

Quantum dynamics of a wave packet for a Cantor spectrum

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- 2 Analytical study in the case of a Cantor set
 - Appropriate measure
 - Time-averaged return probability
 - Other relevant quantities
- 3 Experiment : cavity polaritons in a Fibonacci potential
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Study systems with a (spatial and/or spectral) **fractal feature**.

Motivation :

- Little is known about systems with **singular continuous** spectra (which includes fractal spectra)
- Ubiquity of such spectra (quasi-crystals, quasi-periodic potentials)
- Explain experimental and numerical observations

Objectives :

- Identify typical behaviour of relevant physical quantities in the presence of a fractal feature (spatial and/or spectral) \rightarrow power-law modulated by log-periodic oscillations
- Derive analytical expressions

Fractal :

- a set with a discrete scaling symmetry
- fractal dimension d_f
(length scale l ; volume scales as l^{d_f})

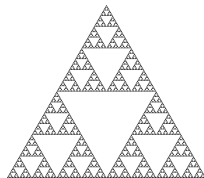


Figure: Sierpinski gasket

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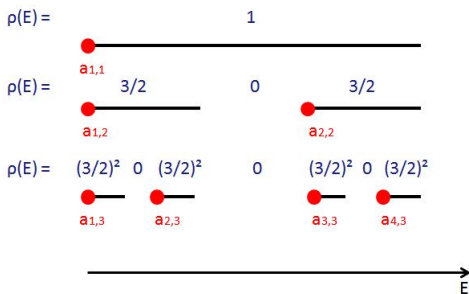
Quantum dynamics for a triadic Cantor set spectrum.

$H = -\frac{d^2}{dx^2} + V(x)$ on $L^2(\mathbb{R})$, with associated triadic Cantor set spectrum.



Figure: Triadic Cantor set. Fractal dimension $d_f = \frac{\ln 2}{\ln 3}$

Triadic Cantor set K : zero (Lebesgue) measure. Degenerate density of states $\rho(\epsilon)$. Define measure : $d\mu(\epsilon) \equiv \rho(\epsilon)d\epsilon$:



Verifies : $\int_K f(x)d\mu(x) = \frac{1}{2} \int_K f\left(\frac{x}{3}\right)d\mu(x) + \frac{1}{2} \int_K f\left(\frac{x+2}{3}\right)d\mu(x)$
 (scaling property)

How does the fractal feature affect the dynamics of the wave packet $|\psi(t)\rangle$?

- 1 RMS displacement $\Delta x(t) = \sqrt{\int (x(t) - x_0)^2 |\psi(x, t)|^2 dx}$
- 2 return probability $p(t) = |\langle \psi(0) | \psi(t) \rangle|^2$
- 3 ...

A relevant quantity : the **time-averaged return probability** :

$$C(t) = \frac{1}{t} \int_0^t |\langle \psi(0) | \psi(t') \rangle|^2 dt'$$

A relevant quantity : the **time-averaged return probability** :

$$C(t) = \frac{1}{t} \int_0^t |\langle \psi(0) | \psi(t') \rangle|^2 dt' = \dots = \iint_{K \times K} \text{sinc}((\epsilon' - \epsilon)t) d\mu(\epsilon) d\mu(\epsilon')$$

Note : ϵ and t are coupled variables.

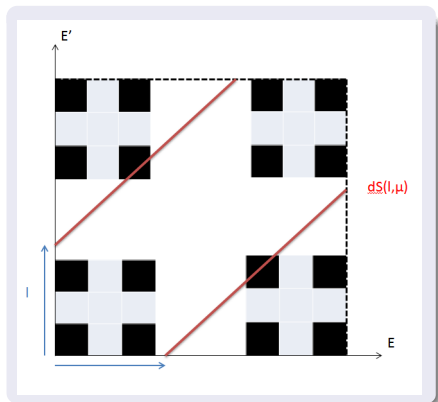
Method

- ① use the scaling symmetry of the measure to obtain a functional equation
- ② apply the Mellin transform

$$C(t) = \iint_{K \times K} \text{sinc}((\epsilon' - \epsilon)t) d\mu(\epsilon) d\mu(\epsilon')$$

