Why is more different: the appearance of microscopic classical particles

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Abstract. Particles (electrons, atoms, molecules) in interaction with large ensembles of atoms, e.g. solids and surfaces, often display properties, which are unexpected, based on experimental and theoretical investigations of small ensembles. A frequently cited phrase has been coined by P.W. Anderson to focus on this problem: "More is different". Theoretical descriptions of the unexpected properties commonly use ad hoc assumptions, justified by referring to the vogue word "emergence". In this contribution some striking examples of behaviour changes are outlined with the transition from "few" to "more". It is suggested that entanglement between the observable local system and unobservable continua of the environment (phonons, electron-hole pairs, gravitons) can contribute much to the understanding of the relationship between the behaviour of "few" and "more". Solving the time dependent Schrödinger equation for coherent model worlds, comprising both the local system and the entangled continua of the environment, adsorbate motion at surfaces at low temperature is examined. In the time-dependent formalism the entanglement of the core movement of a gas atom to the high dimensional continuum of substrate environs leads to a qualitative behaviour as it is observed experimentally. The focus in the present article is the emergence of classical appearance of a local quantum system entangled with the excitations of the environment. The dynamical evolution of the quantum system is coherent and according to the time dependent Schrödinger equation. The environmental excitations can be phonons, tomonagons, gravitons, either observable or not observable in experiment.

1. Introduction

It is frequently observed that microscopic particles - atoms and molecules - do not apparently obey the rules of standard quantum mechanics when they are in interaction with solid surfaces and, hence, coupling to the high dimensional phase space of the solid excitations. In this case atoms often behave like classical particles and we refer to this phenomenon as dimensionality effect and the appearance of microscopic classical particles.

This kind of observations has been addressed nearly four decades ago by Anderson in a very influential paper published in 1972 [1]. Anderson tried to subsume these phenomena under the principle of spontaneous symmetry breaking, but obviously not all kinds of classical behaviour can be classified as broken symmetry. Therefore many scientists prefer now to talk about emergence, meaning perhaps that everyday intuition combined with some brilliant mathematical idea are the proper tools for attacking these phenomena.

This neglect of reductionism contains the danger of overlooking hidden aspects and influences
in the environment which might be responsible for the observed non-quantal behaviour. There might be acting something behind the scene which is the causal origin - in a reductionist sense - of what is observed. But using the concept of emergence we will neither be interested nor able of discovering the causal origin.

The purpose of this contribution is to explore this possibility for some apparently classical behaviour of microscopic particles at solids. As the classical behaviour of microscopic particles at surfaces is perhaps not too widely known outside the area of surface science, we shall describe some prominent examples. For the last example - localization at surfaces - we shall discuss the hidden aspects which might be responsible for the experimental observations. Classical appearance is usually described by decoherence theory which in its application to surface science has been summarized in ref. [2].

2. Experimental evidence of classical behaviour at solid surfaces

2.1. Scattering of noble gas beams at surfaces
Experiment demonstrates that rare gas atoms behave as expected from standard quantum mechanics, if they are scattered from nano gratings [3]. The situation is quite different, if rare gas atoms are scattered from solid surfaces. In this case only He scattering displays sharp diffraction peaks [4], whereas all other rare gases show a scattering distribution which can be described by classical mechanics [5]. This includes the classical rainbow. He and Ne scattering results in diffraction patterns imposed on a so called inelastic background, whereas for Kr and heavier rare gas atoms scattering the structureless background dominates to such an extent that diffraction patterns are no longer discernible.

