

DECOHERENCE?

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Planning to write a birthday note for John Klauder the first thing I tried to remember was: "when and where did I meet John the first time?". I tried hard, but I could not remember that! A possible explanation is that I am getting old, but this is an unrealistic hypothesis; usually, old men are wise men, but I feel as crazy as I always have been. I still belong to Joan Baez and John Lennon company, I still believe that *the truth will make us free, some day, that we shall overcome some day*, I still *imagine all the people living life in peace*, and my papers do not show any improvement in the Physics I used to do. This is enough to exclude that I am getting old.

There is then another hypothesis: I have known John Klauder since ever, since the time of my own, personal "big bang".

I think that I have a strong evidence that such an hypothesis is the good one. The notion of "coherence" is so deeply built in my view of the world that I cannot even think of Physics without that notion. Coherent states belong to my "imprinting experiences", they are to me like the toys of one's childhood. And *I know* that this comes to me from John Klauder work and teaching. So I have known John since "the beginning". And it must be also for that reason that I cannot take seriously people speaking of "de-coherence"! At least in the way some people speak about it.

Once I tried to do an exercise. Together with Eleonora Alfinito and with Rosario Vigiore, we tried to understand if and how the statement of a popular commercial, "the diamond is for ever", is consistent with the decoherence mechanism as it is commonly known in Quantum Mechanics.

The purely quantum phenomenon of decoherence is believed to signal in many cases the *appearance of a classical world in quantum theory*. Decoherence is normally triggered by the interaction of the system with the environment and formally consists in suppressing the off-diagonal elements of the reduced density matrix. Its effect is such that quantum superposition in the system wave function is destroyed and thus, provided the time-scale τ_{dyn} characteristic of the dynamics is much greater than the decoherence time-scale τ_{dec} , $\tau_{dyn} \gg \tau_{dec}$, the classical behavior may be approached.

Decoherence provides an interesting explanation why we do not experience superpositions of objects in the macroscopic world. In fact interaction with the environment produces decoherence in the superposition of macroscopically separate positions so that the familiar classical behavior of non-superposing macroscopic objects is obtained.

However, I also see that here a puzzle waits to be solved: if all of it is so simple, why the "diamond" does not decohere? Does it escape to such a law of Nature? Why the diamond is for ever? Are the advertisement people cheating?

If decoherence would also corrupt the beautiful diamond, the problem would be a serious one: not so much because the diamond sellers would be upset, but because our beloved wives and fiancés would give us a lot of troubles since we give them diamonds, perishable stones, as gifts. They would think that also our love is "not" lasting for ever...

The puzzle is there, and involves the actual existence of *macroscopic quantum systems*. These are systems, such as superconductors, superfluids, ferromagnets, crystals (e.g. the diamond!), presenting ordered patterns, where *coherence* over macroscopically large distances is in fact observed to be particularly stable against environment perturbations (in contrast to any decoherence process!).

Any system is made by quantum components. It is, of course, not in such a trivial sense that macroscopic quantum systems are quantum systems. These are quantum systems in the specific, non-trivial sense that their macroscopic (classical) behavior cannot be explained without recourse to quantum theory. It is then natural, and necessary, asking the question of the consistency between the decoherence phenomenon and the existence and stability of macroscopic quantum systems. This is our puzzle.

Then, with Eleonora and Rosario (Mod. Phys. Lett. B15, 127 (2001)) I went to compute the decoherence time involved in the process of the crystal formation.

To be specific, we have focused our attention on the usual chemical recipe for the formation of, e.g., the binary crystals listed in Table 1.

I want to stress that the system under study is *not* the *already formed* crystal, but the solution of ions out of which one expects (observes) the crystal will be formed.

