Adsorbate localization versus diffusion: a coherent time dependent theory of coupling to gravitons in hidden large dimensions

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Abstract. A long standing unsolved puzzle is the very small rate of surface diffusion of adsorbates in the low temperature STM in the regime of quantum diffusion, differing by orders of magnitude from the results of modern quantum theories of surface diffusion (QTSD) based on ab initio potential energy surfaces (refs. [1]-[5]). We investigate whether decoherence mechanisms, neglected in QTSD, can shed some light on these discrepancies. A quantum-mechanical theory is presented treating the entanglement of adsorbates with their environment (phonons, electron-hole pairs, gravitons) [6]. Time dependent wave packet evolution including the environmental modes indicates possible paths towards an explanation of the observed discrepancies and gives an insight into phenomenological descriptions like adsorbate localization, quantum Zeno effect (permanent "measurement" by specific environmental excitations) and wave function collapse.

1. Introduction
Within the same experiment, using the scanning tunnelling microscope (STM) at 9K, Lauhon and Ho observed the transition between the classical and quantum behaviour of a single hydrogen atom adsorbed on the Cu(001) surface [7]. The adsorbate displays classical behaviour, being imaged as a localized particle on the same adsorption site for thousands of seconds, which competes with the quantum tunnelling diffusion from one adsorption site to the next one. This is not a singular observation in surface science and it is not limited to light atoms like hydrogen. We mention that even a heavy fullerene \(\text{C}_{70}\) and a fullerene derivative \(\text{C}_{60}\text{F}_{48}\) are displayed as stationary wave packets in the STM, whereas beams of these molecules show interference patterns from nanolattices in a Talbot-Lau interferometer [8].

Decoherence theory aims at explaining the transition to classical appearance and localization of microscopic particles. The state-of-the-art decoherence theory, based on collapse and wave function reduction, yields results for the time for particle localization due to "measurement" by the environment [9], which is orders of magnitude longer than the localization time needed to reproduce the experimentally measured rate of hydrogen quantum diffusion above Cu(001) at the low temperature of 9K [7].
In the present article we approach the problem of the localization of an adsorbate on a solid surface. The two-dimensional (2D) periodicity of the surface implies that the adsorbate should be delocalized in a 2D Bloch wave on a time scale of $10^{-10}$ seconds [6]. This is, however, not observed in STM. The adsorbates in the low temperature STM are imaged as localized wave packets, which are no eigenstates. The localization of adsorbates at low temperature can be responsible for the extremely low diffusion rates, measured experimentally. The entanglement to gravitons is suggested as an ubiquitous decoherence mechanism and as the only relevant decoherence mechanism for particle localization at low temperature. This mechanism is crucially dependent upon the high dimensinality of the graviton field, as suggested by string theory, and on the hidden space dimensions where gravitons can propagate. The entanglement to the rest excitations of the sample (phonons, photons, tomonagons, plasmons), though it is effective at high temperature, cannot be the mechanism for particle localization at low temperature. The typical wave lengths of the order of 180 Å of phonons and tomonagons at low temperature are too long to allow to distinguish a hydrogen atom on two neighbouring adsorption sites, for instance.

In the next section a brief summary is presented of the main ideas suggested by 11D spacetime string theory, made use of in our theory of particle localization. The major features of our theory are described in previous papers [6] and in the contribution by Doyen and Drakova in the present volume [10]. In a separate section we present the adaptation of the formalism to the geometric model of adsorbate diffusion, followed by the results and their interpretation.

2. The hidden large dimensions of string theory and gravitation in 11 dimensional spacetime

The gravitational interaction $V_{\text{grav}}^{(4D)}(r) = -\frac{G^{(4D)} M}{r}$ between two electrons in four dimensional spacetime (4D) is 41 orders of magnitude weaker than their electrostatic interaction, though the distance dependence of the two interactions is the same. Increasing the dimensionality in 11D M-theory and supergravity yields the distance law:

$$V_{\text{grav}}^{(11D)}(r) = -\frac{G^{(11D)} M}{\pi r^8},$$

which means a much stronger gravitational interaction at small distances. The additional 7 spacial dimensions must be rolled up to radii of upto millimeter [11] to avoid discrepancy with Newton’s gravitational law at distances larger than distances of the order of $10^6$ bohr, at which the classical law is experimentally verified. Equating eq. 1 with Newton’s law at $r = 10^6$ bohr yields an enhancement of the gravitational constant $G^{(11D)}$ in 11D of 39 orders of magnitude compared to Newton’s gravitational constant $G^{(4D)}$ in 4D at distances smaller than the rolled up hidden dimensions. This result justifies the use of the gravitational interaction as an environmental interaction, contributing to the localization of quantum particles.

