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Peer-Review Record:

A Realization of a Quasi-Random Walk for Atoms in Time-Dependent Optical Potentials

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Reviewer 1: Anonymous
Reviewer 2: Anonymous
Editor: Jonathan Goldwin and Duncan O'Dell (Guest Editors of Special Issue “Cavity Quantum Electrodynamics with Ultracold Atoms”)

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Reviewer 1: Report and Author Response

The autors present a proposal for realizing a (classical) random walk in one dimension with an atom optically trapped inside a cavity under bichromatic driving conditions. Numerical simulations predict quasi-random jumps to neighbouring lattice sites at regular time intervals leading to diffusive motion over long times. Analytic approximations of the effective trapping forces give some insight into the origin of the special form of the optical potential and delineate the regimes in which random walks are expected to occur.The proposal of this somewhat unconventional random-walk regime in cavity-QED is interesting and deserves publication. The numerical and analytical analysis is thorough, and the manuscript is quite well written. The authors could help readers by better putting their work into context and improving some of their explanations.

Detailed comments:

(1) It remains unclear how the quantum regime (with coherent spatial delocalization and interference of probability amplitudes of different paths) could possibly be reached in a real experiment, as spontaneous scattering of photons (of the cavity light or of the side pumper) into free space would localize the atomic wavefuction into one lattice site and thus decohere any spatial delocalization.

(2) For a quick orientation it would be helpful to indicate the x-axis in Fig.1 and an (angular) frequency axis in Fig.2.

(3) In Section I the authors write: "The mechanism is similar to the ones exploited in the creation of artificial potentials in optical lattices [17]". This statement is a bit misleading since [17]

uses coherent (quantum-mechanical) tunnelling with complex tunnel amplitudes, whereas the present manuscript deals with classical trajectories and classical jump probabilities.

(4) "This is similar to previous works on implementation of the quantum random walk with photons [18], atoms in optical lattices [19], ions in traps [20] or on a one-dimensional lattice of superconducting qubits [21]": This statement is also misleading, because the cited references have reached the coherent quantum walk regime, while the present manuscript only hypothesizes about an (unspecified) possibility to enter the quantum regime.

(5) In Section II it should be clearly stated that this is a one-dimensional model, transverse forces or motion are not considered.

(6) In Fig. 2: "such that c < 0 corresponding to the stable regime of cavity QED with moving atoms": what does this mean? The regime of cavity cooling?

(7) In Section III the numerical value of \kappa is not given (only in the caption of Fig. 3 it is mentioned that \kappa is set to unity).

(8) The numerical values of the parameters used for the simulation are in the bad cavity regime (g << \kappa, \gamma). Does the special spatio-temporal shape of the potential, which is shown in Fig. 3, and which enables the effective random walk motion, originate in genuine cavity quantum effects, or could a similar potential be generated also in the classical (bad cavity) limit (g -> 0, \eta_L -> infinity and \kappa large), or for a classical standing wave laser beam interfering with a classical transverse running wave?

(9) In describing the action of the optical potential as quasi-random potential kicks, is there some long-term heating effect (i.e. an increase of the average energy of the atom)? Does cavity cooling play a role to counteract this in the numerical simulations?Response

Response

We thank the referee for an extremely careful reading of the manuscript, his/her appreciation of it and for the very constructive criticism expressed in this report.

Detailed comments:

(1) We agree with the referee that in any open system as we have here , information will leak out and a corresponding backaction on the wavefunction cannot be avoided. However, by operating with ultra-cold quantum particles far of any internal resonance, the coherence time can be pretty long. This was shown with BEC'S trapped in cavities (see e.g. Ref 9). The effect of localization via cavity transmission can be reduced by working at higher cavity photon numbers. Ultimately the interplay between measurement induced localization and coherence spreading by unitary evolution could be one of the most interesting points in setting up such an experiment. One should study a transition from classical to quantum behavior depending on the degree of observation of the system.

(2) Axes added.

(3) We have reformulated to avoid confusion and unsubstantiated claims: "The mechanism is reminiscent of the one exploited in the creation of artificial potentials in optical lattices~\cite{Struck2012Tunable} applied here to the classical regime"

(4) We have rephrased: “In this sense, this work is a stepping stones towards a proposal for implementing a quantum random walk mirroring progress already achieved with photons…”.

(5) We have added a clarifying statement in the beginning of section 2: “We consider an effective one-dimensional model”.

(6) The referee is correct; in the convention that we specify the negative detuning corresponds to the regime where motional instabilities are avoided and cavity cooling is possible. We included this in the figure caption.

