Telegraph signals as a solution of the time dependent Schrödinger equation let standard Copenhagen quantum mechanics emerge

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Abstract. A particle switching between two sites of a symmetric system in weak interaction with an environmental continuum of high density of states exhibits a telegraph-signal-like time development without the need of the Born-Bohr principle of reduction on eigenstates of the measuring equipment. The origin of the telegraph signal is a very weak local coupling of the particle to the continuum of gravitons which is connected with an enormous slow down of the particle motion. The proposed mechanism envisages entanglement to gravitons in high dimensional spacetime, which, in accord with Gauss law, gives rise to a local and much stronger gravitational law compared to classical gravitation. The physics behind the quantum jumps and the telegraph-signal-like time development is elucidated. The model might be useful for studying environmental decoherence effects on adsorbate localization and quantum diffusion on solid surface.

1. Introduction
Standard Copenhagen quantum mechanics needs in addition to the unitary time development according to Schrödinger’s equation a strange dynamics called collapse or wave function reduction. This dynamics is not predictable by any theoretical method but has statistical character. It leads to telegraph signals in the recorded experimental data. The Copenhagen formalism is believed to describe any known quantum phenomenon. ”It is often said that quantum theory is eminently successful, that its predictions are verified in countless cases and that no phenomenon has been found which contradicts it” [1]. And further ”A fundamental fact of orthodox quantum theory is that the evolution of the state of the physical system between the collapse events is mathematically very different from the evolution of this state associated with the collapses: the former are ”unitary” and ”local” whereas the latter are neither” [2].

The message of the present contribution will be that there is no random statistical element in the time development resulting from the time dependent Schrödinger equation. The time development of a local quantum system entangled to quantum fields in its environment of high dimensions and high density of states resembles telegraph-signal-like ”quantum jumps”.

Telegraph-signal-like quantum jumps have been observed in experiments of very different nature. They are displayed as sudden changes of a measured signal between two or more values with
time, appearing in a random, statistical manner (cf. for instance [3]-[11]). The time development of two-level Rydberg atoms entangled with a finite small number of electromagnetic quanta in optical cavities shows also statistical quantum jumps between the two states, rather than Rabi oscillations [12]-[16].

To our knowledge a telegraph-signal-like behaviour has not been reported theoretically within a unitary coherent quantum description. We present a coherent dynamics of an entangled adsorbate-graviton system in the framework of quantum field theory leading to telegraph-signal-like changes of state of an adsorbate on a solid surface. This theory is completely different from the treatment within the Jaynes-Cummings quantum mechanical theory in earlier approaches to collapse and revival (cf. refs. [17]-[23] and the theory presented in refs. [24, 25]).

In decoherence theory the environmental coupling leads to vanishing interference between the two quantum states, because the corresponding pointer states in the environment become orthogonal [26]. However, there exist abundant experiments which cannot be explained in the spirit of the decoherence interpretation. These are experiments in the low temperature scanning tunnelling microscopy (STM) concerning adsorbates. For instance Eigler et al. [27] find that an isolated adsorbed Xe atom on a solid Ni(110) surface remains localized on the same adsorption site for days on end. A Xe atom interacts weakly with metal surfaces and the potential hardly varies parallel to the surface. Applying Schrödinger's equation to follow the time dependence of an initially localized Xe wave packet one finds that already after $10^{-10}$ s the Xe wave packet will be delocalized over several hundred lattice sites [28]. Localization of atoms and molecules, which according to Schrödinger's equation should be delocalized, is explained by decoherence theory as due to a mechanism of continuous “measurement” by environmental particles [29]. However, the time needed to localize a Xe atom via interaction with the rest gas in the best laboratory vacuum in the low temperature STM experiments amounts to $\approx 10$ days. During this time, Schrödinger's law would have delocalized the Xe atom over the whole surface, the Xe atom would have completely vanished for the STM. Other quasi particles in the nickel surface, available for localization of the Xe atom, might be the phonons, the tomonagons, excitons, etc. However, at the low temperature in the STM experiments (below 5 K) according to the dispersion relations of the excitations of the solid only quasi particles of long wave length are available and they cannot localize adsorbed atoms on one of several closely situated adsorption sites.

