

Delocalization of quasimodes on the disk

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Abstract

This note deals with semiclassical measures associated to quasimodes (u_h) of the Laplace-Dirichlet operator on the disk. In this time-independent set-up, we simplify the statements of [ALM14] and their proofs. We describe the restriction of semiclassical measures to every invariant torus in terms of two-microlocal measures. As corollaries, we show regularity and delocalization properties for limit measures of $|u_h|^2 dx$: these are absolutely continuous in the interior of the disk and charge every open set intersecting the boundary.

Abstract

Délocalisation des quasimodes sur le disque. Dans cette note, on s'intéresse aux mesures semiclassiques associées aux quasimodes (d'ordre suffisamment élevé) (u_h) du laplacien de Dirichlet sur le disque. Dans ce contexte stationnaire, les résultats obtenus dans [ALM14] et leurs preuves sont simplifiés. On décrit la restriction de ces mesures à chaque tore invariant au moyen de mesures deux-microlocales. En corollaire, on montre des propriétés de régularité et de délocalisation des mesures limites des $|u_h|^2 dx$: celles-ci sont absolument continues à l'intérieur du disque et chargent tout ouvert qui touche le bord.

1 Introduction

We consider the unit disk $\mathbb{D} = \{z = (x, y) \in \mathbb{R}^2, |z|^2 = x^2 + y^2 < 1\} \subset \mathbb{R}^2$, and study quasimodes of the euclidean Laplacian Δ endowed with Dirichlet boundary conditions:

$$(-h^2 \Delta + h^2 V - E_0) u_h = r_h, \quad \text{in } \mathbb{D}, \quad u_h|_{\partial \mathbb{D}} = 0, \quad \|u_h\|_{L^2(\mathbb{D})} = 1. \quad (1.1)$$

where $V = V(z)$ is a bounded potential and $E_0 > 0$ a fixed energy level (say $E_0 = 1$). Here, $h > 0$, $h \rightarrow 0$ is a semiclassical parameter and the remainder r_h satisfies some boundedness/smallness assumptions in $L^2(\mathbb{D})$:

Definition 1.1. *Let (s_h) be a family of positive real numbers indexed by $h \in (0, 1)$. We say that $(u_h)_{h>0}$ is a family of $O(s_h)$ (resp. $o(s_h)$) quasimodes if u_h satisfies (1.1) with $\|r_h\|_{L^2(\mathbb{D})} = O(s_h)$ (resp. $\|r_h\|_{L^2(\mathbb{D})} = o(s_h)$) as $h \rightarrow 0^+$.*

The aim of this note is to prove delocalization properties for sufficiently accurate quasimodes. Remark that the latter may be deduced from similar properties of solutions to the semiclassical Schrödinger evolution equation $\frac{h}{i} \partial_t w_h = h^2 (-\Delta + V) w_h$, proven in [ALM14]. If (u_h) solves (1.1), then the solution $w_h(t)$ of the evolution equation such that $w_h|_{t=0} = u_h$ satisfies $\|w_h(t) - e^{itE_0/h} u_h\|_{L^2(\mathbb{D})} = O(\frac{t}{h} \|r_h\|_{L^2(\mathbb{D})})$. Hence, properties of $w_h(t)$ over a time interval $[0, \tau_h]$ can be translated into properties of u_h if $\|r_h\|_{L^2(\mathbb{D})} \sim \frac{h}{\tau_h}$. In the present setting, properties of solutions of the time dependent Schrödinger equation on time intervals of length $1/h$ can be transferred to quasimodes of order h^2 , see also [ALM14, Remark 2.5]. Hence, all results we present are special cases of those in [ALM14]. However, considering stationary solutions allows to simplify the statements and the proofs significantly. This is the motivation of the present note.

Examples of quasimodes are provided, for instance, by high-energy eigenfunctions of $(-\Delta + V)$ or clusters of eigenfunctions. Indeed, denoting by (ψ_j) a Hilbert basis of $L^2(\mathbb{D})$ constituted by orthonormal eigenfunctions of the operator $-\Delta + V$ with Dirichlet conditions, associated to the eigenvalues $\lambda_j \rightarrow +\infty$, then the family

$$v^\lambda = \sum_{\lambda_j \in [\lambda - R(\lambda), \lambda + R(\lambda)]} v_j \psi_j, \quad \text{with} \quad \sum_{\lambda_j \in [\lambda - R(\lambda), \lambda + R(\lambda)]} |v_j|^2 = 1, \quad \lambda \rightarrow +\infty,$$

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is a family of $O(s_h)$ quasimodes for $s_h = R(\lambda)/\lambda$ and $h = E_0\lambda^{-1/2} \rightarrow 0$.