(7) As we specify now in the beginning of section 3: “We treat η_T as a free varying parameter. In the following we set $\kappa=1$ for numerical simulations and normalize the time in units of κ^{-1}”.

(8) As the referee correctly infers the random walk is merely an effect of the time modulation of the potential. The classical limit without time delayed action (characteristic of the cavity) will reproduce the kind of walk obtained in the LT limit where Fig. 3 and the analysis has been performed. The other regime where the transverse field kicks the particle out of the longitudinal trap is a cavity effect as the effective force (transverse) has a different modulation than the simple cosine of the free space transverse wave. However, for fine tuning of parameters and to insure stability of trajectories we have used the cavity cooling effect.

(9) Yes, some momentum diffusion can be expected. In principle using a sufficiently narrow cavity and suitable operation parameters cavity cooling could be tuned to cancel such unwanted heating. However, this is connected to dissipative dynamics and will change the effective operating parameters of the system.

In the bad cavity limited on the other hand, one can expect some “cavity heating” instead of cooling, but the rate of this heating should be slow enough to allow for many kicks before it gets relevant.

Reviewer 2: Report and Author Response

The manuscript reports a theoretical study of the dynamics of an atom inside a time-dependent optical potential, generated in a two-color pumped cavity. The simultaneous driving at two different frequencies gives rise to interference terms in the optical force acting on the particle. In particular, a force term contains a time modulation at the beat note between the two frequencies of the pump fields. The consequence is a sign change in the effective potential that induces the atom to perform an erratic motion, hopping between neighbouring lattice sites. The resulting trajectory closely resembles a random walk. In this respect the Authors meet their goal to provide a possible quantum optical setting for the observation of a classical random walk. Indeed, the analysis here is restricted to the classical regime for both the field and atomic variables. However, the Authors outline possible generalizations to the quantum regime in the concluding section.

The manuscript is generally well organized and clearly written. The idea is clever and original and lends itself to further extensions: for instance, to simulate a kicked rotor, by means of a frequency comb drive, or towards hybrid optomechanics, when the two-level atom is replaced by a doped nano-sphere. The approach is scientifically sound and convincing. Therefore, the manuscript is worthy of publication.

However, I have a few comments and suggestions to improve the overall quality and readability of the paper.

In the paragraph following Eq. (2), please check the commutation relations between the raising (sigma^+) and lowering (sigma^-) operators and the Pauli matrix sigma^z. I suspect it should be [sigma^+,sigma^z] = - 2 sigma^+ and [sigma^-,sigma^z] = + 2 sigma^- .

A couple of lines below Eq. (4), the Authors write "We proceed in a standard way to derive equations of motion for classical quantities." I would suggest to provide a reference to guide the less experienced reader.

In the equations of motion for the atoms [Eqs. (6) and (7)] it is introduced the quantity gamma, which, I guess, is the atomic decay rate. Please, provide a definition of gamma. What is, if any, the role of gamma (spontaneous atomic decay rate) in the physical process under consideration? In the analytical results, derived in the adiabatic limit, gamma is eliminated and does not play any role. I wonder if one can draw any conclusion from the numerical simulations, where other regimes could have been explored.

At the end of Section IV C. "Optical forces" the time independent value of the force is derived. Please, check this value. I'm afraid there is a factor k missing (simple dimensional analysis shows that something is wrong with it).

The same argument (dimensional analysis) applies to Eqs. (24), (25) and (27). Please check again these expressions.

In section VI E. "Trapping by longitudinal pumping", one can analytically estimate the threshold value for the transverse pumping. How does this analytical result compare with the numerical simulations?

Finally, some stylistic considerations:

Please, be consistent with the choice of subscripts and superscripts: in the first column of page 2 the Pauli operator is denoted as sigma^z (superscript), whereas in the second column becomes sigma_z (subscript).

Figure 4 is mentioned in the main text AFTER Fig. 5. It would be more logical to exchange their presentation order and, consequently, the figures numbering. Indeed, the same Authors already refer to the single trajectory plot as Fig. 4 (c) [see paragraph below Eq. (13)].

Page 4, first paragraph, the particle initial conditions are chosen in the interval [- 0.1, 0.1] (in the text a comma is missing).

Page 5, first column, second paragraph "... one can inspect Eq. (11) b) where the right-hand side ...". Please, eliminate "b)" since it is simply Eq. (11). The same misprint appears at page 8 in the paragraph between Eqs. (32) and (33).

Page 6, "Optical forces": there is a missing subscript L in the first force term at the end of the first paragraph, just before Eq. (21).

