Quantum mechanics beyond Galileo

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Frankfurt, 30/11/2016

Outline

1. Introduction
   - Foldy's relativistic QM
2. QM in reference frames
   - (non) inertial frames
3. Dynamical maps
   - covariance, characterization, collapse models
4. Conclusions
   - summary, some other results

Relativistic QM of particles - heuristic motivation

(a) suppress particle / antiparticle interactions

$$\text{K-G eq.} \xrightarrow{\text{Foldy-Wouthuysen}} i\frac{d}{dt}|\psi\rangle = \hat{H}|\psi\rangle$$

Foldy, Leslie L., and Siegfried A. Wouthuysen. "On the Dirac theory of spin 1/2 particles and its non-relativistic limit." Physical Review 78.1 (1950): 29.

(b) integrate field degrees of freedom (e.g. $A^\alpha = (\frac{\phi}{c}, \vec{A})$)

classical Darwin Hamiltonian: $H(\vec{x}_\mu, \vec{p}_\mu)$

Darwin, Charles Galton. "LI. The dynamical motions of charged particles." The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 39.233 (1920): 537-551.

$$\hat{H} = \hat{H}^{(0)} + \frac{1}{c^2}\hat{H}^{(1)} + \frac{1}{c^4}\hat{H}^{(2)} + \dots$$

Foldy's relativistic QM framework

- fixed number of particles (no antiparticles, no mediating field)
- non-relativistic kinematics

$$[\hat{r}^i_\mu, \hat{r}^j_\nu] = [\hat{p}^i_\mu, \hat{p}^j_\nu] = 0 \qquad [\hat{r}^i_\mu, \hat{p}^j_\nu] = i\delta_{\mu\nu}\delta_{ij}$$

- relativistic dynamics

$$i\frac{d}{dt}|\psi\rangle = \hat{H}|\psi\rangle \qquad \hat{H} = \sum_\mu \hat{H}_\mu + \hat{U} \qquad \hat{H}_\mu = (\hat{p}^2_\mu c^2 + m^2_\mu c^4)^{1/2}$$

Lämmerzahl, Claus. "The pseudodifferential operator square root of the Klein–Gordon equation." Journal of mathematical physics 34.9 (1993): 3918-3932.

Poincaré algebra

- time evolution $\mathscr{H}$, translations $\mathscr{P}_i$, boosts $\mathscr{K}_i$, rotations $\mathscr{J}_i$

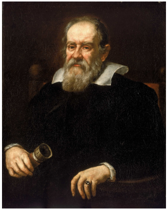
$$[\mathscr{P}_i, \mathscr{P}_j] = 0 \quad [\mathscr{J}_i, \mathscr{J}_j] = i\varepsilon_{ijk}\mathscr{J}_k \quad [\mathscr{K}_i, \mathscr{H}] = i\mathscr{P}_i$$
$$[\mathscr{P}_i, \mathscr{H}] = 0 \quad [\mathscr{J}_i, \mathscr{P}_j] = i\varepsilon_{ijk}\mathscr{P}_k \quad [\mathscr{K}_i, \mathscr{K}_j] = -i\varepsilon_{ijk}\mathscr{J}_k/c^2$$
$$[\mathscr{J}_i, \mathscr{H}] = 0 \quad [\mathscr{J}_i, \mathscr{K}_j] = i\varepsilon_{ijk}\mathscr{K}_k \quad [\mathscr{K}_i, \mathscr{P}_j] = i\delta_{ij}\mathscr{H}/c^2$$

Galilei algebra

- Galilei algebra (central extension)

$$[\mathscr{P}_i, \mathscr{P}_j] = 0 \qquad [\mathscr{J}_i, \mathscr{J}_j] = i\varepsilon_{ijk}\mathscr{J}_k \qquad [\mathscr{K}_i, \mathscr{H}] = i\mathscr{P}_i$$
$$[\mathscr{P}_i, \mathscr{H}] = 0 \qquad [\mathscr{J}_i, \mathscr{P}_j] = i\varepsilon_{ijk}\mathscr{P}_k \qquad [\mathscr{K}_i, \mathscr{K}_j] = 0$$
$$[\mathscr{J}_i, \mathscr{H}] = 0 \qquad [\mathscr{J}_i, \mathscr{K}_j] = i\varepsilon_{ijk}\mathscr{K}_k \qquad [\mathscr{K}_i, \mathscr{P}_j] = i\delta_{ij}m$$

