Absorption-induced coherence in quantum systems

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We have studied scattering from locally periodic optical potentials. The band-structure characteristics of periodic potentials along with resonances are observed. These features are solely due to the interference from absorptive potentials. Contrary to assertions in the literature, we show that the absorption along with the enhanced reflection induces coherence in quantum systems. We also discuss some conceptual aspects of absorptive potentials.

There are several physical situations where one encounters the absorption of elementary particles or excitations due to impurities in the media, one recent example being light (photon) propagation in a lossy dielectric medium.[1] The absorption (or dissipation) corresponds to the actual removal of the particle (or energy in the case of electromagnetic wave propagation) by a recombination process. To allow the possibility of inelastic decay on otherwise coherent tunneling through potential barriers, several studies invoke absorption.[2,3] Inelastic scattering arises due to thermal phonons, and introduces decoherence in tunneling systems. Here one would like to understand the crossover from coherent to sequential tunneling. In these studies the absorption depletes the spectral weight from the elastic channel, and the total absorption is identified as the spectral weight lost in the inelastic channel. As an example, in the case of one-dimensional double-barrier structures the absorbed or attenuated part is assumed to tunnel through both the left- and the right-hand sides of the barriers in proportion to the transmission coefficient of each barrier,[3] and this is added to the coherent transmission coefficient to get the overall transmission coefficient. Till now all treatments have been phenomenological, and to describe the absorption (or the effect of inelastic scattering) one introduced optical potentials or imaginary potentials. In that case the Hamiltonian becomes non-Hermitian and leads to the absorption of the probability current. These treatments are also quite well known in nuclear physics.

It has been widely thought that the effect of absorption on classical waves is analogous to that of inelastic scattering of electrons. In fact, recently Weaver[4] has shown that absorption does not provide a cutoff length scale (similar to an inelastic scattering length) for the renormalization of wave transport in a random media. In other words, the absorption does not reestablish the diffusive behavior of the wave propagation by destroying the localization of eigenfunctions. The wave energy transport seems to remain nondiffusive even in the presence of the absorption. Very recently, in a related development, Rubio and Kumar[5] have emphasized the dual role of the imaginary potentials (or optical potential), as an absorber and a reflector. For double-barrier structures they have shown that the mismatch caused by an optical potential leads to a nonmonotonic dependence of the absorption on the strength of the potential. It also causes enhanced reflection due to the potential dispersion, and absorption without reflection is not possible. In view of these recent developments we have explored some additional features arising due to absorption along with enhanced reflection. We have studied a simple periodic system comprising a series of δ-function scatterers with pure imaginary weights. This is our analog to the classic Kronig-Penny model, well studied in solid-state physics for optical potentials. We do not invoke any periodicity in the real part of the potential. This is to make sure that the results are associated solely with the optical potentials. We show explicitly that absorption along with enhanced reflection can induce coherence in quantum systems. This is in contradiction to the earlier view that absorption causes decoherence. This reinforces some results arrived at by Weaver. In addition, we show that the absorption is a highly nonmonotonic function of the potential strength, and certain features are observed which we believe have been not noticed so far.

For the simple case of a single purely absorptive δ-function potential $V(x)=-iV_0\delta(x)$, the corresponding reflection coefficient R, transmission T, and absorption σ coefficients are given by[5]

$$R(E)=\frac{V_0^2}{(\hbar^2k/m+V_0)^2}\ , \tag{1a}$$

$$T(E)=\frac{(\hbar^2k/m)^2}{(\hbar^2k/m+V_0)^2}\ , \tag{1b}$$

$$\sigma(E)=\frac{2\hbar^2kV_0/m}{(\hbar^2k/m+V_0)^2}\ , \tag{1c}$$

where k is the wave vector, m the mass, and V_0 the strength of the absorption potential. One can readily verify from Eq. (1c) that $\sigma(E)$ is a nonmonotonic function of V_0, i.e., it initially rises as a function of V_0 and then, after exhibiting a maxima, decreases toward zero. We now consider series of purely imaginary δ functions $V(x)=-iV_0\delta(x)$, placed at a distance L apart. We have considered periodic systems because of their simplicity, and in these systems one can readily observe interference effects. As an example, in a real-valued periodic potential multiple scatterings lead to Brillouin zones and forbidden energy gaps due to Bragg reflection. In our system, throughout the real part the potential is taken to be identically zero, and we have periodicity only in the imaginary part of the potential, taking values of zero and V_0 periodically.