2.2. Accommodation at surfaces
This classical behaviour of scattering rare gas atoms is not only observed for elastic diffraction, but also for inelastic scattering at low temperatures. In this case even He behaves classically as can be seen from the analysis of the so called accommodation coefficient \( \alpha \) which measures the deviation of the energy of the scattered atom from the average energy of the substrate atom. If \( \alpha \) equals unity, the scattered atom is fully accommodated with the substrate motion. At zero temperature and low scattering energy quantum theory predicts \( \alpha = 0 \) [6], while classical theory predicts \( \alpha = 1 \) [8, 9]. Obviously experiment obeys classical theory [6, 7]. Stationary state 3D scattering theory and the generalized Ehrenfest theorem have been used earlier to explain the classical behaviour within the deformation resonance approach, accounting for the different dimensionality of the gas atom and substrate movement [10].

2.3. Metastable survival probabilities
One might expect that classical behaviour should be restricted to core movement, but electronic transitions are affected as well. There is a spectacular example: a He atom is electronically excited by transferring an electron from the 1s-orbital to the 2s-orbital with the two spins being parallel. This is a metastable state with a lifetime of the order of seconds. If such an electronically excited He atom is scattered from a CO molecule in the gas phase, there is a probability of roughly 10% that the He atom gets de-excited by an Auger process into its electronic ground state, i.e., 90% of the atoms survive in the electronically excited state. This process can quantitatively be described and calculated by standard quantum mechanics.

If we now form a densely packed overlayer of CO molecules on a smooth solid surface (e.g. Pd(111)) and scatter electronically excited He atoms from this layer, we would expect similar de-excitation probabilities as in the gas phase. But surprisingly the survival probability decreases by a factor of \( 10^4 \). This cannot be understood by the standard quantum mechanical description of Auger processes [11]. Even more surprisingly the scattering distribution is purely classical,
whereas the scattering of ground state helium shows the diffraction peaks predicted by quantum theory.

2.4. Adparticle localization
At cold solid surfaces adparticle movement does not follow the laws as predicted by Schrödinger’s equation for static potential energy surfaces even if phonons are included in the calculations [12, 13]. The entanglement to gravitons is suggested as an ubiquitous decoherence mechanism and as the only relevant process for particle localization at low T. This mechanism is crucially dependent upon the high dimensionality of the graviton field and on the hidden dimensions where gravitons can propagate. The entanglement to the rest excitations of the sample (phonons, photons, tomonagons), 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 these excitations at low temperature are too long to allow to distinguish a H atom on two neighbouring adsorption sites, for instance.

3. The coherent world model
3.1. The model
We describe a particle (atom, electron) coupling to two continua of different dimensionality. The continuum of plane waves, if used to describe surface diffusion, is two-dimensional compared to the highly dimensional continuum of the environs. The different dimensionality should be retained in the calculations and still the method should be made possible on a computer. The model is illustrated in fig. 1. Via a localized state the particle couples to the environment. This localized state together with the perturbation it induces in the environment is called a deformation resonance. This can e.g. describe a gas particle incident from the vacuum onto a solid surface thereby deforming the solid surface locally. The environs will then be phonons. The deformation consists of a transient displacement of the substrate atoms near the point of impact.
Alternatively it could describe an adsorbed particle moving across the surface thereby hitting a substrate atom. If hidden dimensions are present, particle and substrate atom could experience a small but significant gravitational attraction. In this case the environs will be gravitons and the deformation resonance will be termed warp resonance.

3.2. Hamiltonian
The Hamiltonian includes terms describing all particles and their interactions:

\[
H = H_{\text{gas atom}} + H_{\text{phonon}} + H_{\text{gas atom} - \text{phon}} + H_{\text{graviton}} + H_{\text{gas atom} - \text{graviton}}
\]

\[
= \sum_g E_g n_g + E_w n_w + \sum_p E_p n_p + \sum_g V_{\text{loc}}(g) c_g^+ c_g + \sum_g V_{\text{phon}}(g) c_g^+ c_g
\]

\[
+ \sum_p V_{\text{phon}}(p) c_p^+ c_p + \sum_p V_{\text{phon}}(p) c_p^+ c_p
\]

