What Is "System": The Information-Theoretic Arguments

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Abstract The problem of "what is 'system'?" is in the very foundations of modern quantum mechanics. Here, we point out the interest in this topic in the information-theoretic context. E.g., we point out the possibility to manipulate a pair of mutually non-interacting, non-entangled systems to employ entanglement of the newly defined "(sub)systems" consisting the one and the same composite system. Given the different divisions of a composite system into "subsystems", the Hamiltonian of the system may generate in general non-equivalent quantum computations. Redefinition of "subsystems" of a composite system may be regarded as a method for avoiding decoherence in the quantum hardware. In principle, all the notions refer to a composite system as simple as the hydrogen atom.

Keywords What is system · Decoherence · Information theory

1 Introduction

A physical system is defined by its degrees of freedom (and, usually, by the conjugate momenta) and by the system's parameters (such as the mass, electric charge etc.). While this reasoning is taken for granted in the classical physics domain, it is not so in the context of quantum mechanics. E.g.—as Bohr pointed it out—quantum mechanics does not in general allow the *a priori* introduction (definition) of the system observables, that elevates almost to a paradox for the complex systems. Actually, quantum entanglement—typical for complex systems—prevents us from determining the states of the entangled subsystems. On the other side, however, without the possibility to pose (in the classical-physics-like manner) a border line between the (sub)systems, one can not even pose certain quantum mechanical problems

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(such as e.g. the measurement problem) [1]. Therefore, there is a strong need for a method determining the system's observables and the border line between the systems.

The problem of "what is 'system'?" stems from our classical intuition that deals with *objects*, and it seems natural to seek for an answer to the problem in the context of the decoherence theory—which is widely believed to be the missing link between the "quantum" and "classical" [1–4]. Following partly the reasoning of [1], an operational method for defining a subsystem is proposed in [5] that is based on the foundations of the decoherence theory [6, 7]. Fortunately enough, targeting equally the issue of the entanglement formation [8], the method of [5] may be applied even for the isolated systems. The main observation of [5] is the *relativity of the concept of physical system*. And this is the starting point of the present paper.

The system relativity assumes a redefinition of a complex system in terms of certain new subsystems: the *canonical transformations* of the degrees of freedom (and, in general, of the conjugate momenta—cf. Appendix 1) of the subsystems consisting the composite system may introduce the new subsystems, thus implementing the question "what is '(sub)system'?" [5]. To this end, the re-arrangement (or regrouping) of the subsystems of a composite system—typical for quantum measurement theory—as well as introducing the new variables of the unique subsystem are merely trivial (relative to the general (linear) canonical transformations) and will not be considered in this paper. As defined by the canonical transformations, the new "subsystems" *need not bear any intuitive contents* as "physical (sub)systems" (cf. Appendix 1).

In this paper, we make slightly a turn in our perspective to the problem. Actually, we give an information-theoretic re-formulation of the problem at issue by starting from the following plausible assumption: any reasonable definition of "system" should be based on certain *information* (about "system"). An information acquired by measurement distinguishes accessibility of the measurement i.e., accessibility of certain system's observables. And these are exactly those observables that might constitute a definition of the system.

As an output of our considerations, we point out that the relativity of the concept of "system" makes some of the aforementioned, plausible notions also to be relative; i.e., one should always *take care about the actual division* of a composite system into subsystems. Depending on the answer to the question of which division is in question, it is plausible to expect that the answers would not mutually be equivalent. E.g., neither entanglement nor quantum-computation-routes need to be equivalent for the different divisions of the composite system into subsystems. Interestingly enough, the method for defining subsystems may be considered as a method for avoiding decoherence in the quantum hardware. Finally, we briefly emphasize the relevance of our general considerations for the *realistic* physical models.

2 Hydrogen Atom as an Isolated Quantum System

Paradigmatic for our discussion is a system as simple as the hydrogen atom. Actually, we are concerned with a bipartite quantum system $\mathcal{C}$ consisting of the two subsystems, $\mathcal{A}$ and $\mathcal{B}$ ($\mathcal{C} = \mathcal{A} + \mathcal{B}$). Let us assume that the subsystems are not in any mutual interaction. Then, it is generally assumed that such a system can *not* be *directly* used for quantum information processing as long as entanglement is required for information processing.

