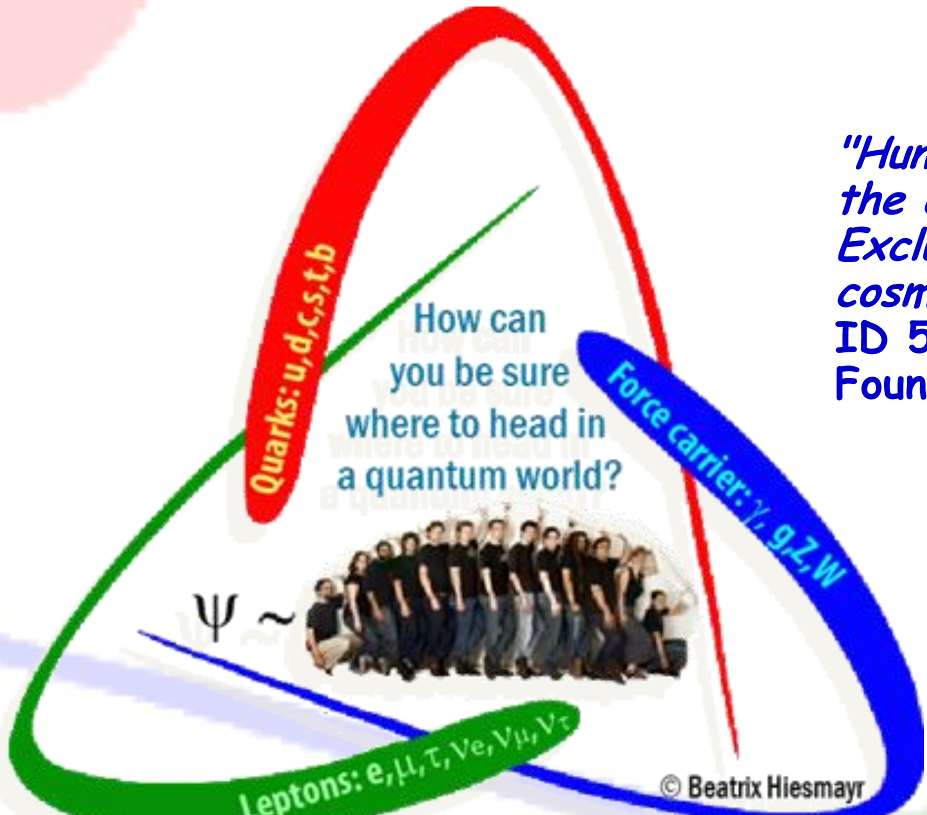
The Pauli principle or other fundamental questions: how to test?

by

Beatrix C. Hiesmayr, University of Vienna



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Outline

$$\left|Physics\right\rangle = \alpha\left|Particle\ Physics\right\rangle + \beta\left|Quantum\ Theory\right\rangle$$

"Testing Foundational Issues of QM in High Energy Physics"

Today: … by looking at extensions/deviations from the quantum theory…how to come to experimental tests?

Pauli Exclusion Principle

Surprisingly there are only two possibilities for spins with very distinct behaviour:

1. Half integer spin
2. Integer spin

The more surprising: even for composite systems that seems to be strict

Pauli Exclusion Principle

What is the intuitive picture behind it???

The VIP experiment

LNGS underground laboratory looks for 2p to 1s transitions in copper, a sign for a violation of the Pauli exclusion principle.

Approach: looking for extensions of the quantum theory, providing a framework that allows to develop experimental tests

Pichler et al. arXiv:1602.00867

Curceanu et al. Foundations of Physics (2015)

Quantum Theory

Quantum theory is very successful (=all experiments are in agreement) in the *microscopic* regime:

Schrödinger equation:

Hamiltonian

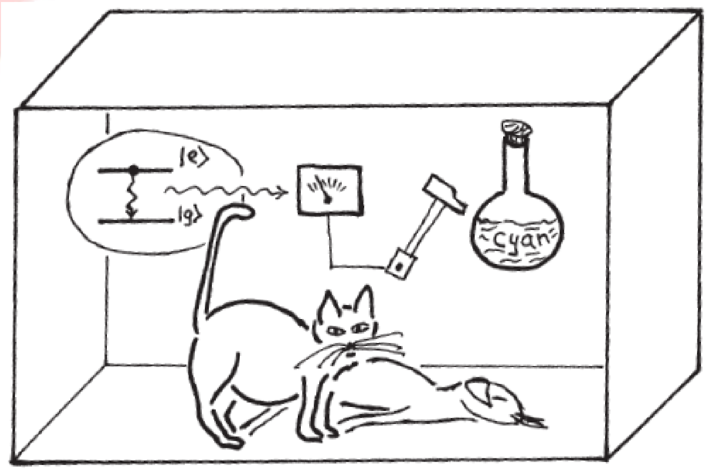
$$\frac{d}{dt}\rho = -\frac{i}{\hbar}[H,\rho]$$

- linear differential equation $\Longrightarrow$ superposition
- deterministic
- reversible

…many particles are included by tensorising the one particle Hilbertspaces→symmetrisation

The measurement problem

Why do we see no (position) superposition for macroscopic objects?



In particular: when and how does Pauli exclusions principle (=particles cannot be in the same state) get lost, when performing a limit to the `classical world'

What is the role of observation?

Relation Quantum and Classical Dynamics

-> tend to agree that classical dynamics should be kind of limit of quantum dynamics

Why do we see no (position) superposition for macroscopic objects?

→ its at the heart of the measurement problem

→ to say something about the quantum system we have to bring it in contact with an macroscopic system (measurement apparatus)

Micro/Macro?

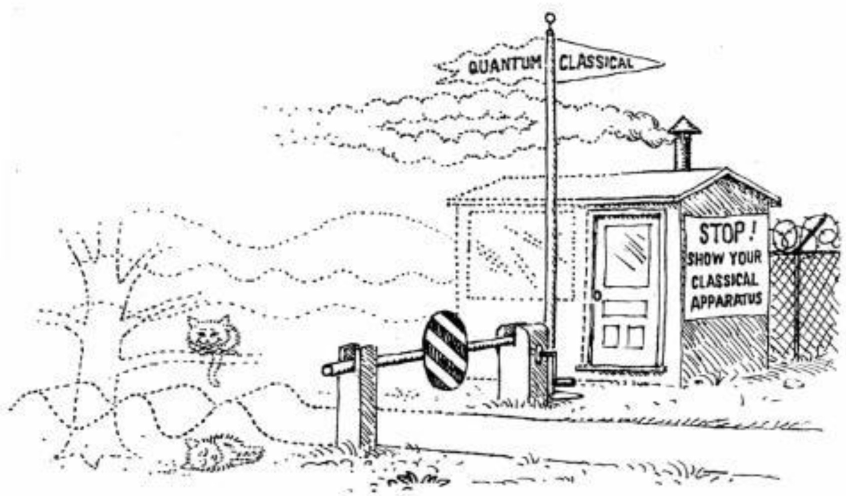
When do we call a system microscopic or macroscopic?

Kopenhagner Interpretation: does use the concept, but does not define it!

Is there a border between a quantum and classical world? And if, where is it?

- SCHRÖDINGER EQUATION:
  linear, deterministic, reversible
- WAVE PACKET REDUCTION (measurement):
  nonlinear, stochastic, irreversible

Is there some universal theory describing both regimes ?



Delineating the border between the quantum realm ruled by the Schrödinger equation and the classical realm ruled by Newton's laws is one of the unresolved problems of physics. **Figure 1**

Zurek, Physics Today (1991)

General properties of such theories

- **Nonlinear (allowing breakdown of superpositions during measurement)**
- **Stochastic (negligible for micro such that Schrödinger evolution *deterministic*; must explain why events are *randomly* and distributed to the *Born probability rule*; is need otherwise we could have faster-than-light communication)**
- **Non unitary evolution (to allow processes from micro to macro [amplification mechanism])**
- **Should NOT allow for superluminal signaling since we want the causal structure of space-time**

Why do we see no macroscopic superpositions?

