Low temperature motion of hydrogen on metal surfaces signals breakdown of quantum mechanics in 3+1 dimensions

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Abstract. The low temperature motion of hydrogen on solid metal surfaces displays some unexplained experimental features: in the quantum diffusion regime more than nine orders of magnitude difference between the diffusion rates on different metal surfaces have been measured, the lowest diffusion rates being established in the low temperature scanning tunnelling microscope. Furthermore telegraph-signal-like adsorption site change, rather than Rabi oscillations predicted by Schrödinger equation in 3+1 dimensions, is observed, signaling the breakdown of quantum mechanics in 3+1 dimensions. A theory is presented to resolve these problems, involving the entanglement of the adsorbate motion to gravitons in high-dimensional spacetime. Soft local massive gravonons, induced in the presence of the adsorbate, determine the time scale for surface diffusion. The $\gamma \eta$-model is used for the evaluation of the soft gravonon modes. Weak and local entanglement of the adsorbate motion with a nearly degenerate graviton continuum of high density of states are the conditions for the telegraph-signal-like time development of adsorption site change. In contrast to the Copenhagen interpretation of quantum mechanics, this apparent "classical" behaviour of the adsorbate in 3+1 dimensional spacetime is the result of the solution of Schrödinger’s time dependent equation in high-dimensional spacetime.

1. Introduction
The low-temperature regime of hydrogen and deuterium diffusion on metal surfaces is often discussed as being due to adsorbate tunnelling, both temperature independent or thermally-assisted. In a logarithmic plot the diffusion rates show regions of thermally activated, overbarrier diffusion where the slope of the curve allows to evaluate the barrier height for diffusion using Arrhenius relation. In the low temperature region, below the temperature for transition from overbarrier to tunnelling diffusion $T_{\text{trans}}$, the diffusion rate does not depend on temperature and quantum diffusion of the adsorbate is the assumed mechanism. The quantum diffusion rates vary over many orders of magnitude depending on the adsorption system and the experimental technique used. As it is illustrated in fig. 1 (left panel) with the examples of $^1$H, $^2$H and $^3$H on W(110) [1] and $^1$H and $^2$H on Cu(001) [2], the hopping rate $\nu_o$ in the quantum regime varies over 6 orders of magnitude, the lowest hopping rate being measured in the low temperature scanning tunnelling microscope (STM) [2], higher values being due to the field-emission microscope (FEM) experiments of Gomer et al. [1], [3]-[6]. Even higher values result from the optical diffraction experiments performed by Zhu et al. on adsorbate gratings [7]-[10],
Figure 1. Temperature dependence of the diffusion rate $\nu_o$ of $^1$H, $^2$H and $^3$H on W(110) and Cu(001) (Wang, Gomer [1] and Lauhon, Ho [2]) (left panel). Temperature dependence of the diffusion rate $\nu_o$ of hydrogen and deuterium on Ni(001) in a field emission microscope (FEM) measurement by Lin and Gomer [3] and for hydrogen on Ni(001) in an optical diffraction measurement on adsorbate gratings by Zhu et al. [9]. The numerical results for $^1$H and $^2$H diffusion on Ni(001) are shown in the right panel [11].

where high electric field and laser radiation are used in the measurements (cf. fig. 1, right panel).

Using the idea of tunnelling through a static barrier we can estimate the diffusion rate in the quantum regime. Diffusion barrier height for $^3$H/W(110) of 208 meV is reported in ref. [1], a lower value of 197 meV for the diffusion barrier height of $^1$H on Cu(100) is estimated in the low temperature STM experiment [2]. The mass of tritium is larger than that of hydrogen, therefore if tunnelling through a static barrier were the diffusion mechanism we would expect tritium to diffuse slower than hydrogen. However, in experiment the diffusion rate of $^3$H on W(110) is nearly six orders of magnitude faster than that of $^1$H on Cu(100). In a more sophisticated treatment of hydrogen and deuterium quantum diffusion on Ni(001), based on conventional quantum mechanics in 3+1 dimensional spacetime, the reproduction of the experimentally established trends fails as well (cf. the plots log$_{10}\nu_o$ in fig. 1, right panel, due to Mattson and Wahnström [11]). Roughly nine orders of magnitude is the discrepancy between the experimental and the theoretical values of the diffusion rates in the quantum tunnelling regime. We have to conclude that tunnelling through static barriers cannot be the diffusion mechanism of hydrogen in the quantum regime.