3. A world model for adsorbate diffusion and localization

We reformulate the formalism of decoherence in a closed quantum world, as it is described in detail in ref. [6], in view of the geometric model for adsorbate diffusion, which is represented on fig. 1. It consists of two adsorption sites coupling to a warp resonance, which mediates the coupling to the gravitons. The basis states are many-particle product states with components describing the local adsorption states and the state of the graviton field: $|g_1\rangle |0\rangle$ and $|g_2\rangle |0\rangle$ with $|0\rangle$ denoting the vacuum state of the graviton field. $|g_1\rangle$ and $|g_2\rangle$ are the basis functions used to describe the adsorbate on site 1 and site 2, respectively. With the adsorbate in the warp resonance $|w\rangle |\gamma\rangle$ the state of the graviton field $|\gamma\rangle$ deviates from the vacuum state $|0\rangle$ because
The geometrical model for adsorbate diffusion and localization includes two adsorption sites 1 and 2 described by the basis states $|g1⟩|0⟩$, $|g2⟩|0⟩$ and a contracted warp resonance $|w⟩|γ⟩$, mediating the diffusion from site 1 to site 2. Upper part: no interaction with gravitons, lower part: interaction with gravitons within the warp resonance.

Gravitons are excited, emitted and absorbed, into and from the hidden dimensions. Coupling of the adsorbate to the gravitational field within the warp resonance means deformation of 11D spacetime, which is warranted by graviton excitations. Continuum gravitons, projected on the warp resonance, belong to the local system and their excitation state is labelled by $γ$ or by $grav$. The rest gravitons, belonging to the graviton continuum, are labelled by $κ$.

The Hamiltonian is:

$$H = \sum_{g=1}^{2} E_g n_g + E_w n_w + \sum_{g=1}^{2} V^g_{loc}(c^+_g c_w + c^+_w c_g) + \varepsilon_{grav} a^+_g a_{grav} + \sum_{κ} \varepsilon_{κ} a^+_κ a_{κ} + \sum_{κ} [V_{grav,w} n_w a^+_g a_{grav} a_{κ} + V_{w,grav} n_w a^+_κ a_{grav}]$$

The meaning of the symbols is:

- $n_g, n_w$: occupation number operators for the gas particle in the core movement states parallel to the surface and in the warp resonance;
- $c^+_i, c_j$: creation and annihilation operators for the gas particle in the respective core movement states;
- $V^g_{loc}$: interaction potential between a gas particle state and the warp resonance;
- $\varepsilon_{grav}, \varepsilon_{κ}$: energy of local and continuum gravitons;
- $a^+_g, a_{grav}, a^+_κ$: creation and annihilation operators for local and continuum gravitons;
- $V_{grav,w}, V_{w,grav}$: interaction between the gas particle and the gravitons within the warp resonance (for the sake of simpler notation the polarization degrees of freedom are not explicitly displayed (cf. [6]).

The procedure for the time dependent solution of this hamiltonian is described in ref. [10].

4. Apparent classical behaviour in a time dependent quantum mechanical theory, taking into account the entanglement to gravitons: results and interpretation

The model for adsorbate diffusion depicted in the upper part of fig. 1 represents two degenerate adsorption states coupling to the warp resonance. The particle is adsorbed initially on site 1. The variation with time of the occupations of the two adsorption sites is plotted in fig. 2. The time for adsorbate diffusion from site 1 towards site 2 can be defined as twice the time needed...
Figure 2. Variation of the occupation of adsorption site 1 and site 2 by an adsorbate with time via coupling to the warp resonance $|w⟩|0⟩$. The geometric model for adsorbate diffusion is the one displayed in the upper panel of fig. 1.

