Coherence of Photons in Disordered Media

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Quantum Engineering with Photons, Atoms and Molecules
Les Houches, February 14-17, 2005
Wave propagation in random media

Mesoscopic regime:
Interferences alter diffusion process

Propagation of light waves
/
Propagation of matter waves
Photonic crystals

Interferences in 1D, 2D and 3D
Energy bandgaps
Localized modes

much more on http://ab-initio.mit.edu/

Anderson localization in random media

Random equivalent of photonic crystals

Coherent transport:
in 1D and 2D: localization for any disorder
in 3D: threshold for localization?
Random walk:

**Diffusion coefficient**

\[ D_0 \approx \frac{l^2}{\tau} \]

Photons ...

... are waves

**Interference correction to Diffusion coefficient**

\[ D \approx D_0 \left(1 - \frac{3}{k \ell}\right) \]

**Strong Localization** \((D=0)\):

Ioffe-Regel criterium:

\[ k \ell \approx 1 \]

(on resonance \( n_{at} \approx 10^{14} \text{ at/cm}^3 \))
Interference of waves propagating along closed loops?

‘random cavities’ : ‘precursor’ modes?

⇒ random laser
Scattering Experiments

* coherent transmission, diffuse transmission / reflection

* far field analysis
Interferences and speckle

\[ \mathbf{E} = \sum_{i=1}^{N} \mathbf{E}_i \]

fixed scatterers : speckle pattern

configuration average

scattered intensity

\( \theta \)
Integrated signal (configuration average)
Configuration Averaged Intensity

- uncorrelated paths add incoherently

- correlated (i.e. reciprocal) paths add coherently

\[ \Delta \varphi = (k_{in} + k_{out}) \cdot (r_{in} - r_{out}) \]
\[ \theta = 0 \implies \Delta \varphi = 0 \text{ for any path} \]

Coherent Backscattering
\[ \frac{<I(0)>}{<I(\theta)>} = 2 \]
Experimentel Setup

cooled CCD

lens ($f=500\text{mm}$)

beamsplitter

scattering medium

laser beam
Coherent backscattering

- **cone with**: $\Delta \theta = 2\pi \frac{\lambda}{\ell_{\text{scat}}}$

- **cone height**: reciprocal amplitudes (phase, intensity)

Young double slits / self-aligned multiple Sagnac interferometer
Light waves:
white paint (TiO$_2$), teflon, milk, paper, tissue rings of Saturn

Acoustic waves:
metal rods
fish (?)

Matter waves:
electrons: negative magneto-resistance

Seismic waves:
Why cold atoms?

- spontaneous emission:
  \[ \Rightarrow \] coherent process?
  \[ \Rightarrow \] role of quantum fluctuations?

- resonant scattering:
  \[ \delta = \omega_{\text{las}} - \omega_{\text{at}} \]
  \[ \Gamma/2\pi = 6 \text{ MHz} \]
  \[ \lambda = 780\text{ nm} \]
  \[ \Rightarrow \] quality factor \( \sim 10^8 \)
  \[ \Rightarrow \] ‘monodisperse’ sample: cold atoms
  \[ \Rightarrow \] ‘delay time’ at resonance: \( \tau_d \sim 50\text{ ns} \)

- \[ \Rightarrow \] matter waves
Magneto-optical trap (MOT)

$6$ independent laser beams

$w = 3 \text{ cm}$

$P = 30 \text{ mW}$

$\{\text{MOT from background}\}$

Magnet field gradient : $10-20 \text{ G/cm}$

$N_{at} \approx 10^{10}$

$b \approx 40$
Probing and manipulating the coherence of photons in disordered systems

- scattering effect (cross section) vs propagation effect (index of refraction)
- time dependant / dynamic analysis
- interference contrast: amplitude vs phase effect (geometrical phase compensated)

\[ E_I e^{i\phi_I} + E_{II} e^{i\phi_{II}} \]
- coherence length
Influence of internal structure

**Amplitude effect**: an example:
Rayleigh scattering on $J = 1/2 \rightarrow J' = 1/2$

- **Direct path**: amplitude $E_1 \neq 0$
- **Reverse path**: amplitude $E_1 = 0$