An even more intricate feature of hydrogen motion on solid surfaces at low temperature is that it occurs as telegraph-signal-like jumps between different sites. In a low temperature STM experiment (T=5 K) on the tautomerization reaction of two imino hydrogen atoms in the central cavity of the molecule naphthalocyanine, adsorbed on a thin insulating bilayer of RbI on a Cu single crystal surface, the site change of the hydrogen atoms appears as telegraph-signal-like changes of the tunnelling current over a time interval of 20 seconds [12]. The telegraph-like site change appears very different from the Rabi oscillations between two binding sites, as predicted.
by Schrödinger’s time dependent equation of an isolated system in 4 dimensional spacetime.

**Why is hydrogen diffusion in the low temperature STM on Cu(100) so slow?** Changes in the dynamics of a local system may be due to entanglement to its environment. Permanent ”measurement” of a quantum particle by the environment is the decoherence mechanism of localization proposed within the decoherence theory by Joos and Zeh [13]. It is tempting to associate the difference between the hopping rates in quantum diffusion of six orders of magnitude with decoherence and localization of the adsorbate due to entanglement with the phonons, tomonagons, photons, the rest gas in the experimental equipment, etc.. However, the evaluated time for the decoherence of the correlated motion of small molecules is too long because the effective cross section for scattering is proportional to the squared extension of the molecules [13]. Furthermore this idea does not work at low experimental temperatures because the environmental excitations, needed to decohere an atom or a small molecule, should have very small wavelength, hence very high energy, to be able to localize a hydrogen atom on a site with atomic dimensions. At low temperature $T \rightarrow 0$ K both phonons and tomonagons have long wavelengths of the order of 100-200 Å. Therefore phonons and tomonagons at low $T$ cannot couple to the motion of a hydrogen atom on a lengthscale of 2-3 Å.

We suggest entanglement to gravitons in high spacetime dimensions as a mechanism for telegraph-signal-like changes of the state of a quantum system, as it appears in 3+1 dimensional spacetime structure. In the next section we present the idea and a summary of a formalism for the treatment of the gravitational field within quantum field theory (QFT) and general relativity (GR) in the limit of weak gravity and linearization of Einstein’s field equations [14]. In the presence of the adsorbate soft local graviton modes are created, termed gravonons. The formalism leads to a nonrelativistic Schrödinger equation for the gravonons. A model with two parameters $\gamma$ and $\eta$, used to evaluate the soft modes, is briefly outlined, followed by the presentation of the results and their interpretation.

**2. Gravitons in high dimensional spacetime**

In 10+1 dimensional spacetime (10 spatial dimensions) the gravitational potential has the form:

$$V_{grav}^{(11)}(r) = -\frac{G^{(11)}M}{\pi^7 r^8}. \quad (1)$$

Up to distances of 0.05 mm = $5 \times 10^{-5}$ m $\approx 10^6$ bohr the classical gravitational law of Newton has been proved to be valid, therefore at this distance both laws have to yield the same value:

$$-\frac{G}{10^6} = -\frac{1}{\pi^7} \frac{G^{(11)}}{10^{48}} \rightarrow G^{(11)} = 10^{39}G \quad (2)$$

This means that at distance of 1 bohr the 10+1 dimensional gravitational interaction is $10^{39}$ times as strong as the classical interaction in 3+1 dimensional spacetime and it is very localized. The additional seven spatial dimensions are compactified to avoid discrepancy with the classical law, an estimate of the dimension of the compactification we need to explain many experimental observations being of the order of $a = 10000$ bohr [15, 16]. Arkani-Hamed et al. [17]-[21] were the first to claim that the hidden dimensions need not be compactified on the Planck scale. The hidden dimensions can be as large as a fraction of a millimeter or even infinite [21]. No experimental observation comes into conflict with this claim.

We use linearized weak field gravity as described within QFT (see e.g. [22]) and apply the usual procedure for deriving nonrelativistic quantum mechanics from QFT. In QFT the
interaction Lagrangian includes terms due to the interaction between the gravitons and all matter fields (electromagnetic field, massive scalar boson field - the adsorbate, massless boson fields - tomonagons etc.).

2.1. Emerging nonrelativistic matter particles

The adsorbate is treated as a massive boson field. Since the kinetic energy \( \epsilon \) of the moving adsorbate is much smaller than its mass \( m \) the relativistic energy \( E \) is written as \((c = 1)\):

\[
E = m + \epsilon. \tag{3}
\]

A matter boson field \( \psi \) varying slowly with time can then be defined as:

\[
\phi(x) = e^{-imt} \psi(x). \tag{4}
\]

Starting from the Klein-Gordon equation, Schrödinger’s equation for \( \psi(x) \) for a free adsorbate is obtained:

\[
i \frac{\partial}{\partial t} \psi = -\frac{\nabla^2}{2m} \psi \tag{5}
\]

with \( \nabla = (\frac{\partial}{\partial x^1}, \frac{\partial}{\partial x^2}, ..., \frac{\partial}{\partial x^N}) \). More details on the derivations will be presented in a forthcoming paper [14].