for the probability of occupying site 1 to reduce by 0.5 and the probability for occupying site 2 to rise by 0.5. The diffusion rate is therefore approximately 1 particle per 0.4 seconds, which compares nicely to the ab initio result of Wahnström et al. for hydrogen diffusion on Ni(100) [5]. In the system of two degenerate adsorption states, coupling to the warp resonance $|w⟩|0⟩$ (fig. 1 upper panel), the particle, initially adsorbed on the first site 1, is scattered by the interaction with the warp resonance into the second adsorption site 2. Two scattering channels are available: backscattering in the initial state $|g1⟩|0⟩$ and forward scattering in $|g2⟩|0⟩$. The two adsorbate states $|g1⟩|0⟩$ and $|g2⟩|0⟩$ give rise to two degenerate linear combinations $ψ_{s} = N_{s}(|g1⟩|0⟩ + |g2⟩|0⟩)$ and $ψ_{as} = N_{as}(|g1⟩|0⟩ − |g2⟩|0⟩)$. The symmetric combination alone can couple to the warp resonance. Their coupling lifts the degeneracy between $ψ_{s}$ and $ψ_{as}$. The adsorbate is involved in Rabi oscillations between $ψ_{as}$ and the $ψ_{s}$-warp derived states, displayed in fig. 2, with a frequency corresponding to diffusion forth and back of the adsorbate between site 1 and site 2 with the rate of 2.5 particles per second. The scattering potential in the warp resonance is chosen such, that the diffusion time from the first adsorption site to the second site is of the same order as resulting from the ab initio theory of Wahnström et al. [5].

The entanglement of the adsorbate dynamics to the gravitons within the warp resonance (fig. 1 lower panel) leads to nearly four orders of magnitude slow down of diffusion, compared to the case when the entanglement to the gravitons is neglected, as the plots in figs. 3 and 2 show. The slow down of particle diffusion between the adsorption sites is defined as localization of the adsorbate. The diffusion rate equals $8 \times 10^{-4}$ particles per second, which is in nice agreement with the experimental measurement on the rate of hydrogen quantum diffusion on Cu(001) in the low temperature STM [7]. Localization of the hydrogen atom due to entanglement to gravitons is associated with this effect.

The strong warp-graviton coupling splits the warp resonance into bonding- $|w⟩|γ_1⟩$ and antibonding $|w⟩|γ_2⟩$ parts, straddling widely around energy zero (cf. eqs. 9). In fig. 4 the spectral
energy distribution of the eigensates on the basis states in the 4D world (fig. 4a) and in the world model, including the gravitons (fig. 4b), is displayed for the static case. The lower right panel in fig. 4b shows the splitting between $|w⟩|γ1⟩$ and $|w⟩|γ2⟩$, whereas in the lower left panel a detailed spectral distribution of the eigenstates around energy zero is plotted. If $E_{bonding} + E_{anti-bonding}$ were equal to zero, the states, resulting from the interaction of $ψ_s$ with $|w⟩|γ1⟩$ and $|w⟩|γ2⟩$ would lie exactly at energy zero. Since $E_{warp} \neq 0$ and $E_{warp} \ll V_g−warp$, the resulting $ψ_{as}$-derived state is not exactly at energy zero, but significantly nearer to zero than without graviton coupling (cf. fig. 4a and 4b, left panel). This reduced energy difference $ΔE_{±} = E_{ψ_s} - E_{ψ_{as}}$ between the states $ψ_s$ and $ψ_{as}$, involved in the diffusion of the particle, is responsible for the slow down of diffusion, when the entanglement to the gravitons is accounted for. In the dynamic situation the straddling warp energies result in fast vibrations of the gas atom between $ψ_{as}$ and the state derived from entanglement of the adsorbate $ψ_s$-state to gravitons in the warp resonance. One can say that the fast vibrations of the adsorbate back and forth towards the warp resonance are the stamp mark of the coupling, which forces $ΔE_{±}$ to small values. In this way the fast $g−warp$ vibrations are responsible for the slow down. This effect appears similar to the quantum Zeno effect [21] and will be discussed later in this section.

