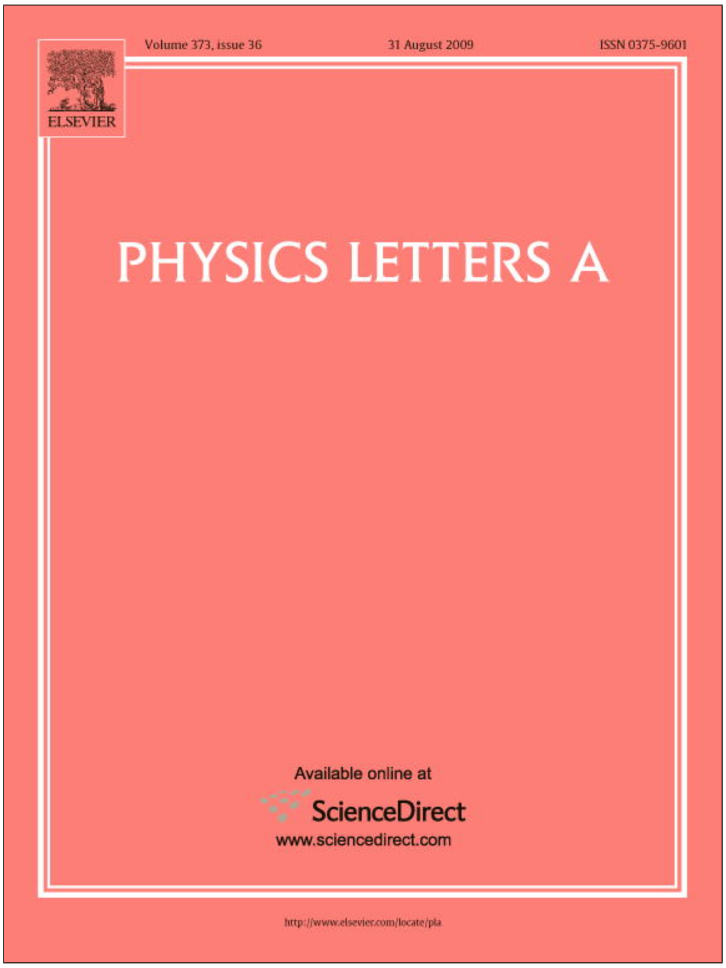
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Particle trapping induced by the interplay between coherence and decoherence

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ABSTRACT

We propose a novel scheme to trap a particle based on a delicate interplay between coherence and decoherence. If the decoherence occurs as a particle is located in the scattering region and subsequently the appropriate destructive interference takes place, the particle can be trapped in the scattering area. We consider two possible experimental realizations of such trapping: a ring attached to a single lead and a ring attached to two leads. Our scheme has nothing to do with a quasi-bound state of the system, but has a close analogy with the weak localization phenomena in disordered conductors.

1. Introduction

Quantum theory of scattering has been a powerful tool to investigate various physical properties of nature [1]. One nice feature of the scattering theory is that all the important information is contained in the *unitary* scattering matrix or simply S-matrix. The unitarity of the S-matrix guarantees that the incoming particle should completely go out of a scattering region so that any part of the incoming particle should not remain. Such a unitarity or the unitary time evolution of a quantum system is based upon the coherent propagation of a wavefunction. The coherence thus plays an important role in ensuring that any particle does not remain in a scattering region. However, one can ask what happens if any decoherence process takes place during the scattering event.

If one measures the location of a particle in the scattering region and acquires complete information on it, the situation is then no longer a normal scattering problem. The particle is not incoming far from the scattering region as a usual scattering setup, but is rather launched inside the scattering region right after the measurement. In this circumstance it is possible for the particle to be trapped in the scattering region if the coherence is maintained after the measurement. The possibility of such an amazing phenomenon was briefly discussed in a somewhat different context in our previous work [2], where we proposed a new mechanism for generating the non-trivial dc current induced by decoherence. In this Letter, we reveal physics of a novel effect of particle trapping originating from the interplay between coherence and decoherence.