A major issue in mathematical quantum mechanics is to describe the possible localization – or delocalization – properties of solutions of the stationary Schrödinger equation (1.1). Here, the main object of our study is the probability density $|u_h(z)|^2 dz$; given $\Omega \subset \mathbb{D}$, the quantity $\int_{\Omega} |u_h(z)|^2 dz$ represents the probability of finding a quantum particle in the set Ω . More precisely, given a sequence $h = h_n \rightarrow 0^+$, we aim at describing the asymptotic properties of the probability densities $|u_h(z)|^2 dz = |u_{h_n}(z)|^2 dz$. After possibly extracting a subsequence, we have the convergence $|u_h(z)|^2 dz \rightharpoonup \nu(dz)$ in $\mathcal{D}'(\mathbb{R}^2)$, where ν is a nonnegative Radon measure describing the asymptotic mass repartition of the sequence of quasimodes (u_h) . One of the goals of this paper is to understand how the fact that (u_h) solves (1.1) influences the structure of the associated measure ν .

Another interesting quantity is the mass left by a quasimode at the boundary: a well-known *hidden regularity* result (see e.g. [GL93, Lemma 2.1]) states that $h\partial_n u_h|_{\partial\mathbb{D}}$ forms a bounded family of $L^2(\partial\mathbb{D})$ for any family of $O(1)$ quasimodes (u_h) . Hence one may also be interested in studying the asymptotic repartition of the densities $|h\partial_n u_h|_{\partial\mathbb{D}}|^2 dS(z)$, where dS denotes the Lebesgue measure on the circle $\partial\mathbb{D}$. After extracting a subsequence, one has $|h\partial_n u_h|_{\partial\mathbb{D}}|^2 dS(z) \rightharpoonup \nu^\partial(dz)$ where ν^∂ is a measure on the boundary $\partial\mathbb{D}$.

Theorem 3.1 below describes precisely the properties of semiclassical measures: these are lifts of the limit measures ν (described above) to the phase space of classical dynamics. The theorem deals with $O(h^2)$ or $o(h^2)$ quasimodes and it yields in particular the following three corollaries.

Corollary 1.2. *Let (u_h) be a sequence of $O(h^2)$ quasimodes.*

1. *For any weak-* limit $\nu(dz)$ of the sequence $|u_h(z)|^2 dz$, $\nu|_{\mathbb{D}}$ is absolutely continuous.*
2. *Any weak-* limit $\nu^\partial(dz)$ of the sequence $|h\partial_n u_h|_{\partial\mathbb{D}}|^2 dS(z)$ is absolutely continuous (with respect to dS).*

This result shows that the weak-* accumulation points of the densities $|u_h(z)|^2 dz$ possess some regularity in the interior of the disk (note that it is easy to exhibit sequences of quasimodes of solutions that concentrate singularly on the boundary, the so-called whispering-gallery modes, having for limit measure $\nu(dz) = (2\pi)^{-1} \delta_{\partial\mathbb{D}}$). Remark that a family of $O(h^2)$ quasimodes for $-h^2\Delta + h^2V - E_0^2$ is a family of $O(h^2)$ quasimodes for $-h^2\Delta - E_0^2$. As Corollary 1.2 applies for $O(h^2)$ quasimodes, no regularity is needed for the potential V and it also holds under the assumption $V \in \mathcal{L}(L^2(\mathbb{D}))$.

Such regularity result is also known to hold on flat tori [Mac10, AM14] and more generally in the case of strictly convex/concave completely integrable systems (without boundary) [AFKM14]. On the sphere \mathbb{S}^d , on which the geodesic flow is still completely integrable, the situation is radically different, for it is known that every measure that is invariant under the geodesic flow (in particular, the uniform measure on an equator) is a semiclassical measure.

Note that it is proved in [AFKM14, Theorem 1.3] that the scale h^2 is the critical delocalization scale for quasimodes on non degenerate completely integrable systems: $O(s_h)$ quasimodes with $s_h \gg h^2$ can have as a semiclassical measure every invariant measure of the geodesic flow.

Another corollary of Theorem 3.1 is the following result:

Corollary 1.3. (a) *Let $\Omega \subset \overline{\mathbb{D}}$ be an open set such that $\Omega \cap \partial\mathbb{D} \neq \emptyset$, and $V \in C^\infty(\overline{\mathbb{D}}; \mathbb{R})$. Then, there exist $C(\Omega) > 0$ such that for any sequence (u_h) of $o(h^2)$ quasimodes, for any weak-* limit $\nu(dz)$ of the sequence $|u_h(z)|^2 dz$, we have $\nu(\Omega) \geq C(\Omega)$.*

(b) *Let $\Gamma \subset \partial\mathbb{D}$ be any nonempty open set, and $V \in C^\infty(\overline{\mathbb{D}}; \mathbb{R})$. Then, there exist $C(\Gamma) > 0$ such that for any sequence (u_h) of $o(h^2)$ quasimodes, for any weak-* limit $\nu^\partial(dz)$ of the sequence $|h\partial_n u_h(z)|_{\partial\mathbb{D}}|^2 dS(z)$, we have $\nu^\partial(\Gamma) \geq C(\Gamma)$.*

