Quantum Measurement Theory from Renormalization Group perspective

A. Jakovác

Dept. of Atomic Physics
Eotvos Lorand University Budapest

Outlines

Outlines

Quantum Mechanics is a consistent, robust theory with few assumptions/axioms

- states are normalized elements $\in H_{ph} \subset H$ Hilbert space
- physical transformations are Hilbert-space homomorphisms:
  $H_{ph} \to H_{ph} \quad \Rightarrow \quad$ (anti) unitary linear transformations
- trf. of states and operators: $|\psi'\rangle = U|\psi\rangle$, $A' = U^\dagger A U$
- continuous unitary groups (Lie-groups): $U = e^{-i\omega_a T_a}$
  $\Rightarrow$ generators T_a hermitian

Special 1-parameter/commutative Lie-groups

- *time translation*, its generator (def.) Hamiltonian

$$e^{-i\hat{H}t}|\psi\rangle = |\psi, t\rangle \quad \Rightarrow \quad i\partial_t|\psi\rangle = \hat{H}|\psi\rangle$$

- *space translation*, its generator (def.) momentum

$$\delta\hat{q} = i\delta a[\hat{p}, \hat{q}] = \delta a \quad \Rightarrow \quad [\hat{q}, \hat{p}] = i$$

Measurement

Perform a transformation which influences the system the least (infinitesimal trf.), and detect the change of the state:
$i\delta|\psi\rangle = \varepsilon T\,|\psi\rangle \quad \Rightarrow \quad$ generator represents a measurement.

- If $i\delta|\psi\rangle = \lambda\varepsilon\,|\psi\rangle$ (eigenstate) then the transformation changes only the phase of the system
  $\Rightarrow$ result of measurement can be represented by a number
  $\Rightarrow$ value of the measurement: λ

But what happens if $i\delta|\psi\rangle \not\sim |\psi\rangle$? In a real experiment we still measure a number! How can we obtain it?

Measurement postulate:

- the possible measurement values are the eigenvalues of the infinitesimal generator $T|n\rangle = \lambda_n |n\rangle \quad \Rightarrow \quad$ usually quantized
- the quadratic norm of the eigenvectors $|\langle\psi|n\rangle|^2$ provides the *probability* to measure λ_n.
- If we measured λ_n, then the system continues time evolution from $|n\rangle$ (*wave function reduction*).

Measurement postulate:

- the possible measurement values are the eigenvalues of the infinitesimal generator $T\,|n\rangle = \lambda_n\,|n\rangle \quad \Rightarrow \quad$ usually quantized
- the quadratic norm of the eigenvectors $|\,\langle\psi|n\rangle\,|^2$ provides the *probability* to measure λ_n.
- If we measured λ_n, then the system continues time evolution from $|n\rangle$ (*wave function reduction*).

Challenge

Measurement is non-deterministic, non-causal! How can one build a consistent theory?

$$\Downarrow$$

Interpretation

Interpretation

A QM interpretation should give an account to the questions like:

- causal vs. probabilistic: could it be possible to predict the result of a QM measurement?
- classicality vs. quantum: how local/macroscopic realism appears in a measurement (cf. EPR paradox, Bell-inequalities, Leggett-Garg inequalities, hidden parameters)

  (A. Leggett and A. Garg, PRL 54 (1985), M. Giustina et. al., PRL 115, 250401 (2015))
- what is a measurement device? Schrödinger's cat, conscious observer, detectors, or even spont. symmetry breaking (SSB)?
- time scale and mechanism of wave function reduction?
- QM measurements: spin (Stern-Gerlach experiment), position, decay of unstable nuclei, etc.

Copenhagen interpretation

- measurement (observation) is not causal, inherently random.
- throw away deterministic time evolution!
- wave function reduction is instant, and it happens at once in the whole space
- what is a measurement device?
  Neumann-Wigner interpretation: consciousness causes measurement.