Two main ingredients of our scheme are the position measurement (decoherence) and the destructive interference of the outgoing waves (coherence). In our scheme, we exploit the spontaneous emission from a two level atom in the excited state as a source of decoherence. The decoherence process occurs *only once* in the scattering region, and after the decoherence process the coherence is maintained. Then the destructive interference of the outgoing waves, which is achieved by utilizing a ring geometry, gives rise to trapping of the particle. We consider two examples: a ring attached to a single lead, and a ring interferometer attached to two leads. It should be emphasized that application of our general concept is not limited to these two simple examples.

In Section 2 the key idea of our scheme is presented by using a ring attached to a single lead. In Section 3 the scheme is extended

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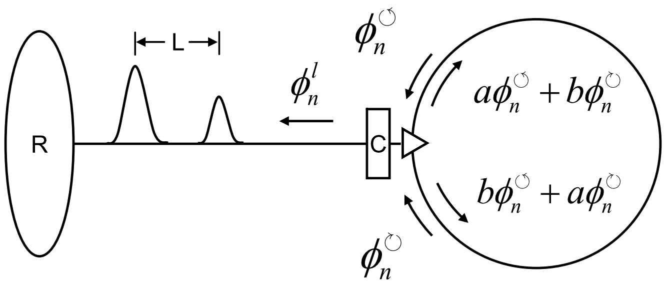

Fig. 1. The schematic picture of the setup for a ring attached to a single lead. R and C represent a reservoir and a microcavity, respectively. The partial waves in the ring entering the junction are represented as $\phi_n^{\circlearrowright}$ (clockwise) and $\phi_n^{\circlearrowleft}$ (counter-clockwise), and the waves outgoing along the leads is labeled as ϕ_n^l. In semiclassical description the successively escaping wavepackets are separated with each other by L.

into a ring attached to two leads, which allows us to observe the trapping phenomenon by current measurement of a steady state. Finally we summarize our Letter in Section 4.

2. A ring attached to a single lead

We first consider the case that a ring is attached to a single lead connected to a reservoir [3] as shown in Fig. 1. To explain a basic idea of our work, we begin with intuitive semiclassical approach, and more rigorous treatment will be followed.

2.1. Semiclassical approach

Atoms with two internal energy levels, which are initially in the ground state, come out of the reservoir and enter the microcavity, which excites them from the ground state to the excited state. We assume that all the atoms are excited after passing through the microcavity due to the Rabi oscillation [4]. The interaction among atoms is ignored. The excited atom is then incident to the atomic Y-shaped junction as shown in Fig. 1, and split into three output ports corresponding to the states rotating clockwise ($\circlearrowright$) and counter-clockwise ($\circlearrowleft$) in the ring and going back to the lead (l). The amplitudes of the incoming (ϕ_{in}^j) and the outgoing (ϕ_{out}^i) partial waves at the junction are related with each other by the relation $\phi_{\text{out}}^i = \sum_j J^{ij}\phi_{\text{in}}^j$, where $i, j = l, \circlearrowright, \circlearrowleft$. The scattering matrix J is given by

$$J = \begin{pmatrix} -(a+b) & \sqrt{\epsilon} & \sqrt{\epsilon} \\ \sqrt{\epsilon} & a & b \\ \sqrt{\epsilon} & b & a \end{pmatrix} \tag{1}$$

where $a = (\sqrt{1-2\epsilon} - 1)/2$, $b = (\sqrt{1-2\epsilon} + 1)/2$, and ϵ represents a coupling parameter ranging $0 \leqslant \epsilon \leqslant 1/2$ [5,6].

The excited atom after crossing the microcavity will release a photon inside or outside the ring relaxing to the ground state. We assume that the wavelength λ of the photon is short enough compared with a circumference of the ring L, and the momentum recoil of the atom due to the emission of the photon is too small to disturb the momentum of the center of mass of the atom. Let τ be the lifetime of the excited energy level and v be the velocity of the atom. If $v\tau \ll L$ and the distance between the cavity and the junction is ignorable, the atom in the ring quickly decays to its ground state emitting a photon so that we can locate the atom in the ring by detecting the released photon.