Points (a) and (b) of Corollary 1.3 are equivalent (after *reductio ad absurdum* and the use of unique continuation for eigenfunctions of the operator $-\Delta_D + V$) to the following resolvent estimates:

Corollary 1.4. (a) *Let $\Omega \subset \overline{\mathbb{D}}$ be an open set such that $\Omega \cap \partial\mathbb{D} \neq \emptyset$, and $V \in C^\infty(\overline{\mathbb{D}}; \mathbb{R})$. Then, there exist $C_0, C_1 > 0$ such that for any $\lambda \in \mathbb{R}$, for any $u \in H^2 \cap H_0^1(\mathbb{D})$ we have*

$$\|u\|_{L^2(\mathbb{D})} \leq C_0 \|(-\Delta + V - \lambda)u\|_{L^2(\mathbb{D})} + C_1 \|u\|_{L^2(\Omega)}$$

(b) *Let $\Gamma \subset \partial\mathbb{D}$ be any nonempty open set, and $V \in C^\infty(\overline{\mathbb{D}}; \mathbb{R})$. Then, there exist $C_0, C_1 > 0$ such that for any $\lambda \in \mathbb{R}$, for any $u \in H^3 \cap H_0^1(\mathbb{D})$ such that $\Delta u|_{\partial\mathbb{D}} = 0$, we have*

$$\|u\|_{H_0^1(\mathbb{D})} \leq C_0 \|(-\Delta + V - \lambda)u\|_{H_0^1(\mathbb{D})} + C_1 \|\partial_n u|_{\partial\mathbb{D}}\|_{L^2(\Gamma)}$$

Roughly speaking, this means that any set Ω touching $\partial\mathbb{D}$ (resp. any subset Γ of $\partial\mathbb{D}$) observes all quantum particles trapped in the disk. Because of the whispering gallery phenomenon, the condition that Ω touch the boundary is necessary for property 1 to hold. This translates the fact that any solution has to leave positive mass on any set Ω touching the boundary $\partial\mathbb{D}$ (resp. any subset Γ of $\partial\mathbb{D}$). In the present very particular geometry, this improves the general bound [LR95] (given by the tunnelling effect) where C_0, C_1 have to be replaced by $Ce^{C\lambda}$ for some $C > 0$. Resolvent estimates such as those of Corollary 1.4 are known to imply observability/controllability for the evolution Schrödinger equation in sufficiently large time [BZ04, RTTT05, Mil05].

It is known that the resolvent estimates of Corollary 1.4 hold in a general domain, in an improved form, i.e. with C_0 replaced by $C_0(1 + |\lambda|)^{-1}$, provided that all trajectories of the billiard enter the observation region Ω or Γ in finite time [Leb92, BZ04, RTTT05, Mil05]. However we know that this strong geometric control condition is not necessary on the torus, for (a) is satisfied as soon as $\Omega \neq \emptyset$ [Jaf90, Mac11, BZ12, Kom92, AM14]. The boundary resolvent estimate of Corollary 1.4 also holds in the square if and only if the observation region Γ contains both a horizontal and a vertical nonempty segments [RTTT05]. On the other hand, on the sphere, it is *necessary* that $\overline{\Omega}$ meets all geodesics for an observation inequality like that of Corollary 1.4 to hold.

Remark 1.5. (i) Arguments developed in [AM14] show that Corollaries 1.3 and 1.4 (as well as Theorem 3.1 below) also hold for $V \in C^0(\overline{\mathbb{D}}; \mathbb{R})$ or even in the case where V is continuous outside a set of zero measure.

(ii) Corollary 1.4 directly yields a polynomial decay rate for the energy of the (internally) damped wave equation on the disk if the damping touches the boundary [AL14, Theorem 2.3].

2 The billiard flow in the disk, and associated Action-Angle coordinates

Semiclassical analysis provides a connection between quasimodes and the billiard on the underlying phase space. Let us clarify what we mean by “billiard flow” in the disk. We first define the symmetry with respect to the line tangent to the circle $\partial\mathbb{D}$ at $z \in \partial\mathbb{D}$ by $\sigma_z(\xi) = \xi - 2z \cdot \xi$ for $z \in \partial\mathbb{D}$. Then, we work on the quotient space $\mathbb{W} = \overline{\mathbb{D}} \times \mathbb{R}^2 / \sim$ where $(z, \xi) \sim (z, \sigma_z(\xi))$ for $|z| = 1$. We denote by π the canonical projection $\overline{\mathbb{D}} \times \mathbb{R}^2 \rightarrow \mathbb{W}$ which maps a point (z, ξ) to its equivalence class modulo \sim . Note that π is one-one on $\mathbb{D} \times \mathbb{R}^2$, so that $\mathbb{D} \times \mathbb{R}^2$ may be seen as a subset of \mathbb{W} . A function $a \in C^0(\mathbb{W})$ can be identified with the function $\tilde{a} = a \circ \pi \in C^0(\overline{\mathbb{D}} \times \mathbb{R}^2)$ satisfying $\tilde{a}(z, \xi) = \tilde{a} \circ \sigma(z, \xi)$ for $(z, \xi) \in \partial\mathbb{D} \times \mathbb{R}^2$. The billiard flow $(\phi^\tau)_{\tau \in \mathbb{R}}$ on \mathbb{W} is the (uniquely defined) action of \mathbb{R} on \mathbb{W} such that the map $(\tau, z, \xi) \mapsto \phi^\tau(z, \xi)$ is continuous on $\mathbb{R} \times \mathbb{W}$, satisfies $\phi^{\tau+\tau'} = \phi^\tau \circ \phi^{\tau'}$, and such that $\phi^\tau(z, \xi) = (z + \tau\xi, \xi)$ whenever $z \in \mathbb{D}$ and $z + \tau\xi \in \mathbb{D}$.