We will demonstrate that gravitons can localize adsorbates on solid surfaces. As it has been suggested by string theory, gravitons and only gravitons exist in hidden dimensions of high-dimensional spacetime. If there are additional spatial dimensions then the gravitational force law will change in the higher dimensional world as compared to the 3+1 dimensional one. The motivation for our approach comes from the fact that the missing diffusion of Xe [27] or the very slow surface diffusion of hydrogen on a copper surface [30] in the low temperature STM cannot be understood by conventional environmental decoherence theory. The hidden dimensions of string theory provide a possibility to explain the experiment within the theoretical framework of quantum field theory.

The question is: can a coherent quantum mechanical description of a local system in interaction with the environment lead to the telegraph signal. In the present paper we give a positive answer to this question. We will demonstrate that it is possible for a system, comprising a local part, entangled to the continua of the environmental excitations, to change state suddenly in an apparently statistical fashion, which comes out of the solution of the time dependent Schrödinger equation. It will be shown that the conditions for a telegraph-signal-like change of state of the system is weak and local coupling to a continuum of gravitons in the environment. The time
development is coherent and deterministic in the phase space of the total system including the environmental excitations. Focusing on the time development of the local system alone, which is assumed to be accessible to measurement in experiment, it appears as if it changes state in a random way.

In the next section we define the model and the Hamiltonian. The method of solution is outlined, describing the entanglement of the adsorbate motion to the continuum of gravitons in 11 dimensional spacetime. The solution of a model with two adsorption sites and two local states, where the interaction with gravitons is effective, reproduces the extremely slow diffusion of a hydrogen atom on the Cu(001) surface in the quantum diffusion regime as measured by Lauhon and Ho below 60 K [30]. As the results show, the adsorption site changes occur in a quantum-jump-like manner and not as the Rabi oscillations predicted by quantum mechanics. The physical background and the conditions for the quantum-jump-like time development of the entangled system are elucidated in a next section.

2. Theory of telegraph-signal-like time development of an adsolate entangled with gravitons in hidden dimensions

The model describes an adsorbate which can jump between two adsorption sites on a solid surface, site $\alpha$ and site $\beta$. We investigate the dynamics of site change. Gravitons in high spatial dimensions, including hidden spatial dimensions are described in ref. [31].

2.1. The Hamiltonian

As the modified gravitational force law is of very short range [32] it is only effective if the adsorbate is near a substrate atom. This is modelled by two localized adsorbate field excitations in the regions $w_\alpha$ and $w_\beta$ in fig. 1, respectively. Only when the adsorbate is in one of these localized regions it can entangle to the gravitons. We assume a symmetric model with the same number and kind of localized regions for the adsorbate hopping between two adsorption sites (cf. fig. 1):

(i) One local region $g_\alpha$ or $g_\beta$ on each adsorption site, respectively. From these local regions the adsorbate can propagate to the places $w_\alpha$ on the same site or $w_\beta$ on the other site.

(ii) One localized place $w_\alpha$ or $w_\beta$. At these places the adsorbate can either entangle to the graviton continua $\{\kappa_\alpha\}$ or $\{\kappa_\beta\}$ on the same site or it can develop amplitude in the local regions $g_\alpha$ and $g_\beta$ on the same adsorption site or on the opposite site.

(iii) Continua of $N$ gravitons $\{\kappa_\alpha\}$ or $\{\kappa_\beta\}$. After being entangled with gravitons near the places $w_\alpha$ and $w_\beta$ the adsorbate can develop amplitude in the local regions $g_\alpha$ and/or $g_\beta$. Due to the large number of spatial dimensions there is a high density of graviton modes with the required wave length of approximately 1 Å [33].

The explicit form of the Hamiltonian is:

\[
H = H_\alpha + H_\beta + H_{\alpha-\beta}
\]

\[
H_\alpha = E_g n_{g_\alpha} + E_w n_{w_\alpha} + \sum_\kappa \varepsilon_\kappa n_{\kappa_\alpha} + V(c_{g_\alpha}^+ c_{w_\alpha} + h.c.)
+ W \sum_\kappa (c_{\kappa_\alpha}^+ c_{w_\alpha} + h.c.)
\]

\[
H_\beta = E_g n_{g_\beta} + E_w n_{w_\beta} + \sum_\kappa \varepsilon_\kappa n_{\kappa_\beta} + V(c_{g_\beta}^+ c_{w_\beta} + h.c.)
+ W \sum_\kappa (c_{\kappa_\beta}^+ c_{w_\beta} + h.c.)
\]

\[
H_{\alpha-\beta} = (V - \Delta V)(c_{g_\alpha}^+ c_{w_\beta} + c_{g_\beta}^+ c_{w_\alpha} + h.c.)
\]
Figure 1. Model of two adsorption sites $\alpha$ and $\beta$ where entanglement to gravitons $\{\kappa_\alpha\}$ and $\{\kappa_\beta\}$ occurs in two regions $w_\alpha$ and $w_\beta$, respectively.

