Coherent photon transport in cold atomic clouds

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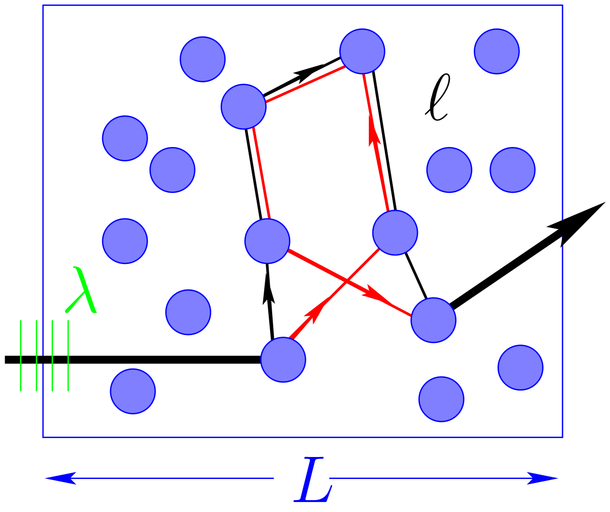
Weak localisation – a tale in space and time

- *Weak localisation* (WL): interference of counterpropagating amplitudes enhances return probability and *reduces* diffusion:

$$D = D_0 - \delta D$$



- Weak scattering, diffusive, mesoscopic regime:

$$\lambda \quad \ll \quad \ell \quad \ll \quad L, l_\phi$$

WL: Measure of phase coherence l_ϕ as function of $B, T, J, \ldots$

- Anderson localisation: absence of diffusion $D = \dfrac{\ell_{\mathrm{tr}} v_{\mathrm{tr}}}{d} \longrightarrow 0$?

Check transport scales in space and time !

$h_{\lambda\mu}$

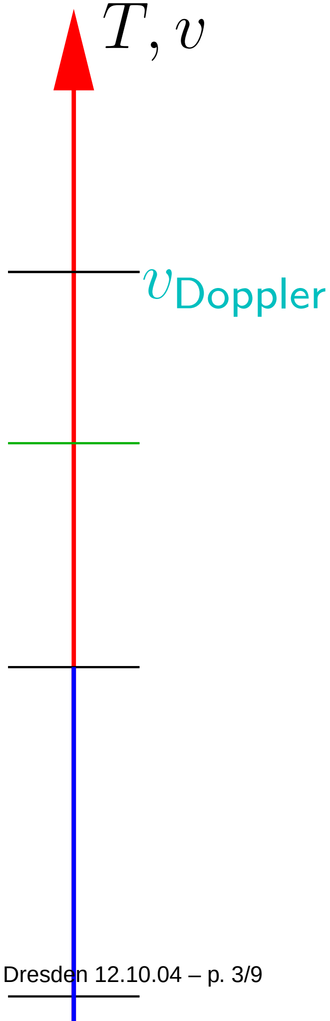
Why light and cold atoms?

- Light scattering by cold atoms:
  - laser: excellent coherence & polarisation control
  - atoms: identical resonant point scatterers
  - photons (almost) don't interact
- Want quenched disorder — need slow atoms: Doppler effect negligible if

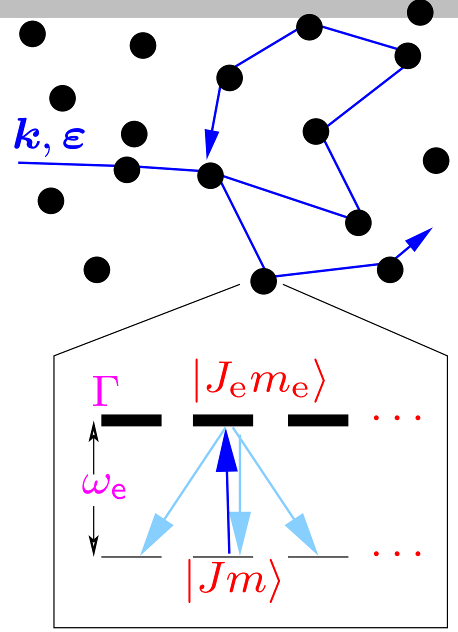
$$v_{\mathrm{rms}} < v_{\mathrm{Doppler}} = \Gamma/k \sim 10\,\mathrm{m/s}$$