In order to understand how the completely integrable dynamics of the flow ϕ^τ influences the structure of Wigner measures, we need to introduce coordinates adapted to these dynamics. We denote by $\Phi : (s, \theta, E, J) \mapsto (x, y, \xi_x, \xi_y)$ the set of “action-angle” coordinates for the billiard flow, defined by:

$$\begin{cases} x = \frac{J}{E} \cos \theta - s \sin \theta, \\ y = \frac{J}{E} \sin \theta + s \cos \theta, \\ \xi_x = -E \sin \theta, \\ \xi_y = E \cos \theta. \end{cases} \iff \begin{cases} E = \sqrt{\xi_x^2 + \xi_y^2}, \text{ (velocity)} \\ J = x\xi_y - y\xi_x = z \cdot \xi^\perp, \text{ (angular momentum)} \\ \theta = -\arctan\left(\frac{\xi_x}{\xi_y}\right), \text{ (angle of } \xi \text{ with the vertical)} \\ s = -x \sin \theta + y \cos \theta, \text{ (abscissa of } (x, y) \text{ along the line } \left(\frac{J}{E} \cos \theta, \frac{J}{E} \sin \theta\right) + \mathbb{R}\xi \text{)}. \end{cases}$$

Here, we denoted $\xi^\perp = (\xi_y, -\xi_x)$, where $\xi = (\xi_x, \xi_y)$. Note that the velocity E and the angular momentum J are preserved along the free transport flow in $\mathbb{R}^2 \times \mathbb{R}^2$, but also along ϕ^τ ; the variables s and θ play the role of “angle” coordinates. We call $\alpha = -\arcsin\left(\frac{J}{E}\right) = -\arcsin\left(\frac{x\xi_y - y\xi_x}{|\xi|}\right)$ the angle that a billiard trajectory makes with the normal to the circle, when it hits the boundary. The quantity α is preserved by the billiard flow.

We set $X_J = z^\perp \cdot \partial_z + \xi^\perp \cdot \partial_\xi$ and $X_E = \frac{\xi}{|\xi|} \cdot \partial_z$ to be the Hamiltonian vector fields associated to $J(z, \xi)$ and $E(z, \xi)$, respectively. Note that R^τ , the flow of X_J , is given by $R^\tau(z, \xi) = (R(\tau)z, R(\tau)\xi)$, where $R(\tau)$ is the rotation matrix of angle τ . Let us denote $T_{(E,J)}$ the level sets of the pair (E, J) , namely

$$T_{(E,J)} = \{(z, \xi) \in \overline{\mathbb{D}} \times \mathbb{R}^2 : (|\xi|, z \cdot \xi^\perp) = (E, J)\}. \quad (2.1)$$

For $E \neq 0$ let us denote $\lambda_{E,J}$ the probability measure on $T_{(E,J)}$ that is both invariant under the billiard flow and invariant under rotations. In the coordinates (s, θ, E, J) , we have

$$\lambda_{E,J}(ds, d\theta) = c(E, J) ds d\theta, \quad c(E, J) = \left(\int_{T_{(E,J)}} ds d\theta \right)^{-1} > 0.$$

Note that for $E \neq 0$ and $\alpha \in \pi\mathbb{Q}$ the billiard flow is periodic on $T_{(E,J)}$ whereas $\alpha \notin \pi\mathbb{Q}$ corresponds to trajectories that hit the boundary on a dense set. More precisely, if $\alpha \notin \pi\mathbb{Q}$ then the billiard flow restricted to $T_{(E,J)}$ has a unique invariant probability measure, namely $\lambda_{E,J}$. For each $\alpha_0 \in \pi\mathbb{Q} \cap (-\pi/2, \pi/2)$ we define

$$\mathcal{I}_{\alpha_0} = \{(s, \theta, E, J) \in \Phi^{-1}(\overline{\mathbb{D}} \times \mathbb{R}^2), J = -\sin \alpha_0 E\} = \{\alpha = \alpha_0\},$$

which is the union of all the lagrangian manifolds $T_{(E,J)}$ with $J = -\sin \alpha_0 E$. The billiard flow ϕ^τ is periodic on \mathcal{I}_{α_0} ; hence, given a function $a : \mathbb{D} \times \mathbb{R}^2 \rightarrow \mathbb{C}$, we may define $\langle a \rangle_{\alpha_0} : \mathcal{I}_{\alpha_0} \rightarrow \mathbb{C}$ its average along the orbits of ϕ^τ on the set \mathcal{I}_{α_0} . In the coordinates (s, θ, E, J) , this function only depends on θ and E .