2.2. Emerging massive gravitons (gravonons)

The field of the gravitons is treated in a similar way. As diffusing particles of molecular size couple only to short wavelength gravitons, we write the relativistic energy \( E \) of a graviton as:

\[
E = kc + \varepsilon \tag{6}
\]

where \( \varepsilon \) is a tiny modification, induced by the adsorbate, \( k = |\vec{k}| \) and \( \vec{k} \) labeling the Fourier component of the graviton field \( h_{\mu \nu} \). The value of \( k \) is fixed by the condition that the wavelength should be of the order of the diffusion distance between two adsorption sites. For adsorbate entanglement to gravitons we need wavelength of the gravitons \( \lambda \approx 1 \) bohr, i.e. \( k \approx 10 \) bohr\(^{-1}\), energy \( E \approx 10^3 \) Hartree [15, 16]. \( \varepsilon \) characterizes the energy interval of the gravitons which couple to the scalar boson field \( \phi \). It is of the order of \( 10^{-12} \) Hartree. This motivates us to write for the gravitational field:

\[
h_{\mu \nu} = e^{-ikct} \zeta_{\mu \nu}(x) \tag{7}
\]

leading to a Schrödinger equation for the field quanta \( \zeta_{\mu \nu} \), termed gravonons:

\[
i \frac{\partial}{\partial t} \zeta_{\mu \nu} = (-\frac{\nabla^2}{2m_g} + V_o)\zeta_{\mu \nu} \tag{8}
\]

with \( m_g = \frac{k}{\varepsilon} \) the mass of the gravonon and \( V_o = -\frac{k^2}{2} \) a constant potential cancelling the zero point energy \( \omega_o = \frac{1}{2}kc \) of the light cone graviton \( h_{\mu \nu}(\vec{k}) \). Thus massive free gravonons have emerged resembling a quantum particle. With \( k = 10 \) bohr\(^{-1}\) the mass \( m_g \) of the gravonon is roughly a tenth of the mass of an electron. The derivation of eq. (8) will be presented in a future publication [14].

The massive local gravonons can be mathematically treated as in standard quantum mechanics. An interaction potential can be added to eq. 8, for instance a harmonic potential due to springs. The upper panel in fig. 2 illustrates this situation for the local gravonons induced by the metal atoms in the absence of the adsorbate. In the presence of the adsorbate, soft gravonon modes...
Figure 2. The upper panel illustrates the local gravonon structure induced by metal atoms in a clean metal surface approximated by harmonic potentials. In the presence of the adsorbate the local gravonon structure changes, giving rise to soft gravonon modes (lower panel). The coherence of the adsorbate-gravonon motion is retained within a small region, the so called deformation resonance (drawing on the l.h.s. in the lower panel). The wavy curves in both panels symbolize the local spacetime deformations due to the presence of the atoms, described by excitation of local gravonons.

are induced, which are entangled with the adsorbate motion, determining the time scale of this motion. Adsorbate-induced soft gravonons of lower frequency determine slower adsorbate movement on the metal surface since within the gravonon lifetime the adsorbate cannot change the adsorption site. The adsorbate-induced effects are confined to a small region, called a deformation resonance, and affect some 5-15 metal atoms. The deformation resonance is defined as consisting of the matter particles and the deformation of spacetime due to the adsorbate and the metal atoms and it is schematically represented by the drawing on the l.h.s. in the lower panel of fig. 2. Within the deformation resonance the adsorbate motion is coherently entangled with the gravonons.

The effective Hamiltonian of the total system in $D$ spatial dimensions reads [14]:

$$H_{\text{eff}} = \int d^D x \left[ -\frac{\nabla^2}{2m} \psi^+ \psi - \frac{\nabla^2}{2m_g} \zeta^+ \zeta + V_0 \zeta^+ \zeta + L_{\text{int}} \right]$$  \hspace{1cm} (9)
with the following Lagrangian $L_{\text{int}}$ of the matter - gravonon interaction:

$$
L_{\text{int}} = \int d^D x \left[ \frac{G^{(D)} M}{r^{D-2}} \psi^+ \psi + 2m \left( \frac{G^{(D)} M}{r^{D-2}} \right)^2 \zeta_0^+ \zeta_0 \psi^+ \psi \right]
$$

(10)

The first term in eq. (10) is the Schrödinger-Newton term and it corresponds to the $\frac{1}{r^8}$ power law in 10+1 dimensional spacetime. The second term describes the interaction between the adsorbate field and the gravonons ($m$: adsorbate mass, $M$: metal atom mass). Being a second order term it satisfies a $\frac{1}{r^{16}}$ power law in 10 spatial dimensions [14]. This is the quantum field theoretical Hamiltonian which is solved in a many-body basis [16]. The many-body basis configurations involved have components, describing the states of the gravonon continuum and the adatom diffusion states or states within the deformation resonance, where the local coupling to gravonons is effective.