Figure 8, Force correlation functions and numerical solutions of the variance: when printed in grey scale some lines are very faint (especially those in green and cyan). Try to use other colors and/or thicker lines.

Response

We thank the referee for an extremely careful reading of the manuscript, his/her appreciation of it and for the very constructive criticism expressed in this report.

“However, I have a few comments and suggestions to improve the overall quality and readability of the paper. In the paragraph following Eq. (2), please check the commutation relations between the raising (sigma^+) and lowering (sigma^-) operators and the Pauli matrix sigma^z. I suspect it should be [sigma^+,sigma^z] = - 2 sigma^+ and [sigma^-,sigma^z] = + 2 sigma^- .”

We have corrected the sign in the commutation relation.

“A couple of lines below Eq. (4), the Authors write "We proceed in a standard way to derive equations of motion for classical quantities." I would suggest to provide a reference to guide the less experienced reader.”

We have added a proper reference as Ref. [23].

“In the equations of motion for the atoms [Eqs. (6) and (7)] it is introduced the quantity gamma, which, I guess, is the atomic decay rate. Please, provide a definition of gamma. What is, if any, the role of gamma (spontaneous atomic decay rate) in the physical process under consideration? In the analytical results, derived in the adiabatic limit, gamma is eliminated and does not play any role. I wonder if one can draw any conclusion from the numerical simulations, where other regimes could have been explored.”

We have added the definition for \gamma in the text. Here we focus on a dispersive regime of weak atomic excitation, where the so called dipole force dominates the mechanical atom field interaction and spontaneous emission plays a negligible role. In this limit the mechanical forces can be derived from a deterministic (time dependent) optical potential (see refs. 7-9 for details).

However, as the referee points out, in the nonlinear dynamical regime, the effects stemming from the inclusion of a random spontaneous emission could be amplified. A similar randomness is connected to cavity cooling in a regime of weak coherent intra-cavity fields. This certainly will have to be considered in a quantum treatment.

In our simulation we got the “quasi random” dynamics from deterministic motion connected to details of the initial conditions without including random forces.

“At the end of Section IV C. "Optical forces" the time independent value of the force is derived. Please, check this value. I'm afraid there is a factor k missing (simple dimensional analysis shows that something is wrong with it). The same argument (dimensional analysis) applies to Eqs. (24), (25) and (27). Please check again these expressions.”

Indeed all the above mentioned expressions were missing a factor of \kappa as the referee correctly observed.

“In section VI E. "Trapping by longitudinal pumping", one can analytically estimate the threshold value for the transverse pumping. How does this analytical result compare with the numerical simulations?”

The analytical considerations fit very well with numerical results. Indeed, in this regime, we have performed the simulations by choosing parameters derived from analytical considerations. The emergence of the jump regime is directly connected with the increase of the LT force to the value of the longitudinally-induced force but the fine tuning of the parameters is a bit tricky in order to insure that only jumps to neighbouring sites occur. Therefore we have restricted our presentation to the other regime where the jumps are strictly occurring owing to the transverse-longitudinal time modulation of the potential.

“Finally, some stylistic considerations:

Please, be consistent with the choice of subscripts and superscripts: in the first column of page 2 the Pauli operator is denoted as sigma^z (superscript), whereas in the second column becomes sigma_z (subscript).”

We have fixed this mistake.

“Figure 4 is mentioned in the main text AFTER Fig. 5. It would be more logical to exchange their presentation order and, consequently, the figures numbering. Indeed, the same Authors already refer to the single trajectory plot as Fig. 4 (c) [see paragraph below Eq. (13)].”

We changed the order of the figures and corrected the reference to the wrong figure.

“Page 4, first paragraph, the particle initial conditions are chosen in the interval [- 0.1, 0.1] (in the text a comma is missing).”

Comma has been introduced.

“Page 5, first column, second paragraph "... one can inspect Eq. (11) b) where the right-hand side ...". Please, eliminate "b)" since it is simply Eq. (11). The same misprint appears at page 8 in the paragraph between Eqs. (32) and (33).”

The b) has been eliminated.

“Page 6, "Optical forces": there is a missing subscript L in the first force term at the end of the first paragraph, just before Eq. (21).”

Subscript has been introduced.

“Figure 8, Force correlation functions and numerical solutions of the variance: when printed in grey scale some lines are very faint (especially those in green and cyan). Try to use other colors and/or thicker lines.”

We have restricted the analysis to 2 curves (full and dashed) and a thinner red dashed curve corresponding to the analytical solution in the lower plots. The visibility is clearly increased and the message stays the same.

Decision: Accept after minor revision

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