However, as we show in the sequel, this is not necessarily the case. Actually, a proper definition of the *new subsystems* (cf. [5]), $\mathcal{E}$ and $\mathcal{F}$ of $\mathcal{C}$ ($\mathcal{C} = \mathcal{E} + \mathcal{F}$), may help in providing entanglement without introducing any interaction between $\mathcal{A}$ and $\mathcal{B}$ as well as without any

further operations exerted locally on $\mathcal{A}$ and/or $\mathcal{B}$. This observation comes *directly* from the *relativity of* the concept of physical *system* [5].

In order to make our discussion more intuitive, we shall mainly refer in this section to the model of the hydrogen atom as an isolated quantum system. Let us suppose that the system "electron + proton ($e + p$)" is an isolated quantum system out of any external field. The standard theory of the hydrogen atom (neglecting spin) gives rise to a redefinition of the atom as it is well known: "center-of-mass of the atom + the relative particle ($CM + R$)"—cf. (4), (5) as the special case of the general transformations as defined in Appendix 1. While there is the Coulomb interaction in the $e + p$ system, there is not any interaction in the system $CM + R$. The later allows one exactly to solve the problem of the internal energies of the atom by the variables separation. Apart from this mathematical subtlety, we point out a new moment in this concern.

Actually, the fact that we can define the atom (the system $\mathcal{C}$) in the two ways, $e + p$ (the interacting subsystems $\mathcal{E} + \mathcal{F}$) and $CM + R$ (the noninteracting subsystems $\mathcal{A} + \mathcal{B}$), distinguishes this issue as an issue falling within the context of the question of what is system.

The method stemming from the decoherence theory may help in this regard as pointed out in [5]. Apart from the mathematical subtleties, one may note that the *separable* (Coulomb) interaction [5] in the system $e + p$ allows re-definition of the original pair of "particles" (e and p) as the newly defined (sub)systems ($CM + R$) of the one and the same composite system—of the hydrogen atom. But, now, one may pose the question: what actually *is* the system—the electron (or the proton) or the relative particle (or the center-of-mass of the atom)? For an isolated system $\mathcal{C}$, one would expect, at least in principle, the full equivalence of the two possible divisions of the composite system into subsystems. Needless to say, this way posed, this question is the essence of the problem what is system.

As to the hydrogen atom, we know that the system R appears effectively as "system", not yet the electron. Actually, the (internal atomic) energy we measure (by detecting the photons emitted by the atom) and accessibility to measurement of the relative position of the electron—as recently demonstrated by Maeda et al. [4]—refer to the system R; the small numerical margin for distinguishing R from e is just unimportant for our discussion. Certainly, the accessible measurements (observables) provide the (accessible) information about the "system" R, and the fact that we have an information is at the hart of answering the question of what is system.

Now, neglecting the fact that the atoms are open systems (cf. Sect. 3), we may re-iterate our question: *if* the atom were an isolated system, would we ever be able positively to answer the question of what is system, or we would be able *equally* to manipulate the electron (proton) states by LOCC? Bearing in mind the (Coulomb) *interaction* (which bears separability [5, 7]) in $e + p$ system, one may expect entanglement of states of e and p. Then, by neglecting the numerical indistinguishability of the electron and R, one may wonder about the possibility to manipulate the entanglement in $e + p$ by the proper operations targeting the observables of e and/or p; certainly, such operations would require simultaneous operations on both CM and R.

From the mathematical point of view, the state of $CM + R$ system is of the separable form $|\psi\rangle_{CM}|\phi\rangle_R$, which in the position-representation becomes a product of the "wave functions" of the form $\psi(\vec{R}_{CM})\phi(\vec{r}_R)$; $\vec{r}_R \equiv \vec{r}_e - \vec{r}_p$, the states $\phi(\vec{r}_R)$ representing the "stationary" states for the atom. On the other side, due to the Coulomb interaction, the states of the $e + p$ system are expected to bear entanglement, which in the position representation obtains the form $\sum_i C_i \Psi_i(\vec{r}_e)\chi_i(\vec{r}_p)$. The fact that we deal with the unique composite system—the hydrogen

atom—stems the equality:

$$\psi(\vec{R}_{CM})\phi(\vec{r}_R) = \sum_i C_i \Psi_i(\vec{r}_e)\chi_i(\vec{r}_p). \tag{1}$$