where $E_g$ and $E_w$ are the energies of the adsorbate field excitations created by $c_{g\alpha}^+$, $c_{g\beta}^+$, and $c_{w\alpha}^+$, $c_{w\beta}^+$, respectively. $\varepsilon_\kappa$ are the excitation energies for the gravitons. $n_{g\alpha}$ and $n_{w\alpha}$ are the number of excited field quanta in the regions $g_\alpha$, $w_\alpha$; $c_{g\alpha}^+$, $c_{g\beta}^+$, $c_{w\alpha}^+$, $c_{w\beta}^+$: creation and destruction operators for the adsorbate field quanta in the respective regions; $c_{\kappa\alpha}^+$ and $c_{\kappa\alpha}$: creation and destruction operators for the gravitons; $V$ and $V - \Delta V$: interaction matrix elements between the various local regions; $W$: interaction matrix elements for coupling to the gravitons. $\{\kappa_\alpha\}$, $\{\kappa_\beta\}$ constitute a quasi-continuum which is modified due to the presence of the adsorbate (cf. ref. [31]). The coupling of the adsorbate field to the environmental degrees of freedom, the gravitons, is extremely weak and extremely localized in the local regions $w_\alpha$ and $w_\beta$. More details can be found in the description in ref. [31].

2.2. Solution method: coherent time evolution of an adsorbate entangled with a continuum of gravitons
The time evolution of the system is according to Schrödinger’s time-dependent equation:

$$i\hbar \frac{\partial \Psi(t)}{\partial t} = H \Psi(t) \tag{2}$$

The eigenfunctions $\Psi_I$, determined by an expansion in the basis states, are used to derive the time dependence according to the unitary time evolution:

$$\Psi_I(t) = \Psi_I(t_0) e^{-iE_I t/\hbar} \tag{3}$$

A basis for the many particle wave function is given by $|g_\alpha 0\rangle$, $|g_\beta 0\rangle$, $|w_\alpha 0\rangle$, $|w_\beta 0\rangle$, $|w_\alpha \kappa_\alpha\rangle$, $|w_\beta \kappa_\beta\rangle$, where the respective adsorbate field excitations and graviton excitations are indicated.
Assume that the system starts in $| g_0 \rangle$. This state, expanded in the eigenfunctions \{ $| I \rangle$ \} of the total Hamiltonian is:

$$| g_0 \rangle = c_{1,g_0} | 1 \rangle + c_{2,g_0} | 2 \rangle + ...$$ (4)

where $c_{I,g_0}$ is the expansion coefficient of the basis state $| g_0 \rangle$ in the $I$-th eigenfunction of the Hamiltonian. Starting from the many particle state $| g_0 \rangle$ at $t = 0$, the further time development of this state is denoted by $| \Psi(t) \rangle$ and is obtained as:

$$| \Psi(t) \rangle = c_{1,g_0} e^{-iE_1 t/\hbar} | 1 \rangle + c_{2,g_0} e^{-iE_2 t/\hbar} | 2 \rangle + ...$$ (5)

The density operator at time $t$ is:

$$\rho(t) = | \Psi(t) \rangle \langle \Psi(t) |$$ (6)

The occupation of site $\alpha$ as displayed in fig. 2 (red curves) is then defined by:

$$\text{occupation of site } \alpha = \langle g_0 | \rho(t) | g_0 \rangle + \langle w_0 | \rho(t) | w_0 \rangle + \sum_{\kappa} \langle w_\kappa | \rho(t) | w_\kappa \rangle$$ (7)

Repeating this procedure for each next time step provides the coherent time evolution of the density operator (in the chosen basis) which can be used to illustrate the state changes of the adsorbate entangled with the continuum of gravitons.

