Atom Interferometry: Matter Waves & Precision Measurements

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What is Interferometry?

Interferometry ⇔ Experimental Techniques

Applications:

- Astronomical Observations
- Test Optical Components
- Quantum Physics
- Metrology, ...

Subfamilies:

Ordinary Interferometry

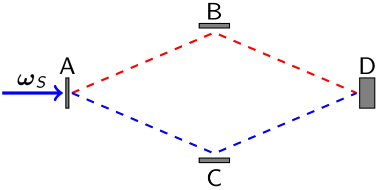
- **Light Beams**
  (LASER beams)

Matter-wave Interferometry

- Electrons
- Neutrons
- **Atoms** & Molecules

Interferometers

Mach-Zender Configuration



$\Gamma_B = A \rightarrow B \rightarrow D$
$\Gamma_C = A \rightarrow C \rightarrow D$

A	"Beam-Splitter"
B,C	"Mirror"
D	"Detector"

Experimental Routine:

1. $\psi_S(\mathbf{x},t) = Ae^{i(\varphi(\mathbf{x})-\omega_S t)}$ with Intensity equal to $I_S = |A|^2$
2. $\psi_S(\mathbf{x},t) \rightarrow \psi_B(\mathbf{x},t) + \psi_C(\mathbf{x},t)$ $(I_B = I_C = I_S/2)$
3. Time Evolution along Γ_B and Γ_C
4. Recombination:

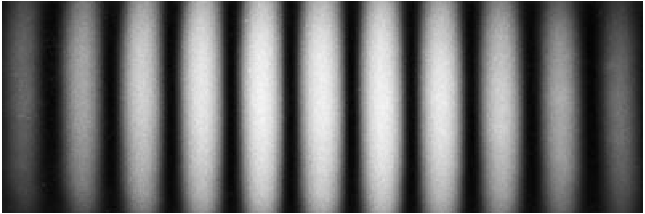
$$I(\mathbf{x}) = I_S\left[1 + \cos(\Delta\varphi_{(B,C)}(\mathbf{x}))\right]$$

being $\Delta\varphi_{(B,C)}(\mathbf{x}) = \varphi_B - \varphi_C$.

Interferometers & Spectral Analysis

$$\textbf{Complex Signal} \iff \{\mathbf{k}_S, I_S\}$$

Interference Pattern



(http://minerva.union.edu/jonesc/Photos Scientific.html)

$$I(\mathbf{x}) = I_S \left[1 + \cos(\Delta\varphi^{GEO}_{(B,C)}(\mathbf{x})) \right] ,$$

Position of maxima: $\mathbf{k}_S$, **Height of Maxima:** I_S

Interferometers & Interactions

$$I(\mathbf{x}) = I_S\left[1 + \cos(\Delta\varphi_{(B,C)}(\mathbf{x}))\right]$$

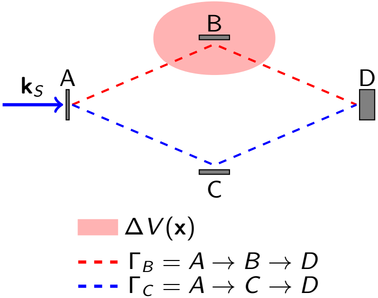
Wave propagation & Media

In this case:

- well-known source $\mathbf{k}_S$

Different Potentials

- Γ_B: $V(\mathbf{x}) + \Delta V(\mathbf{x})$
- Γ_C: $V(\mathbf{x})$



$$\Delta\varphi_{(B,C)}(\mathbf{x}) = \Delta\varphi^{GEO}_{(B,C)}(\mathbf{x}) + \Delta\varphi^{INT}_{(B,C)}$$

Ordinary Interferometry & Atom Interferometry

Atoms Vs Photons

Atoms are extremely sensitive objects (if compared with Photons):

- Electromagnetic fields (**Stark Effect**, **Zeeman Effect**, etc)
- they interact with each other (**Interatomic Potentials**)
- Inertial Effects (**Gravitational Effects**, **Rotations**)

Atomic Properties + **Principles of Interferometry** = **Atom Interferometry**

Bad News...

