Conceptual issues in quantum cosmology

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- Boundary conditions (afternoon contribution)
- Singularity avoidance
- Arrow of time
- Predictions of quantum cosmology
- Decoherence in quantum cosmology

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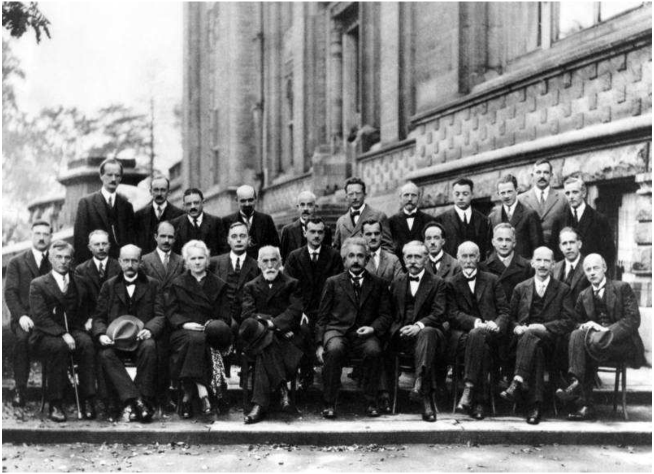
Fifth Solvay Conference, Brussels, October 1927



The physical essence of quantum theory

- Physical states are described by wave functions Ψ, which are defined on the space of all configurations that a system can assume (‘configuration space’)

- Relation to classical concepts proceeds via the probability interpretation: the absolute square of Ψ gives, for example, the probability to find in a ‘measurement’ a ‘particle’ in a given small volume

The superposition principle

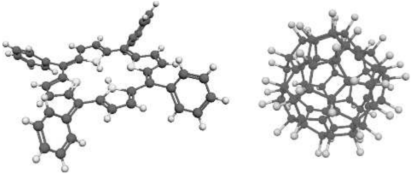
- Let Ψ_1 and Ψ_2 be physical states. Then, $\alpha\Psi_1 + \beta\Psi_2$ is again a physical state.
  For more than one degree of freedom, this leads to the entanglement between systems (*Verschränkung*).
- Linearity of the Schrödinger equation: the sum of two solutions is again a solution.

'Classical states' form only a tiny subset in the space of all possible states.

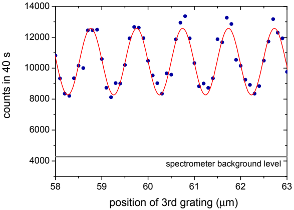
Erwin Schrödinger 1935:

I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ-functions) have become entangled. . . . Another way of expressing the peculiar situation is: the best possible knowledge of a *whole* does not necessarily include the best possible knowledge of all its *parts*, even though they may be entirely separated . . .

A particular example (Vienna experiment)



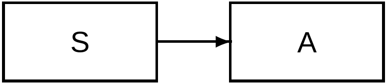
tetraphenylporphyrin ($C_{44}H_{30}N_4$) (left) and fluorofullerene $C_{60}F_{48}$ (right)



Interference pattern of tetraphenylporphyrin

L. Hackermüller *et al*., *Phys. Rev. Lett.* **91** (2003) 090408

The measurement problem



$$|n\rangle|\Phi_0\rangle \xrightarrow{t} |n\rangle|\Phi_n(t)\rangle$$

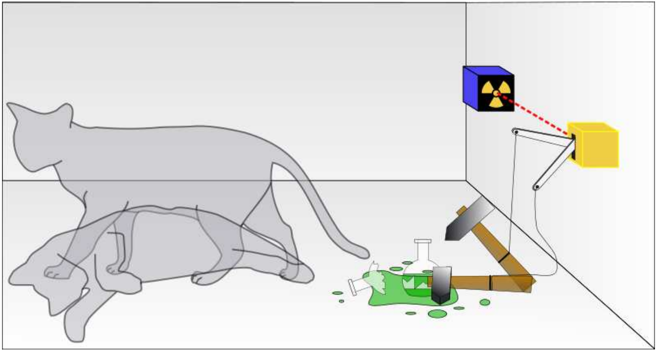
The superposition principle leads to

$$\left(\sum_n c_n|n\rangle\right)|\Phi_0\rangle \xrightarrow{t} \sum_n c_n|n\rangle|\Phi_n(t)\rangle$$

But this is a macroscopic superposition!

