a\frac{1}{4}\int_{\mathbb{R}^3} d^3x \left|\frac{1}{\sqrt{2}}\left[\psi_{\rm in}(\mathbf{x}) + \psi_{\rm in}(\mathbf{x}-\mathbf{\Delta})\right]\right|^2 + (1-a)\frac{1}{4}\int_{\mathbb{R}^3} d^3x \left|\psi_{\rm in}(\mathbf{x})\right|^2$$

$$= \frac{1}{8}\left[1 + a + 2a e^{-\frac{\Delta^2\sigma_p^2}{2\hbar^2}} \cos\left(\frac{\mathbf{p}_0\cdot\mathbf{\Delta}}{\hbar}\right)\right]$$

Experimental results





- Experiments performed with different absorbers
- Experiment feasible due to the macroscopic separation between the paths
- Different visibility of the interference pattern despite the same number of detected neutrons
- Complementary informations:
  path knowledge or fringes visibility

Light versus *matter*

Optics:

optical elements made up of matter

(slits, gratings, mirrors, dispersive materials)

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Matter optics:

optical elements realized through external fields, due to interaction with both matter and electromagnetic waves

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Matter optics:

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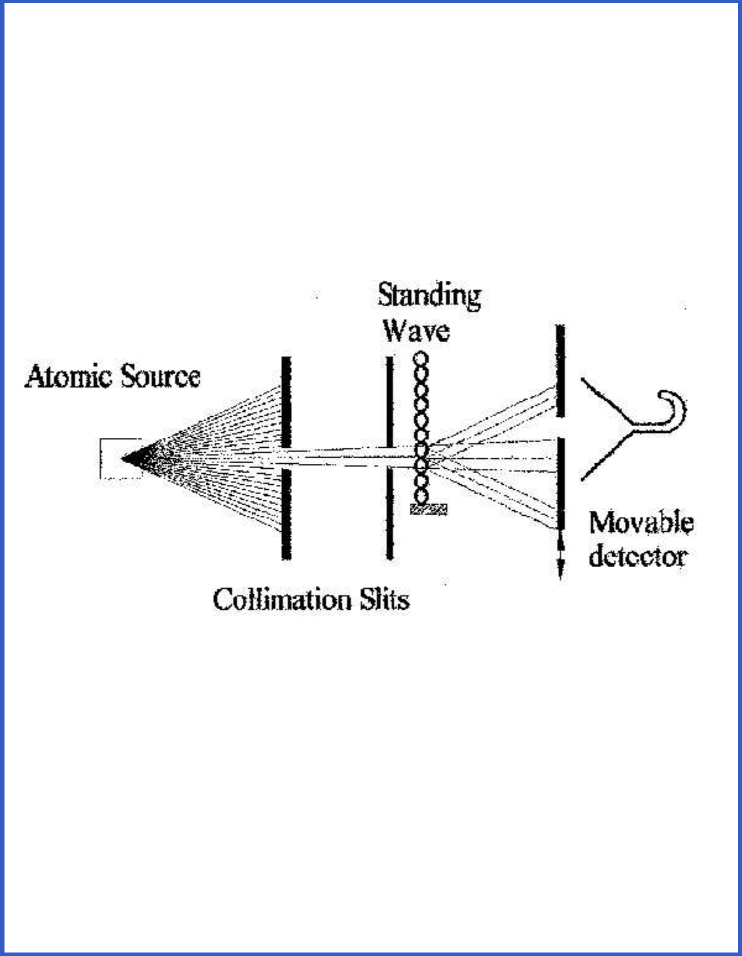
Kapitza–Dirac effect:

diffraction of matter by light gratings, stationary electromagnetic wave

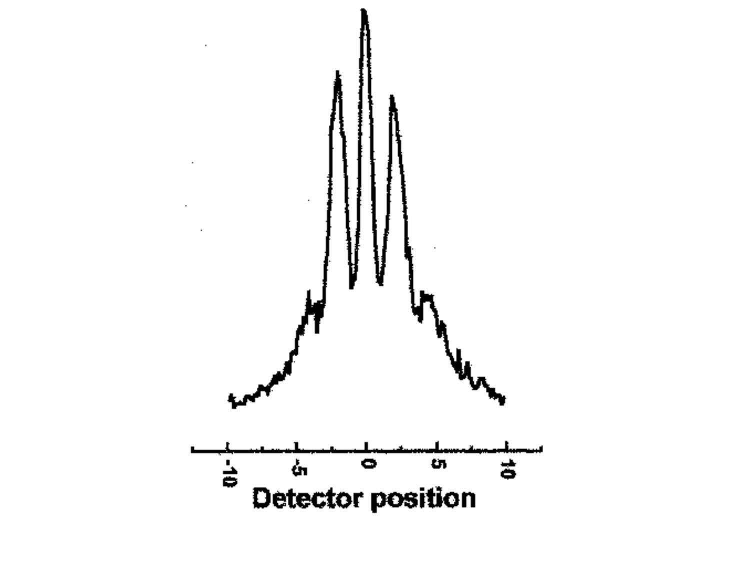
obtaining through two counterpropagating laser beams

Atom optics I



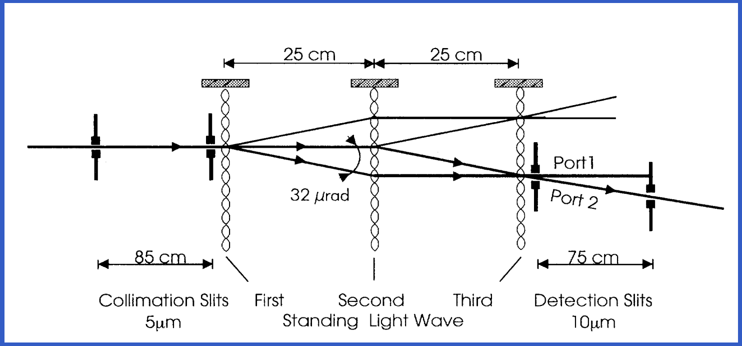
- Diffraction by a light grating
- Sodium atoms
- Source: high temperature oven
- Phase: dipole interaction with the electric field of the stationary wave
- Values: $m \approx 10^{-23}\mathrm{g} \quad \lambda_{\mathrm{dB}} \approx 20\mathrm{pm}$
- Single particle experiment

Experimental results



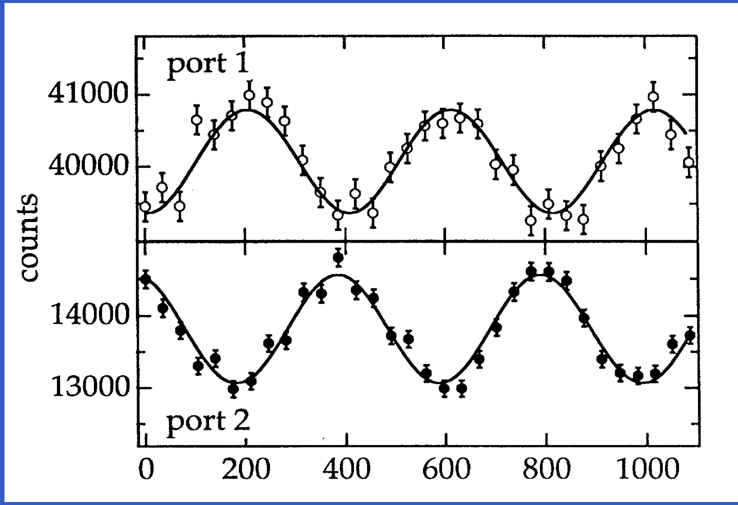
- Similar experiments performed with matter gratings
- Realization of the Kapitza–Dirac effect
- Complex description of light matter interaction:
  correlation between internal and translational degrees of freedom