The interpretation of these results is in the spirit of the dynamics of a many-body system consisting of both localized adsorbate states as well as delocalized graviton states belonging to a high dimensional continuum of states. The warp resonance provides an additional channel for scattering of the adsorbate, i.e. scattering into states entangled with the gravitons. The interaction with the gravitons leads to splitting into bonding $|w⟩|γ1⟩$ and antibonding $|w⟩|γ2⟩$ many-particle states with dominating component due to the warp resonance. The remaining graviton continuum states are decoupled due to orthogonalization in the diagonalization of the Hamiltonian. Due to state splitting the Rabi oscillations between the split states, dominated by the warp resonance, are very fast. The fast oscillations of the occupation of the warp resonance on a very short time scale can be seen on the right panel of fig. 5. Within each oscillation of the warp resonance the gravitons entangle to the local particle and gain weight (the red curve in fig. 5).

Figure 3. Entanglement to gravitons is included: variation of the occupation of adsorption site 1 and site 2 by the adsorbate with time. The warp resonance $|w⟩|γ⟩$ mediates the entanglement of the adsorbed particle dynamics to the gravitons (cf. the lower panel of fig. 1).
Figure 4. Spectral energy distribution of the eigenstates of the 4D world (a), derived from $\psi_s$ (red) and $\psi_{as}$ (blue) and of the eigenstates of the world model (b) in the static case. The energy positions of the split warp-derived bonding- and anti-bonding states due to the strong warp-graviton coupling are shown in the lower right panel (gray). The lower left panel shows a more detailed view of the splitting between $\psi_{as}$ and the $\psi_s$-derived state around energy zero. As a consequence of the entanglement to gravitons within the warp resonance their splitting is significantly reduced, compared to the case, when the entanglement to the gravitons is neglected (panel a).

Figure 5. Entanglement to gravitons is included. Left panel: variation of the occupation of the gravitons (red curve) and the second adsorption site (green curve) at short time. The right panel shows the oscillations of the occupation of the warp resonance on a very short time scale.
5). This happens because the gravitons are slower due to degeneracy with the particle states \( |g1⟩ | 0⟩ \) and \( |g2⟩ | 0⟩ \). Furthermore, they need time to span the hidden dimensions, the so-called recurrence time. Therefore, in a single recurrence cycle of the gravitons the particle can oscillate many times into the warp resonance, leading to enhancement of the graviton occupation. The gravitons are just a component of the total wave function, which involves the rest local state components in a product with the graviton part. Therefore, before the recurrence of the gravitons from the hidden dimensions the particle cannot leave the local state \( |g1⟩ | 0⟩ \), because otherwise energy conservation will be violated. Hence the particle is localized on site 1 in \( |g1⟩ | 0⟩ \) via the entanglement to the gravitons. This entangled state evolves coherently with time and with each next (fast) oscillation of the particle into the warp resonance the occupation of the gravitons enhances. Slow diffusion and partial occupation of site 2 \( |g2⟩ | 0⟩ \) occur even before the gravitons recur back from the hidden dimensions because the graviton continuum entangles to the other localized state as well.

5. Discussion

5.1. Collapse models

To make contact with other theories we remind that particle localization comes out of the collapse model of decoherence theory as well [9, 12]. Wave function reduction induced by gravity in three-dimensional space is treated by Ghirardi et al. [13], Diósi [14] and Frenkel [15] within a stochastic modification of the coherent Schrödinger quantum dynamics. However, localization within the collapse model is the result of the collapse of the total wave function on a local state due to ”permanent measurement” of the particle by the environmental excitations. Actually in this model collapse is measurement. Hence, collapse means interrupted coherent time evolution and it is introduced for the sake of interpreting measurement within quantum mechanics. In terms of the many-worlds interpretation [16]-[20], though the world wave function is a superposition of all alternative states of the local system+environment and evolves unitarily with time, ”favoured” classical states are singled out via the interaction with the environment and the dynamical reduction, i.e. collapse, of the density matrix is the result. It should be emphasized that in our theory collapse does not occur and it is not the mechanism for particle localization. Localization is a consequence of the coherent time evolution of the total wave function of the local system entangled with the gravitons. The coherent quantum behaviour results in the appearance of the adsorbates as localized particles, because of entanglement to the gravitons in 11-dimensional spacetime.