In the following, we need to perform semiclassical analysis in the variables (s, θ, J, E) instead of (z, ξ) and hence to quantize the symplectic change of variables Φ .

Lemma 2.1. *There exist a Fourier Integral Operator \mathcal{U} satisfying*

- (i) $\text{Op}_h(a(z, \xi)) = \mathcal{U}^* \text{Op}_h(a \circ \Phi(s, \theta, J, E)) \mathcal{U} + O(h)$ for any $a \in C_c^\infty(T^*\mathbb{R}^2)$ supported away from $\xi = 0$.
- (ii) The operator \mathcal{U} is unitary from $L^2(\mathbb{R}^2)$ to $L^2(\mathbb{R} \times \mathbb{R}/2\pi\mathbb{Z})$: $\mathcal{U}^* \mathcal{U} = I$.
- (iii) For $f \in C_c^\infty(\mathbb{R}^2)$, we have $\partial_s^2 \mathcal{U} f = \mathcal{U} \Delta f$, i.e. $-\hbar^2 \mathcal{U} \Delta \mathcal{U}^* = -\hbar^2 \partial_s^2$.

3 Semiclassical measures and the structure theorem

Following [GL93], we extend the problem from \mathbb{D} to \mathbb{R}^2 : starting with $u_h \in H^2 \cap H_0^1(\mathbb{D})$ we extend this function to \mathbb{R}^2 by the value 0 outside \mathbb{D} (we still denote by u_h the extended function). The extended function u_h satisfies $u_h \in H^1(\mathbb{R}^2)$, as well as

$$(-\hbar^2 \Delta + \hbar^2 V - E_0^2) u_h = r_h + \hbar^2 \partial_n u_h|_{\partial\mathbb{D}} \otimes \delta_{\partial\mathbb{D}}, \quad \text{in } \mathbb{R}^2, \quad \|u_h\|_{L^2(\mathbb{R}^2)} = 1. \quad (3.1)$$

The *semiclassical Wigner distribution* associated to u_h (at scale h) is a distribution on the cotangent bundle $T^*\mathbb{R}^2 = \mathbb{R}_z^2 \times \mathbb{R}_\xi^2$, defined by

$$W_h : a \mapsto \langle u_h, \text{Op}_h(a(z, \xi)) u_h \rangle_{L^2(\mathbb{R}^2)}, \quad \text{for all } a \in C_c^\infty(T^*\mathbb{R}^2), \quad (3.2)$$

where Op_h denotes the standard semiclassical quantization. After possibly extracting a subsequence, we have,

$$W_h(a) \xrightarrow{h \rightarrow 0} \mu(a), \quad \text{for all } a \in C_c^\infty(T^*\mathbb{R}^2), \quad (3.3)$$

where μ is a nonnegative measure on $T^*\mathbb{R}^2$ called the semiclassical measure associated to the subsequence (u_h) . Our main goal is to describe as precisely as possible the semiclassical measures μ associated to quasimodes. It follows from [GL93] that the limit μ in (3.3) has the following properties (on any convex domain):

(i) If (u_h) is a family of $o(1)$ quasimodes, then μ is a nonnegative probability measure supported in $S_{E_0}^* \overline{\mathbb{D}} = \{(x, \xi) \in T^*\mathbb{R}^2, x \in \overline{\mathbb{D}}, |\xi| = E_0\}$.

(ii) If (u_h) is a family of $o(h)$ quasimodes, then we have $\int_{\overline{\mathbb{D}} \times \mathbb{R}^2 \times \mathbb{R}^2} \xi \cdot \partial_z a \mu(dz, d\xi) = 0$ for every smooth a such that $a(z, \xi) = a(z, \sigma_z(\xi))$ for $|z| = 1$. Equivalently,

$$\int_{\overline{\mathbb{D}} \times \mathbb{R}^2} a \circ \phi^\tau \circ \pi(z, \xi) \mu(dz, d\xi) = \int_{\overline{\mathbb{D}} \times \mathbb{R}^2} a \circ \pi(z, \xi) \mu(dz, d\xi)$$

for every $a \in C^0(\mathbb{W})$, $\tau \in \mathbb{R}$. In other words, $\pi_* \mu$ is an invariant measure of the billiard flow.

