Testing quantum mechanics fundamental principles with time projection chambers

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1. The Mott problem. . . revisited for time projection chambers

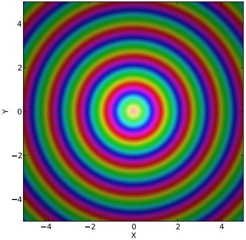
2. Project: deterministic quantum statistical detector model

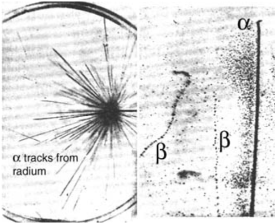
3. First results for a one-dimensional detector model

4. Conclusions and open questions

The Mott problem: α particle in a cloud chamber [Mott 1929]

- S-wave α emitter in Wilson cloud chamber
- Spherical highly non local wave function $\psi(\boldsymbol{r}) = \frac{e^{ikr}}{r}$
- But linear classical tracks detected, because of
  - measurement? (wave function reduction)
  - or simply decoherence?





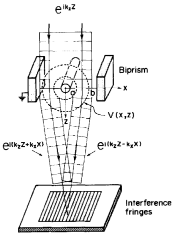
[Wilson 1912]

Do you recognize Wilson?

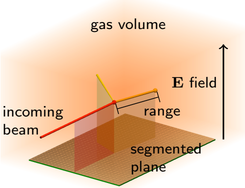
Solvay conference, Brussels 1927

When does decoherence take place in a TPC?

1. Imagine any matter-wave interferometry (Young-type) experiment in an empty time projection chamber and measure interference pattern
2. Increase pressure continuously. . .
   check pattern
3. Switch on voltage. . .
   check pattern
4. Switch on electronics readout. . .
   check pattern
5. Become aware of tracks. . .
   check pattern

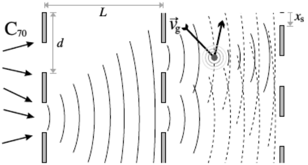


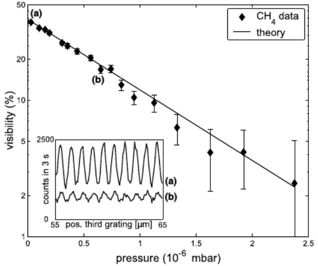
electron biprism
[Tonomura et al. 1989]

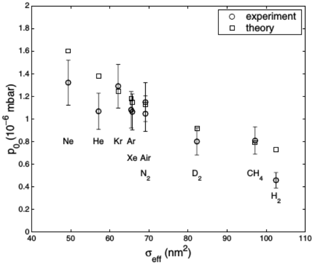


ACTAR TPC principle
[CDR 2012]

A similar experiment for (heavy!) molecules



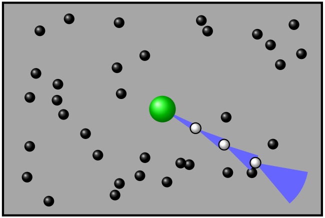




- Matter-wave interferences for fullerene molecules [Hornberger, Zeilinger et al. PRL 2003]
- Collisional decoherence due to background gas
  - fringe visibility $V(p) = V_0 e^{-p/p_0}$
  - decoherence pressure p_0
  - effective cross section $\sigma_{\rm eff}$
- Gas dependence well understood

Project: deterministic quantum statistical detector model

- Inspired by [Mott 1929]'s original question: why no multiple tracks?
  - because of state-space structure
  - in "unaided" wave mechanics
- New question: why a particular track?
  - hypothesis: because of detector microscopic state [JMS et al. 2013] (fixed atom positions in simplest case)
  - deterministic statistical mechanics



- α-particle source
- Unexcited atom
- Hit/excited/ionized atom

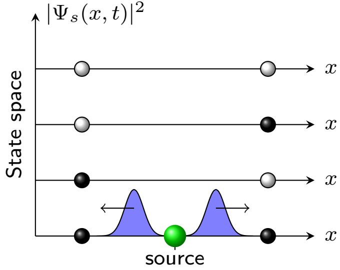
- Directly related to slowing-down (stopping power) through
  - (in)elastic scattering
  - ionization
- First revisited as a 1D model with contact interactions [Carlone et al. 2015]