Collapse of the wave function? (John von Neumann 1932)

Schrödinger’s cat



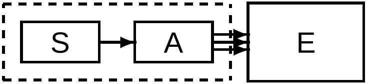
The classical appearance of our world

Einstein an Born, 1.1.1954:

Es ist mit den Prinzipien der Quantentheorie unvereinbar zu fordern, daß die Ψ-Funktion eines “Makro”-Systems bezüglich der Makrokoordinaten und -impulse “eng” sein soll. Eine solche Forderung ist unvereinbar mit dem Superpositionsprinzip für Ψ-Funktionen.

Dann muß man sich aber sehr wundern, daß ein Stern oder eine Fliege, die man zum ersten Mal sieht, so etwas wie quasilokalisiert erscheinen . . .

The key: Inclusion of the environment (Zeh 1970)



Now, the superposition principle leads to

$$\left(\sum_n c_n|n\rangle|\Phi_n\rangle\right)|E_0\rangle \quad \xrightarrow{t} \quad \sum_n c_n|n\rangle|\Phi_n\rangle|E_n\rangle$$

All *local* observations follow from the reduced density matrix of system plus apparatus:

$$\rho_{\mathrm{SA}} \approx \sum_n |c_n|^2|n\rangle\langle n| \otimes |\Phi_n\rangle\langle\Phi_n| \qquad \text{if} \qquad \langle E_n|E_m\rangle \approx \delta_{nm}$$

“The interferences exist, but they are not *there*.”

Decoherence

Decoherence: Irreversible emergence of classical properties through the unavoidable interaction with the environment.

Objects then *appear* classically, although they are fundamentally described by quantum theory.

Important conceptual and quantitative developments in the early years by Zeh (1971, 1973), Kübler and Zeh (1973), Zurek (1981, 1982), Harris and Stodolsky (1981, 1982), Caldeira and Leggett (1983), Joos (1984), Joos and Zeh (1985), . . . ;

experimental tests since 1996 (in part by the winners of the Nobel prize 2012: S. Haroche and D. Wineland)

The preferred basis

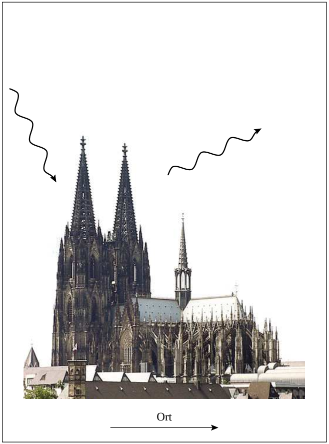
The interaction with the environment distinguishes locally at the system a basis of states that is stable in time (‘robust’):

‘pointer basis’ (Zurek 1981),   ‘memory states’ (Zeh 1973)

$$\boxed{H = H_{\mathcal{S}} + H_{\mathcal{E}} + H_{\mathcal{S}\mathcal{E}}}$$

- If $H_{\mathcal{S}\mathcal{E}}$ dominates (typical situation in measurements): pointer basis given by the eigenstates of $H_{\mathcal{S}\mathcal{E}}$ (typically position);
- if $H_{\mathcal{S}}$ dominates: pointer basis given by the energy eigenstates of $H_{\mathcal{S}}$;
- In the general situation, there is a compromise between these cases, e.g. decoherence distinguishes coherent states for the harmonic oscillator.

Localization of objects



$$|x\rangle|\chi\rangle \xrightarrow{t} |x\rangle|\chi_x\rangle = |x\rangle S_x|\chi\rangle$$

Superposition leads to

$$\int \mathrm{d}^3x\ \varphi(x)|x\rangle|\chi\rangle \xrightarrow{t} \int \mathrm{d}^3x\ \varphi(x)|x\rangle S_x|\chi\rangle$$

Reduced density matrix:

$$\begin{aligned}\rho(x,x',t) &= \varphi(x)\varphi^*(x')\left\langle \chi|S_{x'}^\dagger S_x|\chi\right\rangle \\ &= \rho(x,x',0)\exp\left\{-\Lambda t(x-x')^2\right\}\end{aligned}$$

Λ: ‘Localization rate’

(Joos and Zeh 1985)