Our main result describes finer properties of semiclassical measures μ arising from quasimodes (u_h) of order h^2 . To state it, we need to introduce some more notation. Given $\alpha_0 \in \pi\mathbb{Q} \cap (-\pi/2, \pi/2)$, we will denote by $m_a^{\alpha_0, E_0}(s)$ the operator on $L_{\text{loc}}^2(\mathbb{R}_\theta)$ ¹ acting by multiplication by the function $a(\Phi(s, \theta, E_0, -E_0 \sin \alpha_0))$. If a is a symmetric function (or a function on \mathbb{W}), remark that $m_{\langle a \rangle_{\alpha_0}}^{\alpha_0, E_0}$ does not depend on the variable s . For our potential V , the function $\langle V \rangle_{\alpha_0} \circ \Phi$ depends only on θ . Given $\omega \in \mathbb{R}/2\pi\mathbb{Z}$, we next define the operator

$$P_{\alpha_0, \omega} = -\frac{1}{2} \partial_\theta^2 + \cos^2 \alpha_0 \langle V \rangle_{\alpha_0} \circ \Phi, \quad \text{acting on } \mathcal{H}_\omega = \{v \in L_{\text{loc}}^2(\mathbb{R}) : v(\theta + 2\pi) = v(\theta) e^{i\omega}, \text{ for a.e. } \theta \in \mathbb{R}\}, \quad (3.4)$$

i.e. with Floquet-periodic condition. In the statements below, each \mathcal{H}_ω is identified with $L_\theta^2(0, 2\pi)$ by taking restriction of functions to $(0, 2\pi)$. We are now in position to state our main result.

¹The notation $L_{\text{loc}}^2(\mathbb{R}_\theta)$ is used here to emphasize that the space $L_{\text{loc}}^2(\mathbb{R})$ consists in functions of the variable θ .

Theorem 3.1. *Let (u_h) be a family of $O(h^2)$ quasimodes and μ be a weak- $*$ limit of a subsequence of W_h . Then, the measure μ can be decomposed into a countable sum of nonnegative measures*

$$\mu = \nu_{Leb} + \sum_{\alpha_0 \in \pi\mathbb{Q} \cap [-\pi/2, \pi/2]} \nu_{\alpha_0}, \quad \text{such that}$$

- (i) *Each term of the sum is carried by the set $\{E = E_0\}$ and invariant under the billiard flow.*
- (ii) *ν_{Leb} is of the form $\int_{|J| \leq E_0} \lambda_{E_0, J} dv'(J)$ for some nonnegative measure ν' on \mathbb{R} . In other words ν_{Leb} is a combination of Lebesgue measures on the invariant ‘‘tori’’ $T_{(E_0, J)}$.*
- (iii) *For $\alpha_0 = \pm \frac{\pi}{2}$, ν_{α_0} is carried by $(z, \xi) \in T^* \partial \mathbb{D}$, and is invariant under rotations around the origin.*
- (iv) *For every $\alpha_0 \in \pi\mathbb{Q} \cap (-\pi/2, \pi/2)$, ν_{α_0} is carried by the set $\mathcal{I}_{\alpha_0} \cap \{E = E_0\}$ and there exists a nonnegative measure $\ell_{\alpha_0}(d\omega)$ on $\mathbb{R}/2\pi\mathbb{Z}$, and a function*

$$\sigma_{\alpha_0} : (\mathbb{R}/2\pi\mathbb{Z})_{\omega} \rightarrow \mathcal{L}_+^1(L_{\theta}^2(0, 2\pi)),$$

integrable with respect to ℓ_{α_0} , taking values in the set of nonnegative trace-class operators on $L_{\theta}^2(0, 2\pi)$ so that

$$\int_{\mathcal{I}_{\alpha_0}} a d\nu_{\alpha_0} = \int_{\mathcal{I}_{\alpha_0}} \text{Tr}_{L_{\theta}^2(0, 2\pi)} \left(m_{\langle a \rangle_{\alpha_0}}^{\alpha_0, E_0} \sigma_{\alpha_0} \right) d\ell_{\alpha_0}, \quad \text{for all } a \in C_c^{\infty}(T^*\mathbb{R}^2) \quad (3.5)$$

- (v) *If in addition $V \in C^{\infty}(\overline{\mathbb{D}}; \mathbb{R})$ and (u_h) is a family of $o(h^2)$ quasimodes, then for ℓ_{α_0} -almost every ω , we have $[P_{\alpha_0, \omega}, \sigma_{\alpha_0}(\omega)] = 0$ in $L_{\theta}^2(0, 2\pi)$.*

4 Sketch of proofs

4.1 Decomposition of an invariant measure of the billiard

Phase space can be partitioned into $\overline{\mathbb{D}} \times (\mathbb{R}^2 \setminus \{0\}) = \alpha^{-1}(\pi\mathbb{Q} \cap [-\pi/2, \pi/2]) \sqcup \alpha^{-1}(\mathbb{R} \setminus \pi\mathbb{Q})$, where α is the function defined in §2. It follows that the invariant measure μ on $\overline{\mathbb{D}} \times \mathbb{R}^2$ decomposes as a sum of nonnegative measures:

$$\mu = \mu|_{\alpha \notin \pi\mathbb{Q}} + \sum_{r \in \mathbb{Q} \cap [-1/2, 1/2]} \mu|_{\alpha = r\pi}. \quad (4.1)$$