- Inönü-Wigner contraction: Poincaré --→ Galileo



Foldy's relativistic QM framework - generators

$$\mathscr{P} = \sum_\mu \hat{p}_\mu \qquad \mathscr{K} = \sum_\mu \hat{K}_\mu + \hat{V} \quad K_\mu = \frac{1}{2c^2}\left\{\hat{r}_\mu, \hat{H}_\mu\right\} - t\hat{p}_\mu$$

$$\mathscr{J} = \sum_\mu (\hat{r}_\mu \times \hat{p}_\mu) \quad \mathscr{H} = \sum_\mu \hat{H}_\mu + \hat{U} \quad H_\mu = (\hat{p}_\mu^2 c^2 + m_\mu^2 c^4)^{1/2}$$

$$\hat{H}_\mu \approx m_\mu c^2 + \frac{\hat{p}_\mu^2}{2m_\mu} + \mathscr{O}(\tfrac{1}{c^2}) \quad \hat{K}_\mu \approx m\hat{r}_\mu - t\hat{p}_\mu + \mathscr{O}(\tfrac{1}{c^2})$$

Poincaré algebra constrains U, V

Krajcik, R. A., and L. L. Foldy. "Relativistic center-of-mass variables for composite systems with arbitrary internal interactions." Physical Review D 10.6 (1974): 1777.

Foldy's relativistic QM framework - center of mass

- Single particle form (definition of CM coordinates)

$$\mathscr{P} = \hat{P} \qquad \mathscr{K} = \frac{1}{2c^2}\left\{\hat{R},\hat{H}\right\} - t\hat{P}$$
$$\mathscr{J} = \hat{R}\times\hat{P} \quad \mathscr{H} = \hat{H} = (\hat{P}^2c^2 + \hat{h}^2)^{1/2}$$

$$[\hat{R}_i,\hat{R}_j] = [\hat{P}_i,\hat{P}_j] = 0 \qquad [\hat{R}_i,\hat{P}_j] = i\delta_{ij} \qquad [\hat{h},\hat{R}_i] = [\hat{h},\hat{P}_i] = 0$$

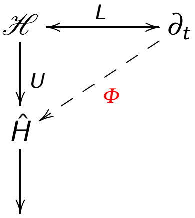
- Krajcik & Foldy construction of CM coordinates

$$\hat{r}_\mu,\hat{p}_\mu \rightarrow \text{non-relativistic CM} \xrightarrow[\text{iterative}]{\text{unitary transformation}} \text{relativistic CM}$$

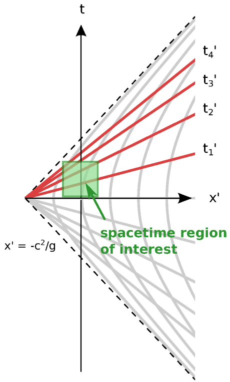
$$\hat{r}_\mu \approx \hat{\rho}_\mu + \hat{R} + \mathscr{O}(\tfrac{1}{c^2}) \qquad \hat{p}_\mu \approx \hat{\pi}_\mu + \frac{m_\mu}{M}\hat{P} + \mathscr{O}(\tfrac{1}{c^2})$$

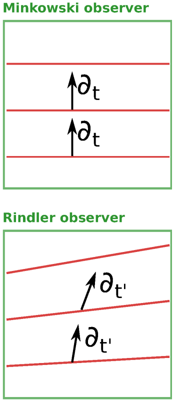
Non-inertial frames I

inertial reference frames



$$\hat{U}_t = e^{-i\hat{H}t}$$





Non-inertial frames II

- family of inertial reference frames instantaneously at rest with the Rindler observer: (cT,X,Y,Z)
- Φ in inertial reference frames

$$\begin{array}{ccc} \hat{H}_{\text{Rindler}}\,? & & \hat{H} + \frac{g}{2c^2}\{\hat{X}, \hat{H}\} \\ \uparrow & & \uparrow \Phi \\ \partial_{t'} & = & \left(1 + \frac{g\,X}{c^2}\right)\partial_T \end{array}$$

on $T = 0$ hypersurface.