Change of variable : $l = |\epsilon' - \epsilon|$
 $dS(l, \mu) = \text{area in the sense of } \mu$
 of the 2D Cantor set ("Cantor dust") within the red strips

$$C(t) = \int_0^1 \text{sinc}(lt) dS(l, \mu)$$



(cf. energy integrals : D. Bessis et al., Phys. Rev. A, Vol. 36, number 2, July 15, 1987)

The main steps :

① Mellin transform : $\zeta(\alpha) = \int_0^1 l^{-\alpha} dS(l, \mu)$

② scaling property :

$$\zeta(\alpha) = \int_0^1 l^{-\alpha} dS(l, \mu) = \iint_{K \times K} \frac{d\mu(x)d\mu(y)}{|x-y|^\alpha} = \frac{3^\alpha}{2} \zeta(\alpha) + \epsilon(\alpha)$$

③ $\zeta(\alpha) = \frac{\epsilon(\alpha)}{1 - \frac{3^\alpha}{2}}$

④ inverse Mellin transform $\rightarrow dS(l, \mu) \rightarrow C(t)$

Time-averaged return probability for triadic Cantor set

$$C(t) = \frac{t^{-\ln 2 / \ln 3}}{\ln(3)} \sum_n \epsilon_n e^{-\frac{2i\pi n}{\ln(3)} \ln t} \sin\left(\frac{\pi}{2}(d_n - 1)\right) \Gamma(d_n - 1)$$

$d_n = \frac{\ln(2)}{\ln(3)} + \frac{2i\pi n}{\ln(3)}$, $\epsilon_n = \int_{K \times K} \frac{d\mu(x)d\mu(y)}{|x-y+2|^{d+\frac{2i\pi n}{\ln(3)}}}$, Γ the Euler gamma function

$\Rightarrow C(t) = t^{-\ln 2 / \ln 3} G_p(\ln t / \ln 3)$, $G_p(y+1) = G_p(y)$

- 1 power-law modulated by log-periodic oscillations.
- 2 $C(t) \propto t^{d_f}$, with $d_f = \frac{\ln 2}{\ln 3}$ (fractal dimension) for a triadic Cantor set.

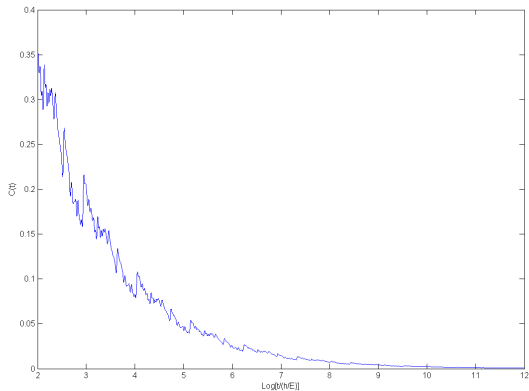


Figure: Return probability $C(t)$ for a Cantor spectrum

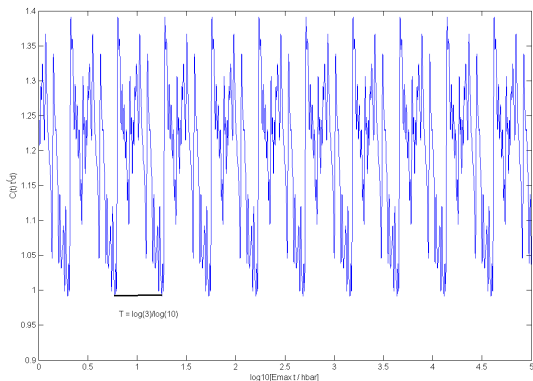


Figure: Return probability divided by $t^{-\ln 2/\ln 3}$, $C(t)t^{-\ln 2/\ln 3}$ for a Cantor spectrum

Partial summary :

- General method :
 - scaling property
 - functional equation $f(x) = \frac{1}{b}f(ax) + g(x)$
 - Mellin transform
 - $f(x) = x^{\ln(b)/\ln(a)} G_p\left(\frac{\ln x}{\ln a}\right)$
- Typical behaviour due to a fractal spectrum : power-law modulated by log-periodic oscillations
- The method gives an intuition of which are the relevant physical quantities to observe typical behaviour