Since μ is a nonnegative invariant measure on \mathbb{W} , supported in $\{|\xi| = E_0\}$, the same is true for every term in the decomposition (4.1). Moreover, $\mu|_{\alpha \notin \pi\mathbb{Q}}$ is invariant under the rotation flow (R^r) , as well as $\mu|_{\alpha = \pm\pi/2}$. The assertion for $\alpha = \pm\pi/2$ comes from the fact that the rotation flow coincides with the billiard flow (up to time change) on the set $\{\alpha = \pm\pi/2\}$. The assertion for $\alpha \notin \pi\mathbb{Q}$ is a standard fact. It comes from the remark that, for any given value α_0 (such that $\alpha_0 \notin \pi\mathbb{Q}$) we can find $T = T(\alpha_0) > 0$ such that ϕ^T coincides with an irrational rotation on the set $\{\alpha = \alpha_0\}$. Thus, for $\alpha \notin \pi\mathbb{Q}$ or $\alpha = \pm\pi/2$, there is nothing to prove to get Theorem 3.1. Hence, it only remains to study each invariant measure $\mu|_{\alpha = \alpha_0}$, where $\alpha_0 \in \pi\mathbb{Q} \cap (-\pi/2, \pi/2)$ is fixed. This is the aim of the remainder of the proof.

4.2 Second microlocalization on \mathcal{I}_{α_0}

The angle $\alpha_0 \in \pi\mathbb{Q} \cap (-\pi/2, \pi/2)$ being fixed, we wish to study the concentration of W_h around the set $\{J = -E \sin \alpha_0\}$. Since the limit measure $(\Phi^{-1})_* \mu$ is supported on the set $\{E = E_0\}$ this is equivalent to studying the concentration of W_h around $\{J = -E_0 \sin \alpha_0\}$. For this, we define an appropriate class of symbols depending on an additional variable η , which later in the calculations will be identified with $\frac{J'}{h}$ for $J' = J + E_0 \sin \alpha_0$. We denote by \mathcal{S} the functions $b = b(s, \theta, E, J', \eta)$ supported in E away from 0 and $+\infty$, positively homogeneous of degree zero at infinity in the variable η . We say that $b \in \mathcal{S}^{\sigma}$ if $b \in \mathcal{S}$, and b and its derivatives are symmetric with respect to the boundary, which means that $b(\cos \alpha, \theta, E, J', \eta) = b(-\cos \alpha, \theta + \pi + 2\alpha, E, J', \eta)$. We now introduce two auxiliary distributions which describe more precisely how W_h concentrates on the set $\{E = E_0\} \cap \{J = -E_0 \sin \alpha_0\}$. Let $\chi \in C_c^{\infty}(\mathbb{R})$ be a nonnegative cut-off function that is identically equal to one near the origin and let $R > 0$. For $b \in \mathcal{S}$, we define, with $v_h = e^{-i\theta E_0 \sin \alpha_0} \mathcal{U} u_h$ and $J' = J + E_0 \sin \alpha_0$,

$$\begin{aligned} \langle w_{h,R}^{\alpha_0}, b \rangle &:= \left\langle v_h, \text{Op}_h \left(\left(1 - \chi \left(\frac{J'}{Rh} \right) \right) \chi_0(\theta) b(s, \theta, E, J', \frac{J'}{h}) \right) v_h \right\rangle_{L^2(\mathbb{R}_s \times \mathbb{R}_{\theta})}, \\ \langle w_{\alpha_0, h, R}, b \rangle &:= \left\langle v_h, \text{Op}_h \left(\chi \left(\frac{J'}{Rh} \right) \chi_0(\theta) b(s, \theta, E, J', \frac{J'}{h}) \right) v_h \right\rangle_{L^2(\mathbb{R}_s \times \mathbb{R}_{\theta})}. \end{aligned}$$

The Calderón-Vaillancourt theorem ensures that both $w_{h,R}^{\alpha_0}$ and $w_{\alpha_0,h,R}$ are bounded in \mathcal{S}' . After possibly extracting subsequences, we have the existence of a limit: for every $b \in \mathcal{S}$,

$$\langle \mu^{\alpha_0}, b \rangle := \lim_{R \rightarrow \infty} \lim_{h \rightarrow 0^+} \langle w_{h,R}^{\alpha_0}, b \rangle, \quad \text{and} \quad \langle \mu_{\alpha_0}, b \rangle := \lim_{R \rightarrow \infty} \lim_{h \rightarrow 0^+} \langle w_{\alpha_0,h,R}, b \rangle. \quad (4.2)$$

These two limit distributions enjoy the following preliminary properties:

Proposition 4.1. (i) *The distribution μ^{α_0} is a nonnegative Radon measure. In addition, μ^{α_0} is nonnegative, 0-homogeneous and supported at infinity in the variable η ; hence, μ^{α_0} may be identified with a nonnegative measure on $\mathbb{R}^4 \times \{-1, +1\}$.*