Other interpretations

(cf. A.J. Leggett, J. Phys.: Condens. Matter 14 (2002), 415)

- statistical interpretations $\Rightarrow$ improved versions of the Copenhagen interpretations
- many-worlds interpretation: many worlds, in each of them wave function reduction, but in a collection of them all possibility occurs
  (H. Everett H, Rev. Mod. Phys. 29 (1957) 454)
- objective wave function reduction: nonlinear/non-unitary time evolution
  - due to gravity effects (Diosi-Penrose-interpretation)
    (L. Diosi, J.Phys.Conf.Ser. 701 (2016) 012019, [arXiv:1602.03772])
  - effective approaches: Caldeira-Leggett model
    (O. Caldeira, A.J. Leggett, Ann.Phys. 149, 374 (1983))
    Lindblad/Gross-Pitaevski approach
    (P. Vecsernyes, J.Math.Phys. 58 (2017) 10, 102109, arXiv:1707.09821)

Corollary

Within strict QM the explanation of decoherence phenomenon requires external influence/new physics.

Outlines

Quantum Field Theory (QFT) point of view

- QFT: ambition to explain the whole world from strings to stars
- everything should come from TOE (or at from least Standard Model), no independent physics should appear at nano scales
- linear theory $\Rightarrow$ Path Integral
- QM is an approximation, where one particle propagation does not mix with multiparticle propagation.
  One particle propagator equation is not linear!
  (Dyson-Schwinger equations)

- QFT: ambition to explain the whole world from strings to stars
- everything should come from TOE (or at from least Standard Model), no independent physics should appear at nano scales
- linear theory $\Rightarrow$ Path Integral
- QM is an approximation, where one particle propagation does not mix with multiparticle propagation.
  One particle propagator equation is not linear!
  (Dyson-Schwinger equations)

Educated guess

Exact solution of QFT for the measurement device would provide decoherence / "wave function reduction"

Why measurement theory is much harder than QCD?

- both require the exact solution of a field theory
- both are complicated many-body problems that can only treated numerically
- prediction of proton mass is possible, because we know microscopically what a proton is
- a measurement device shows properties that is completely irrelevant from the microscopic point of view (what is the difference between a metal tube and a Geiger-Müller counter?)

Lesson

Direct microscopical simulation is not an option.

A pragmatic approach

- Start from a complete quantum description of the measurement device $\Rightarrow$ H_{tot}
- The measurement device contains a lot of unimportant details (screws, geometry, type of matter we use, etc.)
- Leave out (integrate out) these details! $\Rightarrow$ H_{eff} (renormalization group philosophy)

A pragmatic approach

- Start from a complete quantum description of the measurement device $\Rightarrow$ H_{tot}
- The measurement device contains a lot of unimportant details (screws, geometry, type of matter we use, etc.)
- Leave out (integrate out) these details! $\Rightarrow$ H_{eff} (renormalization group philosophy)

Finally we arrive at a minimal choice for H_{eff}!

- QCD at low energy $\Rightarrow$ hadron physics
- ferromagnets at large distance $\Rightarrow$ Ising/Heisenberg model

A pragmatic approach

- Start from a complete quantum description of the measurement device $\Rightarrow$ H_{tot}
- The measurement device contains a lot of unimportant details (screws, geometry, type of matter we use, etc.)
- Leave out (integrate out) these details! $\Rightarrow$ H_{eff} (renormalization group philosophy)

Finally we arrive at a minimal choice for H_{eff}!

- QCD at low energy $\Rightarrow$ hadron physics
- ferromagnets at large distance $\Rightarrow$ Ising/Heisenberg model

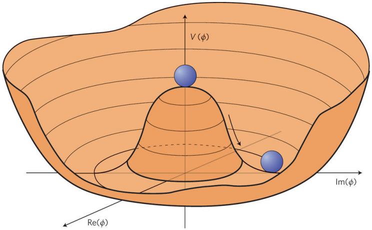
Question

What is the effective theory of Quantum Measurement?