3. Results

The model, solved neglecting the entanglement to gravitons, leads to the time development displayed in the left panel of fig. 2. The quantity plotted is the expression eq. (7) over site $\alpha$ (red curve) and site $\beta$ (blue curve) as a function of time. The interaction parameters are chosen so that it takes approximately 0.1 seconds for a hydrogen atom to change site: $V = 0.05$ peV, $V - \Delta V = 0.032$ peV and $W = 0$ peV [34]. The solution of the Schrödinger equation eq. (2) has the sinusoidal behaviour with time, representing Rabi-oscillation, as it is expected. These are just coherent Rabi oscillations between the two sites $\alpha$ and $\beta$, mediated by coupling to the local regions $w_\alpha$ and $w_\beta$. The frequency of site transition is determined by the energy difference $\Delta \varepsilon$ between the eigenstates of the system involving no gravitons.

Only with entanglement to the gravitons included, does a telegraph-signal-like site switching arise, as it is seen in the right panel of fig. 2 (the value of $W = 0.007$ peV is used). Apparently statistical quantum jumps of the adsorbate between the two adsorption sites occur, reminiscent of collapses, however, resulting from the solution of Schrödinger’s equation. Furthermore, a significant slow down of the hopping rate between the adsorption sites results, compared to the period of the Rabi oscillation, neglecting the entanglement to the gravitons. The residence time on one adsorption site has increased by roughly a factor of $10^4$. In the regime leading to the telegraph-signal-like adsorbate hopping the average frequency of the telegraph signal is determined by a much smaller energy difference $\Delta \varepsilon = 2.2 \times 10^{-6}$ peV equal to the energy separation of the gravitons which entangle to the adsorbate movement. This behaviour resembles the experimental signal obtained in the quantum jumps of adsorbates in low temperature STM measurements ([7]-[11]).

4. Analysis of the theoretical telegraph-signal-like time development

The experimental observation of quantum jumps is interpreted as collapse, which allegedly cannot be described by unitary solutions of Schrödinger’s equation. To the contrary, the analysis in the present section shows that, when certain limiting conditions concerning the density of
states and the coupling strength with the environmental continua are fulfilled, the unitary time development of a local quantum system entangled with the environmental excitations can display quantum jumps resembling collapse. More details of the derivation are avilable in ref. [34]. First we discuss the entanglement of the adsorbate movement to a degenerate graviton continuum, which, however does not yield the quantum jumps. The weak coupling to a non-degenerate graviton continuum results in graviton scattering which underlies the telegraph-signal-like quantum diffusion of the adsorbate.

4.1. A degenerate continuum of gravitons has no effect on the adsorbate dynamics
The symmetry of our geometric model permits two possible solutions: either symmetric or antisymmetric with respect to the interchange of site $\alpha$ and site $\beta$. The Hamiltonian can be rewritten in terms of the symmetric $c_{g+}, c_{w+}, c_{\kappa+}, c_{g+}, c_{w+}, c_{\kappa+}$ and antisymmetric combinations $c_{g-}, c_{w-}, c_{\kappa-}, c_{g-}, c_{w-}, c_{\kappa-}$ of the creation and destruction operators as:

$$
H = H_+ + H_-
$$

$$
H_+ = E_g n_{g+} + E_w n_{w+} + \sum_{\kappa} \varepsilon_{\kappa} n_{\kappa+}
+ (2V - \Delta V)(c_{g+}^+ c_{w+} + c_{w+}^+ c_{g+}) + W \sum_{\kappa} (c_{\kappa+}^+ c_{w+} + c_{w+}^+ c_{\kappa+})
$$

$$
H_- = E_g n_{g-} + E_w n_{w-} + \sum_{\kappa} \varepsilon_{\kappa} n_{\kappa-}
+ \Delta V(c_{g-}^+ c_{w-} + c_{w-}^+ c_{g-}) + W \sum_{\kappa} c_{\kappa-}^+ c_{w-} + c_{w-}^+ c_{\kappa-})
$$

(8)
Figure 3. Schematic energy diagram resulting from the coupling within the symmetric (a) and antisymmetric (b) basis states. The degeneracy between the transformed graviton continua \{ | \kappa^+ \rangle \} and \{ | \kappa^- \rangle \} is lifted due to coupling to \( | w^+ \rangle \) (a) and to \( | w^- \rangle \) (b), respectively. The adsorbate in the \( | g^- \rangle \)-component alone stays approximately on-shell with the initial state because of the weaker interaction of the order of \( \Delta V \) with \( | w^- \rangle \).