(ii) *The projection of μ_{α_0} on $\mathbb{R}_{s,\theta,E,J}^4$, is a nonnegative measure, carried on $\{J' = 0\}$, which we denote $\nu_{\alpha_0} = \int_{\mathbb{R}} \mu_{\alpha_0}(d\eta)$ (in view of the statement of Theorem 3.1).*

(iii) *If (u_h) is a family of $o(h)$ quasimodes, the distributions μ_{α_0} and μ^{α_0} are carried by the set $\{E = E_0\}$ and satisfy*

$$\langle \mu_{\alpha_0}, \partial_s b \rangle = 0, \quad \langle \mu^{\alpha_0}, \partial_s b \rangle = 0, \quad \text{for every } b \in \mathcal{S}^\sigma.$$

In particular, Item (iii) states that both μ_{α_0} and μ^{α_0} are, as μ , supported by the set $\{|\xi| = E_0\}$ and invariant under the billiard flow.

Theorem 4.2. *Assume (u_h) is a family of $O(h^2)$ quasimodes. Then, the measure μ^{α_0} restricted to \mathcal{I}_{α_0} satisfies the additional invariance property: $\langle \mu^{\alpha_0}|_{\mathcal{I}_{\alpha_0}}, \partial_\theta b \rangle = 0$, for every b in \mathcal{S}^σ .*

This is the key point to prove that, once projected to the (s, θ, E, J) variables, $\mu^{\alpha_0}|_{\mathcal{I}_{\alpha_0}}$ is proportional to the Lebesgue measure on \mathcal{I}_{α_0} , and hence contributes to ν_{Leb} in the statement of Theorem 3.1. The proof of Theorem 4.2 relies on the equation (3.1) and involves a commutator argument. Technical problems arise when dealing with the boundary term $h^2 \partial_n u_h|_{\partial \mathbb{D}} \otimes \delta_{\partial \mathbb{D}}$: we need to go back and forth from action angles variables to polar coordinates (in which the Dirichlet boundary condition is easily expressed), developing the Fourier integral operator involved up to second order.

There remains now to study the structure of the distribution μ_{α_0} and its invariance properties.

4.3 Structure and propagation of μ_{α_0}

Proposition 4.3. *There exists a nonnegative $\mathcal{L}^1(L^2(0, 2\pi))$ -valued measure ρ_{α_0} , on $\mathbb{R}/2\pi\mathbb{Z}_\omega \times \mathbb{R}_s$, supported in $\{s \in [-\cos \alpha_0, \cos \alpha_0]\}$, such that for every $b \in \mathcal{S}$,*

$$\int b(s, \theta, E, J, \eta) \mu_{\alpha_0}(ds, d\theta, dE, dJ, d\eta) = \text{Tr}_{L^2_\theta(0, 2\pi)} \int b(s, \theta, E_0, 0, D_\theta) \rho_{\alpha_0}(d\omega, ds) \quad (4.3)$$

Similarly to Proposition 4.1 (iii), one can prove that the operator-valued measure ρ_{α_0} satisfies some invariance property with respect to s -translation. The very particular structure of μ_{α_0} exhibited in (4.3) is sufficient to prove that its projection on the variables (s, θ) is absolutely continuous. Thus, this is also the case for the measure $\nu_{\alpha_0} = \int_{\mathbb{R}} \mu_{\alpha_0}(d\eta)$ appearing in Theorem 3.1.

The operator-valued measure ρ_{α_0} also possesses an additional (two-microlocal) invariance property that we now explain. Setting $\bar{\rho}_{\alpha_0}(d\omega) = \int \rho_{\alpha_0}(d\omega, ds)$ and according to [Gér91, Appendix], there exists a nonnegative measure $\ell_{\alpha_0}(d\omega)$ on $\mathbb{R}/2\pi\mathbb{Z}$, and a function $\sigma_{\alpha_0} : (\mathbb{R}/2\pi\mathbb{Z})_\omega \rightarrow \mathcal{L}^1_+(L^2_\theta(0, 2\pi))$, integrable with respect to ℓ_{α_0} , such that $\bar{\rho}_{\alpha_0} = \sigma_{\alpha_0} \ell_{\alpha_0}$.

Theorem 4.4. *Assume that $V \in C_c^\infty(\overline{\mathbb{D}}; \mathbb{R})$ and that (u_h) is a family of $o(h^2)$ quasimodes. Then, for ℓ_{α_0} almost every ω , we have $[P_{\alpha_0, \omega}, \sigma_{\alpha_0}(\omega)] = 0$ in \mathcal{H}_ω , where $P_{\alpha_0, \omega}$ is defined in (3.4).*

This commutation property implies that both operators are simultaneously diagonal. Combined with a unique continuation principle for eigenfunctions of the elliptic operator $P_{\alpha_0, \omega}$ from a nonempty open set, this is a key point in the proof of the observability/resolvent estimates, Corollaries 1.3 and 1.4 (the paper [AL14, Section 10] contains a similar argument on the torus).

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