Outlines

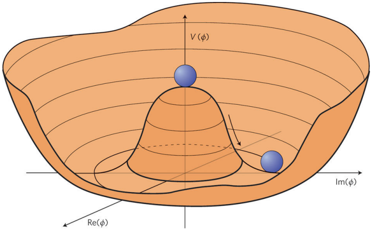
Spontaneous Symmetry Breaking (SSB)

- SSB: the microscopic theory possesses a symmetry which is not manifested in the IR observables
- usual interpretation: the ground state does not respect the symmetry $\Rightarrow$ minima of $\Gamma[\Phi]$



Spontaneous Symmetry Breaking (SSB)

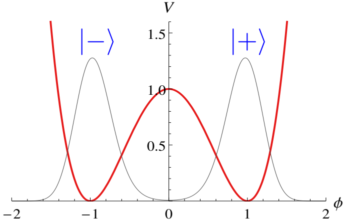
- SSB: the microscopic theory possesses a symmetry which is not manifested in the IR observables
- usual interpretation: the ground state does not respect the symmetry $\Rightarrow$ minima of $\Gamma[\Phi]$



- consistency question: ground state in QM is unique
  (L. Gross, J. of Func.Anal. 10 (1972) 52)
  why we do not see the ground state?

Breaking discrete symmetry

Example 1: 2-state system with a double-well potential



- States corresponding to classical minima are $|+\rangle$ and $|-\rangle$
- Ground state is $|0\rangle = \frac{|+\rangle + |-\rangle}{\sqrt{2}}$, symmetric, entangled.
- $E_0 < E_\pm$, but the difference can be small $\Rightarrow$ for $|\Psi\rangle = \alpha\,|+\rangle + \beta\,|-\rangle \quad \Rightarrow \quad E_0 \approx E_\Psi$
- Experiments: local spins, domains $|++---+\dots\rangle$ instead of $\alpha\,|+++\dots\rangle + \beta\,|----\rangle$.

Breaking a continuous symmetry

Example 2: QFT with continuous symmetry, e.g. O(2) model:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \Phi_n)^2 - \frac{m^2}{2}\Phi_n^2 + \frac{\lambda}{24}(\Phi_n^2)^2$$

- quantum state corresponding to a classical minimum

$$|SSB\rangle = |\eta\rangle_{k=0} \otimes |0\rangle_{k_1} \otimes |0\rangle_{k_2} \otimes \dots ,$$

  coherent state $\otimes$ vacuum states.
- Goldstone-theorem: continuous spectrum around $|SSB\rangle$
- We cannot single out a state from a continuum!
  (convolution of creation function and density of state, locality)
  $\Rightarrow$ $|SSB\rangle$ will spread/decay!
- Therefore Goldstone-theorem $\leftrightarrow$ stable SSB
  we observe both beacause continuous local measurements.

Breaking a continuous symmetry

Example 2: QFT with continuous symmetry, e.g. O(2) model:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \Phi_n)^2 - \frac{m^2}{2}\Phi_n^2 + \frac{\lambda}{24}(\Phi_n^2)^2$$

- quantum state corresponding to a classical minimum

$$|SSB\rangle = |\eta\rangle_{k=0} \otimes |0\rangle_{k_1} \otimes |0\rangle_{k_2} \otimes \ldots ,$$

  coherent state $\otimes$ vacuum states.
- Goldstone-theorem: continuous spectrum around $|SSB\rangle$
- We cannot single out a state from a continuum!
  (convolution of creation function and density of state, locality)
  $\Rightarrow$ $|SSB\rangle$ will spread/decay!
- Therefore Goldstone-theorem $\leftrightarrow$ stable SSB
  we observe both beacause continuous local measurements.

Consequence

SSB is a classical phenomenon with quantum origin $\Rightarrow$ serves as an effective model for Quantum Measurement!

Describe SSB with purely quantum tools, no classical fields

- Usual approach: first determine $\Gamma[\Phi]$, later the ground state
- Quantum treatement: Φ is a bookkeeping variable, $\Gamma[\Phi]$ is the 1PI action around the vacuum state.
- $\Rightarrow$ symmetry breaking explicitly appears in the action.
- Remnant of the symmetry: Ward identities.