The time dependent Schrödinger equation for the world wave function $\Psi(t)$ is solved in the many body basis basis:

$$
i\hbar \frac{\partial \Psi(t)}{\partial t} = H_{\text{eff}} \Psi(t).
$$

(11)

$\Psi(t)$ describes a wave packet consisting of the adsorbate particle and gravonons excited out of the vacuum state. The time development of the squared projection of $\Psi(t)$ on the many-particle basis states, confined to a particular adsorption site, is evaluated to provide data on the diffusive movement of the adsorbate on the solid surface.

2.3. Model for the non-interacting gravonon structure

The gravonon field in the second and third term of the effective Hamiltonian eq. (9) is a free field in a constant potential. The adsorbate motion, which we want to investigate, occurs, however, in the presence of other masses, which have already induced a structure in the gravonon field. This paragraph describes, how the pre-existing gravonon structure is modelled.

The field $\zeta_{00}(\vec{x})$ is expanded in functions centered and localized near the solid atoms:

$$
\zeta_{00}(\vec{x}) = \sum_i q_i g(\vec{x} - \vec{x}_i)
$$

(12)

$g(\vec{x} - \vec{x}_i)$ is a gaussian centered at $\vec{x}_i$. $\vec{x}_i$ is the $D$-dimensional position of the solid atom with $x_1 = \ldots = x_D = 0$. $q_i$ are expansion coefficients, which become operators upon quantization. $g(\vec{x} - \vec{x}_i)$ is normalized such that:

$$
\int d^D x \ g^2(\vec{x} - \vec{x}_i) = 1,
$$

(13)

i.e. $g^2(\vec{x} - \vec{x}_i)$ tends to $\delta(\vec{x} - \vec{x}_i)$ for strong localization.

The product of the gravonon field becomes then

$$
\zeta_{00}^+(\vec{x}) \zeta_{00}(\vec{x}) = \sum_{i,j} q_i q_j g(\vec{x} - \vec{x}_i) g(\vec{x} - \vec{x}_j).
$$

(14)

The gaussians are assumed to be $\delta$-function-like so that

$$
\zeta_{00}^+(\vec{x}) \zeta_{00}(\vec{x}) \rightarrow \sum_i q_i^2 \delta(\vec{x} - \vec{x}_i).
$$

(15)
The gravonon integrand in the Hamiltonian without any adsorbate induced gravonon-gravonon interaction is then transformed as follows:

\[-\frac{\nabla^2}{2m_g} \zeta_{00} \zeta_{00} + V_O \zeta_{00} \zeta_{00} \rightarrow \frac{1}{2} \omega_A q_A^2 \delta(\vec{x} - \vec{x}_A) + \sum_i \frac{1}{2} \omega_S^2 q_i^2 \delta(\vec{x} - \vec{x}_i)\]  

(16)

where \(\omega_A\) and \(\omega_S\) are the frequencies of the non-interacting adsorbate induced and metal atom induced gravonons. Performing the integration \(\int d^Dx\) yields the Hamiltonian of the non-interacting gravonons:

\[\int d^Dx \left(-\frac{\nabla^2}{2m_g} \zeta_{00} \zeta_{00} + V_O \zeta_{00} \zeta_{00}\right) \rightarrow H_A + H_S = \frac{1}{2} \omega_A q_A^2 + \sum_i \frac{1}{2} \omega_S^2 q_i^2.\]  

(17)

2.4. Adsorbate-induced gravonon structure

Now we add a component to \(\zeta_{00}(\vec{x})\) to describe the influence of the adsorbate on the gravonon structure:

\[\zeta_{00}(\vec{x}) = \sum_i \left[q_i g(\vec{x} - \vec{x}_i) + q_i f(\vec{x}, \vec{x}_i)\right].\]  

(18)

\(f(\vec{x}, \vec{x}_i)\) is delocalized so that it has amplitude on all defined sites \(\vec{x}_i\). It is normalized such that

\[\int d^Dx f^2(\vec{x}, \vec{x}_i) = 1.\]  

(19)

In this way:

\[\zeta_{00}^+(\vec{x}) \zeta_{00}(\vec{x}) = \sum_i \left[q_i^2 \delta(\vec{x} - \vec{x}_i) + q_i^2 f^2(\vec{x}, \vec{x}_i)\right] + \sum_{i,j} q_i q_j g(\vec{x} - \vec{x}_i) f(\vec{x}, \vec{x}_j).\]  

(20)

This has to be inserted in eq. (10) and the integration has to be performed.