Let us consider the case where the photon emission takes place when the atom rotates clockwise in the ring. Note that the situation is exactly the same if the photon is emitted when the atom rotates counter-clockwise. Since the position of the atom is known by detecting a photon emitted, one considers that the atom now begins to move from somewhere *in* the ring. It is emphasized that the size of an atomic wavepacket δx determined from the measuring process should satisfy $\delta x \ll L$ to make sure that the meaningful information on the position is acquired. Now we need to calculate the escaping probability of such a wavepacket. Note that without decoherence the escaping probability is trivially one due to the conservation of a particle number. Since the two output ports of the Y-junction are connected with each other to form a ring (see Fig. 1), the amplitudes $\phi_n^{\circlearrowright}$ and $\phi_n^{\circlearrowleft}$ of the clockwise ($\circlearrowright$) and counter-clockwise ($\circlearrowleft$) partial waves entering the junction at the nth collision are inevitably related to the amplitudes $\phi_{n+1}^{\circlearrowright}$ and $\phi_{n+1}^{\circlearrowleft}$ at the $(n+1)$th collision. This recursion relation is given by [see Eq. (1)]

$$\begin{pmatrix} \phi_{n+1}^{\circlearrowright} \\ \phi_{n+1}^{\circlearrowleft} \end{pmatrix} = e^{i\theta} \begin{pmatrix} b & a \\ a & b \end{pmatrix} \begin{pmatrix} \phi_n^{\circlearrowright} \\ \phi_n^{\circlearrowleft} \end{pmatrix}, \tag{2}$$

where $\theta = kL$ represents the phase accumulated during one round trip along the ring. Assume that the initial condition is given as $\phi_1^{\circlearrowleft} = 0$ and $\phi_1^{\circlearrowright} = 1$ with probability ϵ, implying the atom is launched in the ring and rotates clockwise. The escaping amplitude ϕ_n^l at the nth collision with the junction is then obtained from Eqs. (1) and (2): $\phi_{n+1}^l = \sqrt{\epsilon}(\phi_n^{\circlearrowright} + \phi_n^{\circlearrowleft}) = e^{i\theta}(1-2\epsilon)^{1/2}\phi_n^l$ leading to the escaping probability

$$P_{\text{esc}} = \epsilon \left| \sum_{n=1}^{\infty} \phi_n^l \right|^2 \approx \epsilon \sum_{n=1}^{\infty} \left|\phi_n^l\right|^2 = \frac{\epsilon}{2}. \tag{3}$$

Here note that to a good approximation the escaping probability is given by an incoherent sum of the individual probabilities $|\phi_n^l|^2$. It is because due to the fact that $\delta x \ll L$ the successively escaping wavepackets do not overlap with each other as illustrated in Fig. 1. The total reflection probability of the ring is then given as $R = (1-2\epsilon) + 2P_{\text{esc}}$, where the first term represents the probability for back scattering when the atom initially scatters with the junction. We eventually end up with the simple form of the trapping probability

$$P_{\text{tr}} = 1 - R = \epsilon. \tag{4}$$

To get a more intuitive understanding let us consider the simplest case with $\epsilon = 1/2$. For the moment the phase accumulation while traversing along the circumference is ignored since it plays no essential role in our scheme. If the atom emits a photon, it begins to travel namely clockwise from somewhere in the ring and collides with the junction. $\sqrt{1/2}$ (amplitude) of the wavepacket is escaped to the lead, while $1/2$ is transmitted so that continues to rotate clockwise and $-1/2$ is reflected back to rotate counter-clockwise. Two wavepackets remaining in the ring, i.e. rotating clockwise and counter-clockwise, coherently propagate along the ring and collide again with the junction simultaneously and are split. $1/2\sqrt{1/2}$ and $-1/2\sqrt{1/2}$ of each wave incident to the junction are respectively escaped to the lead and vanishes due to the destructive interference. The remaining parts, either reflected or transmitted into the ring again, continue to propagate along the ring. This process thus runs on for ever. Consequently, a half of the incoming wave cannot escape from the ring so that it is trapped.