One considers a solution (typically, the water is the solvent) of the constituent elements (e.g. a solution of Na^+ ions and Cl^- ions) and waits, in specific conditions of temperature, density, etc., till the crystallization occurs. This happens when the saturation of the solution is reached. At the crystallization point, the saturation concentrations can be quite different in different cases, depending on the crystal one wants to obtain, ranging, for example, from 1 ion of K^+ for 4 molecules of water for KF , or 1 ion of Na^+ for 10 molecules of water for $NaCl$, to 1 ion of Ag^+ for 10^8 molecules of water for $AgBr$, till 1 ion of Pb^+ for 10^{15} molecules of water for PbS . The ions in the solution are normally bound, due to Coulomb forces, to water molecules, for example the Na^+ ion is surrounded by four water molecules. The shielding of the ionic charge by the surrounding water molecules lowers the intensity of the Coulomb interaction among ions. Sometimes one adds a "germ", namely a small crystal of the same kind of the one to be formed. Such a germ will act as a catalytic structure making more favorable the aggregation, in the wanted crystal structure, of the ions in the solution. Sometimes the nucleation is simply produced by some "defect" or "impurity", e.g., on the walls of the bowl or container of the solution. One observes the crystal formation in the vicinity of these defects. At the crystallization point, lowering the temperature of the solution normally helps the

crystal formation, which can occur within a short lapse of time (from fractions of a second to several seconds) or in a longer one (from minutes to hours).

The interaction among the ions in the solution is of Coulomb type and the ion-ion collisions and the interactions with distant ions are considered to be two possible sources of decoherence. There are also other sources of decoherence such as, e.g., the interaction with the environment (the water in our case), with the crystal germ or with the defects or impurities, or else with dipole and higher moments of charge distribution. However, according to our computation, the decoherence effect from ion-ion collisions and distant ion interactions are so strong that we can neglect any other decoherence source. Moreover, it appears that the decoherence time does not strongly depend on the different concentrations of the different ionic solutions.

By using the standard formulas used in the study of the decoherence mechanism in QM (see the papers and books quoted in our paper) we obtain the decoherence time for ion-ion collisions (τ_1) and for interactions with distant ions (τ_2) in the ionic solutions for the formation of a set of crystalline binary compounds. These results are reported in the following Table 1.

Table 1. Decoherence time for ion-ion collisions (τ_1) and for interactions with distant ions (τ_2)

salts	$\tau_1/10^{-40}s$	$\tau_2/10^{-38}s$
NaF	2.6	4.9
NaCl	4.6	4.4
NaBr	5.5	4.9
NaI	7.1	5.8
KF	5.1	5.2
KCl	8.3	7.1
KBr	9.6	7.9
CsF	13.4	12.0
CsCl	17.3	21.0
CsBr	19.6	25.6
CsI	23.6	27.8
AgCl	9.5	9.2
AgBr	10.7	10.0
AgI	15.3	12.7
ZnS	7.2	7.2
PbS	16.2	14.7

According to Table 1, due to the very short decoherence time, there would be no possibility for the formation of the considered crystals to occur, which of course contradicts the common experience (in practice the crystal formation lasts for a time many orders of magnitude longer than τ_1 and τ_2 in Table 1).

According to Table 1, disappointingly, even the familiar kitchen salt $NaCl$ would not exist (it would not have enough time to be formed in its crystal form)!

I note that in the computation of the decoherence time we have used for the ions in the solution the shortest possible inter-ionic distances (and therefore the most favorable to avoid decoherence). I also remark, that in the case in which the crystal is described as a quantum mechanical n-body system, the wave functions of the constituent ions are centered at the proper lattice sites and present spatial superposition over a distances of the order of the lattice length. Then one could be tempted to mistakenly conclude that the above results could apply to the ions which form the crystals. This conclusion is, however, clearly wrong. The crystal would not even be stable in this case, in evident contradiction with common experience.

The inter-ionic distances used in our computations are of course comparable with the wavelength used in the X -ray diffraction experiments with the systems we consider, which is $\lambda \sim 1.5\text{\AA}$. This corresponds to oscillation time τ_X of the order of 0.5×10^{-18} s, much longer than $\tau_{1,2}$ in Table 1. Suppose, however, one wants to insist in using the decoherence formulas, then the X -ray typical diffraction time τ_X would turn out to correspond to an extremely diluted solution where the density n_X of the scatterer centers, say Na and Cl ions, is of the unacceptable order of 10^{-18} Kg/m^3 , and one would get the equally absurd ion spacing of the order of $a \sim 10^{-3}m = 10^7\text{\AA}$.