Laboratory reference frame I

- metric near a timelike curve in Fermi normal coordinates $\dashrightarrow$ Rindler

$$g_{\mu\nu}dx^{\mu}dx^{\nu} = \left(1 + \frac{gX}{c^2}\right)^2 c^2 dT^2 + dX^2 + dY^2 + dZ^2 \qquad (1)$$

Manasse, F. K., and Charles W. Misner. "Fermi normal coordinates and some basic concepts in differential geometry." Journal of mathematical physics 4.6 (1963): 735-745.

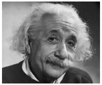
- first step: gravity $\dashrightarrow$ non-inertial frames

Pikovski, Igor, et al. "Universal decoherence due to gravitational time dilation." Nature Physics 11.8 (2015): 668-672.

Laboratory reference frame II

- coupling between
  - CM position X (Foldy's relativistic QM framework)
  - "total energy" of the system
- coupling related to relative acceleration

		apparatus	
		free fall	suspended
system	free fall	/	$\frac{g}{2c^2}\left\{\hat{X},\hat{H}\right\}$
	suspended	$\frac{g}{2c^2}\left\{\hat{X},\hat{H}\right\}$	/



Outline

- ✓ Foldy's relativistic QM formalism
- ✓ dynamics in (non) inertial reference frames
- dynamical maps
    - Poincaré covariance
    - (non)-unitary modifications
    - collapse models

Introduction to dynamical maps

- Schrödinger eq., von Neumann eq.

$$i\frac{d}{dt}|\psi\rangle = \hat{H}|\psi\rangle \qquad \frac{d}{dt}\hat{\rho} = -i\left[\hat{H},\hat{\rho}\right]$$

- von Neumann map

$$\hat{\rho}_{t_2} = \mathscr{M}(t_2, t_1)[\hat{\rho}_{t_1}]$$
$$\mathscr{M}(t_2, t_1)[\,\cdot\,] = e^{-i\hat{H}(t_2-t_1)}[\,\cdot\,]e^{i\hat{H}(t_2-t_1)}$$

Introduction to dynamical maps -$\mathscr{M}(t_2, t_1)$ motivation

- Open quantum systems
  - integrate the environment degrees of freedom
- intrinsic non-unitary modifications
  - classical limit (collapse models)
  - classicalization maps (measure of macroscopicity)
  - General relativity (Penrose)

Introduction to dynamical maps - framework

- Foldy's framework
  - non-relativistic kinematics ✓
  - relativistic dynamics ✓
  - Poincaré algebra ✓
  - non-relativistic limit ✓
- generic map

$$\mathscr{M}^{(I)}(t_2,t_1)[.] = \sum_i \hat{A}_i(t_2,t_1)[.]\hat{B}_i(t_2,t_1)$$

Translational and Lorentz boost covariance I

- covariance

$$\mathscr{M}^{(I)}(t_2, t_1) = \tilde{\mathscr{G}}^{-1} \circ \mathscr{M}^{(I)}(t_2, t_1) \circ \mathscr{G}$$

- translations and Lorentz boosts

$$\mathscr{P} = \hat{p}$$
$$\mathscr{K} = \frac{1}{2c^2}\left\{\hat{x}, \hat{H}\right\} \qquad \hat{H} = (\hat{p}^2 c^2 + m^2 c^4)^{1/2}$$