It is noted that the trapping mechanism has nothing to do with the persistent current in a mesoscopic ring [7] since in our case there is no net current in it: the probability of the clockwise rotating current is exactly equivalent to that of the counter-clockwise one. It looks rather similar to the weak localization in disordered conductors [8] in that the atom is *localized* in the ring according to the interference of two time-reversal paths. It is well known that the weak localization is vulnerable to the perturbation breaking time reversal symmetry, e.g. the external magnetic field. We thus expect that the trapping achieved in our scheme is also sensitive to the magnetic field. Consider an ion with charge q instead of a neutral atom and apply the magnetic flux localized inside the ring. The ion rotating clockwise then experiences the phase accumulation different from that for counter-clockwise, which is Aharonov–Bohm (AB) effect [10]. The matrix in Eq. (2) is modified as

$$\begin{pmatrix} b & a \\ a & b \end{pmatrix} \to \begin{pmatrix} be^{i\phi} & ae^{i\phi} \\ ae^{-i\phi} & be^{-i\phi} \end{pmatrix}, \tag{5}$$

where $\phi = (q/h)\oint \mathbf{A}\cdot ds$. Here, $\mathbf{A}$ and h are a vector potential and the Planck constant, respectively. We find that for a non-zero ϕ the trapping probability vanishes. Note that how fast the trapping probability in the ring decays depends on ϕ, so that for small enough ϕ the trapping phenomenon persists for a long time.

It is also worth mentioning that our trapping mechanism is not associated with a quasi-bound state of the ring, which is evident from the following two reasons. First, the trapping probability still remains finite, in principle, even when time goes to the infinity. The usual quasi-bound state always decays with the characteristic time scale, namely the life time. Second, the trapping probability does not depend on the (kinetic) energy of the incident particle, while the transmission shows strong dependance on the energy of the incoming particle when a quasi-bound state exists, which is called as a resonance. Note that when the atom escapes from the ring, it crosses the microcavity once more and is excited again. However, the subsequent spontaneous decay taking place at the lead makes no influence on the above discussion since it occurs outside the interferometer.

In the context of the usual scattering theory it is guaranteed by the micro-reversibility that any part of an incoming particle cannot be trapped in the scattering region [11]. In fact, any legitimate unitary scattering matrix cannot be constructed in our case because the decoherence takes place in the ring during the scattering process. In some sense the particle is not injected from the outside, but it is rather launched from inside the ring upon the emission of a photon. It implies that this is no longer a usual scattering problem. Although the unitarity of the scattering matrix is no longer available, the conservation of a particle number is still intact because the sum of the reflection and the trapping probability is equal to one. It is noted that breaking the micro-reversibility is achieved by increase of the entropy of environment induced by the spontaneous emission, i.e. decoherence.

2.2. *Rigorous treatment*

So far our argument has been mainly based upon semiclassical treatment; the incoming wave is namely collapsed to the localized wavepacket due to the measurement process induced by the spontaneous emission, and then repeats coherent propagation and scattering at the junction. Here we develop a fully quantum mechanical treatment.

At a given time t, the total wavefunction consists of three parts: (i) the wavepacket describing the center of mass (COM) of the atom $\int dk\,\phi(k)e^{i(kx-\omega t)}$, where $\phi(k)$ is a normalized wavefunction in momentum space and $\hbar\omega$ is the COM kinetic energy, (ii) the atomic internal state, either $|g\rangle$ for the ground state or $|e\rangle$ for the excited state, and (iii) the photonic state, either $|0\rangle$ for the vacuum or $|\nu\rangle$ for a photon released from the atom as it undergoes a transition $|e\rangle \to |g\rangle$. Once the atom passes through the microcavity it is assumed to be perfectly excited without loss of generality; the initial wavefunction is thus given by

$$\big|\Psi_{\mathrm{in}}(x_l,t)\big\rangle = \int \frac{dk}{\sqrt{2\pi}}\phi(k)e^{i(kx_l-\omega t)}|e\rangle\otimes|0\rangle. \tag{6}$$