Atom optics II



- Mach-Zender interferometer realized with light gratings
- Argon atoms
- Source: high temperature oven
- Phase: dipole interaction with the electric field of the stationary wave
- Values: $m \approx 10^{-23}\mathrm{g} \quad \lambda_{\mathrm{dB}} \approx 12\mathrm{pm}$

Experimental results



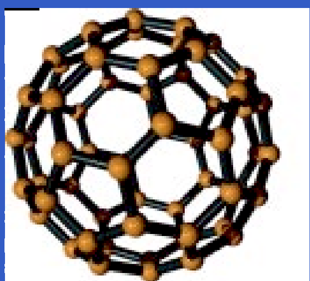
- Real spatial separation between the two paths of the interferometer
- Higher accuracy in the determination of the grating period with respect to material gratings
- Similar experiments performed with fullerene molecules

Atom interferometry

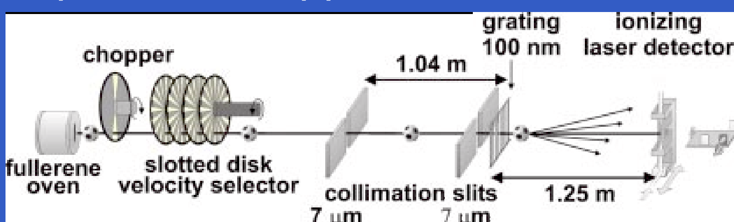
- Wide variety of atom species, with many internal degrees of freedom (addressable through interaction with electromagnetic fields)
- Higher measurement accuracy: $\lambda_{\mathrm{light}} \gg \lambda_{\mathrm{dB}}$ ($\mathrm{pm} \ldots \mu\mathrm{m}$, room temperature $\ldots$ laser cooling)
- Sensitivity to gravitational effects
- Cheap sources
- Efficient detectors