Translational and Lorentz boost covariance II

- generalized Weyl - Wigner decomposition
  $(\hat{\chi} = \xi \hat{x} \xi^{\dagger}, \hat{\pi} = \xi \hat{p} \xi^{\dagger})$

$$\mathscr{M}^{(I)}(t_2, t_1)[.] = \int d\alpha_L \int d\beta_L \int d\alpha_R \int d\beta_R \, g(t_2, t_1, \alpha_L, \beta_L, \alpha_R, \beta_R) \times e^{i(\alpha_L \cdot \hat{\chi} + \beta_L \cdot \hat{\pi})}[.] e^{-i(\alpha_R \cdot \hat{\chi} + \beta_R \cdot \hat{\pi})}$$

- $1/c^0$ (with $\xi = \mathbb{I}$):
  - $g(t_2, t_1, \alpha_L, \beta_L, \alpha_R, \beta_R) \propto \delta(\alpha_L - \alpha_R)\delta(\beta_L - \beta_R)$
- $1/c^2$ $(\forall \xi)$:
  - $g(t_2, t_1, \alpha_L, \beta_L, \alpha_R, \beta_R) \propto \delta(\alpha_L)\delta(\alpha_R)\delta(\beta_L)\delta(\beta_R)$

Translational and Lorentz boost covariance III

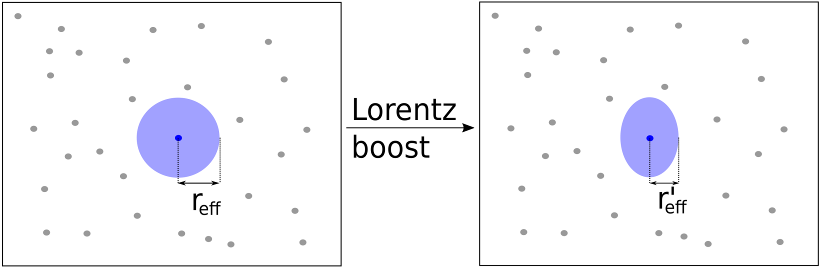
non-relativistic: Holevo result (not in standard form)

$$\mathscr{M}^{(I)}(t_2,t_1)[.] = \int d\alpha_1 \int d\beta_1 \int d\alpha_2 \int d\beta_2 \, G(t_2,t_1,\alpha,\beta) \times e^{i(\alpha\cdot\hat{x}+\beta\cdot\hat{p})}[.]e^{-i(\alpha\cdot\hat{x}+\beta\cdot\hat{p})}$$

relativistic (at $1/c^2$): trivial map

$$\mathscr{M}^{(I)}(t_2,t_1)[.] = C(t_2,t_1)\mathbb{I}[.]$$

Translational and Lorentz boost covariance - physical insight



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- ✓ Foldy's relativistic QM formalism
- ✓ dynamics in (non) inertial reference frames
- ✓ dynamical maps
  - ✓ Poincaré covariance
  - (non)-unitary modifications
  - collapse models

Map from a minimal set of assumptions I

- (i)Probabilistic interpretation
  - $\mathrm{Tr}[\rho_t] = 1$
- (ii) Gisin's no superluminal signaling theorem
  - $\mathscr{M}[\cdot] = \sum_i K_i \cdot K_i^\dagger$

Generic CP linear map

$$\hat{\rho}_{t_2} = \mathscr{M}(t_2, t_1)[\hat{\rho}_{t_1}]$$

Map from a minimal set of assumptions II

(iii) stationary initial conditions
(iv) translational and rotational covariance
(v) asymptotic Gibbs state

Map from a minimal set of assumptions III

(vi) Gaussian maps

$$\mathscr{M}_t = \mathscr{T} \exp\left\{ \int_0^t d\tau \int_0^t ds\, D_{jk}(\tau, s) \cdot \left(\hat{A}^k_{s,L} \hat{A}^j_{\tau,R} - \theta_{\tau,s} \hat{A}^j_{\tau,L} \hat{A}^k_{s,L} - \theta_{s,\tau} \hat{A}^k_{s,R} \hat{A}^j_{\tau,R} \right) \right\}$$

Diósi, Lajos, and Luca Ferialdi. "General non-markovian structure of gaussian master and stochastic schrödinger equations." Physical review letters 113.20 (2014): 200403.