At the junction between the lead and the ring, a portion of the incident wave is reflected and the other goes into the ring, where the process is described by the unitary scattering matrix J in Eq. (1) [5,6]. The partial wave that enters the ring will scatter multiple times at the junction. If the whole process is fully phase coherent, its multiple scattering inside the ring and, eventually, escape out of the ring can be described by a sum of all possible Feynman paths associated with different scattering processes, which leads to an overall unitary scattering matrix [9].

In our case, the atom may decay from the excited to ground state emitting a photon, which causes a decoherence, and hence the usual scattering approach mentioned above breaks down (see the discussion in Section 2.1). At a given time the atom can still remain in the excited state with the probability amplitude β. The probability amplitude that the atom decays to be in the ground state γ is then given as $\sqrt{1-|\beta|^2}$. When summing up all possible Feynman paths, we also have to distinguish photons emitted during different stages of the multiple scattering. We denote by $|\nu_n^{\circlearrowright}\rangle$ ($|\nu_n^{\circlearrowleft}\rangle$) a photon released from the atom rotating clockwise (anti-clockwise) in between the nth and $(n+1)$th collision with the junction.

As time goes to the infinity the wavefunction $|\Psi(x_l,t)\rangle$ (x_l is the COM coordinate along the lead) on the lead is given by

$$\begin{aligned}
&\big|\Psi(x_l,t)\big\rangle \\
&= \int dk\frac{\phi(k)}{\sqrt{2\pi}}e^{i(kx_l-\omega t)}\Bigg[\sum_{n=1}^{\infty}\big\{-(1-2\epsilon)^{\frac{1}{2}}\delta_{n1} \\
&\quad + 2\beta^{n-1}\epsilon(1-2\epsilon)^{\frac{n-2}{2}}e^{i(n-1)kL}(1-\delta_{n1})\big\}|g\rangle\otimes|0\rangle \\
&\quad + \sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\gamma\beta^{n-1}\epsilon(1-2\epsilon)^{\frac{n+m-2}{2}} \\
&\quad \times e^{i(n+m-1)kL}|e\rangle\otimes\big(\big|\nu_n^{\circlearrowright}\big\rangle+\big|\nu_n^{\circlearrowleft}\big\rangle\big)\Bigg].
\end{aligned} \tag{7}$$

The first term consists of two parts; the former describes the direct reflection from the junction without entering the ring, and the latter represents the situation where the particle enters and then rotates along the ring, and finally escapes from it without any spontaneous emission of a photon after scattering n times at the junction. Note that the particle finally resides at the ground state since it crosses the microcavity overall twice (incoming and outgoing). The second term gives the probability amplitude that a photon is emitted in the ring after n collisions with the junction and then escapes from it after additional m collisions with the junction. Since the absolute square of Eq. (7) provides the probability for the particle to escape, the trapping probability is given by

$$P_{\mathrm{tr}} = 1 - \int dx_l\,\big\langle\Psi(x_l,t)\big|\Psi(x_l,t)\big\rangle \tag{8}$$

$$= \sum_{n=1}^{\infty}\gamma^2\epsilon\big(1-\mathrm{Re}\big\langle\nu_n^{\circlearrowright}\big|\nu_n^{\circlearrowleft}\big\rangle\big)\big\{(1-2\epsilon)\beta^2\big\}^{n-1}. \tag{9}$$

Here we have assumed that

$$\big\langle\nu_n^{\circlearrowright}\big|\nu_{n'}^{\circlearrowright}\big\rangle = \big\langle\nu_n^{\circlearrowleft}\big|\nu_{n'}^{\circlearrowleft}\big\rangle = \big\langle\nu_n^{\circlearrowright}\big|\nu_{n'}^{\circlearrowleft}\big\rangle = \delta_{nn'}, \tag{10}$$

which physically implies that a measurement device distinguishes a photon emitted at $n\tau_L$ from that at $n'\tau_L$ when $n \neq n'$, where τ_L represents the round trip time of the atom, namely $\tau_L = L/v$. This assumption is reasonable since the width of the wavepacket is always much smaller than L, which is discussed below, so that two wavepackets with different n has a vanishing overlap.