Louis de Broglie

Wave-Particle Duality Principle:

$$\lambda_{dB} = \frac{h}{p}$$

Atoms do not behave as plane-waves:

- **Wave-Packets**
- $\Delta \mathbf{p} \leftrightarrow k_B T$

Visibility of Fringes $\Leftrightarrow \zeta$

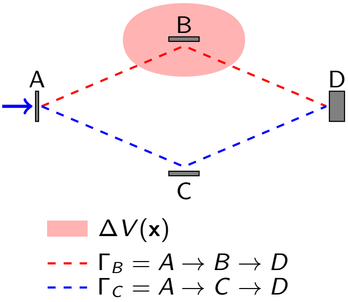
being $\zeta =$ **Coherence Length**

$$\zeta = \frac{h}{\Delta \mathbf{p}}$$

Feynman Path-Integral:
Interactions & Phase Differences

Interactions & Phase Differences

(P.Storey, C.Cohen-Tannoudji -Journal de Physique II, EDP Sciences, 1994)



The time-evolution along the two paths is modified by the presence of the **weak local potential** $\Delta V(\mathbf{x})$:

- Γ_B Interacting Particle
- Γ_C Free Particle

$\Delta V(\mathbf{x})$ affects the transition amplitude!

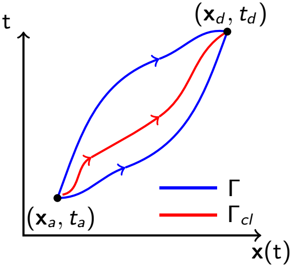
$$\psi(\mathbf{x}_d,\, t_d) = \langle \mathbf{x}_d | U(t_d,\, t_a) | \psi(t_a) \rangle =$$

$$= \int_{-\infty}^{+\infty} d\mathbf{x}_a K(\mathbf{x}_d,\, t_b;\, \mathbf{x}_a,\, t_a) \psi(\mathbf{x}_a,\, t_a)$$

$$\boxed{K(\mathbf{x}_d,\, t_d;\, \mathbf{x}_a,\, t_a) = \langle \mathbf{x}_d | U(t_d,\, t_a) | \mathbf{x}_a \rangle = \textbf{Quantum-Propagator}}$$

Amplitudes & Path-Integral Formalism:

$$K(\mathbf{x}_d,\ t_d;\ \mathbf{x}_a,\ t_a) = \mathcal{N}\sum_{\Gamma} \exp(iS_\Gamma/\hbar)$$



where

$$S_\Gamma = \int_{t_a}^{t_d} \mathrm{d}t\mathcal{L}[\mathbf{x}(t),\, \dot{\mathbf{x}}(t)], \quad \mathcal{L} = \frac{1}{2}M\dot{\mathbf{x}}^2 - V(\mathbf{x})$$

Interesting Result for Plane-Waves

If $S_\Gamma \gg \hbar$ and $\mathcal{L}$ is a quadratic function of $\mathbf{x}$ and $\dot{\mathbf{x}}$:

$$\boxed{\psi(\mathbf{x}_d,\ t_d) \propto \exp\left[iS_{cl}(\mathbf{x}_d,\ t_d;\ \mathbf{x}_a,\ t_a)/\hbar\right]\psi(\mathbf{x}_a,\ t_a)}$$

Therefore:

$$\boxed{\Delta\varphi^{INT}_{(B,C)} = \Delta S/\hbar = (S^{int}_{cl,B} - S^{free}_{cl,C})/\hbar \approx -\frac{1}{2}k_0\int \mathrm{d}\mathbf{x}\frac{\Delta V(\mathbf{x})}{E_0}}$$

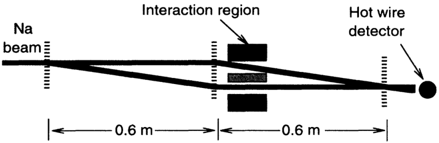
Experimental Results

Measurement of the electric polarizability of sodium with an atom interferometer

(C.R.Ekstrom, J.Schmiedmayer, M.S.Chapman, T.D.Hammond,D.E.Pritchard-1995 Phys. Rev. A 51, 3883)

$$V(\mathbf{x}) = -\frac{1}{2}\alpha\mathbf{E}^2(\mathbf{x}) \Longrightarrow \Delta\varphi^{INT}_{(B,C)} = \frac{1}{\hbar v}\int d\mathbf{x}\frac{1}{2}\alpha\mathbf{E}^2(\mathbf{x})$$

Experimetal Apparatus



- Three Diffraction Gratings
- Mach-Zender Configuration

Applications

Knowledge of the **ground-state polarizability** α:

- Dielectric Constant
- Index of Refraction
- van der Walls Int.
- Excited States Properties

What else can we measure?