Stationary initial conditions

- $\mathscr{M}_{t_1+u}^{t_2+u} = \mathscr{M}_{t_1}^{t_2}$
- $\mathscr{M}_0^t = \mathscr{M}_t$

Kernel condition

$$D_{jk}(\tau+u, s+u) = D_{jk}(\tau, s)$$

Translational and rotational covariance

$$\mathscr{M}_t = \tilde{\mathscr{G}}^{-1} \circ \mathscr{M}_t \circ \mathscr{G}$$
$$\hat{A} = \int d\alpha \int d\beta \, g(\alpha, \beta) e^{i(\alpha\hat{x} + \beta\hat{p})}$$
$$\mathscr{D}(\alpha_1, \beta_1, \alpha_2, \beta_2, \tau, s) = D_{jk}(\tau, s) g_\tau^{j*}(\alpha_1, \beta_1) g_s^k(\alpha_2, \beta_2)$$

Kernel conditions

$$\mathscr{D}(\alpha_1, \alpha_2, \beta_1, \beta_2, \tau, s) = \delta(\alpha_1 - \alpha_2)\mathscr{D}(\alpha_1, \alpha_2, \beta_1, \beta_2, \tau, s)$$

$$\mathscr{D}(R\alpha_1, R\beta_1, R\alpha_2, R\beta_2, \tau, s) = \mathscr{D}(\alpha_1, \beta_1, \alpha_2, \beta_2, \tau, s)$$

Intermediate result

Characterization of translational covariant map

$$
\begin{aligned}
\mathscr{M}_t = \mathscr{T} \exp\Big\{ \int_0^t d\tau \int_0^t ds \int d\alpha \, D_{jk}(\tau, s) \\
\big([J_L^k(\hat{p}, \alpha) e^{i\alpha \hat{x}_L(s)}] [J_R^{j\dagger}(\hat{p}, \alpha) e^{-i\alpha \hat{x}_R(\tau)}] \\
- \theta_{\tau,s} [J_L^{j\dagger}(\hat{p}, \alpha) e^{-i\alpha \hat{x}_L(\tau)}] [e^{i\alpha \hat{x}_L(s)} J_L^k(\hat{p}, \alpha)] \\
- \theta_{s,\tau} [J_R^k(\hat{p}, \alpha) e^{i\alpha \hat{x}_R(s)}] [e^{-i\alpha \hat{x}_R(\tau)} J_R^{j\dagger}(\hat{p}, \alpha)] \Big\}
\end{aligned}
$$

Asymptotic Gibbs state

$$t \gg \tau_C \implies D_{jk}(\tau, s) \to \delta(\tau - s) D_{jk}$$

$$\hat{\rho}_t = \mathscr{M}_t[\hat{\rho}_0] \implies \frac{d\hat{\rho}}{dt} = \mathscr{L}_t[\hat{\rho}]$$

$$\mathscr{L}_t = \int dQ \left(e^{i/\hbar Q \hat{x}_t} J(\hat{p}, Q) \hat{\rho} J^\dagger(\hat{p}, Q) e^{-i/\hbar Q \hat{x}_t} - \frac{1}{2} \{ J^\dagger(\hat{p}, Q) J(\hat{p}, Q), \hat{\rho} \} \right)$$

$$\hat{\rho}_{\text{asm}} = \left(\frac{\beta}{2m\pi} \right)^{3/2} \exp(-\beta \hat{H}) \quad \beta = 1/(k_B T)$$