In Φ^4 theory

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{M^2}{2}\Phi^2 - \frac{g}{6}\Phi^3 - \frac{\lambda}{24}\Phi^4,$$

and the Ward identity requires

$$g^2 = 3\lambda M^2 \quad \Rightarrow \quad R^2 = \frac{g^2}{3\lambda M^2} = 1.$$

Evolution equations of the couplings

- Treatment technique: functional renormalization group
- LPA approximation $\Rightarrow$ evolution equation for the potential

$$\partial_k U = \frac{1}{2}\hat{\partial}_k \int \frac{d^d p}{(2\pi)^d} \ln(p_k^2 + \partial_\Phi^2 U), \qquad p_k = \max(|p|, k)$$

where U effective potential

- Expand left and right hand side using the Ansatz
- Match the coefficients; take into account Ward identity

Result $\omega^2 = k^2 + M^2$

$$\partial_k M^2 = \frac{k^{d+1}}{\omega^4}\left(-\lambda + \frac{g^2}{M^2}(1 + \frac{M^2}{\omega^2})\right)$$

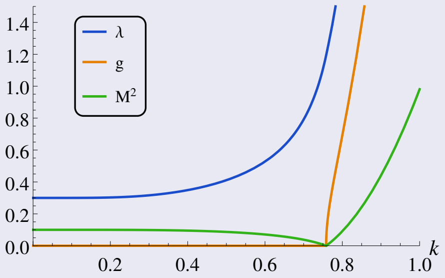
$$\partial_k \lambda = \frac{6k^{d+1}\lambda^2}{\omega^6}$$

$$\partial_k g = \frac{gk^{d+1}}{\omega^6}\left[\frac{9\lambda}{2} + \frac{g^2\omega^2}{3M^4}\right]$$

Results of the scalar model

Renormalized parameters: $\lambda_0 = 0.3$, $\frac{M_0^2}{\Lambda^2} = 0.1$, $g_0 = \pm 0.001$

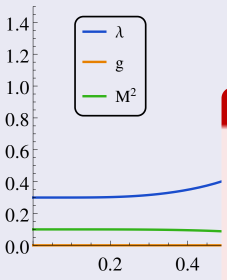
Mass and couplings



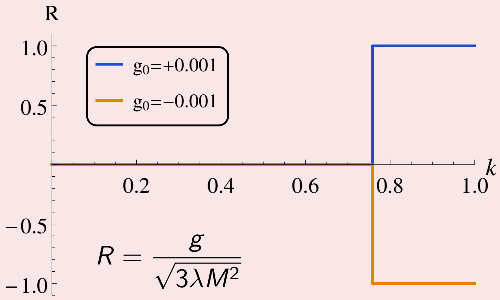
Results of the scalar model

Renormalized parameters: $\lambda_0 = 0.3$, $\frac{M_0^2}{\Lambda^2} = 0.1$, $g_0 = \pm 0.001$

Mass and couplings



The Ward-identity ratio



$$R = \frac{g}{\sqrt{3\lambda M^2}}$$

Lessons to be generalized

- fully deterministic
- phase transition at a certain scale (at $k_{ph} = 0.7581430242$)
- described SSB through couplings, without any reference to (classical) fields
- "order parameter" is also a coupling: g, or R
- initiation of phase transition: $m^2 \to 0$.
- partial fixed points in R: near phase transition point

$$\partial_t R^2 = \frac{C}{m^2} R^2 (1 - R^2), \qquad \partial_t m^2 = C(1 - 3R^2),$$

$(t = \ln k)$ $\Rightarrow$ $R = 0, \pm 1$ partial fixed points.

- instead of inequivalent vacua $\to$ multiple fixed points
- symmetry is represented on the set of fixed points
- changing between fixed points is very fast ($R'(k_{ph}) = 1.1 \cdot 10^8$!)

Outlines

Elements of quantum measurement effective theory

- (generalized) coupling R (not necessarily 1D real) corresponding to the measurement operator
- A "timer" coupling m^2 initiating the measurement
  - geometric process, e.g. flying towards the device
  - internal process, e.g. in a particle decay
- Measurement process: R reaches partial fixed point

  $\Rightarrow$ in later times their value is fixed, R is "measured"

  $\Rightarrow$ only a part of the system will be measured

Corollary

Each classically distinguishable state corresponds to a **separate partial fixed point** of the general effective action, these can be characterized by the fixpont value of R.