5.2. Quantum Zeno effect

We try to reformulate the features and the results of our localization theory in terms of the traditional decoherence theory, pointing out the differences. Due to the entanglement to gravitons, in the short time the particle is within the warp resonance, it appears exactly like being ”permanently measured”. However this entanglement does not lead to collapse, as it is assumed within decoherence theory. It appears as a non-destructive von Neumann type of measurement, in which the local system changes negligibly or not at all (in the ideal von Neumann measurement), whereas the environment is changed. The gravitons are propagated in the hidden dimensions, but their entanglement to the local system is not broken, the coherent time development of the system is not interrupted by the entanglement. The entanglement of the adsorbed particle and the gravitons via the warp resonance to the two adsorption sites warrants the diffusion of the particle from site 1 towards site 2 and backwards, similar to the case, when the entanglement to the gravitons is ignored. However, the occupation of site 2 grows with time on a much slower time scale, as it is displayed by the green curve in fig. 5. The slow down of adsorbate diffusion is due to particle localization, induced by the entanglement to the gravitons within the warp resonance. The fast vibrations of the adsorbed particle between
the adsorption site and the warp resonance, induced by the coupling to gravitons, appears similar to the quantum Zeno effect [21]. The latter implies no change in the particle state, if it is measured very fast by the environmental excitations, due to collapse of the particle on the initial state after each ”measurement”. Two issues make the difference between our theory of particle localization and the quantum Zeno effect [21]. The first issue refers to what determines how fast the environmental measurement is. In our theory, since the entanglement to the gravitons occurs within the warp resonance, the rate of localization is an indication of how often the particle is within the warp resonance. And this depends, of course, on the gravitational interaction, which influences the rate of particle Rabi oscillations between the local states. The second difference is that in our theory coherence is not lost at each ”measurement” by the environment, as it is the case with the quantum Zeno effect. The total system continues its coherent time development, taking into account the entanglement to the gravitons. The localization mechanism we suggest may be regarded as the coherent version of the quantum Zeno effect. Each ”measurement” by the environment ensues in a slight change of the total system. Both the local part and the environment are slightly changed, but no collapse on the initial state of the adsorbate has occurred. The amplitude squared of the component $|g_2\rangle |0\rangle$ enhances coherently with time, but only very slowly, because the particle is localized on the initial site $|g_1\rangle |0\rangle$ due to the entanglement to the gravitons within the warp resonance.

5.3. Why gravitons?

Why do we need the gravitons? Why do the other excitations of the solid, e.g. phonons, electron-hole pairs, magnons, etc., not do the job of localizing the adsorbate and slowing down adsorbate diffusion? The reason is: we need environmental excitations with short wave length. In the hidden dimensions we have very many gravitons with small wave length and high energy, which constitute our vacuum state of the 11-dimensional gravitational field. We need deformation with energy of the order of peV which extends only over a region of the order of 1 bohr. This is not possible with solid excitations which at small energies are necesseraly of very long wave length. On the other hand we can assume that the hidden dimensions contain a huge energy reservoir with gravitons of short wave length. This energy reservoir constitutes the ”vacuum state” and therefore we have short wavelength deformations of 11-dimensional spacetime. Only this kind of short wavelength deformations are capable of including fast warp-g vibrations and slow down of diffusion.

All solid state excitations have very long wave lengths at $T \rightarrow 0$K and very low energy. They would excite a joint vibration of both the adsorbate and the warp resonance, however no vibration of the adsorbate and the warp resonance relative to each other. The interaction with the warp resonance is therefore weak and not local, hence no split off states (of the order of some hundred peV) with the warp resonance as component are generated. The result is very slow oscillations of the occupation of the warp resonance and very slow entanglement of the adsorbate to excitations of this kind, i.e. the entanglement and adsorbate localization by these environmental excitations is very slow. The scattering of the adsorbate from one adsorption site to the neighbouring one via the warp resonance will not be hindered, diffusion will not be slowed down. Split off states with the warp resonance as component, which are responsible for the fast localization of the adsorbate via entanglement to gravitons, are generated only by the local interaction with gravitons. The strong and very local coupling of the warp resonance to gravitons is the only entanglement to environmental excitations which can warrant this effect.