It is an elementary exercise to calculate the complex amplitude of reflection and transmission for a single δ-function scatterer. After doing that, we have used M-matrix formalism to compute the transmission probability containing a series of n equispaced δ-function scatterers with purely imaginary weights. If the potential consists of $(n+1)$ isolated parts, then the M matrix of the total system decomposes into a product of the M matrices of individual system. We follow exactly the same procedure as given in Ref. 6. Following this, one can readily compute the transmission, reflection, and absorption coefficients for n scatterers analytically. However, in our present analysis, for the sake of clarity, we explore results graphically. In Figs. 1–3 we have plotted the transmission, reflection, and absorption coefficients, respectively, as a function of kL, for a fixed value of dimensionless absorption potential strength $mV_0L/\hbar^2=1$, and for six scatterers in series. In Figs. 4–6 we have repeated similar graphs with 11 scatterers. Let us analyze graphs for the transmission coefficient. One can readily observe the emergence of a band structure characteristic of a real-valued periodic potential in our case even for a small number (∼6) of scatterers. The energy bands are identified with region of large transmission separated by distinct valleys. Each band for n scatterers contain $(n-1)$ ripples or resonances. These resonances are of course elementary consequences of quantum-mechanical interference due to coherent multiple scattering; however, in the present case it arises due to purely absorptive potential. At these resonance energies the incident particle spends a relatively long time inside the scattering region before reemerging. Consequently the absorption shows peaks at these resonance energies. Overall, the transmission coefficient within the band increases as we go from lower to higher bands. For a band lying at higher energy, the energy being large, the particle traverses the region quickly (or at a smaller capture time) and accounts for the broader peak of the resonance as well as the lesser absorption. The transmission coefficient

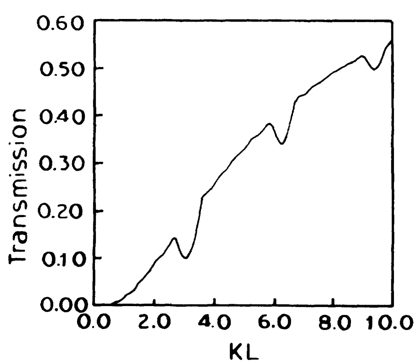

FIG. 1. The transmission vs kL for a fixed value $mV_0L/\hbar^2=1$ and with six scatterers.

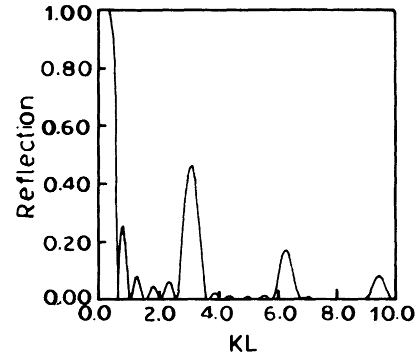

FIG. 2. The reflection vs kL for a fixed value $mV_0L/\hbar^2=1$ and with six scatterers.

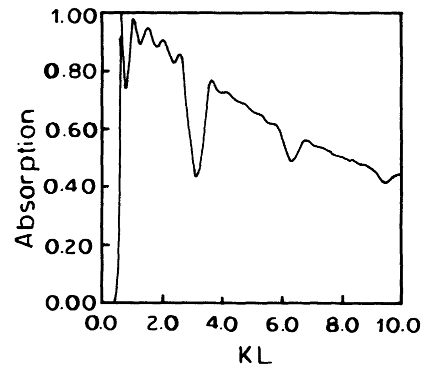

FIG. 3. The absorption vs kL for a fixed value $mV_0L/\hbar^2=1$ and with six scatterers.

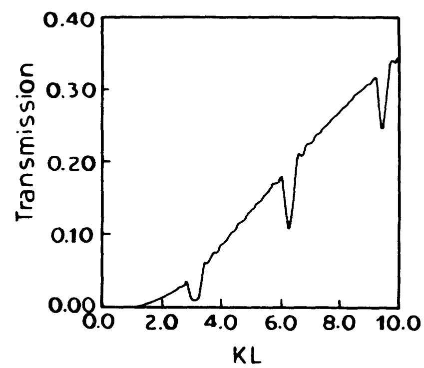

FIG. 4. The transmission vs kL for a fixed $mV_0L/\hbar^2=1$ and with 11 scatterers.

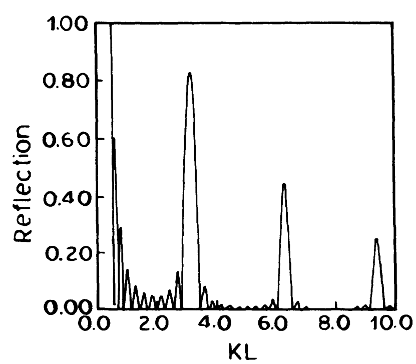

FIG. 5. The reflection vs kL for a fixed $mV_0L/\hbar^2=1$ and with 11 scatterers.

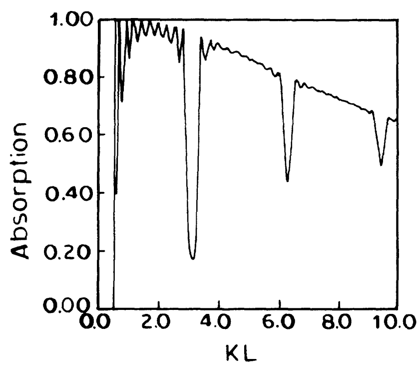

FIG. 6. The absorption vs kL for a fixed $mV_0L/\hbar^2=1$ and with 11 scatterers.