Operator

$$J(\hat{p}, Q) = \sqrt{\lambda \frac{m^2}{m_0^2} \left(\frac{r_C}{\sqrt{\pi}\hbar} \right)^3} \exp\left(-\frac{r_C^2}{2\hbar^2} \left((1 + k_T) Q + 2 k_T \hat{p} \right)^2 + \frac{\beta}{8 m^3 c^2} \hat{p}^4 \right)$$

$$k_T = \frac{\beta \hbar^2}{8 m r_C^2}$$

Map from a minimal set of assumptions - final result

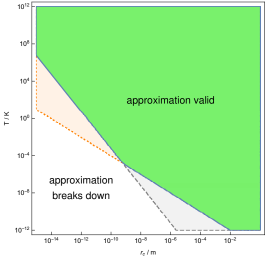
CD map

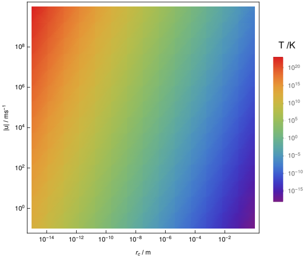
$$\mathscr{M}_t = \mathscr{T} \exp\Big\{ \int_0^t d\tau \int_0^t ds \int dQ\, D_{\tau,s} \Big([J_L(\hat{p},Q) e^{i/\hbar Q \hat{x}_L(s)}] [J_R^\dagger(\hat{p},Q) e^{-i/\hbar Q \hat{x}_R(\tau)}] - \theta_{\tau,s} [J_L^\dagger(\hat{p},Q) e^{-i/\hbar Q \hat{x}_L(\tau)}] [e^{i/\hbar Q \hat{x}_L(s)} J_L(\hat{p},Q)] - \theta_{s,\tau} [J_R(\hat{p},Q) e^{i/\hbar Q \hat{x}_R(s)}] [e^{-i/\hbar Q \hat{x}_R(\tau)} J_R^\dagger(\hat{p},Q)] \Big\}$$

$$J(\hat{p},Q) = \sqrt{\lambda \frac{m^2}{m_0^2} \left(\frac{r_C}{\sqrt{\pi}\hbar}\right)^3} \exp\left(-\frac{r_C^2}{2\hbar^2} \left((1+k_T)Q + 2k_T \hat{p}\right)^2 + \frac{\beta}{8m^3c^2} \hat{p}^4 \right)$$

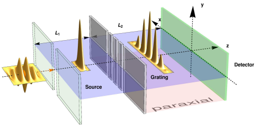
CD map parameters (non-relativistic)

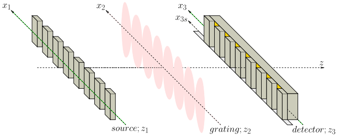
- $\lambda, r_C,\ D(\tau, s),\ T,\ \mathbf{u} \dashrightarrow\ (\lambda, r_C)$ for a range of $(\tau_C, T, |\mathbf{u}|)$
- (λ, r_C) remain in the Galilei boost covariant, Markovian limit
- $\Delta x \lesssim 10^{-5} m,\ \tau_C \lesssim 10^{-13} s$





Interferometry - KDTL

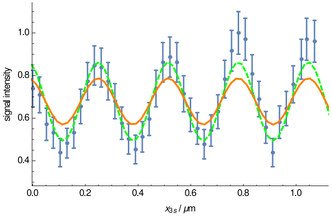




Probability density

$$p(x)=\int_{-\infty}^{+\infty}dx_2\int_{-\infty}^{+\infty}dx_2'\,D(x_2-x_2')\,t(x_2)t^*(x_2')e^{-i\frac{mv}{\hbar}(x_2-x_2')(\frac{x_1}{L_1}+\frac{x}{L_2})}e^{i\frac{mv}{\hbar}\frac{L_1+L_2}{2L_1L_2}(x_2^2-x_2'^2)}$$

KDTL

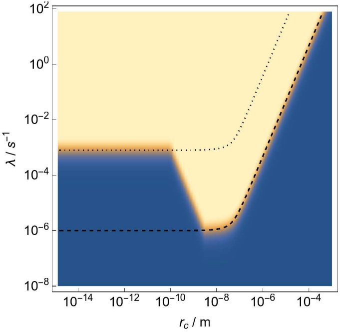


L12

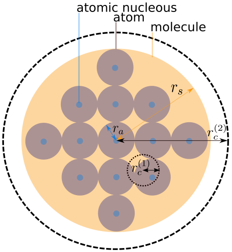
$C_{284}H_{190}F_{320}N_4S_{12}$

$m \approx 10000$amu

Eibenberger, Sandra, et al. "Matter–wave interference of particles selected from a molecular library with masses exceeding 10000 amu." Physical Chemistry Chemical Physics 15.35 (2013): 14696-14700.