In order to evaluate the gravonon structure we replace the adsorbate field \(\psi^+ \psi\) by its expectation value \(\langle \psi^+ \psi \rangle\). Among the sites we distinguish a particular one \(q_S\) as the one which is nearest to the adsorbate site \(q_A\). The interaction terms involving the function \(f(\vec{x}, \vec{x}_i)\) are then:

\[V_{A-S} = \int d^Dx J(\vec{x}) q_S^2 f^2(\vec{x}, \vec{x}_S) + \sum_{m \neq S} \int d^Dx J(\vec{x}) q_m^2 f^2(\vec{x}, \vec{x}_m)\]

\[+ \int d^Dx J(\vec{x}) q_S g(\vec{x}, \vec{x}_S) \sum_{m \neq S} q_m f(\vec{x}, \vec{x}_m)\]

\[+ \int d^Dx J(\vec{x}) \sum_{m, n \neq S} q_m q_n g(\vec{x} - \vec{x}_m) f(\vec{x}, \vec{x}_n)\]

\[+ \int d^Dx J(\vec{x}) q_S a g(\vec{x} - \vec{x}_S) f(\vec{x}, \vec{x}_A)\]  

(21)

with

\[J(\vec{x}) = 2m \sum_i \frac{G^{(D)} M}{|\vec{x} - \vec{x}_i|^{D-2}} \langle \psi^+ \psi \rangle.\]  

(22)

Introducing two parameters \(\gamma\) and \(\eta\), the coupling terms between the gravonons are parameterized as follows:

\[\int d^Dx J(\vec{x}) q_S^2 f^2(\vec{x}, \vec{x}_S) = \frac{1}{2} \eta \gamma q_S^2 g^2\]  

(23)
After the gravonon structure has been determined, the mean field approximation leading to destruction of the gravonon coherence within the deformation resonance. Since softer and in external fields of the rest universum, which can be the origin of external disturbances, deformation resonance is embedded in the rest of the surface and its induced gravonon structure. The local intrinsic gravonon coherence is retained unless it is destroyed by external effects. The gravonons of lower frequency adsorbate-gravonon system is extended over a broader deformation resonance and results in soft mode in the substrate gravonons.

For larger values of $1 - \eta$ is obvious from eq. (28) the smaller the value of $\gamma$. Hence, $1 - \eta$ is a measure whether the coherence of particle movement is of long range nature. For larger values of $1 - \eta$, i.e. smaller values of $\eta$, the coherent dynamics of the adsorbate-gravonon system is extended over a broader deformation resonance and results in soft gravonons of lower frequency $\omega_{soft}$. Hence, $1 - \eta$ correlates with the strength of many-body forces between substrate gravonons.

The adsorbate induced gravonon interactions $V_{A-S}$ depends on the following assumptions:

- Mean field approximation with respect to $\psi^+ \psi$.
- $\psi^+ \psi$ describes only the adsorbate. All other matter fields are static.
- Gravonon structure is warped only at certain sites near the matter particles.

After the gravonon structure has been determined, the mean field approximation $\psi^+ \psi \rightarrow \langle \psi^+ \psi \rangle$ is no longer used. The determined gravonon structure is plugged into eqs. (9,10) and the time-dependent many-body problem is solved with this gravonon structure.

The gravonon coupling eq. (28) includes two parameters $\gamma$ and $\eta$. $\gamma$ is the coupling strength defined as:

$$\gamma = \frac{\omega_A^2}{\omega_S^2}$$

The soft mode in the $\gamma \eta$ - gravonon model is an adsorbate induced coherent motion within the deformation resonance involving typically 5 to 15 spacetime deformations which are assumed to be perfectly localized before adsorbate interaction sets in (cf. fig. 2, upper panel). As it is obvious from eq. (28) the smaller the value of $\eta$ is, the more important the many-particle forces are. Hence, $1 - \eta$ is a measure whether the coherence of particle movement is of long range nature. For larger values of $1 - \eta$, i.e. smaller values of $\eta$, the coherent dynamics of the adsorbate-gravonon system is extended over a broader deformation resonance and results in soft gravonons of lower frequency $\omega_{soft}$.