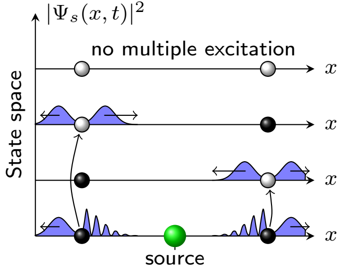
Why no multiple track? [Carlone et al. 2015, JMS & DG arXiv 2016]

- Spin model Hamiltonian for two-level atoms at fixed positions x_n

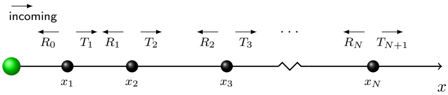
$$H = \underbrace{-\frac{\hbar^2}{2m}\partial_x^2}_{\text{free particle}} + \sum_{n=1}^{N} \underbrace{\begin{pmatrix} \varepsilon_n & 0 \\ 0 & 0 \end{pmatrix}}_{\text{atoms}} + \sum_{n=1}^{N} \underbrace{\begin{pmatrix} \beta_n & \gamma_n \\ \gamma_n & \beta_n \end{pmatrix} \delta(x - x_n)}_{\text{contact coupling}},$$

  - ε, β, γ to be related to realistic physical values
  - state-space structure: 2^N-dimensional spinor Ψ
- One particle with 2 symmetric atoms: no left *and* right excitation



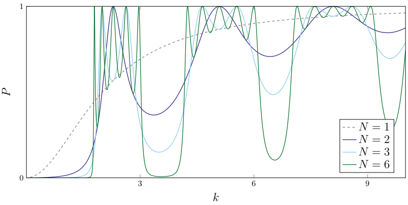


Why a particular track (no-coupling case)?

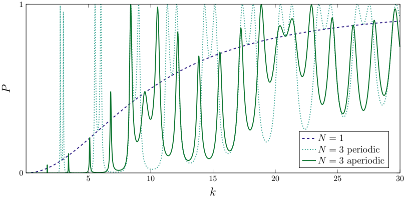


- Single-sided detector, N atoms
- Stationary transmission probability P, energy $E = k^2$
- Band-like perfect transmission when equally-spaced mesh
- Anderson localisation (reflection) when random positions

$\Rightarrow$ detected trajectories determined by perfect-transmission conditions?



$\epsilon = \gamma = 0, \beta = 2, x_n = n$



$\epsilon = \gamma = 0, \beta = 10, \langle x_n \rangle = n$

[Ceulemans, Master thesis 2016]

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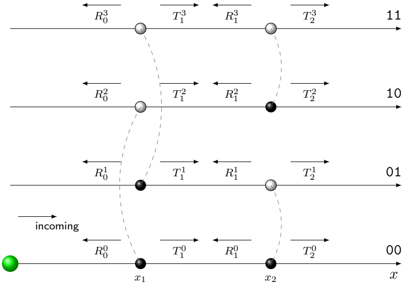
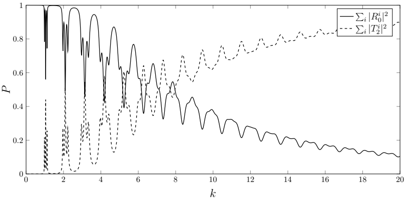
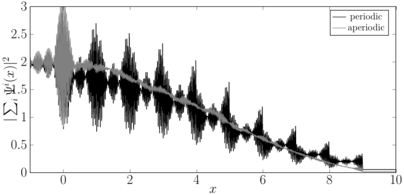
Why a particular track (coupled case)?



- No perfect transmission anymore (already with two atoms!)
  $\Rightarrow$ phase-space localisation
- Adds up to Anderson localisation
  (analysis in progress)



$\epsilon = \beta = 0, \gamma = 5, N = 2, x_2 - x_1 = 10/3$



$\epsilon = 0, \beta = 10, \gamma = 100,$
$N = 10, \langle x_n \rangle = n$
[Ceulemans, Master thesis 2016]

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Conclusions and open questions

- New research project: deterministic quantum statistical model for quantum particle in gaseous environment
  - new approach to decoherence, localisation and measurement problems
  - best tested with matter-wave interferometry
    (new experiment welcome!)
- Promising one-dimensional preliminary model
  - Anderson localisation
  - phase-space localisation
  - short-term project: realistic ordrers of magnitudes
    $\Rightarrow$ new corrections to Bethe formula in Bragg peak?
    (experimental data welcome!)
- Longer-term projects
  - 3D model: reduced Anderson localisation but enhanced phase-space localisation?
  - interest for atmospheric cloud formation [CLOUD@CERN]?

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