5.4. Pointer states and emergence

As it was argued in ref. [6], the use of stationary state scattering theory and the generalized Ehrenfest theorem (GET) in the 4D world plus environment is equivalent to the reduced density
matrix approach used to evaluate the expectation value of an operator \( A \), which acts in the 4D world and corresponds to an observable in the 4D world:

\[
A \otimes I_{env} = A \otimes (|0\rangle\langle0| + |grav\rangle\langlegrav|),
\]

(3)

where \( I_{env} \) is the identity operator acting on the environment. \( |grav\rangle \) is a superposition of excited graviton states, which is defined later in the context of the present model (eq. 10). Moreover, in ref. [6] the pointer states, introduced by Zurek [22] in conjunction with decoherence, are mathematically exactly defined and it was proven that, in the presence of decoherence, scattering can occur out of pointer states or into pointer states. The pointer states are many-particle product states, involving the scattering state of the particle due to the gravitational potential it experiences within the warp resonance, and the state of the environmental gravitons, which are mutually orthogonal. Having this in mind, in the present two-state world model we define the scattering state \( |g1+\rangle \), generated from \( |g1\rangle \), approximately as:

\[
|g1+\rangle \approx |g1\rangle + a |w\rangle
\]

(4)

\(|w\rangle\) is the adsorbate component in 4D in the warp resonance, which is mixed in with a small coefficient \( a \). The pointer states in the GET cannot be the asymptotic incoming and outgoing scattering states of three dimensional scattering theory, because they are not directly entangled to the environment of the measured local system. The pointer states can be only states, which entangle the environment directly to the measured local system. In the present model for adsorbate localization the pointer state is just the warp resonance entangled to the gravitons \( |w\rangle |\gamma\rangle \), with \( \gamma \) denoting the graviton continuum deformed by the adsorbate, when it is in \( |w\rangle \), and \( |w\rangle \) denoting the 4D part of the pointer state.

The operator \( A \) for the localization rate is equivalent to the operator for the rate of change of the population of the initial adsorbate state \( |g1+\rangle \). Localization via entanglement to gravitons in the warp resonance, being associated with the gravitational interaction potential \( V_{grav}^{(11D)} \) in 11D string theory, allows to express the operator \( A \) in the form:

\[
A = \frac{2\pi}{\hbar} V_{grav}^{(11D)} |w\rangle\langle w| V_{grav}^{(11D)} \delta(E)
\]

(5)

In the last equation the 4D part of the warp resonance \( |w\rangle \) serves as an intermediate state, mediating the coupling of the 4D states to the gravitons in the hidden dimensions. When and only when the adsorbed particle is in \( |w\rangle \), it can be strongly entangled to the gravitons. Otherwise, if the diffusion process does not involve the intermediate \( |w\rangle \) state, the result for the expectation value of \( A \) would be identically equal to zero. The effect of the entanglement of the adsorbate in the intermediate state to gravitons is as if the pointer of a measuring apparatus has indicated its presence in the gravitons. The strong interaction with the gravitons means fast entanglement and adsorbate localization in the 4D state \( |g1+\rangle \).

In the stationary case the world wave function \( |\Psi\rangle \) is an expansion over all many-particle basis states:

\[
|\Psi\rangle = \sum_i \alpha_i |g1\rangle |\gamma_i\rangle + \sum_i \beta_i |w\rangle |\gamma_i\rangle
\]

(6)

and it can be written as:

\[
|\Psi\rangle = \sum_i d_i |g1+\rangle |\gamma_i\rangle
\]

(7)
using eq. 4 and a correct choice of the coefficients $d_i$, so that both expressions for $|\Psi\rangle$ eq. 6 and 7 are identical. $|\Psi\rangle$ resulting from the solution of the Hamiltonian is the superposition of the dominating bonding and antibonding states, generated by the strong coupling of the warp resonance to the gravitons:

$$|\Psi\rangle \approx |g1\rangle|0\rangle + c1|w\rangle|\gamma_1\rangle + c2|w\rangle|\gamma_2\rangle$$

$$= |g1\rangle|0\rangle + |w\rangle|grav\rangle$$ (8)

where $|\gamma_1\rangle$ and $|\gamma_2\rangle$ are the bonding and antibonding superpositions of the unperturbed gravitons and the gravitons, perturbed by the adsorbate, when it is in the warp resonance:

$$|\gamma_1\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |\gamma\rangle)$$

$$|\gamma_2\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |\gamma\rangle)$$ (9)

and

$$| grav\rangle = c1|\gamma_1\rangle + c2|\gamma_2\rangle.$$ (10)