\[
+ \sum_k \omega_{\text{phon}} b_k^+ b_k + \sum_k \sum_{p} E_k b_k^+ b_k + V_{\text{phon}} n_w(b_{\text{phon}} + b_{\text{phon}}^+) + \sum_k V_{k} b_k^+ b_k
\]

\[
+ \sum_{\kappa} \varepsilon_{\text{grav}} a_{\kappa}^+ a_{\kappa} + \sum_{\kappa} \varepsilon_{\kappa} a_{\kappa}^+ a_{\kappa} + \sum_{\kappa} V_{w,\text{grav}} n_w a_{\kappa}^+ a_{\kappa} + V_{w,\text{grav}} n_w a_{\kappa}^+ a_{\kappa}
\]

The meaning of the symbols is: \( n_g, n_w \): occupation number operators for the gas particle in the vibrationally ground (parallel to the surface) core movement states and in the deformation resonance; \( c_p^+, c_p \): creation and annihilation operators for the gas particle in the respective core movement states; \( V_{\text{loc}} \): interaction potential between a gas particle state and the deformation resonance; \( V_{\text{phon}} \): interaction potentials between the gas particle states and plane waves; \( E_g, E_w, E_p \): energies of the respective gas particle states and plane waves. \( \omega_{\text{phon}}, E_k \): energy of the local and continuum phonon modes; \( b_{\text{phon}}^+, b_{\text{phon}}, b_k^+, b_k \): creation and annihilation operators for the local and continuum phonon modes; \( \varepsilon_{\text{grav}}, \varepsilon_{\kappa} \): energy of local and continuum environs (gravitons); \( a_{\kappa}^+, a_{\kappa}, a_{\kappa}^+ \): creation and annihilation operators for gravitons; \( V_{w,\text{grav}} \): interaction between the gas particle and the gravitons within the warp resonance (for the sake of a simpler notation the polarization degrees of freedom are not explicitly displayed); \( V_{\text{phon}}, V_k \): interaction between the gas particle and the phonon modes within the deformation resonance (cf. [2]).

3.3. Formalism
The basis for the representation of the Hamiltonian is similar to CI in quantum chemistry. We have many-particle states, which are product states from basis states. The basis states involve states for the local particle (ground \( | g \) and local deformation state (warp resonance) \( | w \)) and for its delocalized movement (plane waves) \( \{ | p \} \). The environ field consists of local environs and continuum environs: \( | \text{grav} \rangle \), \( | \kappa \rangle \) and \( | \text{phon} \rangle \), \( | \kappa \rangle \). In a many-particle picture the dynamics of the system is described with the help of both localized and delocalized basis states for all particles in the model: adsorbate, solid excitations, gravitons. The interactions are between many-body states, which are product states with components referring to the gas particle core movement parallel to the surface, its vibrational state and environmental excitations.

The initial state of the particle depends upon the experiment to be described. For instance it is a plane wave if we describe electrons in a metal, it is a state with a local component if we describe adparticle diffusion on a solid surface. The time evolution of the initial states is visualized by following the time evolution of the density matrix. The density matrices are defined in the initial basis and in the basis of the 4D world.

The different dimensionality of the continua, the local region is entangled to, means different time and energy scales. However, it is not possible to have continua states at all energies. This difficulty is surmounted by an adequate discretization procedure.
In a coherent world model we follow the time evolution of an adsorbed particle localized on a substrate surface with 2D periodicity at its equilibrium position in the adsorption well. The localized wave packet used to represent the particle is not an eigenstate in a 2D periodic potential, hence it changes its shape with time as the time-dependent Schrödinger equation requires. The entanglement with different elementary excitations in the environment will affect the evolution of the local adsorbate state, leading eventually to particle localization, hence to decoherence. The competition between the environmental decoherence and the coherent time evolution depends upon their relative rates. As we showed in a recent paper [2], the entanglement with the lattice phonons and tomonagons in the solid surface is not fast enough to decohere a single adsorbed atom as it is seen in the low temperature STM images. A more efficient decoherence mechanism was suggested due to entanglement with the gravitons within the spacetime deformation (warp) resonance.

