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# Roots and Fruits of Decoherence

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**Abstract.** The concept of decoherence is defined, and discussed in a historical context. This is illustrated by some of its essential consequences which may be relevant for the interpretation of quantum theory. Various aspects of the formalism are also reviewed for this purpose.

## 1. Definition of concepts

The concept of decoherence has become quite popular during the last two decades. However, while its observable consequences have now been clearly confirmed experimentally [1, 2] (see also contributions to this seminar), some misunderstandings regarding its meaning seem to persist in the literature. The phenomenon itself obviously does not depend on any particular interpretation of quantum theory, but its relevance for them may vary considerably [3, 4]. I am indeed surprised about the indifference of most physicists regarding the potential consequences of decoherence in this respect, since this concept arose as a by-product of arguments favoring either a collapse of the wave function as part of its dynamics, or an Everett-type interpretation. In contrast to the Copenhagen interpretation, which insists on fundamental classical concepts, both these interpretations regard the wave function as a complete and universal representation of reality (cf. [5]).

So let me first emphasize that by decoherence I do neither just mean the disappearance of spatial interference fringes in the statistical distribution of measurement results, nor do I claim that decoherence without additional assumptions is able to solve the infamous measurement problem by *explaining* the stochastic nature of measurements on the basis of a universal Schrödinger equation. Rather, I mean no more (and no less) than the *dynamical dislocalization of quantum mechanical superpositions*, which are defined in an abstract Hilbert space with a local basis (given by particle positions and/or spatial fields, for example). The ultimate nature of this Hilbert space basis (the stage for a universal wave function) can only be found in a unifying TOE (theory of everything).

Dislocalization arises through the formation of entanglement of any system under consideration (with states $\phi$) with another one, such as its unavoidable environment (described by states $\Phi$). This is often achieved by means of a von-Neumann type "measurement" interaction

$$\left(\sum c_i\phi_i\right)\Phi_0 \rightarrow \sum c_i\phi_i\Phi_i \quad , \tag{1}$$

which would represent a logical *controlled-not* operation in the case $i = 1, 2$ and $\Phi_0 = \Phi_1$. Ideal measurements, that is, those without recoil or change of the state $\phi_i$, define "pure decoherence". After the interaction, these superpositions still *exist*, even though they *are not there* any more [6, 7]. The difference between these two traditionally equivalent phrases reflects the essential character of nonlocal quantum reality. I am indeed convinced that the importance of decoherence was overlooked for the first 60 years of quantum theory precisely because entanglement was regarded just as an aspect of quantum mechanical methods of calculation rather than of physical reality.

Dislocalization of superpositions may be reversible ("virtual") or irreversible in practice ("real" decoherence). In the first case it would either allow the complete relocalization of the superposition ("recoherence"), or at least its reconstruction (the "quantum erasure" of measurement results). The distinction according to the reversibility or irreversibility of decoherence *explains* also the virtual versus real nature of other "quantum events", such as radioactive decay, particle creation, or excitation. For example, decayed systems remain in a superposition with their undecayed sources until partial waves corresponding to different decay times are decohered from one another. (This has the dynamical consequence of giving rise to an *exact* exponential decay law – see the contribution by Erich Joos to these proceedings.) In contrast to recoherence (complete reversal of the dislocalization), quantum erasure is compatible with the irreversible and non-unitary dynamics of open systems – related to a local entropy decrease at the cost of an entropy increase in the environment [8].

According to (1), dislocalization of superpositions requires a distortion of the environment $\Phi$ by the system $\phi$ rather than a distortion of the system by the environment (such as by classical "noise"). This leads to the important consequence that decoherence in quantum computers cannot be error-corrected for in the usual manner by means of redundant information storage. Adding extra physical quantum bits to achieve redundancy, as it would be appropriate to correct spin or phase flips *in the system*, would in general even raise the quantum computer's vulnerability against decoherence – for the same reason as the increased size of an object normally strengthens its classicality. (Error correction codes proposed in the literature for this purpose are based on the presumption of decoherence-free auxiliary qubits, which may not be very realistic.)

In special situations, decoherence may be observed as a disappearance of spatial interference fringes. Only for mass points, or center of mass positions of extended objects, are wave functions isomorphic to *spatial* waves, and only after