The symmetry adapted form of the Hamiltonian is split into two independent parts. For each part a schematic level diagram is displayed in fig. 3. After interaction with the local states the antisymmetric combination of the adsorbate states is energetically much closer to the energy shell than the symmetric combination. Since the coupling to the gravitons is very weak, the antisymmetric solution has to dominate the dynamics. To surmount the problem with the enormous number of nearly degenerate gravitons as a first attempt we consider all graviton states exactly degenerate and construct a single graviton state which alone couples to the antisymmetric adsorbate states:

\[
| w^-_\kappa \rangle = \frac{1}{\sqrt{N}} \sum_\kappa | \kappa^- \rangle \quad \text{with} \quad | \kappa^- \rangle = \frac{1}{\sqrt{2}} (| w_\alpha \kappa_\alpha \rangle - | w_\beta \kappa_\beta \rangle).
\]

(10)

Defining

\[
| w^- \rangle = \frac{1}{\sqrt{2}} (| w_\alpha 0 \rangle - | w_\beta 0 \rangle) \quad \text{and} \quad | g^- \rangle = \frac{1}{\sqrt{2}} (| g_\alpha 0 \rangle - | g_\beta 0 \rangle)
\]

(11)

(12)

we end up with a 3 x 3 matrix which has to be diagonalized:

\[
\begin{array}{ccc}
| w^- \rangle & | w^-_\kappa \rangle & | g^- \rangle \\
\langle w^- | & E_w & \sqrt{NW} & \Delta V \\
\langle w^-_\kappa | & \sqrt{NW} & 0 & 0 \\
\langle g^- | & \Delta V & 0 & 0 \\
\end{array}
\]
By forming a suitable linear combination out of the graviton state and the antisymmetric adsorbate state:

\[ | w_{\kappa g}^- \rangle = \sqrt{N} | w_{\kappa}^- \rangle + \Delta V | g^- \rangle \sqrt{N W^2 + (\Delta V)^2} \]  

and orthogonalizing the adsorbate state to this linear combination:

\[ | g_{\perp}^- \rangle = \sqrt{N W^2 + (\Delta V)^2} \left( | g^- \rangle - \langle w_{\kappa g}^- | g^- \rangle | w_{\kappa g}^- \rangle \right) \],

we see that the orthogonalized adsorbate state \( | g_{\perp}^- \rangle \) exactly decouples from the gravitons:

\[
\begin{array}{c|c|c}
\langle w^- | & | w^- \rangle & | w_{\kappa g}^- \rangle \\
\langle w_{\kappa g}^- | & \sqrt{N W^2 + (\Delta V)^2} & 0 \\
\langle g_{\perp}^- | & 0 & 0 \\
\end{array}
\]

This kind of Hamiltonian signifies that the adsorbate state \( | g_{\perp}^- \rangle \) eq. (14) would never couple to gravitational degrees of freedom if the graviton continuum is degenerate. The error in this analysis arises, because the gravitons have been assumed exactly degenerate. Environment of this kind cannot have significant influence on the adsorbate dynamics.

4.2. Induced scattering in the graviton continuum leads to telegraph signals

We apply Dyson’s equation to study the influence of lifting the degeneracy and accounting for the scattering of graviton states.

In an expansion over the graviton eigenstates (exact or approximate) \{ | \tilde{\kappa}_{\perp}^- \rangle \} the coefficients \( \langle g_{\perp}^- | \tilde{\kappa}_{\perp}^- \rangle \) can be evaluated using Lippmann-Schwinger equation [35]:

\[
\langle g_{\perp}^- | \tilde{\kappa}_{\perp}^- \rangle = \langle g_{\perp}^- | \kappa_{\perp}^- \rangle + \sum_{\lambda} \langle g_{\perp}^- | G(E = E_{\tilde{\kappa}_{\perp}}) | \lambda_{\perp}^- \rangle \langle \lambda_{\perp}^- | H - H_o | \kappa_{\perp}^- \rangle 
\]

where \( H_o \) is the last but one line of eq. (8) and the summation over \( \lambda \) is over all states in the antisymmetric on-shell continuum. \( G(E) = (E - H_-)^{-1} \) is the Green operator. Using Dyson’s equation and expanding the Green function in a Born series in the environmental states \{ | \kappa_{\perp}^- \rangle \}:

\[
| \kappa_{\perp}^- \rangle = \frac{1}{\sqrt{1 - \langle \kappa^- | w_{\kappa g}^- \rangle^2}} \left( | \kappa^- \rangle - \frac{W}{\sqrt{N W^2 + (\Delta V)^2}} | w_{\kappa g}^- \rangle \right)
\]

yields:
the on-shell projected state from the graviton continuum is the energy separation between two neighbouring states in the which allows to sum up the infinite series:

\[
\langle \lambda_\perp | G_o | \lambda_\perp \rangle \sum_{\nu} \langle \lambda_\perp | H_\perp - H_o | \nu_\perp \rangle \langle \nu_\perp | G_o | \nu_\perp \rangle \langle \nu_\perp | H_\perp - H_o | \mu_\perp \rangle \langle \mu_\perp | G_o | \mu_\perp \rangle
+ \langle \lambda_\perp | G_o | \lambda_\perp \rangle \sum_{\nu} \langle \lambda_\perp | H_\perp - H_o | \nu_\perp \rangle \langle \nu_\perp | G_o | \nu_\perp \rangle \langle \nu_\perp | H_\perp - H_o | \mu_\perp \rangle \langle \mu_\perp | G_o | \mu_\perp \rangle
\]

Terminating the Born series at any finite order does not yield the telegraph-signal-like behaviour. Instead we assume short range scattering:

\[
\langle \nu_\perp | H_\perp - H_o | \mu_\perp \rangle = U
\] (17)

which allows to sum up the infinite series:

\[
\langle \lambda_\perp | G | \mu_\perp \rangle = \langle \lambda_\perp | G_o | \lambda_\perp \rangle \langle \mu_\perp | G_o | \mu_\perp \rangle \frac{U}{1 - U \sum \langle \nu_\perp | G_o | \nu_\perp \rangle}
\] (18)

It has to be emphasized that this assumption implies, of course, a very local interaction with the gravitons. The expansion coefficient eq. (15) then becomes

\[
\langle g_\perp | \bar{\kappa}_\perp \rangle \approx i \frac{\Delta \varepsilon \Delta V}{\pi W E_{\kappa_\perp}}
\] (19)

and has the right dependence on the energy \(E_{\kappa_\perp}\) to yield the telegraph signals (cf. fig. 4). \(\Delta \varepsilon\) is the energy separation between two neighbouring states in the \(|\kappa_\perp\rangle\) continuum. Defining the on-shell projected state from the graviton continuum \(|\tilde{\kappa}_\perp \rangle\):

\[
| A\kappa_\perp \rangle = \frac{1}{\sqrt{N}} \sum_{\kappa_\perp} | \tilde{\kappa}_\perp \rangle
\] (20)

and projecting the time dependent wave packet on \(| A\kappa_\perp \rangle\), one obtains:

\[
\langle A\kappa_\perp | \Psi(t) \rangle = i \frac{\Delta \varepsilon \Delta V}{\pi W} \sum_{\bar{\kappa}_\perp} \frac{1}{E_{\bar{\kappa}_\perp}} \sqrt{\frac{NW^2}{NW^2 + (\Delta V)^2}} \frac{1}{\sqrt{2N}} e^{-iE_{\bar{\kappa}_\perp}t/h}
\]

\[
= \frac{1}{\pi W} \frac{\Delta V}{\sqrt{2N}} \sqrt{\frac{NW^2}{NW^2 + (\Delta V)^2}}
\]

\[
\times \left( \sin(\Delta \varepsilon t/h) + \frac{\sin(3\Delta \varepsilon t/h)}{3} + \frac{\sin(5\Delta \varepsilon t/h)}{5} + \cdots \right).
\] (21)

The Fourier series in the last line yields a telegraph-signal-like behaviour.