Elements of quantum measurement effective theory

- symmetry is represented in the collection of fixed points, it is explicitly broken in any of them

Elements of quantum measurement effective theory

- symmetry is represented in the collection of fixed points, it is explicitly broken in any of them
- interpretation of time
  - pure FRG: start from an UV scale, build up correlations, arrive at IR (partial) fixed point; assignment $t = \ln k$
    (D. Boyanovsky, Annals Phys. 307 (2003) 335-371)
  - practical approach: time can be an adiabatic variable, modifying the stability of fixed points.

Elements of quantum measurement effective theory

- symmetry is represented in the collection of fixed points, it is explicitly broken in any of them
- interpretation of time
  - pure FRG: start from an UV scale, build up correlations, arrive at IR (partial) fixed point; assignment $t = \ln k$
    (D. Boyanovsky, Annals Phys. 307 (2003) 335-371)
  - practical approach: time can be an adiabatic variable, modifying the stability of fixed points.
- status of QM:
  - can be a good approximation in the UV fixed point
  - in general one/few-particle wave function not relevant
  - instead wave function reduction abrupt change from one fixed point to another

Elements of quantum measurement effective theory

- symmetry is represented in the collection of fixed points, it is explicitly broken in any of them
- interpretation of time
  - pure FRG: start from an UV scale, build up correlations, arrive at IR (partial) fixed point; assignment $t = \ln k$
    (D. Boyanovsky, Annals Phys. 307 (2003) 335-371)
  - practical approach: time can be an adiabatic variable, modifying the stability of fixed points.
- status of QM:
  - can be a good approximation in the UV fixed point
  - in general one/few-particle wave function not relevant
  - instead wave function reduction abrupt change from one fixed point to another
- causality
  - fully deterministic process
  - $R \ll 1$ near the UV fixed point $\Rightarrow$ initially unmeasureable
  - for all practical purposes it is random.

Classical analogy

analogies: pencil placed on its tip, coin flipping, chaos/bifurcation

pencil tumbles deterministically, but still unpredictably

$\Rightarrow$ this happens in FRG in the coupling constant space

Comparison to other approaches

- Copenhagen/statistical interpretation: the value of the irrelevant couplings in the QM state decide which fixed point is chosen $\Rightarrow$ practically statistical
- Quantum multiverse: instead of multiple universes: multiple fixed points
- Objective wave function reduction: the process is fully deterministic (but wave function is not a relevant quantity)
- Decoherence picture: there is a point where the QM fixed point becomes unstable $\Rightarrow$ different "UV" and "IR" behavior.

Outlines

Incorporate state into FRG

- $|\Psi\rangle$ state of the system, and we associate $|\eta_n\rangle$ states to the measurement operator
- $\mathcal{A}_n = \langle\eta_n|\Psi\rangle$: influence interaction with the device
  (play no dynamical role in QM fixed point!)
- they change the probability distrbution of measurement
  $\Rightarrow$ explicit symmetry breaking

Let us consider a simple model:

- each possible measured output has an own timer $m_n \in \mathbb{C}$
- m_n is irrelevant in the UV fixed point
  $\Rightarrow$ its distribution is symmetric Gaussian
- near the phase transition, where $\mathcal{A}_n \approx$ constant, we consider the timer evolution

$$\partial_t m_n^2 = -C|\mathcal{A}_n|^2$$

$\Rightarrow$ explicit breaking due to the overlap

Which fixed point is chosen?

Measurement selection

The mode whose timer runs down the first will be measured!

- $t_n \sim \left|\frac{m_n}{\mathcal{A}_n}\right|^2 \quad \Rightarrow \quad$ the probability that t_1 is the minimal value:

$$P\left(\left|\frac{m_1}{\mathcal{A}_1}\right|^2 < \left|\frac{m_n}{\mathcal{A}_n}\right|^2_{n>1}\right) = \frac{|\mathcal{A}_1|^2}{\sum_{n=1}^{N} |\mathcal{A}_n|^2}$$

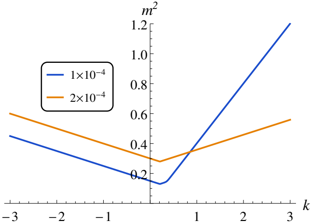
  it is just the expected result!