One solution (existence nontrivial!): COLLAPSE MODELS (Ghirardi-Rimini-Weber, 1986)

→postulate a mechanism of collapse

(dynamical process)

universal theory

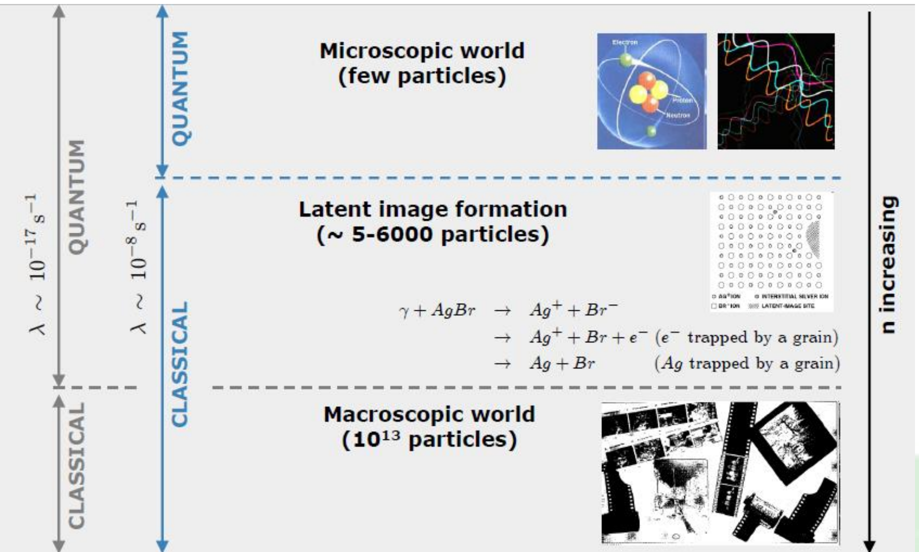
microscopic

macroscopic

mesoscopic

new behaviour

→ Experiments



Guiding Principles

for each particle a mean localization/collapse rate λ

- preferred basis on which reductions (spontaneous localization) takes place
- an amplification mechanism from micro to macro

time interval between two successive localisation processes is governed by the Schrödinger equation

$\Longrightarrow$ coherence length r_C

Collapse model

strength of collapse

Nonlinear stochastic differential equation:

$$d|\phi_t\rangle = [\underbrace{-iHdt}_{\text{Schrödinger equation}} + \sqrt{\lambda}\sum_{i=1}^{N}(A_i - \langle A_i\rangle_t)dW_{i,t} - \frac{\lambda}{2}\sum_{i=1}^{N}(A_i - \langle A_i\rangle_t)^2 dt]|\phi_t\rangle$$

Generators of collapse

Wiener process

Collapse model

Nonlinear stochastic differential equation:

$$d|\phi_t\rangle = [-iHdt + \sqrt{\lambda}\sum_{i=1}^{N}(A_i - \langle A_i\rangle_t)dW_{i,t} - \frac{\lambda}{2}\sum_{i=1}^{N}(A_i - \langle A_i\rangle_t)^2 dt]|\phi_t\rangle$$

Experiment:

$$Observable = \mathrm{E}\left(\langle\phi_t|\mathrm{O}|\phi_t\rangle\right) = Tr(\mathrm{O}\,\mathrm{E}\left(|\phi_t\rangle\langle\phi_t|\right))$$

Stochastic average

$$\mathrm{E}\left(dW_{i,t}{}^2\right) \cong dt$$

$$\mathrm{E}\left(\frac{dW_{i,t}}{dt}, \frac{dW_{j,s}}{ds}\right) \cong \delta(t-s)\delta_{i,j}$$

Most advanced collapse model

Effective Schrödinger equation:

$$i\frac{d}{dt}|\phi_t\rangle = \left[\hat{H} - \sqrt{\lambda}\sum_{i=1}^{N}\hat{A}_i w_{i,t}\right]|\phi_t\rangle := \left[\hat{H} + \hat{N}(t)\right]|\phi_t\rangle$$

$$\mathrm{E}\left(\frac{dW_{i,t}}{dt}, \frac{dW_{j,s}}{ds}\right) \cong \delta(t-s)\delta_{i,j}$$

CSL…continuous spontaneous localization (1990 Ghiradi, Pearle and Rimini, *mass dependence* Pearle and Squires, 1994)

CSL collapse model

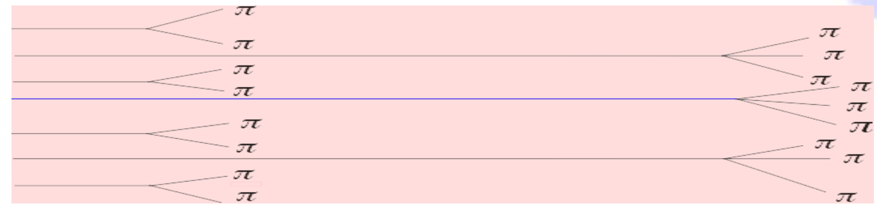
→ we have well-defined model with two new fundamental constants of Nature (if we take it seriously)

→ Can start to think about experiments !!