Neglecting all other components, \(| \Psi(t) \rangle\) can be approximated as:

\[
| \Psi(t) \rangle \approx \langle A\kappa_\perp | \Psi(t) \rangle | A\kappa_\perp \rangle + \langle A\kappa_+ | \Psi(t) \rangle | A\kappa_\perp \rangle
\] (22)

with

\[
| A\kappa_+ \rangle = \frac{1}{\sqrt{N}} \sum_{\kappa_+} | \tilde{\kappa}_\perp \rangle
\] (23)

Projecting on the states \(| g_\alpha 0 \rangle, | w_\alpha 0 \rangle, | w_\alpha \kappa_\alpha \rangle\) as required by eq. (7), one obtains e.g.:

\[
\langle w_\alpha \kappa_\alpha | \Psi(t) \rangle \approx \langle A\kappa_\perp | \Psi(t) \rangle \langle w_\alpha \kappa_\alpha | A\kappa_\perp \rangle + \langle A\kappa_+ | \Psi(t) \rangle \langle w_\alpha \kappa_\alpha | A\kappa_+ \rangle
\] (24)
Figure 4. Spectral distribution of the coupling to the environmental gravitons. The coupling in the subspace of the antisymmetric states varies with the inverse energy of the gravitons $\frac{1}{E}$.

The contribution to the occupation of site $\alpha$ (cf. eq. 7) is:

$$\langle w_\alpha \kappa_\alpha | \rho(t) | w_\alpha \kappa_\alpha \rangle = |\langle w_\alpha \kappa_\alpha | \Psi(t) \rangle|^2$$

$$= |\langle A\kappa^- | \Psi(t) \rangle|^2 |\langle w_\alpha \kappa_\alpha | A\kappa^- \rangle|^2 + |\langle A\kappa^+ | \Psi(t) \rangle|^2 |\langle w_\alpha \kappa_\alpha | A\kappa^+ \rangle|^2$$

$$+ 2Re\langle \Psi(t) | A\kappa^+ \rangle\langle A\kappa^- | \Psi(t) \rangle\langle A\kappa^- | w_\alpha \kappa_\alpha \rangle\langle w_\alpha \kappa_\alpha | A\kappa^+ \rangle$$

(25)

The first term on the r.h.s. in the last but one line is approximately time independent, because the square of the infinite Fourier series in eq. (21) is exactly constant. The second term on the r.h.s. in the last but one line is approximately time independent, because $\langle A\kappa^+ | \Psi(t) \rangle$ is nearly time independent with respect to long time variations (only high frequency noise-like variations). The last term in eq. (25) has telegraph character, because $\langle A\kappa^- | \Psi(t) \rangle$ has telegraph character. Similar time dependent terms with telegraph character are found in the expressions for $\langle g_\alpha 0 | \rho(t) | g_\alpha 0 \rangle$ and $\langle w_\alpha 0 | \rho(t) | w_\alpha 0 \rangle$. These are the time dependent contributions to the quantity plotted in fig. 2, implying that the occupation of site $\alpha$ will jump between two values.

5. Conclusion

Concluding, we showed that 3+1 dimensional quantum theory is incomplete in the case of adsorbate localization and surface diffusion. Introducing the entanglement of the adsorbate motion to the field of gravitons in high spatial dimensions (for instance 11 spacetime dimensions) results in the slow down of adsorbate quantum diffusion between different adsorption sites and in quantum-jump-like adsorption site changes, rather than Rabi oscillations, with time. The necessary conditions for the telegraph-signal-like variation of adsorption site with time can be summarized:
• On-shell (degeneracy coupling) between the initial many particle configuration and the graviton modes is effective.

• Weak coupling between the many particle initial state and the graviton modes.

• The weak coupling leads to a time dependent many particle wave function which is an entanglement between the adsorbate movement state and the continuum of gravitons. The frequency of the soft local graviton states determines the lifetime of the entangled state on a given site in the local region and the diffusion rate.

Schrödinger’s equation is local and determines a unitary time development. The effect of the entanglement of the adsorbate motion to the gravitons is a telegraph-signal-like change of adsorption site, resembling a quantum jump. However, a quantum jump is a collapse on a different state. This is usually considered to indicate non-locality as it is implied within the Bohr-Born concept in quantum mechanics: collapse is a nonlocal effect.

We emphasize that in our theory nonlocality and quantum jumps of an adsorbate are the outcome of Schrödinger’s quantum mechanics in the limit, when the following conditions are fulfilled:

• extremely localized coupling of the adsorbate to a continuum of environmental excitations;

• extremely high density of states of the continuum of environmental excitations as described in ref. [33];

• extremely weak coupling to the continuum of environmental excitations.

In this limiting case near perfect telegraph-signal-like site changes of an adsorbate between different adsorption sites are obtained. If the above requirements are relaxed, deviations from the zero-time quantum jumps will result. As suggested here environmental excitations which closely approach the requirements for telegraph-signal-like change of state of the quantum system are the gravitons.

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