The expectation value of the operator $A$ (eq. 3) in the 4D world, using $|\Psi\rangle$ eq. 7, eqs. 5 and 10 and the orthogonality of the many-particle states, equals:

$$\langle \Psi | A \otimes I_{env} | \Psi \rangle = \sum_{i,j} d_i d_j \langle g1+| A | g1+\rangle \{\langle \gamma_i | 0 \rangle \langle 0 | \gamma_j \rangle + \langle \gamma_i | grav \rangle \langle grav | \gamma_j \rangle\}$$

$$= \frac{2\pi}{\hbar} |a|^2 V_{grav}^{(11D)} |^2 \sum_{i,j} d_i d_j \langle \gamma_i | grav \rangle \langle grav | \gamma_j \rangle \delta(E)$$

$$= \frac{2\pi}{\hbar} |V_{grav}^{(11D)}|^2 |a|^2 (d_1 c_1 + d_2 c_2)^2 \delta(E) = |a|^2 |V_{grav}^{(11D)}|^2 \delta(E)$$ (11)

It is obvious that this result plays a role in the 4D world alone. Apparently the gravitons have disappeared from the last equation. But only apparently. Their effect is hidden in the values of $a$ and $V_{grav}^{(11D)}$. Evaluating $a$ and the perturbing potential in the 4D world, we recover the results of the ab initio theory [5] and the missing agreement with experiment. Hence, reducing the theory to 4D, we might claim that quantum mechanics fails. However, including the gravitons in the hidden dimensions of an 11D world, yields different values for $a$, $V_{grav}^{(11D)}$ and diffusion rate, which is in agreement with experiment.

Using the generalized Ehrenfest theorem of stationary state scattering theory leads to a single term for the expectation value of the localization rate, weighted by $|a|^2$, the modulus squared of the coefficient of the initial adsorbate state in the warp resonance (eq. 4). This result gives the impression as if in our coherent theory collapse has occurred and as if the coupling to gravitons destroys coherence in the 4D world, if coherence is defined as the result of Schrödinger’s time-dependent theory in 4D. The appearance of collapse in the 4D world is interpreted as decoherence. In this sense the notion of pointer states, introduced by Zurek [22], is meaningful. However, in the 11D world model there is no collapse. We emphasize that coherence in 11D spacetime is not lost. In the present world model the pointer state is $|w\rangle|\gamma\rangle$, being a superposition of $|w\rangle|\gamma_1\rangle$ and $|w\rangle|\gamma_2\rangle$, it is not a world eigenstate. It has an energy expectation value of 0 and, since the world eigenstates are not on the energy shell, no selection can occur, because otherwise energy conservation would be violated. If one likes, in the present theory the effect of the graviton continuum can be reduced to the renormalization of the coupling
in the 4D world. In this sense, a new 4D theory has ”emerged”. But in our case the emergence of this new 4D theory can be traced back to its causal origin: the coupling to gravitons in hidden dimensions. This reduction can lead to deeper insight and new predictions, whereas a renormalized 4D description would just be a phenomenological theory.

6. Conclusion
The localization of an adsorbed particle, which leads to slow down of surface diffusion in experiment, is, according to the present theory, the result of the coherent time evolution of the local quantum system in entanglement with the gravitons. The total quantum system involves the gravitons, which propagate in the hidden dimensions of 11D string theory and are not available for experimental measurement in our 4D world. At certain time intervals, however, the local system, which can be experimentally observed, appears as if it behaves classically, e.g. adsorbates appearing as localized wave packets. This seemingly classical appearance of the local system emerges from the coherent quantum mechanical behaviour of the total system, the environmental gravitons included. The hidden dimensions of 11D string theory and supergravity provide presently the only possibility of explaining, within the framework of conventional quantum field theory, the experimentally observed slow adsorbate diffusion in the quantum diffusion regime at low temperature in the STM.

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