The local intrinsic gravonon coherence is retained unless it is destroyed by external effects. The deformation resonance is embedded in the rest of the surface and its induced gravonon structure and in external fields of the rest universum, which can be the origin of external disturbances, leading to destruction of the gravonon coherence within the deformation resonance. Since softer
gravonons correspond to lower values of \( \eta \), and then to lower values of the coupling strength \( \gamma \), this implies that the soft gravonon mode is easier to destroy by external influences. Therefore the transition temperature \( T_{\text{trans}} \) from quantum to overbarrier diffusion must be lower if \( \eta \) is smaller.

This is similar to the effect of temperature increase in experiments with, e.g. scattering of noble gas beams from periodic solid surfaces, which is described by the Debye-Waller factor. In order to make contact with experiment we phenomenologically introduce a similar Debye-Waller-like factor \( \exp(-AT_{\text{trans}}) \) for \( 1 - \eta \):

\[
1 - \eta = \exp(-AT_{\text{trans}}) \approx 1 - AT_{\text{trans}}
\]

which makes \( \eta \) proportional to \( T_{\text{trans}} \), the temperature for transition from the coherent quantum tunnelling diffusion to statistical non-coherent overbarrier diffusion of adsorbates.

3. Results and discussion

3.1. Telegraph-signal-like change of adsorption site with time

The model of hydrogen diffusion on a solid surface has two adsorption sites and two warp resonances where the interaction with the gravonons is effective. The changes with time of the squared projection of the total world wave function eq. (11) on the initial state with the adsorbate on site 1 of the two-site model are plotted in fig. 3. The plot shows indeed that the adsorbate resides long time on the initial adsorption site before it jumps to a neighbouring one. Telegraph-signal-like site changes occur at time intervals, determined by the lifetime, i.e. the energy, of the entangled gravonons of lowest frequency. In the lifetime of the soft gravonon modes, which entangle to the adsorbate on a definite adsorption site, the particle cannot change site. This lifetime depends on the energy of the soft gravonon modes \( \omega_{\text{soft}} \). Therefore the modes of the gravonon subspace determine the diffusion time - low energy modes determine slow diffusion, high energy modes determine fast diffusion. The jump time is the inverse of the frequency of the softest gravonon mode. Of course, the modifications of the gravonon spectrum, induced by the diffusing particle, depend upon the matter fields involved (adsorbate and metal atoms fields), their physical nature and their interaction.

The calculation whose results are shown in fig. 3 is aimed at reproducing the slow diffusion of hydrogen on Cu(100) from the low temperature STM experiments of Lauhon and Ho [2], i.e. a very slow quantum diffusion, slower than the diffusion in the experiments with FEM and optical diffraction (cf. the left panel in fig. 1).

Though the site change appears as a sudden collapse, this is a solution of the coherent time dependent Schrödinger equation, without collapse and state reduction. The physics of the telegraph signal and how the telegraph signal is generated is discussed in the papers by Doyen and Drakova refs. [23, 24].

3.2. Landscape of the soft gravonons

The landscape of the \( \gamma \eta \) model is displayed in fig. 4 as a contour plot of the lines of constant logarithm of the frequency of the softest gravonon mode, \( \log_{10}\omega_{\text{soft}} \), versus the coupling strength \( \gamma \) and the temperature for transition from quantum diffusion to statistical overbarrier diffusion \( T_{\text{trans}} \), i.e \( \eta \) (\( \eta = 0.95 \) corresponds to 200 K and varies linearly with temperature from \( \eta = 0 \) at \( T = 0 \)). It is a contour plot of constant diffusion rates \( \nu_0 \) in the quantum regime. Close to the hyperbolic boundary we have the softest modes. The hyperbolic boundary between the coloured part and the white part of the plot corresponds to the transition from very soft gravonon modes (at the hyperbolic boundary) to zero-frequency modes (within the white part). This parameter
Figure 3. Changes of the squared projection of the world wave function $\Psi(t)$ on the initial state with the adsorbate on site 1 of a two-site model with time. Telegraph-signal-like site changes occur at time intervals, determined by the lifetime, i.e. the energy, of the entangled soft gravonon modes $\omega_{\text{soft}}$.

space yields zero-frequency gravonon modes, the so called Nambu-Goldstone bosons.

