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Fano resonances and decoherence in transport through quantum dots

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Abstract

A tunable microwave scattering device is presented which allows the controlled variation of Fano line shape parameters in transmission through quantum billiards. We observe a non-monotonic evolution of resonance parameters that is explained in terms of interacting resonances. The dissipation of radiation in the cavity walls leads to decoherence and thus to a modification of the Fano profile. We show that the imaginary part of the complex Fano q-parameter allows to determine the absorption constant of the cavity. Our theoretical results demonstrate further that the two decohering mechanisms, dephasing and dissipation, are equivalent in terms of their effect on the evolution of Fano resonance lineshapes.

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1. Introduction

Asymmetric Fano line shapes are an ubiquitous feature of resonance scattering when (at least) two different pathways connecting the entrance with the exit channel exist. Fano resonances have been discussed in many different fields of physics starting with photoabsorption in atoms [1–3], electron and neutron scattering [4,5], Raman scattering [6], photoabsorption in quantum well structures [7], scanning tunneling microscopy [8], and ballistic transport through quantum dots ("artificial atoms") [9–14] and molecules [15,16]. Interest in observing and analyzing Fano profiles is driven by their high sensitivity to the details of the scattering process. For example, since Fano parameters reveal the presence and the nature of different (non) resonant pathways, they can be used to determine the degree of coherence in the

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scattering device. This is due to the fact that decoherence may convert Fano resonances into the more familiar limiting case of a Breit–Wigner resonance. Furthermore, Fano profiles provide detailed information on the interaction between nearby resonances leading to "avoided crossings" in the complex plane [17,18], and to stabilization of discrete states in the continuum ("resonance trapping" [19,20]). Possible technological applications of Fano resonances have recently been suggested in Ref. [21], exploiting the transmission resonances in transport through open quantum dot systems as a means to generate spin polarization of transmitted carriers.

Using the equivalence between the scalar Helmholtz equation for electromagnetic radiation in cavities with conducting walls and the Schrödinger equation subject to hard-wall boundary conditions [22], we have designed a scattering device (Fig. 1) that allows the controlled tuning of Fano resonances for transport through quantum billiards. The evolution of the Fano parameters as a function of the tuning parameter, in the present case the degree of opening of the leads, can be traced in unprecedented detail, since decoherence due to dissipation can be controlled. By comparison with calculations employing the modular recursive Green's function method (MRGM) [11,23], the parametric variation of Fano resonances and the degree of decoherence can be quantitatively accounted for. Furthermore, the relevant pathways can be unambiguously identified in terms of wavefunctions representing the contributing scattering channels. Due to the equivalence between microwave transport and single-electron motion in two dimensions, our device can be understood as a simulation of ballistic electron scattering through a quantum dot. In contrast to recent investigations of mesoscopic dots and single-electron transistors [9,12,24], where the comparison between theory and experiment has remained on a mostly qualitative level, our model system allows for a detailed quantitative analysis of all features of tunable resonances.

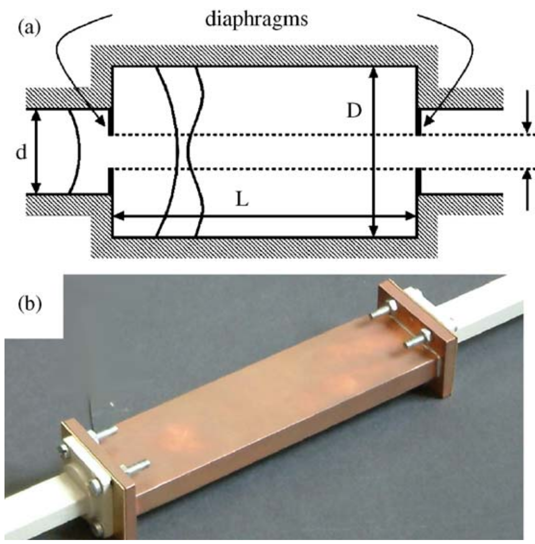

Fig. 1. (a) Schematic sketch of the rectangular cavity with leads attached symmetrically on opposite sides. Exchangeable diaphragms at the lead junctions allow to control the coupling between the cavity and the leads. The open even transverse states are indicated. (b) Photograph of the experimental setup.

2. The model

Our microwave scattering device consists of two commercially available waveguides with height $h = 7.8$ mm, width $d = 15.8$ mm, and length $l = 200$ mm which were attached both to the entrance and the exit side of a rectangular resonator with height $H = 7.8$ mm, width $D = 39$ mm, and length $L = 176$ mm, resulting in a circumference $C = 430$ mm and area $A = 39\,\text{mm} \times 176\,\text{mm}$ (both in the plane). At the junctions to the cavity, metallic diaphragms of different openings were inserted (Fig. 1). The microwaves with frequencies between 12.3 and 18.0 GHz, where two even transverse modes are excited in the cavity and one transverse mode in each of the leads, are coupled into the waveguide via an adaptor to ensure strong coupling.

The experimental results are compared with the predictions of the MRGM. We solve the S matrix for the single particle Schrödinger equation for this "quantum dot" by assuming a constant potential set equal to zero inside and infinitely high outside of a hard-wall boundary. At asymptotic distances, scattering boundary conditions are imposed in the leads. The coupling of the leads to