Degenerated ground state: $\Rightarrow$ reduced contrast!
2 MOT in Nice

Rubidium (F=3 → F’=4)
- vapor trap: optical thickness: 40

Strontium (J=0 → J’=1)
- Zeeman slower: optical thickness: 3
Influence of internal structure

Sr$^{88}$ : $J=0 - J'=1$
Rb$^{85}$ : $F=3 - F'=4$

Enhancement factor vs. angle (mrad) for Sr and Rb.
Restoring Coherent Backscattering with Magnetic Fields

Restoring Coherence Length with Magnetic Fields

\[ \mu B \gg \Gamma \] effective 2 level system

Coherence length:
- REDUCED by internal structure (3-4')
- RESTORED by magnetic field
negative magneto-resistance

increased weak localization:

magnetic impurities + magnetic field

FIG. 2. Resistance changes as a function of the magnetic field for the wires of $n$-Cd$_{1-x}$Mn$_x$Te with $x = 0$ (a) and $x = 1$% (b) at various temperatures between 30 mK and 4.2 K (traces for the lowest temperatures are shifted upward). Dashed lines represent magnetoresistance calculated in the framework of 3D weak-localization theory [4,11]. Dotted lines are guides for the eye, and visualize a strong temperature dependence of the resistance features in Cd$_{0.99}$Mn$_{0.01}$Te (b).

### Time Resolved Experiments:

- **Phase velocity**: \( c = \frac{c_0}{n} \) propagation of phase for a monochromatic wave
  \[ c > 0 \quad c \gtrless c_0 \]

- **Group velocity**: \( v_g = \frac{\partial \omega}{\partial k} \) propagation of transmitted gaussian pulse
  - cold atoms on resonance: \( v_g < 0 \quad |v_g| << 0 \)

- **Transport velocity**: propagation of scattered wave energy \( 0 < v_{tr} < c_0 \)

\[ \tau_{\text{Wigner}} \quad \frac{L}{v_g} \]
### Time Resolved Experiments: Radiation Trapping

**Radiation Trapping**

**Diffusion Theory**

\[
D = \frac{1}{3} \frac{l_{tr}^2}{\tau_{tr}} = \frac{1}{3} l_{tr} v_{tr}
\]

- **Transport Mean-Free Path**
- **Transport Time**
- **Transport Velocity**

**Fundamental (Holstein) Mode**

\[
\tau_0 \approx \frac{L^2}{\pi^2 D} = \frac{3}{\pi^2} b^2 \tau_{tr}
\]

\[
b = \frac{L}{l} \quad \text{Optical Thickness}
\]
Slow Diffusion of Light

\[ t_0 \approx \frac{L^2}{\pi^2 D} \Rightarrow D \approx 0.66 \text{m}^2/\text{s} \]

for \( b = 34 : t_0 \approx 52 \tau_{\text{nat}} \quad L = 4 \text{mm} \)

NO interference effect!
≠ Localization

Slow transport of Light

\[ I_{\text{in}}(t) \propto e^{-t/\tau_0} \]

\[ I_{\text{sc}}(t) \]

\[ \delta/\Gamma \]

\[ \frac{V_{\text{tr}}}{c_0} = \frac{l}{\tau_{\text{tr}}} \approx 3 \cdot 10^{-5} \]

Transport time for light in cold atoms

\[ \tau_0 \approx \frac{L^2}{\pi^2 D} = \frac{3}{\pi^2} b^2 \tau_{tr} \]

Transport Time: Independent of \( \delta \)

\[ \tau_{tr} \approx \tau_{Wigner}(\delta) + \frac{l(\delta)}{v_{gr}(\delta)} \]

scatterer should not move faster than light

A.A. Golubenstev, Sov. JETP 59, 26 (1984)

‘fast’ atomic dynamics vs ‘slow’ light transport

\[ v \tau_{tr} << \lambda \]

at resonance: \[ kv << \Gamma \]
Experimental Observation of Dynamical Breakdown

heating by intense near-resonant optical molasse

- MOT laser
- ∇B
- δMOT repumper
- CBS probe

Experimental Observation of

Dynamical Breakdown

![Graph showing CBS enhancement vs. v_{rms} (m/s)]
Dynamical breakdown of CBS

Doppler effect

\[ \Rightarrow \]

\( \neq \) frequencies

2 contributions:

- scattering:
  
  \[ \text{attenuation: } \sqrt{\sigma} = \frac{1}{\left[1+4(\delta/\Gamma)^2\right]^{1/2}} \]
  
  \[ \text{phase shift: } \phi = \arctan(\Gamma/2\delta) \]

- propagation in effective medium:
  
  \( n = 1 + N\alpha/2 \)
  
  \[ \text{attenuation: } e^{-d/2} \]
  
  \[ \text{phase shift: } \phi = 2\pi.n.d / \lambda_0 \]
Dynamical Breakdown of CBS

large detuning : $\delta >> kv$

$\Rightarrow$ partial restoration of interference contrast

$\Rightarrow$ room temperature CBS possible?
Inelastic light scattering

In localized regime $\Rightarrow$

large build-up factors expected

$\Rightarrow$ saturation of atomic transition

$\Rightarrow$ inelastic scattering : phase coherence ?
Influence of larger saturation on CBS

Inelastic scattering: Mollow triplet ...

Inelastic scattering effects similar to Doppler induced frequency redistribution

Some questions concerning matter wave scattering by light potential

**Light scattering**
- Polarization of light
- Internal structure of atoms
- Electric field: $\partial_t^2 E$
- Resonant point scatterers
- Classical fields / bosons

**Matter wave scattering**
- Internal structure of atoms
- Polarization of light
- Matter wave: $\partial_t \Psi$
- Continuous potential
- Bosons / Fermions
Perspectives

Light scattering

Coherent light transport beyond CBS
⇒ (quantum) statistics
⇒ fluctuations, correlations
⇒ Sagnac interferometer (v_tr/c=10^{-5})
⇒ random laser (+ gain)

Strong Localization: \( n\lambda^3 \approx 1 \)
⇒ dynamical analysis, spectroscopy
⇒ cold collisions & super-/subradiance
⇒ dipole blockade?

Matter wave scattering

Rb: BEC
Sr: ‘red’ MOT
CBS with matter waves
Strong Localization
Current Status of our experiments:

Rb :
⇒ new scaling law : $L \propto \varphi N$ : ✓
⇒ compression : $n\lambda_{\text{opt}}^3 \approx 1$
⇒ random laser (add pump) : 4 wave mixing : ✓
⇒ plasma physics (mechanical effects) : ✓
MOT size with many cold Atoms \[ \Rightarrow \] compression...
Self Sustained Oscillation of MOT size

MOT Loading

MOT fluorescence

loading time (s)

$N_{th}$
Instability: phase diagram

\[ \frac{\delta}{\Gamma} \]

\[ B \text{ [G/cm]} \]
Current Status of our experiments:

**Rb:**
- new scaling law: \(L \propto \sqrt[3]{N} \checkmark\)
- compression: \(n\lambda_{\text{opt}}^3 \approx 1\)
- random laser (add pump): 4 wave mixing: \(\checkmark\)
- plasma physics (mechanical effects): \(\checkmark\)

**Sr:**
- extra heating on blue MOT: \(\checkmark\)
- Red Mot (50% transfer efficiency): \(\checkmark\)
- \(T=1\mu K: (n\lambda_{\text{DB}}^3 \approx 10^{-4}) \checkmark\)
- more cooling and more atoms: \(n\lambda_{\text{opt}}^3 \approx 1\)
- cold collision (blue MOT): \(\checkmark\)
Atom moving across laser profile: additional fluctuations \(\Rightarrow\) heating (correlation time vs friction)

\[ \tau_c = \tau_v \]

\[ \sigma_I / \langle I \rangle = 0.18 \quad \text{and} \quad L_c = 100 \ \mu m, \ v_\perp = 1 m/s \quad \leftrightarrow \quad \tau_c = 100 \ \mu s \]
Broadband Transfer to Red MOT

Transfer Limitation:
- atoms moving out of the laser
- atoms moving out of resonance

Max transfer: 50%!
Sr : Red MOT

Temperature (µK)

\[ \delta = -500 \text{ kHz} \]

\[ \text{phase space density} \Rightarrow \text{temperature} \]

\[ \text{red MOT} \]

\[ \text{blue MOT} \]
Towards strong localization of light

Ioffe-Regel:

Rb

Sr

Dynamical Breakdown

Weak Localization

BEC

Strong Localization

Nice Sr

Nice Rb

n [cm^{-3}]

T [K]