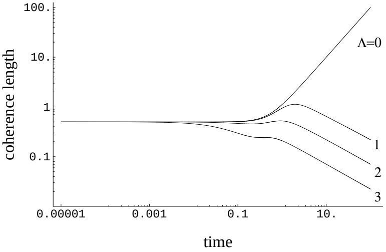
Examples for the localization rate $\Lambda\ [\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$

	$a = 10^{-3}$cm dust particle	$a = 10^{-5}$cm dust particle	$a = 10^{-6}$cm large molecule
Cosmic background radiation	10^{6}	10^{-6}	10^{-12}
Photons with 300 K	10^{19}	10^{12}	10^{6}
Sunlight (on Earth)	10^{21}	10^{17}	10^{13}
Air molecules	10^{36}	10^{32}	10^{30}
Laboratory vacuum (10^3 particles/cm^3)	10^{23}	10^{19}	10^{17}

The results of Joos and Zeh have been experimentally tested!

(Hornberger *et al*. 2003)

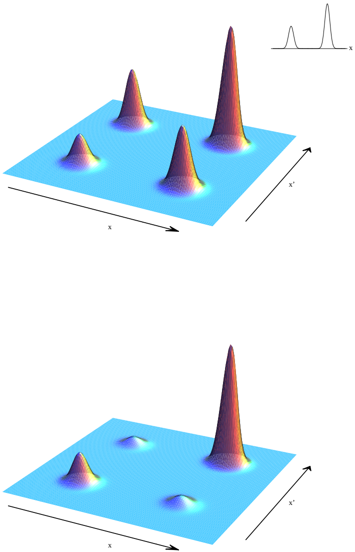
Avoidance of wave-packet dispersion



Time dependence of the coherence length (measure for the spatial extension over which an object can exhibit interference effects); except for vanishing coupling ($\Lambda = 0$), the coherence length decreases for large times.

These and the following figures are from:

E. Joos, H. D. Zeh, C. Kiefer, D. Giulini, J. Kupsch, and I.-O. Stamatescu, *Decoherence and the Appearance of a Classical World in Quantum Theory* (second edition, Springer 2003)

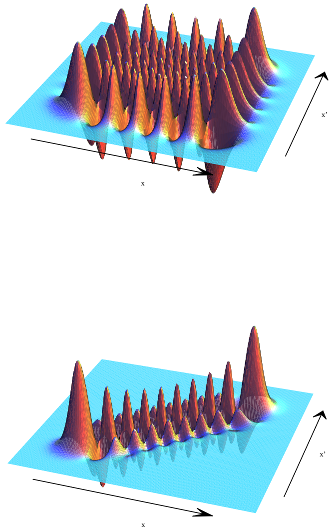


(a)

(b)

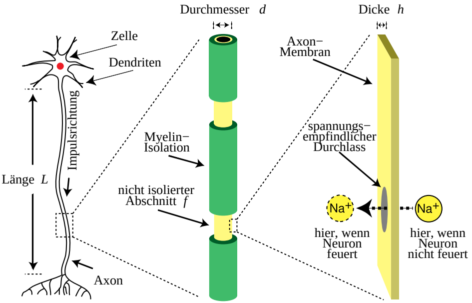
(a)

(b)



Decoherence of the $n = 9$ energy eigenstate of a harmonic oscillator

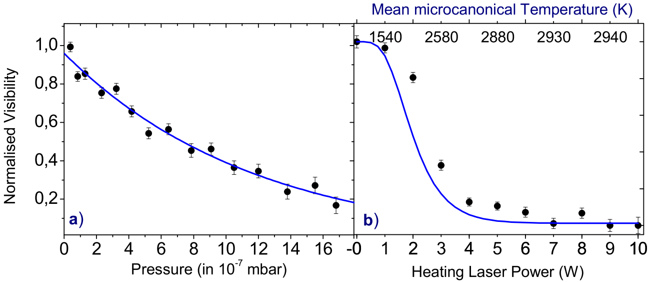
Must consciousness be described quantum mechanically?



A possible superposition between “neuron fires” and “neuron does not fire” is suppressed by decoherence so quickly that processes in the brain can be described entirely by classical physics

(M. Tegmark 2000)

Example: Decoherence of fullerenes



Left: Decoherence through particle collisions.