It is noted that the wavepacket considered here is different from that in the previous semiclassical argument. The wavepacket in the semiclassical treatment is produced by the measurement whereas the wavepacket here represents the initial atomic wavepacket coming from the reservoir. The shape of the initial wavepacket can be predicted from a Maxwell–Boltzmann distribution of atoms in the reservoir with a given temperature. Taking typical values of parameters in experiments (e.g. see [12]) one finds that the width of the wavepacket is extremely small (an order of pico-meter). When the spontaneous emission takes place, the packet size δx may change but remains $\delta x \sim \lambda \ll L$.

In order to show that the result obtained above is compatible with the previous semiclassical treatment, we now additionally assume that $\gamma = 1$ and $\beta = 0$, which means a spontaneous decay takes place immediately after the particle enters the ring. One then obtains

$$P_{\text{tr}} = \epsilon\big(1 - \text{Re}\big\langle \nu_1^{\circlearrowright}\big|\nu_1^{\circlearrowleft}\big\rangle\big), \tag{11}$$

which is to be compared with the semiclassical result $P_{\text{tr}} = \epsilon$ in Eq. (4). The semiclassical result is recovered when the directions $\circlearrowright$ and $\circlearrowleft$ of the atom is discriminated completely, i.e., $\langle \nu_1^{\circlearrowright}|\nu_1^{\circlearrowleft}\rangle = 0$. Eq. (11) thus reveals clearly that the trapping of the atom inside the ring happens only when the emitted photons (described by either $|\nu_n^{\circlearrowright}\rangle$ or $|\nu_n^{\circlearrowleft}\rangle$) should have enough information about the rotation directions of the atom in the ring. In the semiclassical approach (Section 2.1), this condition was implied when setting up the semiclassical wavepackets.

Just locating the atom inside the ring by detecting an emitted photon is not enough to acquire the information about the rotation direction of the atom. In fact, such a process of merely detecting emitted photons without extraction of directional information of $\circlearrowright$ and $\circlearrowleft$ corresponds to a quantum eraser [14], and prevents the particle from being trapped in the ring. Extracting the directional information $\circlearrowright$ and $\circlearrowleft$ of the atomic motion from emitted photons may be challenging in practice. However, the decoherence occurs as long as it is possible in principle.

3. A ring attached to two leads

The key idea of the particle trapping has been discussed based upon the ring attached to a single lead. However, the real experimental observation of the phenomenon in this system is quite difficult because the trapping will be eventually destroyed due to other sources of decoherence inevitably existing in real world so that the atom is trapped only for a finite time. It implies that one needs to measure the decay of the probability of the trapped atom as a function of time, which is a hard task. We thus propose another setup, a ring with two leads [2] or simply a ring interferometer. It will be shown that our trapping mechanism is now revealed by the usual current measurement in a steady state. In principle all the calculation can be done in a rigorous manner as shown above, but for simplicity here we exploit only the semiclassical argument. As in the single-lead case, one can obtain the following recursion relation

$$\begin{pmatrix} \phi_{j,n+1}^{\circlearrowright} \\ \phi_{j,n+1}^{\circlearrowleft} \end{pmatrix} = e^{i\theta} \begin{pmatrix} a^2+b^2 & 2ab \\ 2ab & a^2+b^2 \end{pmatrix} \begin{pmatrix} \phi_{j,n}^{\circlearrowright} \\ \phi_{j,n}^{\circlearrowleft} \end{pmatrix} \tag{12}$$