Molecular optics

Fullerene molecule C_{60}



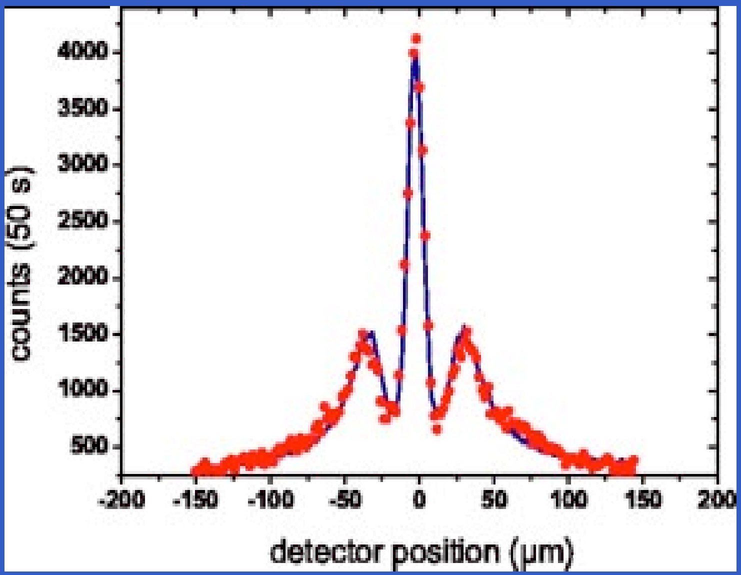
Experimental apparatus



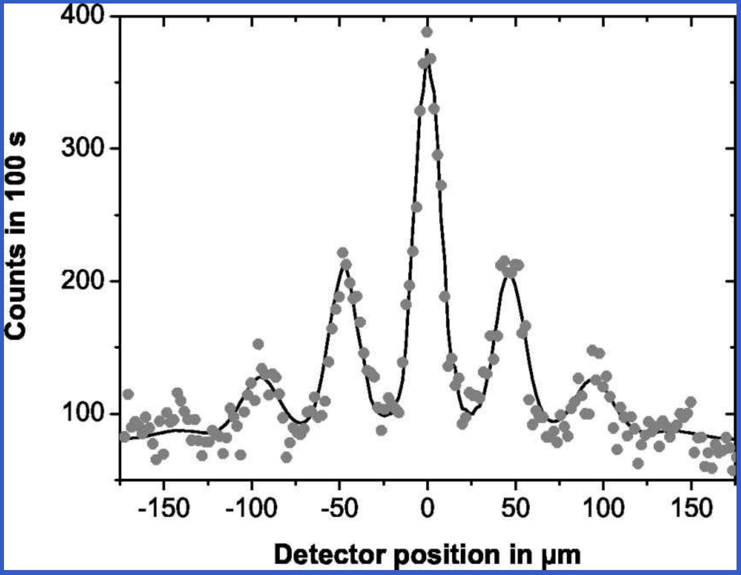
- Diffraction by a material grating
- Fullerene molecules: C_{60} e C_{70}
- Source: high temperature oven
- Values: $m \approx 10^{-21}\mathrm{g} \quad \lambda_{\mathrm{dB}} \approx 3\mathrm{pm}$
- Single particle experiment

Experimental results

$\Delta v/v \approx 60\%$

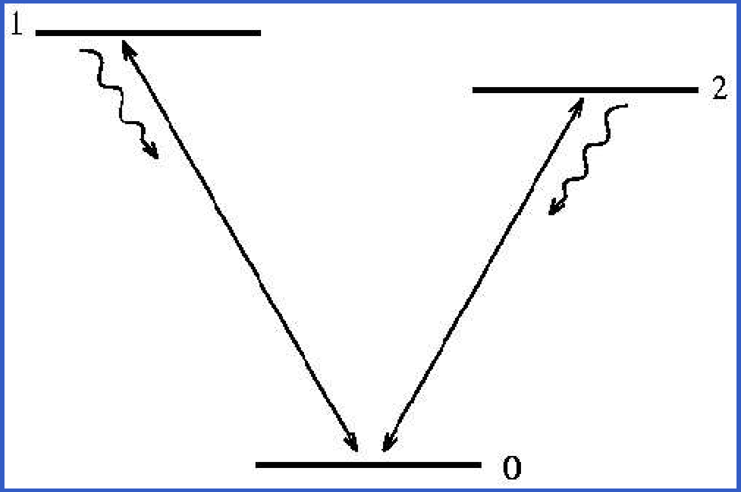


$\Delta v/v \approx 17\%$



- Most massive objects considered up to now
- Very complex internal structure
- Study of the transition between quantum and classical regime

Paul ion trap



- Ion in an electromagnetic trap stored and cooled with laser techniques
- 3 level system, coupled to 2 lasers
- $\tau_1 \ll \tau_2$ strong and weak transition
- Monitoring in time of the strong transition fluorescence