We use the philosophy and formalism of the Quantum Nano Dynamics (QND) theory, a field theoretical approach developed to treat correlated many-particle systems [2, 14, 15]. In the present paper we are concerned with the coherent time evolution of the core motion of a single adsorbed atom entangled with the continuum of delocalized plane waves and the environmental field provided by the surface atoms. Although in the presented numerical calculations the delocalized phonons, in which the local phonons decay, are not explicitly treated together with other environmental degrees of freedom, we present the formalism including bosonized solid excitations (e.g. phonons) in order to demonstrate how bosonized solid excitations can be handled.

The coupling of the local gas particle states to the plane wave continuum leads to energy broadening and finite lifetime in the local gas particle states, hence to delocalization. We take into account the two lowest vibrational states of an adsorbate parallel to the solid surface $|g\rangle$ and $|w\rangle$ which is contracted (of the order of 1 bohr). Tunnelling out of the adsorption site into plane waves, hence delocalization and diffusion, can only occur via the state $|g\rangle$. The coupling of the atom core movement to the environ (graviton) continuum occurs within the deformed space which is represented with the more contracted basis function $|w\rangle$.

4. Coherent time evolution of the localized adsorbate entangled with the plane wave and environ continua

The time evolution of the adsorbate core movement state follows Schrödinger’s time-dependent equation:

$$-i\hbar \frac{d\Psi(t)}{dt} = H\Psi(t)$$

(2)

with $\Psi$ an eigenfunction of the total Hamiltonian eq. 1. We assume that at $t_0 = 0$ the adparticle is in the local state $|g\rangle$ and an environ of high energy is excited: $|\kappa\rangle$. The approximate eigenfunctions $\Psi_I$ (determined by a limited CI-expansion) of the QND hamiltonian eq. (1) are used to determine the time dependence according to the unitary time evolution:

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

(3)

The expansion of the local adsorbate core movement state in the eigenfunctions $\{|I\rangle\}$ at time $t_0 = 0$ is then:

$$|g_{t_0}\rangle = c_{1,g0}^{-1} |1\rangle + c_{2,g0}^{-1} |2\rangle + ...$$

(4)

The time development of $|g0\rangle$ is obtained as:

$$|g_{t_1}\rangle = c_{1,g0}^{-1}e^{iE_1 t_1/\hbar} |1\rangle + c_{2,g0}^{-1}e^{iE_2 t_1/\hbar} |2\rangle + ...$$

(5)
We need the representation of the density operator at $t_1$ in the input basis, for instance:

$$\rho(t_1) = |g_0 t_1\rangle \langle g_0 t_1|$$  \hspace{1cm} (6)

The procedure is repeated for each next time step to provide the coherent time evolution of the density operator (in the input basis) which can be used to illustrate the delocalization and diffusion of a localized adsorbate on a solid surface in interaction with the continua of plane waves and environs.

5. String theory of gravitational induced decoherence

In this section we discuss the background which leads to considering gravitational interaction as relevant for decoherence phenomena [16].

5.1. Large hidden dimensions: The Arkani-Hamed-Dimopoulos-Dvali theory

Arkani-Hamed, Dimopoulos and Dvali (ADD) [17] proposed that large extra dimensions could be underlying the Standard Model and solve the hierarchy problem. Rolled-up extra dimensions can be big, if the particles in our four dimensional world are confined to a brane and are not free to travel in the bulk of a higher dimensional space. This would not contradict experimental results.

In the ADD model all existing particles are confined to a single brane which does not bound space. It simply sits inside the extra curled-up dimensions, like a line along a cylinder. The ADD model may have up to seven extra dimensions. The reason that the extra dimensions are allowed to be large is that gravity is very feeble. The gravitational force between two electrons is $10^{41}$ times weaker than the electromagnetic force. It is therefore extremely difficult to investigate gravity at short distances experimentally. For light objects at close distances, gravity is so weak that its effects are readily overwhelmed by other forces. Based on experimental results, it is known that extra dimensions must be smaller than about a tenth of a millimeter. If gravity is the only force in the bulk of higher dimensional space, the existence of large extra dimensions would not contradict any experimental results.