Right: Decoherence through heating of fullerenes.

From: M. Arndt and K. Hornberger, Quantum interferometry with complex molecules, `arXiv:0903.1614v1`

What can be understood by decoherence?

- One can understand by decoherence why certain quantum objects appear classically.
- Classical properties are not an attribute of an isolated system; they are ‘defined’ by the environment.
- The decoherence time is tiny in macroscopic situations; this leads to the appearance of ‘events, particles, quantum jumps’, . . . (apparent collapse).
- Decoherence is experimentally well established.

What cannot be understood by decoherence?

- One cannot understand from decoherence whether the total wave function (including the environment) experiences a collapse or not.
- The attitude towards the interpretation of quantum theory is therefore to a large extent a matter of taste.
- Important open questions:
  - Why are there local observers?
  - What is the origin of irreversibility?

Interpretation of quantum theory

- The superposition principle is universally valid $\longrightarrow$ 'many-worlds interpretation' ('Everett interpretation'): the dead and the alive Schrödinger cat indeed exist simultaneously in different 'Everett branches'
- The current formalism of quantum theory must be modified in order to accommodate a collapse of the wave function such that only the dead or the alive Schrödinger cat exists
- Change of the kinematical structure (e.g. the de Broglie–Bohm theory)
- Purely operationalistic interpretations (concept of reality?)

Decoherence in quantum cosmology

In quantum cosmology, arbitrary superpositions of the gravitational field and matter states can occur. How can we understand the emergence of an (approximate) classical Universe?

Introduction of inhomogeneities

Describe small inhomogeneities by multipoles $\{x_n\}$ around the minisuperspace variables (e.g. a and ϕ)

$$\left(H_0 + \sum_n H_n(a, \phi, x_n)\right) \Psi(\alpha, \phi, \{x_n\}) = 0$$

(Halliwell and Hawking 1985)

If ψ_0 is of WKB form, $\psi_0 \approx C \exp(\mathrm{i} S_0/\hbar)$ (with a slowly varying prefactor C), one will get with $\Psi = \psi_o \prod_n \psi_n$,

$$\mathrm{i}\hbar \frac{\partial \psi_n}{\partial t} \approx H_n \psi_n$$

with

$$\frac{\partial}{\partial t} \equiv \nabla S_0 \cdot \nabla$$

t: 'WKB time' – controls the dynamics in this approximation

Decoherence in quantum cosmology

- 'System': global degrees of freedom (scale factor, inflaton field, ...)
- 'Environment': small density fluctuations, gravitational waves, ...

(Zeh 1986, C.K. 1987)

Example: scale factor a of a de Sitter universe ($a \propto \mathrm{e}^{H_{\mathrm{I}}t}$) ('system') experiences decoherence by gravitons ('environment') according to

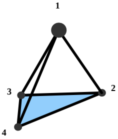
$$\rho_0(a,a') \to \rho_0(a,a')\exp\left(-CH_{\mathrm{I}}^3 a(a-a')^2\right)\ ,\ C>0$$

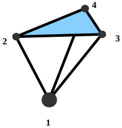
The Universe assumes classical properties at the beginning of inflation

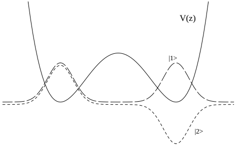
(Barvinsky, Kamenshchik, C.K. 1999)

Time from symmetry breaking

Analogy from molecular physics: emergence of chirality







dynamical origin: decoherence through scattering by light or air molecules

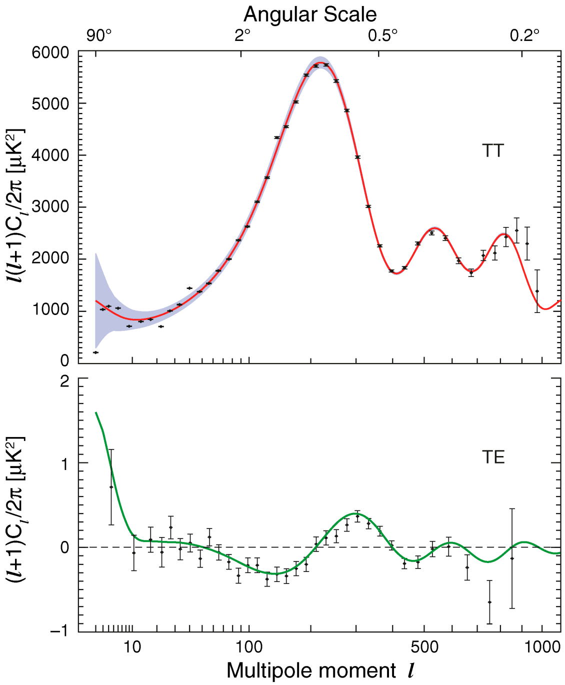
Quantum cosmology: decoherence between $\exp(\mathrm{i}S_0/G\hbar)$- and $\exp(-\mathrm{i}S_0/G\hbar)$-components of the wave function through interaction with e.g. weak gravitational waves