As to the dynamics of the atom, one may write the Hamiltonian of the two divisions of the atom as follows:

$$\hat{H} = \hat{T}_{CM} \otimes \hat{I}_R + \hat{I}_{CM} \otimes (\hat{T}_R + V(\hat{r}_R)), \tag{2}$$

$$\hat{H} = \hat{T}_e \otimes \hat{I}_p + \hat{I}_e \otimes \hat{T}_p + V_{\text{Coul}}(|\hat{\vec{r}}_e - \hat{\vec{r}}_p|) \tag{3}$$

for the pair $CM + R$ and $e + p$, respectively; by $\hat{T}$ we denote the kinetic terms of the Hamiltonian, while $V(\hat{r}_R) \equiv V_{\text{Coul}}(|\hat{\vec{r}}_e - \hat{\vec{r}}_p|)$. As it is apparent, the two divisions of the composite system may be the basis of the different, *non-equivalent quantum computations* generated by the one and the same Hamiltonian $\hat{H}$. Actually, due to the lack of any interaction (and consequently of entanglement) between CM and R, one can not expect any useful *quantum* information/computation directly (i.e., without any external action) to be performed by these subsystems. On the other side, the expected entanglement between e and p may in principle be useful for the information/computation processing. Therefore, the hydrogen atom initially defined as the $e + p$ system (of mutually non-entangled, non-interacting subsystems e and p) still bears a "hidden" entanglement as well as the possibility of performing the entanglement-based quantum computations.

Operationally, in the more general terms, our question reads: along with accessibility of the observables (information) of e.g. $\mathcal{A}$, we wonder about the possibility of the information processing on the basis of accessibility of the observables of e.g. the system $\mathcal{F}$. To this end, the approach of Zanardi et al. [9] that *stipulates* the "experimentally accessible observables" seem to be an *ad hoc* not yet necessarily the general answer to the question posed. The fact we do not offer a definite answer to this question seems to be a consequence of its deep connection with the fundamental problem of what is system. Unfortunately, as we show in Sect. 3, there is an even more limiting condition that has been neglected so far in our discussion.

But the main observation may seem to be striking in the information-theoretic context: even in a system as *simple* as the (isolated) hydrogen atom, one can in principle perform the information processing by manipulating entanglement in the composite system yet dealing with the *non-interacting*, non-entangled subsystems. Needless to say, in order to do so, experimenter should be able to operate in terms of the observables of the "new" systems (cf. $\mathcal{E}$ and $\mathcal{F}$ above)—that still may be an open question of our considerations. As a consequence, the LOCC referring to the pair $e + p$ seem just to be the composite system operations relative to the pair $CM + R$, and *vice versa*—which is a natural consequence of the relativity [5] of the concept of physical system. Now, the concepts of the "composite observables"—widely used and discussed in the foundations of quantum mechanics and decoherence theory [2, 10, 11]—as well as the "local" observables become relative. E.g., the best known and studied "composite observables", the CM position coordinates [1, 2, 11] relative to the system $e + p$, become just the local observables relative to the $CM + R$ system. Certainly, a definition of the observables does not yet imply the measurement accessibility of the observables.

Finally, one may go even further in this concern by speculating in the following way: what if instead of the bipartite system $\mathcal{E} + \mathcal{F}$, one obtains a higher complexity (coarse graining) of $\mathcal{C}$, such as the one formally presented as follows: $\mathcal{A} + \mathcal{B} = \mathcal{C} = \mathcal{M} + \mathcal{N} + \mathcal{P} \dots$?

Or even more interesting: what if an initially indivisible ("elementary") "particle" can be decomposed following the recipes of the general technique for defining "(sub)systems" [5]?

In conclusion to this section, we want to emphasize that investigating the (as yet open) issue of "what is 'system'?" may in principle help in finding the easier ways and methods for manipulating quantum entanglement and for performing quantum computation yet in the seemingly simple systems. It seems that answering these questions (what is system, and which observables can operationally, e.g. by LOCC, be accessed) should be answered in parallel, and the outcome is not an easy matter to predict. Yet, it seems we have already learnt: in general, there are not *a priori* the "systems" (i.e., *a priory* inaccessible observables of the (isolated) "system")—the lesson sounding very much like the old lesson of Bohr (cf. Sect. 1) stemming from quantum complementarity.

3 The Open Systems Limitations

The hydrogen atom is an *open* system in interaction with the quantum vacuum fluctuations. Without this interaction, the stationary states of the atom would bear the full stability—as expected solely from the Schrodinger equation for the atom [12].