Magnetic-Effects & Contrast Interferometry

$$\Delta V(\mathbf{x}) = -\boldsymbol{\mu} \cdot \Delta \mathbf{B}(\mathbf{x}) \Longrightarrow \Delta \varphi^{INT}_{(B,C)} = \frac{1}{\hbar v} \int \mathrm{d}\mathbf{x} g_F \mu_B m_F \Delta \mathbf{B}(\mathbf{x})$$

Hyperfine Sublevels in Na g.s. $\Longleftrightarrow$ Collapse and Revivals in Fringes

(J.Schmiedmayer, C.R.Ekstrom, M.S.Chapman, T.D.Hammond,D.E.Pritchard-1994 J. Phys. II France 4, 2029)

Index of Refraction of Gases

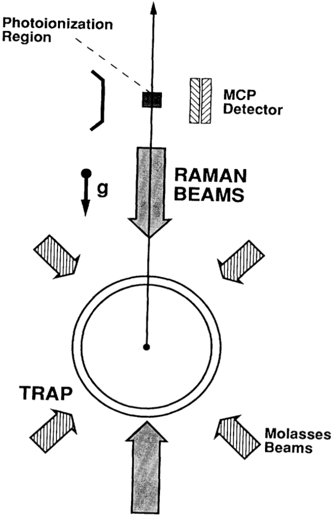
$$\Delta \varphi^{INT}_{(B,C)} \propto \mathrm{Re}\left[f(k,0)\right] / \mathrm{Im}\left[f(k,0)\right]$$

f = Scattering Amplitude $\Leftrightarrow$ V = Interatomic Potential

(J.Schmiedmayer, M.S.Chapman, C.R.Ekstrom, T.D.Hammond, S.Wehinger, D.E.Pritchard-1995 PhysRevLett.74.1043)

Atom Interferometry & Gravitational Interactions

(M. Kasevich and S. Chu 1991-PhysRevLett.67.181)



Na Gravimeter

Levels involved:

$$\mathbf{F} = 1, \mathbf{m}_F = 0$$

$$\mathbf{F} = 2, \mathbf{m}_F = 0$$

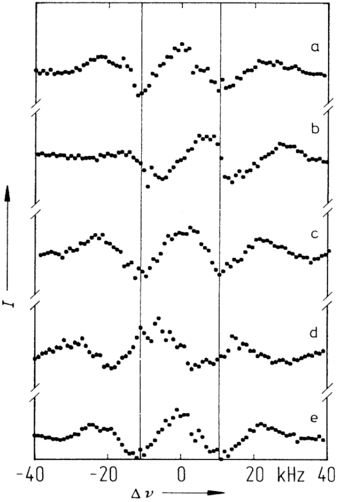
1 Loading in a MOT
2 Launch & Optical Pump. (**F**=1)
3 Raman Pulses $(\pi/2 - \pi - \pi/2)$
4 Detection of atoms in **F**=2 (photoionization)

$$\boxed{\Delta\varphi^{INT}_{(B,C)} = \mathbf{k}_{eff} \cdot \mathbf{g}\, T^2}$$

Left: schematic representation of the experiment

Atom Interferometry & Rotations

(F.Riehle,Th.Kisters,A.Witte,J.Helmcke,Ch.J.Bordé 1991-PhysRevLett.67.177)



Ramsey Interferometry

- ^{40}Ca transition: $^3P_1 \leftrightarrow ^1S_0$
- 4 Light beams $(\omega_L, \pm\mathbf{k}_L)$
- $\mathbf{k}_{AT} + \mathbf{k}_L =$ **Plane**
- $\boldsymbol{\Omega} \perp$ **Plane** $\leftrightarrow$ **Shift in Fringes**

They scan the frequency domain

$$\Delta\varphi^{INT}_{(B,C)} = 2\Omega v T^2 |\mathbf{k}_{eff}|$$

Left: Frequency shift in Ramsey Fringes due to Rotations of the apparatus. (**a**,**c**,**e**: $\boldsymbol{\Omega} = 0$; **b**,**d**: $\boldsymbol{\Omega} = \pm 0.09 s^{-1}$)

Conclusions

- **Atom Interferometry** is a powerful Investigative Tool.
- **Interactions** lead to additional **Phase Differences** in Interference Patterns
- Theoretical Calculation (**Feynman Path-Integral**)
- Experimental Results (**Interferometry**)