Crash course on neutral kaons (K-mesons):

Strangeness: $S\left|K^0\right\rangle = +\left|K^0\right\rangle$

$S\left|\overline{K}^0\right\rangle = -\left|\overline{K}^0\right\rangle$



Mass-eigenstates: $\left|K_S\right\rangle, \left|K_L\right\rangle$

$$\left|K^0\right\rangle \cong \tfrac{1}{\sqrt{2}}\left\{\left|K_S\right\rangle + \left|K_L\right\rangle\right\}$$

„A kaon is a kind of double slit"

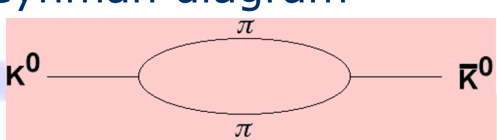
Bramon, Garbarino, H., PRA (2004)

Kaon in time:

short-lived state — long-lived state

$$\left|K^0(t)\right\rangle \cong \frac{1}{\sqrt{2}}\left\{e^{-\frac{\Gamma_S}{2}t - i m_S t}\left|K_S\right\rangle + e^{-\frac{\Gamma_L}{2}t - i m_L t}\left|K_L\right\rangle\right\}$$

Feynman diagram



$\Gamma_S \approx 10^{10}\,\frac{1}{s}$ ...decay width of K_S

$\Gamma_L \approx 1/600\,\Gamma_S$ ...decay width of K_L

$\Delta m = m_L - m_S \approx 0.5\,\Gamma_S$ ...mass difference

Connecting flavor with spatial space

Effective Schrödinger equation:

$$i\frac{d}{dt}|\phi_t\rangle = \left[\hat{H} - \sqrt{\lambda}\sum_{i=1}^{N}\hat{A}_i w_{i,t}\right]|\phi_t\rangle := \left[\hat{H} + \hat{N}(t)\right]|\phi_t\rangle$$

$$\hat{A}_{CSL}(\mathbf{x}) = \int d\mathbf{y}\; g(\mathbf{y}-\mathbf{x})\Big(\frac{m_H}{m_0}\hat{\psi}_H^\dagger(\mathbf{y})\hat{\psi}_H(\mathbf{y}) + \frac{m_L}{m_0}\hat{\psi}_L^\dagger(\mathbf{y})\hat{\psi}_L(\mathbf{y})\Big),$$

$$\hat{N}_{CSL}(t) = -\sqrt{\gamma}\int d\mathbf{y}\; w(\mathbf{y},t)\Big(\frac{m_H}{m_0}\hat{\psi}_H^\dagger(\mathbf{y})\hat{\psi}_H(\mathbf{y}) + \frac{m_L}{m_0}\hat{\psi}_L^\dagger(\mathbf{y})\hat{\psi}_L(\mathbf{y})\Big)$$

$$g(\mathbf{y}-\mathbf{x}) = \frac{1}{(\sqrt{2\pi}r_C)^d}\; e^{-(\mathbf{y}-\mathbf{x})^2/2r_C^2}$$

$\Longrightarrow$ coherence length r_C

CSL collapse models for mesons

Correlation functions: → Heaviside function

$$\int_0^t ds\, \delta(t-s) \;=\; \begin{cases} \theta(t) - \theta(0) = 1 - \theta(0) \text{ for } t-s \geq 0 \\ \theta(0) - \theta(-t) = \theta(0) \quad \text{for } t-s \leq 0 \end{cases}$$

$$\theta(0) \in [0,1]$$

Which value to choose?