The presence of this environment (the vacuum fluctuations $\mathcal{V}$) gives rise to both non-stationary character of the "stationary" states of the atom and to the special status of its ground state. More precisely: the system R is in interaction with $\mathcal{V}$, leaving yet the system CM intact. The environment-induced behavior of R is then rather expected [1–3, 7] thus being the origin of the possibility to define R as "system". In other words: the environment $\mathcal{V}$ is responsible for "accessibility" of R's observables and the related information about the system R, which thus appears effectively to be a "real" physical system accessible to observation in a laboratory.

Certainly, this observation reinforces our main question: whether or not we will ever be able operationally to manipulate the pair (e, p) and to employ their (expected) quantum entanglement?

Therefore, the discussion of Sect. 2 bears certain limitation: it directly refers to the *isolated* systems, while its relevance to the context of open systems will be outlined in the sequel.

4 Extracting Information about "Subsystems"

Due to the general rules of decoherence theory: the environment selects the preferred states of the open system by effectively forbidding their coherent (linear) superpositions [3]. For an independent observer, these states (that bear certain robustness relative to the external actions) appear to be "objective", thus in effect giving rise to a basis of defining the open system.

Prima facie, it seems that the answer as to what is system is already given and the relativity of "system" might seem to be of the secondary importance. While the definition of "system" in general is far from being complete [1, 5, 13], let us focus on the task of extracting the information about the alternative subsystems, again in terms of the hydrogen atom.

The measurements of e.g. the position coordinates of both CM and R can directly lead to an information about the position of both e and p. Actually, by the use of the transformations

inverse to the well-known *canonical transformations* of coordinates of e and p:

$$\vec{R}_{CM} = (m_p \vec{r}_p + m_e \vec{r}_e)/(m_p + m_e), \tag{4}$$

$$\vec{r}_R = \vec{r}_e - \vec{r}_p \tag{5}$$

one can calculate the values for $\vec{r}_e$ and $\vec{r}_p$, in the full analogy with the classical system analysis. Thus obtained information about the position of e and p refers equally to *both*, the isolated as well as the open system.

However, as to the open systems, the operational use of such information bears a subtlety to be emphasized. Actually, in order to be able to extract further information or to manipulate the information obtained about e and/or p, one should, in general, be skilled enough to operate in the time intervals much shorter than the decoherence time referring to the decoherence of R; the decoherence induced by $\mathcal{V}$ (Sect. 3). Namely, the decoherence of R states inevitably affects the system $e + p$, possibly giving rise to affecting the entanglement in $e + p$ system. And this is a general possible obstacle for the operational information processing in the alternative subsystems of an open composite system. On the other side, as to the isolated systems—such as those dealt with in quantum information theory—there seems to be *no such obstacles* for the operational use of the relativity of "system" as distinguished in Sect. 2.

There is another yet general notion and the possible obstacle to our program of extracting information about subsystems. In general, the canonical transformations defining the different divisions of a composite system into subsystems may include the conjugate momenta of the subsystems, not only the position variables as given in (4) and (5)—cf. Appendix 1. Then, as pointed out in [5], such divisions of the composite system become mutually *complementary*: due to incompatibility of the position and momentum observables, the inverse transformations (in analogy with (4) and (5)) can not be defined (due to the *lack* of the *simultaneous* sharp values of the position and the momentum observables). Therefore, in general, even for the isolated composite system, one can not extract information about the states and/or observables of the complementary subsystems of a composite system.

However, if non-sharp (e.g. the mean) values of the position and/or of the momentum observables might be useful, then it seems that the case of the complementary subsystems reduces to the non-complementary subsystems as discussed in Sect. 2. E.g. a decay of an excited state of R may uniquely determine the initial (excited) state. Now, having this information, it is a simple task to calculate the mean value of the position observable $\hat{\vec{r}}_R$. By simultaneous measurement of $\hat{\vec{R}}_{CM}$, one can directly obtain an approximate value of the average position of both, e and p, still with the standard deviations not significantly exceeding the standard deviations of $\hat{\vec{r}}_R$ and $\hat{\vec{R}}_{CM}$.