Example for decoherence factor:
$\exp\left(-\frac{\pi m H_0^2 a^3}{128\hbar}\right) \sim \exp\left(-10^{43}\right)$ (C.K. 1992)

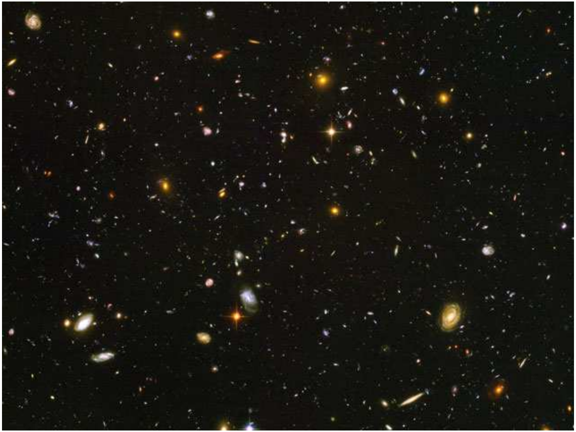
Decoherence of primordial fluctuations

During the inflationary phase (ca. 10^{-34} after the Big Bang) there is a quantum-to-classical transition for the ubiquitous fluctuations of the inflaton and the metric.
The process of decoherence is crucial in understanding this transition (C.K., Lohmar, Polarski, Starobinsky 1998, 2007).

The fluctuations then behave like classical stochastic quantities and yield the seeds for the structures in the Universe.



Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
TT
$l(l+1)C_l/2\pi\ [\mu K^2]$
2
1
0
−1
TE
$(l+1)C_l/2\pi\ [\mu K^2]$
10
100
500
1000
Multipole moment l



Cosmological constant from decoherence

Why has the cosmological constant (‘dark energy’) a small positive value?

Motivated by the cosmic landscape picture, we mimic the dark energy by a scalar field with potential wells and show that other degrees of freedom interacting with it can localize this field by decoherence in one of the wells. This then leads to a small positive energy value, in analogy to the emergence of chirality for sugar molecules.

(C.K., Queisser, Starobinsky 2011)

Decoherence in loop quantum cosmology

- Loop quantum cosmology allows for arbitrary superpositions of the triad variable
- These superpositions can become indistinguishable from a classical mixture by the interaction with fermions
- In this way, the Universe assumes a definite orientation

(C.K. and Schell 2012)

Interpretation of quantum cosmology

Almost all approaches to quantum gravity preserve the linear structure of quantum theory and thus the strict validity of the superposition principle.

Main interpretation of quantum cosmology:
Everett interpretation (with decoherence as a key ingredient)

Bryce S. DeWitt 1967:

Everett's view of the world is a very natural one to adopt in the quantum theory of gravity, where one is accustomed to speak without embarassment of the 'wave function of the universe.' It is possible that Everett's view is not only natural but essential.

- At the fundamental level of quantum gravity, there is no need for a probability interpretation, since there exist neither time nor observers.
- Time and observers appear only in the semiclassical limit; classical properties follow through decoherence.
- The probability interpretation is thus needed only in this limit and can perhaps be derived in the sense of Zurek (2005).
- The origin of the direction of time can be understood in this framework, at least in principle.

Summary

- Quantum theory can be interpreted consistently and without paradoxes as long as no fundamental classical concepts are used; such an interpretation is in accordance with all existing experiments.
- Classical behaviour can be understood by decoherence and can be experimentally explored.
- Decoherence in quantum cosmology leads to the emergence of a classical cosmological background and to the emergence of structure in the Universe