Shelving effect

- Single trapped ion
- Intermittent fluorescence
- Bohr jumps
- Shelving effect

Shelving effect

- Single trapped ion
- Intermittent fluorescence
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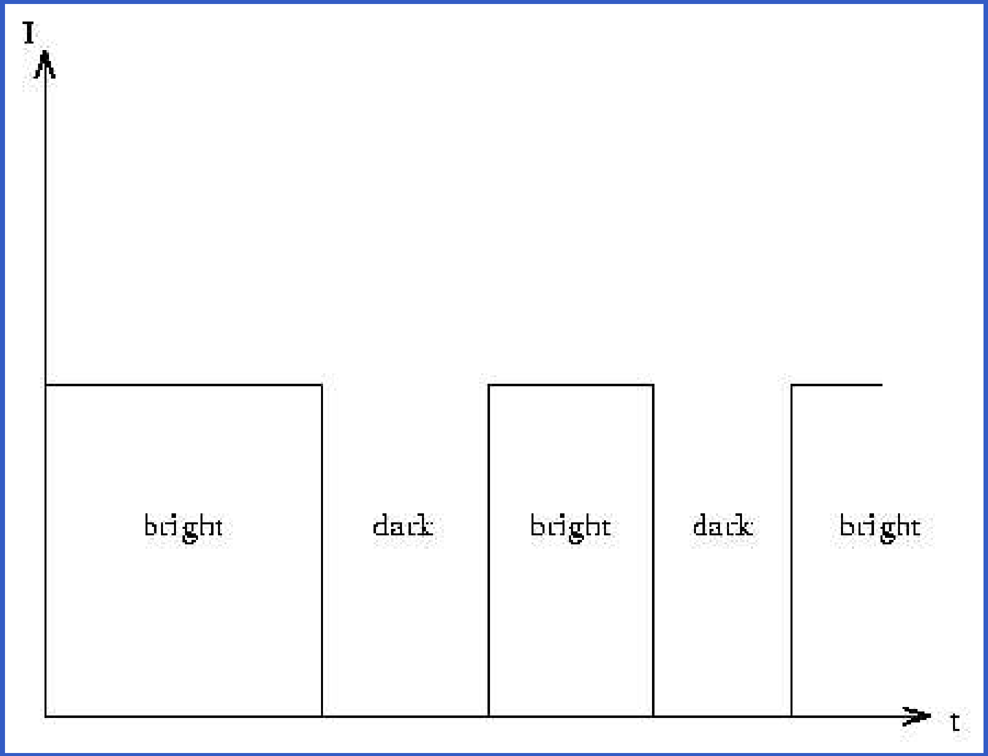
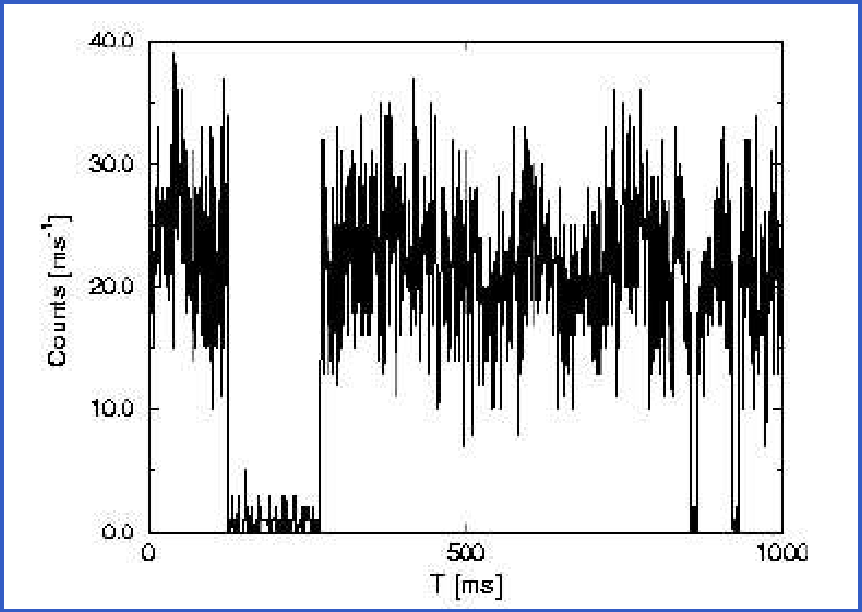


Experimental observation



- Effect observed with different atoms
- Amplification scheme for the weak transition
- Precision spectroscopy
- Telegraphic signal observed in time

Theory

- Quantum description
- Intertime law for the countings $p(t)$:
  probability density to detect the next photon at time t given a counting at time $t = 0$

$$p(t) \approx Ae^{-\frac{t}{\tau_L}} + Be^{-\frac{t}{\tau_B}} \qquad \tau_B \ll \tau_L$$

$$\bar{T}(\text{fluorescence}) = \tau_B \bar{N} \qquad \bar{T}(\text{dark}) = \tau_L$$

- Description of counting statistics
- System evolution conditioned upon the performed measurements

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