5 Discussion and Conclusion

It is essential to re-emphasize: defining a "(sub)system" assumes neither regrouping the subsystems nor a redefinition of a unique subsystem's variables. Rather, it assumes the canonical transformations that *couple the variables of the different (sub)systems* [5, 13] thus, in general, *not providing any intuitive contents* for the newly defined (sub)systems even in the classical-physics context. To this end, in order to circumvent the possible misunderstanding, it is worth re-emphasizing that our considerations apply to the variables transformations allowing a definition of the "new" subsystems, not just giving rise to a definition of a new

composite observable of the composite system. To this end, as an example we point e.g. to the observable defined as the sum $\hat{\vec{J}} = \hat{\vec{l}} + \hat{\vec{s}}$, where $\hat{\vec{l}}$ stands for the angular momentum and $\hat{\vec{s}}$ for the spin of a particle; the observable $\hat{\vec{J}}$ is truly a composite system observable *not yet defining the new subsystems*.

As it is emphasized in [5], a division of a composite system gives rise to *simultaneous* definitions of the subsystems not yet allowing simultaneous observability of the subsystems belonging to the different divisions. While this is a simple consequence of the canonical transformations (as defined in Appendix 1) [5], this fact bears a clear-cut information-theoretic aspect. Actually, the observation of e.g. $\mathcal{A}$ represents a local operation *relative* to the division $\mathcal{A} + \mathcal{B}$, while the observation of $\mathcal{E}$ represents an operation exerted on the composite system $\mathcal{A} + \mathcal{B}$—and therefore can not be simultaneously performed. Certainly, this is another subtlety of the problem at issue.

The coordinates-transformations-defined (sub)systems is virtually a general method in physics, which makes our considerations to be of interest for the *realistic* physical models. Here, we shall outline just a few examples in this regard.

E.g., besides the hydrogen atom (Sects. 2 and 4), we emphasize the relevance of the contents of Sect. 2 for the widely used method of redefinition of mutually interacting systems as a collection of mutually non-interacting quasiparticles—e.g. the "normal coordinates" decoupling the interacting harmonic oscillators (cf. Appendix 2).

As another interesting issue, we emphasize the subject of the molecules structure (a general issue of quantum chemistry), and the problem of the macromolecules conformational transitions [14–16]. Actually, the general method of quantum chemistry reads: a molecule can be modelled as a collection of the atomic nuclei plus the collection of the atomic electrons $\mathcal{N} + \mathcal{E}$. However, as it is generally treated in chemistry, a molecule can be defined as a collection of mutually interacting atoms (the system $\mathcal{A}$)—the interactions (phenomenologically) described as the "chemical bonds" between the atoms. In the context of our considerations, the composite system $\mathcal{N} + \mathcal{E}$ is not quite equivalent with the composite system $\mathcal{A}$, for the rather obvious reasons. Actually, the adiabatic approximation valid for the system $\mathcal{N} + \mathcal{E}$ is not valid for the system $\mathcal{A}$—the atomic mass ratio is a non-negligible fraction of unity. Now, the adiabatic approximation—in its zeroth order—gives rise to the separability of the subsystems $\mathcal{N}$ and $\mathcal{E}$—the presence of quantum entanglement in $\mathcal{N} + \mathcal{E}$ system is considered in the molecular spectroscopy theory as the domain of non-applicability of the adiabatic approximation [17]. On the other side, the interactions between the atoms—to which the adiabatic approximation does not apply—should provide entanglement in the system of the atoms. Similarly, the externally induced conformational transitions [14–16] of the molecules [18, 19] sound different in terms of the two divisions [16]—$\mathcal{N} + \mathcal{E}$ and $\mathcal{A}$—of a molecule, that is also characteristic for our considerations. Being the many-particle systems, the molecules exhibit virtually the general applicability of our considerations to the *realistic* physical models.

As a (conceptually trivial) example of redefining subsystems in the information theory appears the quantum teleportation protocol [20]. Actually, the initial decomposition of a tripartite system $1 + 2 + 3$ as $1 + (2 + 3)$ into $((1 + 2) + 3)$ is essential (through the entanglement swapping) for the success of the protocol. Bearing this example in mind, it may virtually appear that the success of certain quantum information/computation protocols may essentially rely on the redefinition of the composite system's decompositions.

A slight limitation of our considerations may be the fact that our analysis primarily refers to the continuous observables. However, the progress in the continuous-variables-based quantum information processing (cf. e.g. [21, 22]) encourages the applicability of our results to the general quantum information/computation issues.