$\delta(t) = \delta(-t) \longrightarrow \theta(0) = \frac{1}{2}$ ... time symmetric choice

CSL collapse models for mesons

$$\boxed{\Gamma_\mu^{CSL} = \frac{\gamma}{(\sqrt{4\pi} r_C)^d} \cdot \frac{m_\mu^2}{m_0^2} \cdot \Big(1 - 2\theta(0)\Big)}$$

Mass-eigenstate evolution:

$$P^{CSL}_{M_{\mu=L/H}\to M_{\nu=L/H}}(t) = \delta_{\mu\nu}\left(1 - \Gamma_\mu^{CSL}\cdot t + \frac{1}{2}(\Gamma_\mu^{CSL})^2 \cdot t^2 + O(t^3)\right)\cdot e^{-\Gamma_\mu t}$$

$$\Rightarrow \quad P^{CSL}_{M_{\mu=L/H}\to M_{\nu=L/H}}(t) = \delta_{\mu\nu}\, e^{-(\Gamma^{CSL}+\Gamma_\mu)t}$$

[unpublished]

CSL collapse models for mesons

Mass-eigenstate evolution:

$$\boxed{\Gamma_{\mu}^{CSL} = \frac{\gamma}{(\sqrt{4\pi}r_C)^d}\cdot\frac{m_\mu^2}{m_0^2}\cdot\Big(1-2\theta(0)\Big)}$$

$$P^{CSL}_{M_{\mu=L/H}\to M_{\nu=L/H}}(t) = \delta_{\mu\nu}\, e^{-(\Gamma^{CSL}+\Gamma_\mu)t}$$

Flavor evolution: [unpublished]

$$P^{CSL}_{M^0\to M^0/\bar{M}^0}(t) = \frac{e^{-(\Gamma_L+\Gamma_L^{CSL})t}+e^{-(\Gamma_H+\Gamma_H^{CSL})t}}{4}\cdot\left\{1\pm\frac{\cos(\Delta m t)}{\cosh\!\left(\frac{(\Gamma_L+\Gamma_L^{CSL})-(\Gamma_H+\Gamma_H^{CSL})}{2}\cdot t\right)}\cdot e^{-\frac{\gamma}{(\sqrt{4\pi}r_C)^d}\frac{(\Delta m)^2}{2m_0^2}t}\right\}$$

→disentangles effect on interference and decay!!!

Can be compared with experiments:

M. Bahrami, S. Donaldi, L. Ferialdi, A. Bassi, C. Curceanu, A. Di Domenico and B. C. Hiesmayr
Nature: Scientific Reports 3, 1952 (2013)

Sandro Donadi, Angelo Bassi, Catalina Curceanu, Antonio Di Domenico and Beatrix C. Hiesmayr
Foundations of Physics: Volume 43, Issue 7 (2013)

CSL collapse models for mesons

$$\boxed{\Gamma_\mu^{CSL} = \frac{\gamma}{(\sqrt{4\pi}r_C)^d}\cdot\frac{m_\mu^2}{m_0^2}\cdot\Big(1-2\theta(0)\Big)}$$

Flavor evolution:

$$P^{CSL}_{M^0\to M^0/\bar{M}^0}(t) = \frac{e^{-(\Gamma_L+\Gamma_L^{CSL})t}+e^{-(\Gamma_H+\Gamma_H^{CSL})t}}{4}\cdot\left\{1\pm\frac{\cos(\Delta m t)}{\cosh(\frac{(\Gamma_L+\Gamma_L^{CSL})-(\Gamma_H+\Gamma_H^{CSL})}{2}\cdot t)}\cdot e^{-\frac{\gamma}{(\sqrt{4\pi}r_C)^d}\frac{(\Delta m)^2}{2\,m_0^2}t}\right\}$$

→disentangles effect on interference and decay!!!

$$\frac{\Gamma_L^{CSL}-\Gamma_H^{CSL}}{\Gamma_L^{CSL}+\Gamma_H^{CSL}} \overset{\theta(0)\neq\frac{1}{2}}{=} \frac{m_H^2-m_L^2}{m_H^2+m_L^2} = \begin{cases}\text{K-mesons: } 0.996564\left\{\begin{array}{l}+1.27078\cdot10^{-5}\\-1.28124\cdot10^{-5}\end{array}\right.\\[2ex] \text{D-mesons: } 1.29\left\{\begin{array}{l}+0.0014\\-0.0018\end{array}\right.\\ B_s\text{-mesons: } 1.124\left\{\begin{array}{l}+0.011\\-0.011\end{array}\right.\end{cases}$$

[unpublished]

COLLAPSE MODELS can dynamically generate decay!

Summary

- The physics of the noise field can be/has to be investigated
- Rules the dynamic & in particular can generated the decay property
- The measurement process has to be included!

Outlook:

What does the statistics (PEP) imply?

Thank you for Your attention!

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