The experimental diffusion rate of $^1$H, $^2$H and $^3$H on different metal surfaces is plotted on the landscape of the adsorbate-induced soft gravonon frequency, since we know both the diffusion rate and the transition temperature from experiment. We can read off the coupling strength to the gravonons $\gamma$ which reproduces the experimental diffusion rate at the temperature of transition from quantum to overbarrier diffusion. Hence, in this plot we see the ”experimental” values of the coupling strength $\gamma_{\text{exp}}$ to the gravonons, and the ”experimental” value of the transition temperature to quantum diffusion, both needed to reproduce the experimental hopping rate on a map of hopping rates, evaluated theoretically. The experimentally measured adsorption systems lie in a narrow region on the boundary between the parameter spaces, typical for zero quantum diffusion rate and non-zero quantum diffusion rate (red points in fig. 4).

Since in 11 dimensional spacetime the gravitational interaction is very sensitive to the distance, varying with the inverse 16-th power of the distance between the hydrogen atom and the metal atom in the deformation resonance, the theoretical coupling strength $\gamma_{\text{th}}$ is very sensitive to this distance as well. Having in mind the strong distance dependence of the interaction between the adsorbate field and gravonons in $D$ spatial dimensions with $r^{-2(D-2)}$ (cf. eq. 10) and of the coupling strength as $\gamma_{\text{th}} \propto \frac{1}{r^{12}}$ in 11D spacetime, we make the best fit $\gamma_{\text{th}}$ to the experimental
values of the coupling strength $\gamma_{\text{exp}}$ by varying the distance between the hydrogen atom and the metal atom in the deformation resonance in 11D spacetime (fig. 5). The labels below each point in the curve refer to the deformation resonance configuration of the adsorbate and indicate which values of $R_{\text{ads}} - M$ have been chosen for the fit. The theoretical values of $\gamma_{\text{th}}$ evaluated in 11D spacetime are fitting best to the experimental values of the diffusion rates, estimates within 10D and 12D are also not so bad, however, results for $\gamma_{\text{th}}$ in 8D and 26D spacetime diverge.

The best fit to the experimental coupling strength $\gamma_{\text{exp}}$ provides the distances $R_{\text{ads}} - M$ at which entanglement to gravonons in the deformation resonance yields the experimental diffusion rates. In fig. 6 we plot $R_{\text{ads}} - M$ versus the distance between a hydrogen atom and a metal atom due to ab initio electronic structure calculations for the same adsorption geometries. The agreement is exceptionally good, having in mind the strong distance dependence of the results in 11D-theory and the fact that the two theories have no contact points at all.

4. Conclusion
The set of experimental data on diffusion of hydrogen on transition metal surfaces cannot be rationalized by conventional quantum mechanics in 3+1 dimensions. Entanglement between the adsorbate motion with environmental fields at very low temperatures cannot be achieved in 3+1 dimensions by the common excitations (phonons, tomonagons, etc.). If entanglement with the environment plays a role in these experiments, the environmental excitations have to be gravitons in $D + 1$ dimensional spacetime ($D=8,9,10,11$).

In this theory gravonons emerge as nonrelativistic massive bosons describing spacetime deformations very near to the adparticle. The frequency of adsorbate induced soft local gravonon
Figure 5. Theoretical values of the coupling strength evaluated by varying the distance between the adsorbate and a metal atom in the deformation resonance to yield the best fit to $\gamma_{exp}$ and the experimental diffusion rate. The labels of each point in the curve refer to the configuration in the deformation resonance and indicate which value of $R_{ads-M}$ has been chosen for the fit.

Figure 6. Comparison of the distance [Å] between a hydrogen atom and a metal atom in the deformation resonance, derived from the present theory, and ab initio (DFT) distances [Å] between H and metal atoms for the same adsorption geometries.
modes determines the lifetime of the entangled state on a given site in the local region and the
diffusion rate. While the gravonons propagate in the hidden dimensions of 10+1 dimensional
spacetime the adsorbate is localized on one adsorption site entangled to the gravonons and cannot
change site. Adsorption site changes and surface quantum diffusion occur in a telegraph-signal-
like manner with time and not as Rabi oscillations, as a result of the solution of Schrödinger’s
time dependent equation. The conditions for time variation of the adsorption site similar to
telegraph signals are weak and local coupling of the adsorbate motion to a continuum of soft
local graviton modes (gravonons) of high density of states in high spacetime dimensions. The
frequency of the soft gravonons determines the lifetime of the adsorbate-gravonon entangled
state and the diffusion rate of the adsorbate to a neighbouring adsorption site.

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Corrigendum: Low temperature motion of hydrogen on metal surfaces signals breakdown of quantum mechanics in 3+1 dimensions

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Equation (2) and the text after eq. (2) should be replaced by:

\[- \dfrac{G^{(11)} M}{(2a\pi)^7 r} = - \dfrac{GM}{r} \rightarrow G^{(11)} = (2a\pi)^7 G.\] (2)

This means that at distance 1 bohr the 10+1 dimensional gravitational interaction is \((2a\pi)^7\) times as strong as the classical interaction in 3+1 dimensional spacetime and it is very localized.