Interestingly enough, the method for defining new subsystems may also be considered as a method for combating decoherence in the quantum hardware. The separable states of a system (e.g. of *CM + R*, cf. Sect. 2) may (and sometimes do) appear as a consequence of decoherence. If so, the introduction of the new yet entangled subsystems may *directly* help in principle in avoiding entanglement in the composite system.

In conclusion, we want to stress: from the information-theoretic point of view, we justify relativity of the very basic concept of "system" as distinguished in [5], yet with the following benefits. Even a seemingly *simple* yet composite quantum system of mutually nonentangled, noninteracting systems may bear (a "hidden") entanglement as well as the possibility of performing the nonequivalent quantum computations, relative to the different possible divisions of the composite system into subsystems. The method(s) (yet fully to be formulated) in this regard may in principle be applied to both isolated as well as to the open quantum systems—that also may be a general method for avoiding decoherence in the quantum hardware.

Appendix 1:

By "canonical transformations" we assume the standard coordinate transformations within the Hamiltonian formalism of classical mechanics. Their quantum mechanical counterparts directly follow due to the procedure of quantization of the classical variables.

E.g., let us assume that a composite system is defined by the two subsystems, $\mathcal{A}$ and $\mathcal{B}$, each subsystem being defined by the proper degrees of freedom and the corresponding conjugate momenta—$\{x_{Ai}, p_{Ai}\}$ and $\{X_{Bj}, P_{Bj}\}$, respectively. Then, the transformations are defined formally as follows:

$$\xi_{Ek} = \xi_{Ek}(x_{Ai}, p_{Ai}; X_{Bj}, P_{Bj}), \qquad \pi_{Ek} = \pi_{Ek}(x_{Ai}, p_{Ai}; X_{Bj}, P_{Bj}), \tag{6}$$

$$\Xi_{Fk} = \Xi_{Fk}(x_{Ai}, p_{Ai}; X_{Bj}, P_{Bj}), \qquad \Pi_{Fk} = \Pi_{Fk}(x_{Ai}, p_{Ai}; X_{Bj}, P_{Bj}) \tag{7}$$

thus introducing the new "subsystems", $\mathcal{E}$ and $\mathcal{F}$, respectively to (6, 7), still allowing redefinition of the system Hamiltonian function:

$$H = H_A + H_B + H_{AB}, \tag{8}$$

$$H = H_E + H_F + H_{EF} \tag{9}$$

where e.g. H_{AB} describes the interaction between the subsystems $\mathcal{A}$ and $\mathcal{B}$.

It is worth emphasizing: the canonical transformations (6, 7) *substantially redefine* the composite system due to, in general, dependence of the degrees of freedom e.g. of $\mathcal{E}$ of both, degrees of freedom *and* the conjugate momenta of *both* systems, $\mathcal{A}$ and $\mathcal{B}$; being linear, these transformations allow the transformations *inverse* to (6, 7). In the other words: the new "subsystems", $\mathcal{E}$ and $\mathcal{F}$, need *not* bear any *intuitive* contents as the physical systems.

Appendix 2:

A linear interaction of the two harmonic oscillators of the general form $\hat{H}_{12} = C\hat{x}_1 \otimes \hat{x}_2$ allows a redefinition of the composite system $1 + 2$ in terms of mutually noninteracting

harmonic oscillators, $Q_1 + Q_2$. Actually, the "normal coordinates" $\hat{q}_i, i = 1, 2$, as defined by the following expression (a special case of (6, 7)):

$$\hat{x}_1 = 2^{-1/2}(\hat{q}_1 + \hat{q}_2), \qquad \hat{x}_2 = 2^{-1/2}(\hat{q}_1 - \hat{q}_2) \tag{10}$$

that define the new subsystems, $Q_i, i = 1, 2$, give rise to the lack of any interaction of the new subsystems: $\hat{H}_{Q_1 Q_2} = 0$ [17].

As distinct from the pair of microscopic oscillators—that is typical for the quantum information theory—let us assume that one oscillator (e.g. the oscillator 2) in the pair is a "macroscopic" system. Then the linear coupling of the position observable $\hat{x}_1$ of the "microscopic" and the center of mass observable $\hat{X}_{CM2}$ of the macroscopic oscillator may give rise to decoherence of the position states of the microscopic oscillator, $\hat{x}_1$ [23]. Certainly, the oscillators (Q_1, Q_2) described by the "normal coordinates" remain decoupled [17] thus *not* providing any entanglement or decoherence in the pair (Q_1, Q_2).

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