Macroscopic localization

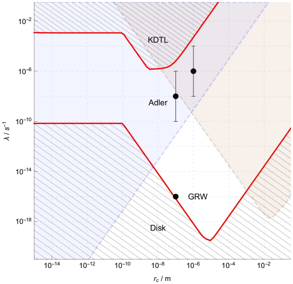


graphene disk

$\Delta x \lesssim 10^{-5} m$, $\Delta t = 10^{-2} s$

$m \approx 10^{11}$amu

Parameter diagram



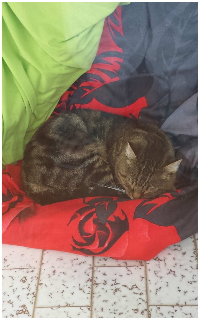
Curceanu, Catalina, Beatrix C. Hiesmayr, and Kristian Piscicchia. "X-rays Help to Unfuzzy the Concept of Measurement." Journal of Advanced Physics 4.3 (2015): 263-266.
Toroš, Marko, and Angelo Bassi. "Bounds on Collapse Models from Matter-Wave Interferometry." arXiv preprint arXiv:1601.03672 (2016).
Carlesso, Matteo, et al. "Experimental bounds on collapse models from gravitational wave detectors." Physical Review D 94.12 (2016): 124036.

Outline

- ✓ Foldy's relativistic QM formalism
- ✓ dynamics in (non) inertial reference frames
- ✓ dynamical maps
  - ✓ Poincaré covariance
  - ✓ (non)-unitary modifications
  - collapse models

Example of non-unitary dynamics - Collapse models

- state vector $|\psi_t\rangle$
  - complete description of the system
- macroscopic superpositions?
  - $|\psi\rangle = \frac{1}{\sqrt{2}}(|\psi_1\rangle + |\psi_2\rangle)$
- modification of the dynamics?
  - reobtain predictions of QM for microscopic systems
  - well-localized macroscopic systems

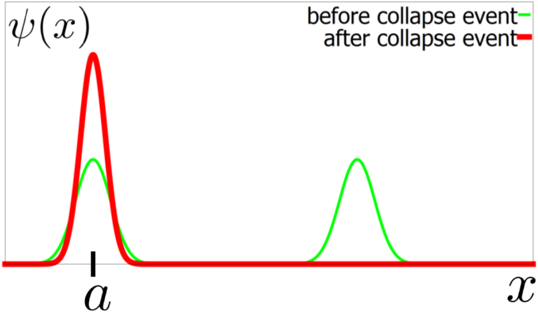


Example of non-unitary dynamics - Collapse mechanism

- Schrödinger dynamics interrupted by collapse events

$$|\psi_t\rangle \to \frac{\hat{L}_a|\psi_t\rangle}{||\hat{L}_a|\psi_t\rangle||}$$

$$\hat{L}_a \propto e^{-\frac{1}{2r_C^2}(\hat{x}-a)^2}$$



- Continuous spontaneous localization (CSL) model
  - noise field $h_t(x)$

Colored and dissipative CSL (cdCSL) model

- dynamics for $|\psi_t\rangle$
  - stochastic (Born rule) and nonlinear (depends on $|\psi_t\rangle$)
  - CD map for $\hat{\rho}_t = \mathbb{E}\big[|\psi_t\rangle\langle\psi_t|\big]$
- heuristic idea
  - partial collapse events generated by a noise field $h_t(x)$