In the absence of branes, millimeter-size extra dimensions would have to be ruled out. However, branes make large extra dimensions conceivable. Branes can trap all known particles so that only gravity experiences the full higher dimensionality of space. In the ADD scenario everything that does not involve gravity would look exactly the same as it would without the extra dimensions.

One can hope to see evidence of sub-millimeter-size dimensions in the ADD scenario only with an extremely sensitive gravity probe. We argue that in fact adsorbed microscopic particles on surfaces would provide such a sensitive probe.

The gravitational potential provided by a pointlike mass $M$ in 4-dimensional space-time is:

$$V_{\text{grav}}^{(4)}(r) = -\frac{GM}{r}$$  \hspace{1cm} (7)

In 11-dimensional space-time (10 space dimensions) the gravitational potential is:

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

$G^{(11)}$ is the gravitational constant in 11-dimensional space-time and has to be determined by comparison with experiment. The gravitational law eq. (8) cannot be valid for large separations $r$ as this would violate the experimentally verified classical law eq. (7). Therefore the hidden
dimensions are rolled-up (compactified) to a diameter $2a$ so that at large distances the separation in the hidden dimensions never exceeds $2a$. Equating the classical and the 11-dimensional gravitational law at large distances yields:

$$\frac{GM}{r} = \frac{G^{(11)} M}{(2a\pi)^7 r} \rightarrow G^{(11)} = (2a\pi)^7 G$$

This choice makes the two laws eq. (7) and eq. (8) agree at separations larger than $2a$. Inserting eq. (9) in eq. (8) yields at $r = 1$ bohr:

$$V^{(11)}_{\text{grav}}(r = 1) = GM(2a)^7$$

This means that at $r = 1$ bohr the gravitational interaction is $(2a)^7$ times as strong as predicted by the classical law eq. (7). Assuming that at $r = 1$ bohr the gravitational interaction strength between two electrons is $0.000027$ meV = $10^{-9}$ Hartree one finds that the compactification radius has to be of order 10000 bohr = 500 nm.

If this is correct then experimenters will find a deviation from Newton’s classical gravitational law at distances smaller than $10^{-3}$ mm. The best experiment we know of up to now concluded that at 100 nm the deviations from Newton’s classical gravitational law are smaller than a factor of $10^9$ [18]. We predict at 100 nm a deviation by a factor $10^7$. So everything is still in agreement with experiment but it is getting close!

5.2. Gravitons, density of states (DOS) and relation to the DOS of the 2D plane waves

As in the electromagnetic case, we expand the gravitational radiation field in the eigenmodes of resonators with fixed frequency, polarization and field distribution. Although the selection of modes is in principle arbitrary, the most popular expansion uses the eigenmodes of rectangular boxes with perfectly reflecting walls. The mirrors at position 0 and $a$ impose the boundary conditions that the field vanishes at those positions. The eigenmodes have field distributions that vary with $\sin(n\pi x/a)$, where $n$ is the mode number, $x$ the spatial variable and $a$ the separation of the two mirrors. The spatiotemporal variation of the field is

$$F_n = \sin(n\pi x/a)e^{i\omega_n t}$$

where the angular frequency is $\omega_n = \frac{n\pi c}{a}$. This defines the wave number as $k = (n\pi/a)$ and consequently the one dimensional density of modes in $k$-space as

$$\rho_k = \frac{a}{\pi}$$

Interestingly this density of $k$-points is the same as for a massive particle (mass $M$) in a perfectly reflecting box of the same size as can be seen by equating the energy levels for a particle in a box with the kinetic energy:

$$E_n = \frac{\pi^2 n^2}{2a^2 M} = \frac{k^2}{2M}$$

yielding as well eq. (12). Using the dispersion relation for gravitons $\epsilon_\kappa = \kappa c$ with $c$ the velocity of light, $\kappa = \sqrt{\kappa_2^2 + \kappa_3^2 + \kappa_4^2 + \ldots + \kappa_d^2}$ and $d$ the dimension of gravitational $k$-space we write for the graviton density of states:

$$\rho_{\text{grav}} = \sum_\kappa \delta(E - \epsilon_\kappa) = \int d^d \kappa \rho_\kappa \delta(E - \epsilon_\kappa).$$
Transforming to spherical coordinates [19], one obtains:

$$
\rho_{\text{grav}} = \int d\eta \eta^{d-1} \delta(E - c\eta) \rho_\eta d\eta^{d/2} \Gamma(1 + \frac{d}{2}) \cdot (15)
$$

Specializing to 10 spatial dimensions and substituting $d\eta = de/c$ one obtains

$$
\rho_{\text{grav}} = \frac{1}{c} \frac{\pi^5}{\Gamma(1 + 5)} \rho_\eta \int d\epsilon \frac{e^{d-1}}{e^{d-1}} \delta(E - \epsilon) = \frac{E^{d-1} \pi^5 L \langle \frac{\lambda}{\pi} \rangle^3 \langle \frac{a}{\pi} \rangle^{d-3}}{c^d \gamma_5 \pi! \pi^{d-1}} (16)
$$

where $L$ is the normalization length of the macroscopic 3-dim space and $a$ is the normalization length of the hidden dimensions. The density of states for the two dimensional movement of an adparticle of mass $M$ is $\rho_{2D} = \frac{2ML^2}{\pi}$. Therefore the relationship between the density of states of gravitons at energy $E$ and the states for two dimensional adparticle motion is:

$$
\frac{\rho_{\text{grav}}}{\rho_{2D}} = \frac{E^{d-1} \pi^5 L a^{d-3}}{2M \pi^d \gamma_5} \approx 10^{34}. (18)
$$

For the wave vector of the decohering graviton we assumed $\kappa \approx 10$, which is valid for a deformation resonance width of 1 bohr ($\lambda = 2\pi/\kappa \approx 1$ bohr), $L \approx 10^7$ bohr, $M = 2000$ and $a \approx 10^4$ bohr and hence a graviton energy of order $\epsilon_\kappa \approx 10^3$ Hartree.

In conclusion the graviton continuum appears infinitely dense compared to the continua describing any particle motion in our 3 dimensional space.

6. Numerical results

The model and its result scale with the energy unit, the time unit being related via the relationship $\Delta E \Delta t = 2\pi\hbar$, if the time is given in atomic units. What determines the behaviour of the model system is the coupling strength between gas particle and environment in relation to the coupling strength to the degrees of freedom of the local system. We do not present here results for a specific experimental situation, but rather give a general consideration without ascribing concrete values to the parameters of the model.

There are three critical couplings in the model:

(i) coupling between the vibrational state and the deformation resonance described by the parameter $\gamma_{\text{penetr}}$.

(ii) coupling between the deformation resonance and the plane wave continuum described by the parameter $\gamma_{\text{escape}}$.

(iii) coupling between the deformation resonance and the environment described by the parameter $\gamma_{\text{environ}}$.

In our example the ratio of the three coupling parameters has been chosen as $\gamma_{\text{penetr}} : \gamma_{\text{escape}} : \gamma_{\text{environ}} = 1 : 10 : 14$. The separation of the energy levels of the local continuum (plane waves) will be $2.2 \times 10^{-3}$ times smaller than $\gamma_{\text{penetr}}$. The absolute values will depend on the particular physical situation. The energy zero is chosen to agree with the energy of the non-interacting vibrational state ($E_o = 0$). Fig. 2 illustrates the energetic situation without including the coupling to the environment. The spectral weights are plotted only for the energy eigenvalues of the local system, where the eigenvalue energy separation corresponds to the number of states in the local continuum.
Figure 2. Spectral energy distribution of the local states without including coupling to the environment. The blue dots represent the spectral distribution of the deformation resonance in the eigenstates of the local system. The red triangles indicate the values for the vibrational state. Note the different scales.