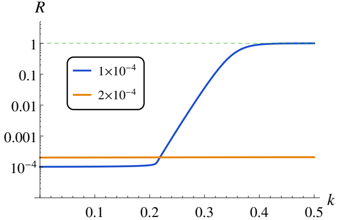
- distribution of the lifetime:

$$\mathcal{P}(t) \sim e^{-|\mathcal{A}|^2 t}$$

  Poissonian distribution.

Result of a toy model with backreaction from the measured mode





$k \to 0.5 + 10^{-4} k$

Proofs:

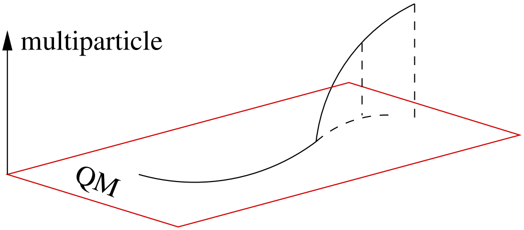
$$P\left(\frac{|x_1|^2}{P_1} < \frac{|x_n|^2}{P_n}\right) \sim \int d^2x_1 \dots d^2x_n \, e^{-\frac{1}{2\sigma^2}(|x_1|^2+\dots|x_n|^2)} \prod_{n=2} \Theta\left(\frac{|x_n|^2}{P_n} - \frac{|x_1|^2}{P_1}\right)$$

$$= \int_0^\infty dr_1 e^{-r_1} \prod_{n=2} \int_{\frac{P_n r_1}{P_1}}^\infty dr_n e^{-r_n} = \int_0^\infty dr_1 e^{-r_1(1+\sum \frac{P_n}{P_1})} = \frac{P_1}{\sum_{n=1} P_n}$$

$$\mathcal{P}(t) \sim \int d^2x \, e^{-\frac{1}{2\sigma^2}|x|^2} \delta\left(t - \frac{|x|^2}{P}\right) \sim e^{-Pt}.$$

Wave function reduction

- QM from the point of view of QFT: Gaussian/free theory
  initial state is marginal:
  $\partial_t |\Psi\rangle = -iH |\Psi\rangle$ neither grows nor decreases
- Near the device: we leave the space of QM operators; but we can project back the running theory to QM:
  describes how the system would evolve if we interrupted the measurement process
  $\Rightarrow$ not QM-unitary time evolution



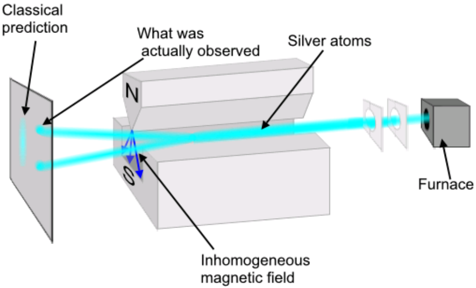
- heuristically: $(1 - R^2) |\Psi\rangle + R_n^2 |\eta_n\rangle \quad \Rightarrow$ very fast process!

Outlines

Experiment: e^- in x-polarized spin state, eg. $|\psi\rangle = \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}}$,

z-inhomogeneous magnetic field separates the $|\uparrow\rangle$ and $|\downarrow\rangle$ components, detect the incoming particles.

Result: only one of 2 detectors will detect particle, the chance to detect is 50%.



Interpretation: time evolution is slow $\Rightarrow$ adiabatic approach

- Creation of e^-: e.g. by photoeffect.
- Flying single e^-: only one fixed point, where the 1-e^- propagation is a good appr. $\Rightarrow$ $\exists\, e^-$ wave function state of environment is irrelevant for the e^-.
- e^- near/in the device: complicated system with
  – one unstable fixed point of the incoming e^- (UV)
  – two stable fixed points of the measured e^- (IR1, IR2)
  1-e^- propagation (QM) is bad appr. $\Rightarrow$ $\nexists$ wave function
- RG trajectory: starts from UV fp., fast approaches one of the IR fp.s, depending on the state of the complete system system-wide "hidden variables" $\Rightarrow$ no macroscopic realism!
- if e^- goes on: the RG flow continues from just one of the fixed points, with definite spin.

Proposition: take a cat, put it into a box with a bomb coupled to unstable U-atoms; if the U-atom decays, the bomb explodes, the cat dies

Challenge: the U-atom is in a mixture of stable and decayed states $\Rightarrow$ is the cat also in a mixture of living and dead state? What does the cat perceive?