The only reasonable conclusion is that in the case here discussed the QM decoherence picture and formulas cannot be used. They are not consistent with familiar observations and experimental methodologies.

Our result does not mean that those QM decoherence formulas are wrong, neither, of course, it means that our system is a classical one. It means that it is wrong to apply QM to such a system: the QM description is not adequate for the *crystal formation process* (the crystal phase transition) and also for *the crystal stability* (the macroscopic quantum system).

But we did know very well all that!

One should not forget in fact that the crystal phase transition process and the crystal system are many-body *Quantum Field Theory* (not Quantum Mechanics!) problems and the binding of the atoms in the crystalline lattice is due to the long range correlation mediated by the Nambu-Goldstone (NG) bosons. In this case, the decoherence mechanism thus points to the borderline between QM and QFT.

The NG bosons are the quanta of long range correlation among the system constituents. The phonons in the crystals, the magnons in the ferromagnets, the Cooper pairs in the superconductors are examples of NG boson quanta. These quanta are of dynamical origin appearing when symmetry is spontaneously broken, namely they are not found in the symmetric or normal phases (which are typically obtained above some critical temperature). The long range correlation manifests itself in the ordering in the ground state of the non-symmetric (ordered) phase: the NG quanta are the carriers of the ordering information throughout the system. It is in this way that order is generated by the quantum dynamics and appears as a macroscopic, diffused property of the system in the non-symmetric phase.

In other words, in the ordered phase the system components get, so to say, "trapped" by the long range correlation, they cannot behave as individual particles. Some of their degrees of freedom get frozen by the NG long range correlation, which is a dynamical consequence of the "lack" (breakdown) of symmetry, and this manifests itself as the system macroscopically observable ordered patterns.

In this way we arrive at the understanding of the existence of macroscopic quantum systems. It is well known that all of this can be formally expressed in terms of *coherent* condensation of NG boson quanta in the ground state. Since these quanta are massless their coherent condensation in the lowest energy mode does not add energy to the ground state and the observed high stability of the ordered phases is thus explained. The diamond *is* for ever!

A given system thus may possess degenerate ground states each corresponding to a physically different phase in which the system may be observed under different boundary conditions. These degenerate ground states are *coherent condensed states of NG quanta*, and are each other unitarily inequivalent, i.e. it does not exist any unitary operator transforming one of them into another one.

In different words, one cannot express the ground state of a specific phase in terms of the ground state of another, different phase: the crystal ground state cannot be expressed in terms of the amorphous ground state, the superconducting ground state cannot be expressed in terms of the normal one, and so on: ordered ground states cannot be reached by building up perturbations around the non-ordered ones. We have a typical non-perturbative phenomenon. This can happen in QFT where there exist infinitely many *unitarily inequivalent* representations of the canonical commutation relations. It cannot happen in QM where all the representations are unitarily, and thus physically, equivalent (the von Neumann theorem). This is why the QM phenomenon of decoherence does not apply to macroscopic quantum systems!

Of course, besides QFT, other phenomenological treatments are also possible, and sometimes are more convenient for the practical applications. For example the treatment of a crystal as a n-body problem may turn out to be convenient for some practical computation of the crystal properties. In such a case, however, one acts at a phenomenological, descriptive level rather than at the basic level of theoretical understanding. Similarly, dealing with phase transition problems, such as the crystal formation, the transition to the superconductive or ferromagnetic phase, QM may be conveniently used for some short-cut, practical computations. However, then one might be facing some puzzling question such as the diamond/decoherence one discussed above. One should always keep in mind that a truly, correct understanding of what is going on may only be achieved by working in the QFT framework.

In conclusion, generally speaking, and contrarily to current common belief, decoherence does not necessarily signal the approaching of the classical mechanics regime; it may also signal the approaching of the QFT regime. One must carefully consider the physics of the system under study in order to correctly conclude on the implications of decoherence.

My old toys, John's coherent states, are indestructible states in the Quantum Field Theory kingdom. Thank you, John! Have my best wishes!