where j represents from which arm the particle enters the junction, namely u (the upper arm) or d (the lower arm) in Fig. 2. Here we assume that two parts of the ring have the equal length, i.e. $L_u = L_d$, which will be shown to be crucial. We are interested in the atom coming from the reservoir R_1 since it passes through the microcavity and is excited to finally decay in the ring. The atom is assumed to be perfectly excited after crossing the microcavity as before. From the relation $t_n^j = \sqrt{\epsilon}(\phi_{j,n}^{\circlearrowright} + \phi_{j,n}^{\circlearrowleft})$ and $r_n^j = e^{i\theta}(1-2\epsilon)^{1/2} t_n^j$, where $\theta = kL_u = kL_d$, and t and r respectively represents the transmission and the reflection amplitude,

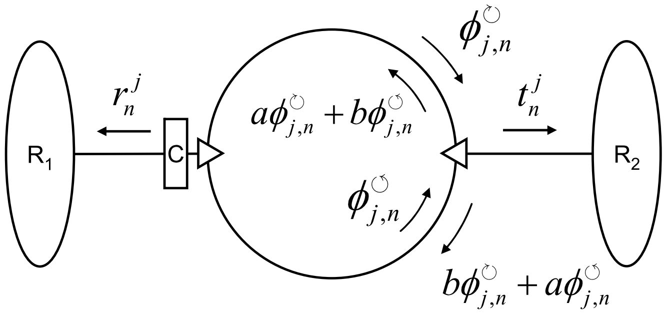

Fig. 2. The schematic picture for the setup of a ring attached to two leads. Two reservoirs are denoted as R_1 and R_2. Like in Fig. 1, the partial waves are labeled as $\phi_{j,n}^{\circlearrowright}$ and $\phi_{j,n}^{\circlearrowleft}$, where j represents from which arm the atom enters the junction, namely u (the upper arm) or d (the lower arm).

the transmission probability T and the reflection probability R are given by

$$T = \epsilon \sum_{n=1}^{\infty} \sum_{j=u,d} \big|t_n^j\big|^2 = \frac{\epsilon}{2-2\epsilon} \tag{13}$$

and

$$R = 1 - 2\epsilon + \epsilon \sum_{n=1}^{\infty} \sum_{j=u,d} \big|r_n^j\big|^2 = \frac{2 - 5\epsilon + 2\epsilon^2}{2-2\epsilon}, \tag{14}$$

respectively. The probability for the atom to be trapped is then obtained as

$$P_{\text{tr}} = 1 - (T + R) = \epsilon. \tag{15}$$

It is interesting to note that the trapping probability is exactly the same as that of the ring attached to a single lead [see Eq. (4)].

Due to other sources of decoherence the trapped atom should eventually escape from the ring either to the left lead or to the right lead with equal probability. In the steady state the transmission probability is thus given as

$$T_{\text{st}} = T + \frac{1}{2} P_{\text{tr}} = \frac{\epsilon(\epsilon-2)}{2(\epsilon-1)}, \tag{16}$$

which is completely different from the usual transmission probability of the fully coherent AB ring interferometer [13]. Again T_{st} does not depend on the energy or the momentum of the incoming atom.

Although the ring with two leads has an advantage compared with that with a single lead in that the measurement can be performed in a steady state, a care should be taken. The trapping mechanism is mainly based upon the destructive interference between two escaping wavepackets rotating clockwise and counterclockwise so that these two wavepackets should collide with the junctions almost simultaneously to make sure that they have considerable overlap at the lead. If $\Delta L = |L_d - L_u| > \delta x$, two packets no longer overlap and the trapping mechanism breaks down. Therefore, in experiments the length of the ring should be controlled up to the precision of the packet size δx. Recall that $\Delta L = 0$ is always guaranteed in a single lead case.

4. Summary

In summary, we have investigated a new mechanism of particle trapping induced by the interplay between coherence and decoherence. If the decoherence occurs when a particle is located in the scattering region and subsequently the appropriate destructive interference takes place, the particle can be trapped in the scattering area. We demonstrate the possibility of such a mechanism using a ring attached to a single lead and a ring interferometer.

Acknowledgements

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