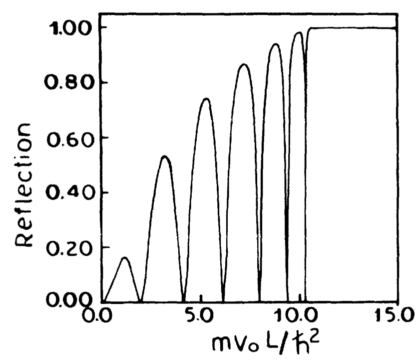

FIG. 8. The plot of the reflection against $mV_0L/\hbar^2$ for a fixed value $kL=1$ and with 21 scatterers.

for a fixed value of the wave vector k and the potential V_0 is a monotonically decreasing function of the number of scatterers. The reflection coefficient is maximum within the band-gap region, similar to the behavior expected for the real periodic potential. The absorption and reflection coefficients exhibit phenomena characteristic of quantum coherence. The above observations explicitly indicate that the absorption induces coherence in quantum systems, contrary to the assumptions of decoherence in earlier literature.

In Figs. 7 and 8 we have plotted the absorption and reflection coefficients, respectively, as functions of the dimensionless potential strength $mV_0L/\hbar^2$ for a fixed value of $kL=1$ and for 21 scatterers in series. The absorption is a nonmonotonic function of V_0 and exhibits several peaks. The absorption becomes identically zero when $mV_0L/\hbar^2$ exceeds the value around 10.5. At this value and onwards the state with $kL=1$ falls in the lowest band gap, and correspondingly the reflection attains a maximum value. As we change the strength of the potential, the resonance energies are shifted. A fixed incident energy coincides with different resonant states for different values of the absorption strength, and we observe a peak in the absorption at these values of the potential strength. As the number of scatterers is large, there is hardly any transmission at resonances, and one can obtain complete absorption without the reflection. In our case with 21 scatterers, the transmission coefficient is

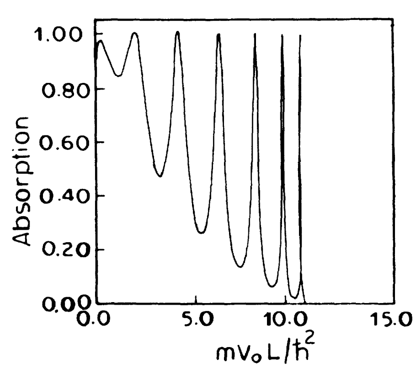

FIG. 7. The plot of the absorption against $mV_0L/\hbar^2$ for a fixed value $kL=1$ and with 21 scatterers.

quite small and decays monotonically (or exponentially) as a function of V_0.

In our analysis we have shown that absorption within the phenomenological treatment via optical potentials explicitly induces coherence. We have taken a simple case of periodic scatterers with a purely imaginary potential. We expect a much more complex structure to emerge in this case, where one has periodicities (which may be different) in both real and imaginary parts of the potential. Classically one would have expected the absorption to increase monotonically as a function of the potential strength. However, the observed behavior in quantum systems is highly nonmonotonic and, moreover, the absorption tends to zero as $V_0 \to \infty$. The absorber in this limit acts as a perfect reflector. In the same classical limit we would have expected the absorber to be a perfect one, in the sense that the particle impinging on the absorber for the first time is absorbed with unit probability. It is not clear at present whether the quantum problem of a perfect absorber is well defined. To our knowledge there is only one quantum treatment[7] which directly addresses the concept of first passage times in the presence of a perfect absorber, but this has met with only partial success. In particular the positivity of the first passage time has not been established. From the viewpoint of the quantum theory of measurement, to have a perfect absorber we have to watch the system continuously at the absorbing site. This is because one has to deplete (or take away) the particle as soon as it arrives at the absorbing site. One knows that such a measurement process blocks the evolution of the state by a repeated collapse of the wave function.[7] In such a situation it may be possible that the quantum particle never reaches the absorber, and hence it may act as a reflector.

In our present phenomenological treatment the counterintuitive behavior of the absorption can be understood as follows. In the vicinity of the absorber the particle experiences mismatch in the potential, and tries to avoid this region by enhanced back reflection. Along with the reflection and reduced transmission, the particle picks up an additional scattering phase shift, which along with multiple interference leads to resonances. In the limit $V_0 \to \infty$, the complex probability amplitude at the absorbing site tends to zero (similar to the hard wall boundary condition), and hence there is total reflection. A simple physically motivated example to explain the dual role of the imaginary potential as an absorber and reflector is given in Ref. 5. It may happen that in real physical situations the absorption will induce decoherence analogous to the inelastic scattering of electrons by phonons. If so, then one has to doubt phenomenological treatments based on optical potentials. We hope that experiments (optical wave propagation) in periodic structures, where one may observe interference effects, can clarify this point.

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