- Magneto-optical traps produce up to $N \sim 10^{10}$ atoms with $v_{\mathrm{MOT}} \sim 10\,\mathrm{cm/s}$
- Below recoil velocity $v_{\mathrm{rec}} \sim 1\,\mathrm{mm/s}$: quantum matter waves with $\lambda_{\mathrm{dB}} > \lambda$

Around v_{MOT}: dilute sample of quasi fixed classical point scatterers in $d = 3$.



Atoms are ideal light scatterers because . . .



- Identical point objects ($a_0 \ll \lambda$) with huge scattering cross-section $\sigma_{\text{tot}} = O(\lambda^2)$
- Monodisperse with razor-sharp resonance

$$\omega_e/\Gamma \sim 10^8$$

  $\longrightarrow$ affects transport time τ_{tr}
- Internal degeneracy $J > 0$
  $\longrightarrow$ induces spin-flip physics for photon polarisation $\boldsymbol{\varepsilon}$
- 'Giant' magnetosensitivity (Zeeman effect)
  Enhanced phase coherence with B-field! [see poster I.29 by O. Sigwarth]
- Dipole transition is easily saturated: non-linear physics
  Inelastic multiphoton processes induce dephasing
  [2-photon scattering: see poster II.30 by Th. Wellens]
  [Master eq. approach: V. Shatokhin et al., quant-ph/0409148]

Microscopic photon scattering theory

- Complete matter-light Hamiltonian with dipole interaction
- Ensemble average $\langle \dots \rangle = \mathrm{Tr}\{\rho_{\text{at}}(\dots)\}$
  $\longrightarrow$ effective photon transport theory
- Diagrammatic single-particle transport theory:
  calculate $\langle G \rangle$, $\langle G^\dagger G \rangle$, $\dots$ for dilute medium $n\lambda^3 \ll 1$
  [Vollhardt & Wölfle, PRB (1980), v. Rossum & Nieuwenhuizen, RMP (1999)]
- Amplitude $\langle G \rangle$: Photon self-energy $\longrightarrow$ elastic mean free path ℓ

$$\Sigma = \otimes + \otimes\!\!\textbf{—}\!\!\otimes\!\!\textbf{—}\!\!\otimes\!\!\textbf{—}\!\!\otimes + \dots$$

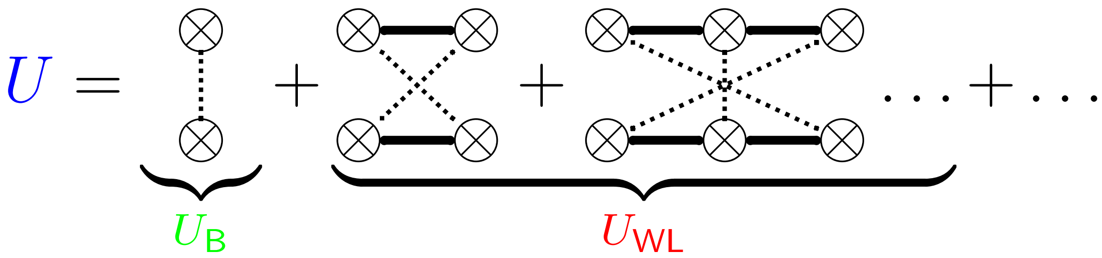
- Intensity $\langle G^\dagger G \rangle$: continuity equation defines resonant transport time $\tau_{\text{tr}} = \ell/c + 1/\Gamma \approx 1/\Gamma$

$\boxed{\text{Localisation time scale } \tau_{\text{tr}} \text{ affected by collective scattering (super-/subradiance) in the dense regime } n\lambda^3 \to 1}$

Transport mean free path

- Linear response: $\dfrac{1}{\ell_{\text{tr}}} = \dfrac{1}{\ell}\Big[1 - \sum_{\boldsymbol{k},\boldsymbol{k}'} SS' U_{\boldsymbol{k},\boldsymbol{k}'} (\hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{k}}')\Big]$

  with Boltzmann scattering and interference corrections:



- U_{WL} is calculated exactly for arbitrary degeneracy $J > 0$.