Ansatz

$$i\frac{d}{dt}|\psi_t\rangle = \hat{H}|\psi_t\rangle + \left(\int h_t(x)\hat{L}(x)dx + \hat{O}(|\psi_t\rangle)\right)|\psi_t\rangle$$

cdCSL model I

cdCSL

$$i\frac{d}{dt}|\psi_t\rangle = \Big(\hat{H} + \int dx\, h_t(x)\,\hat{L}(x) \\ - i\int_0^t d\tau \int dx\, D_{\tau,s}\,\left(\hat{L}(x)+\hat{L}^\dagger(x)\right)\frac{\delta}{\delta h_\tau(x)}\Big)|\psi_t\rangle$$

- $|\phi_t\rangle = |\psi_t\rangle / \big|\big||\psi_t\rangle\big|\big|$, $\mathbb{Q} \dashrightarrow \mathbb{P}$
- $\hat{L}(x) = i\int dQ e^{iQ(\hat{x}-x)}\int dP \int dP' \hat{a}^\dagger(P')\langle P'|J(\hat{p},Q)|P\rangle \hat{a}(P)$
- $\mathbb{E}_{\mathbb{Q}}[h_\tau^*(x_1)h_s(x_2)] = \delta(x_1-x_2)D_{\tau,s}$

cdCSL model II

- generalization of existing models
  - Ghirardi, Gian Carlo, Philip Pearle, and Alberto Rimini. "Markov processes in Hilbert space and continuous spontaneous localization of systems of identical particles." Physical Review A 42.1 (1990): 78.
  - Adler, Stephen L., and Angelo Bassi. "Collapse models with non-white noises." Journal of Physics A: Mathematical and Theoretical 40.50 (2007): 15083.
  - Smirne, Andrea, and Angelo Bassi. "Dissipative Continuous Spontaneous Localization (CSL) model." Scientific reports 5 (2015).
- solves the “collapse models zoo” problem
- simple relativistic model

Summary

- Foldy's relativistic QM
  - Dynamics in (non) inertial frames
  - Dynamical maps
- Results
  - Foldy - Rindler CM dynamics
  - CD map (5 parameters)
  - cdCSL model

Results - Collapse models

- *M. Toroš, A. Bassi: Bounds on Collapse Models from Matter-Wave Interferometry, 2016 (arXiv preprint: 1601.03672)*
- M. Toroš, A. Bassi: *Bounds on Collapse Models from Matter-Wave Interferometry: Calculational details*, 2016 (arXiv preprint: 1601.02931)
- M. Toroš, G. Gasbarri, A. Bassi: *Colored and dissipative continuous spontaneous localization model*, 2017 (in preparation)
- G. Gasbarri, M. Toroš, S. Donadi, A. Bassi: *Gravity Induced Wave Function Collapse*, 2017 (arXiv preprint: 1701.02236)
- G. Gasbarri, M. Toroš, A. Bassi: *General structure of Gaussian Spontaneous Wave Function Collapse Models*, 2017 (in preparation)

Results - Dynamical maps

- M. Toroš, G. Gasbarri, A. Bassi: *Non-unitary modifications of Quantum mechanics*, 2017 (in preparation)
- M. Toroš, G. Gasbarri, A. Bassi: *Relativity and non-unitary modifications of Quantum mechanics*, 2017 (in preparation)
- G. Gasbarri, M. Toroš, A. Bassi: *Galilean covariant Gaussian maps*, 2017 (in preparation)

Results - other

- M. Toroš, A.Großardt, A. Bassi: *Quantum Mechanics in non-inertial reference frames*, 2017 (arXiv preprint: 1701.04298)
- M. Toroš, A. Großardt, A. Bassi: *Charged particles in non-inertial frames*, 2017 (in preparation)
- M. Toroš, S. Donadi, A. Bassi: *Bohmian mechanics, collapse models and the emergence of classicality*, 2016 (J. Phys. A: Math. Theor. 49 355302)

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Thank you