Schrödinger's cat

Proposition: take a cat, put it into a box with a bomb coupled to unstable U-atoms; if the U-atom decays, the bomb explodes, the cat dies

Challenge: the U-atom is in a mixture of stable and decayed states $\Rightarrow$ is the cat also in a mixture of living and dead state? What does the cat perceive?

Interpretation of Schrödinger's cat thought experiment

Interpretation: there are two fixed points in the system:

- living cat with U-atom and intact bomb (UV)
  has one relevant direction! the initial condition decide how long we stay here
- dead cat with decay products and exploded bomb (IR)
  IR stable fixed point
- the crossover is explosively fast

Consequences

- we are always around one fixed point
- no cat wave function (bad approximation of QFT), no living dead quantum state
  Remark: no $|U\rangle + |\text{decayed } U\rangle$ mixed state either
  $\Rightarrow$ elements of different fixed point Hilbert spaces!

Outlines

Conclusions

- Effective model for Quantum Measurement: SSB
  - "timer" $m_n \in \mathbb{C}$ initiates measurement
  - "measurement coupling" $R_n \in \mathbb{C}$ chooses one IR end state
- UV fixed point $\Rightarrow$ to QM approximation
- IR partial fixed points $\Rightarrow$ measured/classical states
- quantum state: explicit symmetry breaking in timer
  - timer counts down $\Rightarrow$ measurement
  - $\sim |\langle \eta_n | \Psi \rangle|^2$ measurement probability
  - Poissonian distribution for lifetimes
- many-world $\rightarrow$ many fixed points
- the scale/time dependence is deterministic
- global "hidden variables" $\Rightarrow$ no macroscopic realism!
- measurement coupling is very small in the UV fixed point
  $\Rightarrow$ for all practical purposes it is random

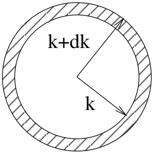
In nonlinear systems (non-quadratic Hamiltonian) radiative corrections result in

- change in the value of the coupling constants of the fundamental theory
- introduce new interactions

In nonlinear systems (non-quadratic Hamiltonian) radiative corrections result in

- change in the value of the coupling constants of the fundamental theory
- introduce new interactions

Take into account radiative corrections down to a certain scale!



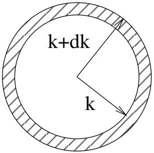
Functional Renormalization Group (FRG)

In nonlinear systems (non-quadratic Hamiltonian) radiative corrections result in

- change in the value of the coupling constants of the fundamental theory
- introduce new interactions

Take into account radiative corrections down to a certain scale!

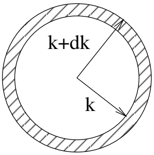
Consequence: the operators ("phenomena") that are important to describe physics, change with scale.

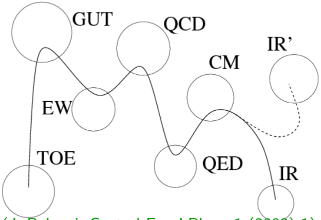


In nonlinear systems (non-quadratic Hamiltonian) radiative corrections result in

- change in the value of the coupling constants of the fundamental theory
- introduce new interactions

Take into account radiative corrections down to a certain scale!
Consequence: the operators ("phenomena") that are important to describe physics, change with scale.





(J. Polonyi, Central Eur.J.Phys. 1 (2003) 1)

Functional Renormalization Group (FRG)

- Exact evolution equation
  for the scale dependence of the effective action (Wetterich-eq.)
  $$\partial_k \Gamma_k = \frac{i}{2} \hat{\partial}_k \, \mathrm{Tr} \ln(\Gamma_k^{(1,1)} + R_k)$$
  Γ_k effective action, k scale parameter, R_k regularization $\hat{\partial}_k = R_k' \frac{\partial}{\partial R_k}$
- fixed points: $\partial_k \Gamma_k = 0$
- around fixed points the effective action can be represented by the relevant operators only

  $\Rightarrow$ FRG Ansatz/effective theory
- scale evolution connects the fixed point regimes

Most important message

The physics should be represented by the relevant operators of the actual fixed point describing the phenomena under investigation.