Figure 3. Time evolution of the occupation of the local states (vibrational state plus deformation resonance, red curve) and the occupation of the local continuum (blue curve) without including the coupling to the environment.

The time development of a wave packet consisting at time zero of the vibrational state only is displayed in fig. 3. After 0.06 relative time units the particle has nearly completely vanished from the vibrational state and delocalized into the local continuum (plane wave). From thereon the particle returns back to the vibrational state because of the discreteness of our model calculations. In the following there is an ongoing oscillation between the vibrational state and the states in the local continuum.

If the coupling to the environment is included we obtain the results displayed in fig. 4. Each discrete value of fig. 2 has turned into a narrow resonance due to coupling to the environment. The spectral distribution of the vibrational state became an on-shell resonance at energy zero comprising many levels of the environmental continuum.

The time development of the wave packet changes dramatically. Figure 5 demonstrates that up to 0.06 relative time units there is a tendency of the particle to escape into the local continuum. At later times, however, the interaction with the environmental continuum has been fully developed.
Figure 4. Spectral energy distribution of the local states including the coupling to the environment. Note the different scales indicated on the left and right hand sides of the figure.

Figure 5. Time evolution of the occupation of the local states including coupling to the environment. In the upper panel the red and blue curve have the same meaning as in fig. 3. In the lower panel the green curve describes the particle in the deformation resonance and the red curve in the vibrational state, respectively.

and the particle is locally captured because of the entanglement with the many degrees of freedom of the environment. Around the time of one relative unit there is a recurrence to be observed which again is solely due to the discreteness of the environmental continuum in our model calculation. For infinitely fine discretization there would be no recurrence.

The energy of the non-interacting deformation resonance is in these calculations chosen as
$E_w = 10^3$ in the relative units indicated. Physically this means a relatively strong potential corrugation: the deformation (warp) resonance lies energetically high and is off-shell relative to the scattering energy. The on-shell coupling between the vibrational state and the environment is therefore indirect and weak, which is the condition for the dimensionality effect to be demonstrated here. If the gas atom vanishes from the vibrational state, it localizes in the deformation resonance and cannot scatter into the Bloch states of the local system. The gas atom localizes in the deformation resonance as a result of the dimensionality effect. The dimensionality effect is recognized by its proportionality to the number of gravitons in an energy interval when starting from a rough discretization. For finer and finer discretizations the results will rather quickly converge to definite limiting values.

The dimensionality effect leads to particle stabilization in the state which results from the weak coupling between the initial particle state and a continuum of states of large dimensions. For instance a particle in a plane wave state, weakly entangled to the graviton continuum, will be localized because the dimensions of the localizing graviton continuum are much higher compared to those of the plane wave continuum. The weak coupling to the environment does not allow indirect mixing (via the deformation resonance) of other plane wave states, hence no scattering in different delocalized states is possible. The dominating scattering channel is in the states with graviton components, hence localization.

Apparent classical behaviour of atoms and molecules near surfaces can qualitatively be rationalized by the theory outlined in this contribution:

- The classical behaviour of inelastic scattering of atoms from surfaces at low temperature can be traced back to the different dimensions of the Hilbert spaces of the system and the environment and the weak interaction limit (dimensionality effect).
- The dimensionality effect explains also the small survival probabilities for metastable rare gas atoms scattering from surfaces.
- The classical scattering angular distributions of metastable rare gas atoms indicate decoherence due to strong system - phonon environment interaction leading to localized pointer states.

String theory’s hidden dimensions provide a possibility of explaining localization experiments where the conventional environmental continua do not serve for this purpose.

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