Equation (9) should be replaced by:

\[H_{eff} = \int d^Dx \left[ -\psi^+ \nabla^2 \psi - \dfrac{\nabla^2}{2m} \zeta_{00}^+ \zeta_{00} + V_0 \zeta_{00}^+ \zeta_{00} \right] - L_{int}.\] (9)

Equation (10) should be replaced by:

\[L_{int} = \int d^Dx \left[ \dfrac{G^{(D)} mM}{r^{D-2}} \psi^+ \psi + \dfrac{m}{2} \zeta_{00}^+ \zeta_{00} \psi^+ \psi \right].\] (10)

The equations and the text starting at eq. (12) upto eq. (20) should be replaced by:

The field \(\zeta_{00}(\vec{x})\) is expanded in functions centered and localized near the solid atoms:

\[\zeta_{00}^+(\vec{x}) + \zeta_{00}(\vec{x}) = \sum_i 2q_i g(\vec{x} - \vec{x}_i).\] (12)

\(\vec{x}_i\) is the \(D\)-dimensional position of the solid atom with \(x_4 = \ldots = x_D = 0\). \(q_i\) are expansion coefficients, which become operators upon quantization.

\[g(\vec{x} - \vec{x}_i) = \sqrt{\dfrac{\omega_i}{2}} \zeta_{00}^{(i)} V_{grav}(\vec{x}_i) \theta.\] (13)

\(\zeta_{00}^{(i)}\) are functions localized near the positions \(\vec{x}_i\) of the atom cores. \(\omega_i\) are the eigenfrequencies of the non-interacting graviton field. \(V_{grav}(\vec{x}_i)\) is the gravitational potential and the factor \(\theta\) takes care of the dimensions.
The product of the gravonon field becomes then

\[
\zeta_{00}^{+}(\vec{x})\zeta_{00}(\vec{x}) = \ldots + \sum_{i,j} q_i q_j g(\vec{x} - \vec{x}_i)g(\vec{x} - \vec{x}_j).
\] (14)

The localized functions are assumed to be δ-function-like so that

\[
\zeta_{00}^{+}(\vec{x})\zeta_{00}(\vec{x}) \to \ldots + \sum_{i} q_i^2 \delta(\vec{x} - \vec{x}_i).
\] (15)

The gravonon integrand in the Hamiltonian without any adsorbate induced gravonon-gravonon interaction is then modified as follows:

\[
-\frac{\zeta_{00}^{+}}{2m_g} \nabla^2 \zeta_{00} + V_0 \zeta_{00}^{+} \zeta_{00} \to \frac{1}{2} \omega_A^2 q_A^2 \delta(\vec{x} - \vec{x}_A) + \sum_{i} \frac{1}{2} \omega_S^2 q_i^2 \delta(\vec{x} - \vec{x}_i) + \ldots
\] (16)

where \( \omega_A \) and \( \omega_S \) are the frequencies of the non-interacting adsorbate induced and metal atom induced gravonons. Performing the integration \( \int d^D x \) yields the Hamiltonian of the non-interacting gravonons:

\[
\int d^D x (-\zeta_{00}^{+} \nabla^2 \zeta_{00} + V_0 \zeta_{00}^{+} \zeta_{00}) \to H_A + H_S = \frac{1}{2} \omega_A^2 q_A^2 + \sum_{i} \frac{1}{2} \omega_S^2 q_i^2 + \text{kinetic energy}.
\] (17)

2.4. Adsorbate-induced gravonon structure

Now we add a component to \( \zeta_{00}(\vec{x}) \) to describe the influence of the adsorbate on the gravonon structure:

\[
\zeta_{00}^{+}(\vec{x}) + \zeta_{00}(\vec{x}) = \sum_{i} 2[q_i g(\vec{x} - \vec{x}_i) + q_i f(\vec{x}, \vec{x}_i)].
\] (18)

\( f(\vec{x}, \vec{x}_i) \) is delocalized so that it has amplitude on all defined sites \( \vec{x}_i \). In this way:

\[
\zeta_{00}^{+}(\vec{x})\zeta_{00}(\vec{x}) = \ldots + \sum_{i} \left[q_i^2 \delta(\vec{x} - \vec{x}_i) + q_i^2 f^2(\vec{x}, \vec{x}_i)\right] + \sum_{i,j} q_i q_j g(\vec{x} - \vec{x}_i)f(\vec{x}, \vec{x}_j).\] (20)