Other relevant quantities :

- Participation ratio : $P_r(t) = \frac{1}{t} \int_0^t \frac{dt'}{|\langle x | \psi(t') \rangle|^4}$
- RMS displacement : $\Delta x(t) = \sqrt{\int (x(t) - x_0)^2 |\psi(x, t)|^2 dx}$

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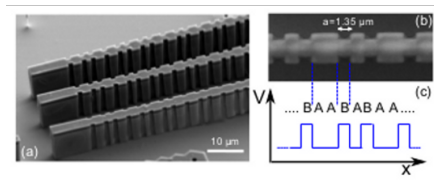
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B
 A
 BA
 ABA
 BAABA
 ABABAABA
 BAABAABABAABA

Figure: $S_1 = B$, $S_2 = A$,
 $S_{j+1} = S_{j-1}S_j$



Photon described by $\psi(x, y, z)$,
confined in z direction :

$$E\psi(x, y) = -\frac{\hbar^2}{2m_{ph}}\Delta_{\perp}\psi(x, y)$$

with $\Delta_{\perp} = \partial_x^2 + \partial_y^2$, m_{ph}
effective mass of the photon.

Mapping to a 1D problem with
effective quasi-periodic potential
 $V(x)$:

$$E\psi(x) = \frac{\hbar^2}{2m_{ph}} \left[-\frac{d^2}{dx^2} + V(x) \right] \psi(x)$$

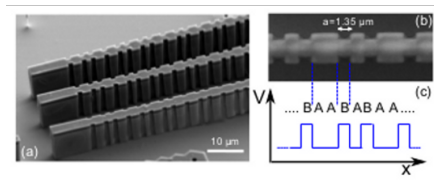
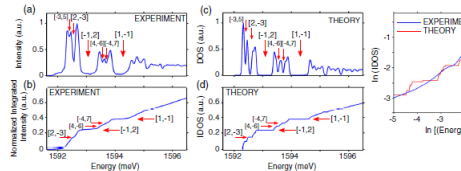
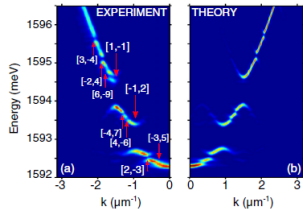


Figure: Fibonacci cavity

Numerical and experimental results



Akkerman, Gurevich et al., Physical Review Letters 112, 146404 (2014)

Integrated density of states (IDOS) :

$$N(\epsilon) = \int_{\text{spectre}} \theta(\epsilon - \epsilon') d\mu(\epsilon')$$

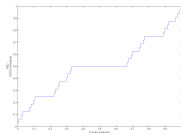


Figure: IDOS for a triadic Cantor set spectrum

Time-averaged return probability :

$$C(t) = \frac{1}{t} \int_0^t |\langle \psi(0) | \psi(t') \rangle|^2 dt'$$

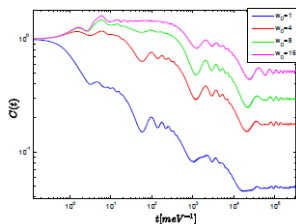


Figure: Time-averaged return probability of a wave packet in a Fibonacci potential. (E. Gurevich)

Log-periodic oscillation, signature of the fractal feature of the spectrum.

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In summary :

- We identified the signature of a fractal spectrum through measurable physical quantities : power-law modulated by log-periodic oscillation, for dynamical and spectral quantities ($C(t)$, integrated density of states)
- Oscillations difficult to observe ; easier with dynamical quantities
- Verified experimentally with polaritons in a Fibonacci potential (Cantor like spectrum)
- General method to study theoretically systems with a fractal feature
- applied to the return probability for a Cantor spectrum

Next : other relevant quantities in quantum mechanics

- Signature of the fractal spectral feature in the Thouless coefficient
- Spatial correlation of the eigenfunction ; adaptation of Thouless formula : $\overline{\phi(0, \epsilon)^* \phi(x, \epsilon)} \propto e^{-|x|\gamma(\epsilon)}$
- Spontaneous emission of a single atom coupled to a fractal continuum
- Superradiance of a two atoms system coupled to a fractal continuum

Thank you ! Questions ?