  [Müller & Miniatura, J. Phys. A (2002)]

- WL reduced by effective dephasing (diffusion approx:)

$$U_{\text{WL}}(q) \approx \sum_{K=0,1,2} \frac{c_K}{Dq^2 + 1/\tau_c(K)}$$

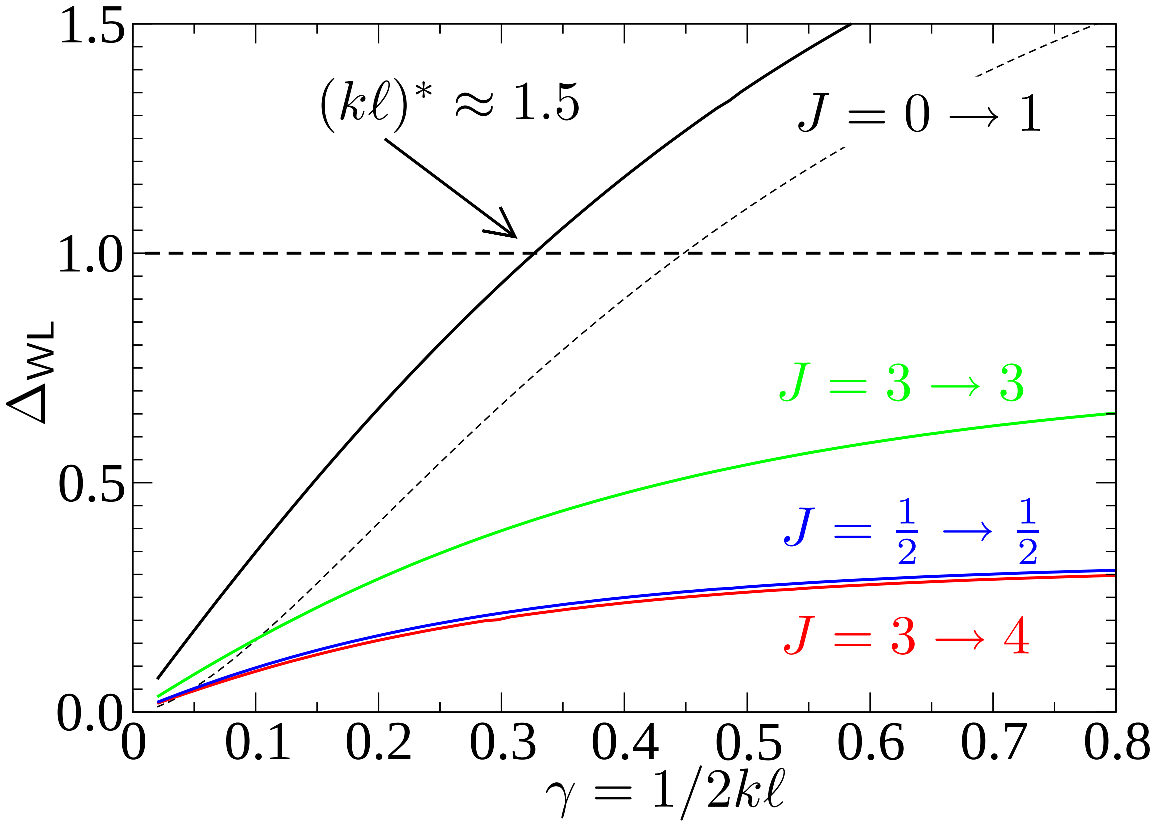
[Akkermans, Miniatura & Müller, cond-mat/0206298]

Absence of localisation with internal degeneracy

- Self-consistent renormalisation of transport m.f.p:

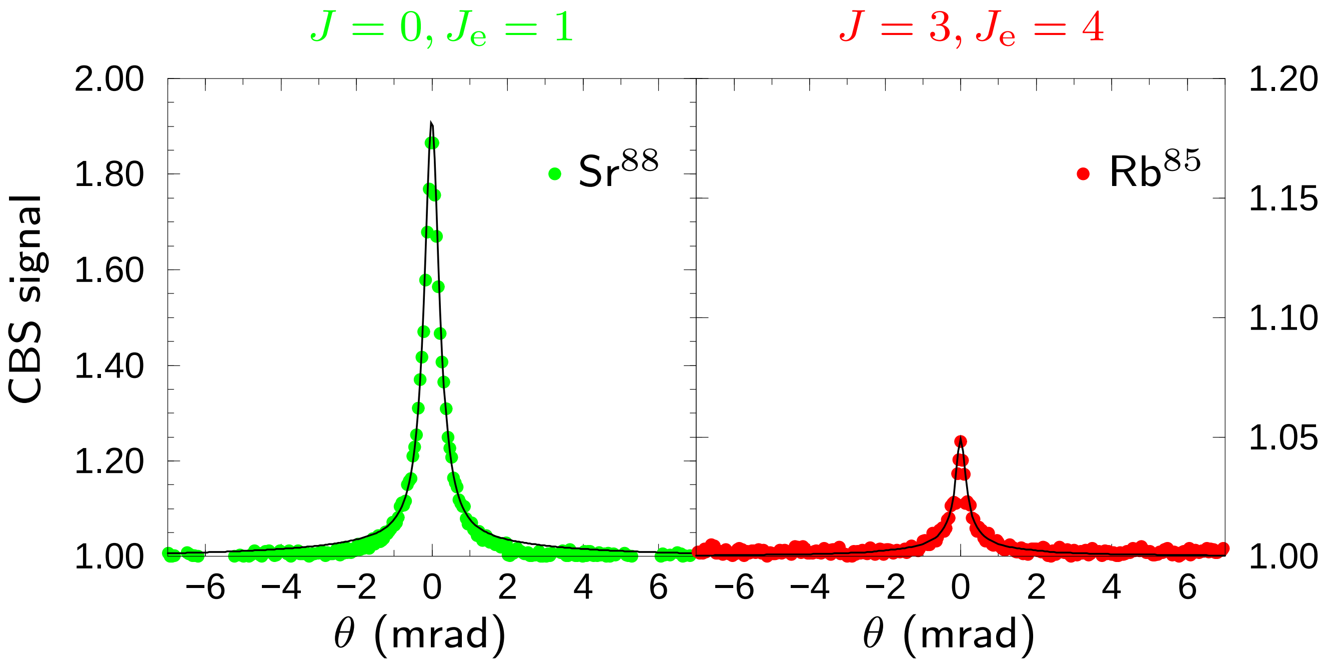
$$\ell_{\mathsf{tr}} = \ell \left[1 - \Delta_{\mathsf{WL}}(k\ell, \tau_c)\right]$$

- Localisation threshold $\Delta_{\mathsf{WL}} = 1$ never reached with $J > 0$!



Experimental signature: coherent backscattering (CBS)

- CBS by atoms without and with internal degeneracy:



[Bidel et al., PRL **88**, 203902 (2002)] [Labeyrie et al., EPL **61**, 327 (2003)]

- Theory: analytic internal degeneracy + MC simulation of photon trajectories [Labeyrie, Delande et al., PRA **67**, 033814 (2003)]
- Recent experiments on residual atomic motion and inelastic scattering: See poster I.25 by G. Labeyrie!

Open questions

- Towards strong localisation of photons in a gas of ‘immobile’ atoms: Self-consistent perturbation (Ward identities, etc.) in strongly disordered limit $n\lambda^3 \to 1$
- Include external degrees of freedom (Recoil, Doppler, quantum statistics, . . .)
- Saturation becomes unavoidable at high density: fundamental limitation to Anderson localisation and random lasing?
- Complementary scenario: weak localisation of matter waves in speckle potential [see poster I.24 by R. Kuhn]

▶ [www.phy.uni-bayreuth.de/~btpj01/]

Quantum Transport of Light and Matter

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