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Probing decoherence through Fano resonances

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Introduction

Fano Resonances

Fano resonances arise in transmission if there is

- a single resonant term
- an additional approximately constant background t_d

Examples: neutron scattering, dissipation spectra, quantum dots
Transmission amplitude:

$$t(k) = z_r \frac{\Gamma/2}{k - k_{\rm res} + i\Gamma/2} + t_d$$

Fano profile:

$$|t(k)|^2 = |t_d|^2 \frac{|\epsilon + q|^2}{\epsilon^2 + 1}, \text{ with } q = i + \frac{z_r}{t_d}$$

- $\epsilon = (k - k_{\rm res})/(\Gamma/2)$: rescaled wavenumber
- q: Fano parameter describes the asymmetry of the resonance
- $q \to 0 \Rightarrow$ window or "anti-resonance"
- $q \to \pm\infty \Rightarrow$ Breit-Wigner resonance

Microwave Experiments - Quantum Mechanics

From Maxwell's equation for microwave resonators with parallel bottom and top plate we obtain the two-dimensional Helmholtz-equation for the z-component of the electrical field $E_z(x, y)$:

$$-\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) E_z(x, y) = k^2 E_z(x, y)\,, \qquad (1)$$

There exists a full correspondence between Eq. (1) with the two-dimensional Schrödinger-equation

$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) \psi(x, y) = E\psi(x, y) \qquad (2)$$

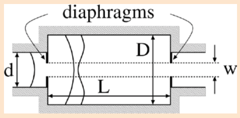
if we identify

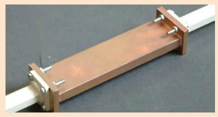
$$\psi \mathrel{\hat{=}} E_z, \qquad E \mathrel{\hat{=}} k^2, \qquad \frac{\hbar^2}{2m} \mathrel{\hat{=}} 1$$

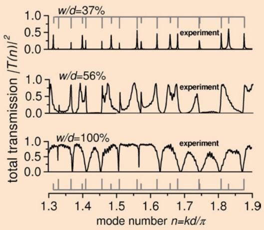
Tuning Fano Resonances

Experimental set-up

- Rectangular copper cavity with width $D = 39$ mm and length $L = 176$ mm
- Excite via channels of width $d = 15.8$ mm
- Varying shutter opening w changes coupling ($1.8\,\mathrm{mm} \le w \le 15.8\,\mathrm{mm}$)
- Mode with $n = 2$ cannot be excited due to symmetry
- Coupling to modes with $n = 1$ and $n = 3$ is different
- Measure complex transmission amplitude t with vector network analyzer

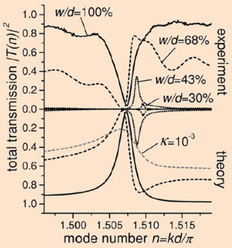






Transmission Spectra

- Transmission $|t(n)|^2$ for different shutter openings
- Shutter opening $d = 5.8$ mm: Breit-Wigner resonances
- Shutter opening $d = 7.8$ mm: asymmetric resonances
- Shutter opening $d = 15.8$ mm: window resonances
- Positions of all eigenstates in the closed cavity are indicated by the gray tick marks
- Long gray ticks marks for $n = 3$ and short for $n = 1$ eigenstates



Individual Fano Resonance

- Effects of dissipation have to be taken into account ($\kappa = 10^{-4}$)
- Shape is sensitive to the dissipation parameter (see $\kappa = 10^{-3}$ curve)
- Fano resonances can be tuned

[S. Rotter, F. Libisch, J. Burgdörfer, U. Kuhl, H.-J. Stöckmann, Phys. Rev. E 69, 046208 (2004).]
[S. Rotter, U. Kuhl, F. Libisch, J. Burgdörfer, H.-J. Stöckmann, Physica E 29, 325 (2005).]

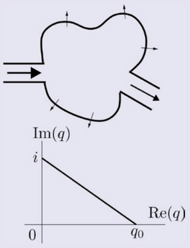
Probing decoherence through Fano resonances [Phys. Rev. Lett. 105, 056801 (2010)]

Model for Dissipation

Dissipation is modelled by many, weakly attached channels, where the flux leaves the cavity.
Effective description by $k \to k + i\kappa$

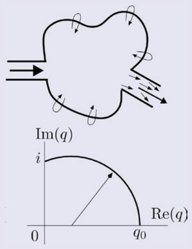
$$q(\chi) = i + \chi \frac{z_r}{t_d} = i + \chi\,(q_0 - i)$$

$\chi = \Gamma_0/(\Gamma_0 + 2\kappa)$: measure for the dissipation strength
q_0: Fano parameter for the system without dissipation
$q(\chi)$: straight line from q_0 to i



Model for Dephasing

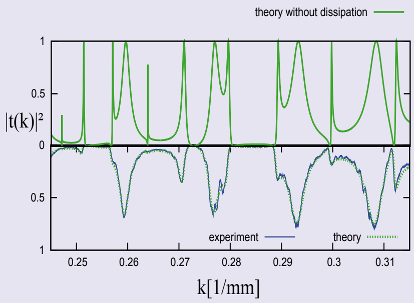
Dephasing is modelled by attached phase breaking channels where the flux into the channel is re-injected with an arbitrary phase.
Also dephasing leads to a complex Fano parameter, but with a circular dependence on the dephasing strength χ
$q(\chi)$: circular dependence
$\chi = \Gamma_0/\Gamma$: measure for the dephasing strength



[A. A. Clerk, X. Waintal, and P. W. Brouwer Phys. Rev. Lett. 86, 4636 (2001).]

Experimental and Numerical Results

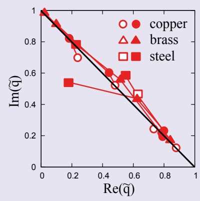
- Three different cavities: copper, brass, and steel (same size as cavity shown above)
- Two temperatures: room temperature and liquid nitrogen
- Shutter opening: $d = 7.8$ mm



- Upper part: corresponding numerical calculation without dissipation (κ=0)
- Lower part: measured transmission for steel cavity and numerical calculation with dissipation (κ is fitted)
- Numerical data coincides very well with experimental data
- Well controlled dissipation in experiment allows us to study the influence on Fano resonances explicitly

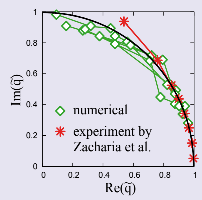
Scaling for Dissipation

- Resonances in microwave transmission fitted with Fano lineshape
- Fano parameter extracted for resonances with different material parameters and temperatures
- Parameters resized to $q_0 = 1$
- Symbols for the same resonances are connected (empty/filled symbols stand for nitrogen/room temperature)
- Linear scaling behavior is successfully reproduced



Scaling for Dephasing

- Numerical calculation with uniform dephasing and experimental data on temperature dependence of transport through quantum dots [PRB 64, 155311 (2001)]
- Parameters resized to unit circle
- Circular scaling behavior is successfully reproduced



[I. G. Zacharia, D. Goldhaber-Gordon, G. Granger et al., Phys. Rev. B 64, 155311 (2001)]

Parametric dependence of the Fano asymmetry parameter $q(\chi)$ can distinguish between different decoherence mechanisms