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This paper deals with semiclassical asymptotics of the three-dimensional magnetic Laplacian in the presence of magnetic confinement. Using generic assumptions on the geometry of the confinement, we exhibit three semiclassical scales and their corresponding effective quantum Hamiltonians, by means of three microlocal normal forms à la Birkhoff. As a consequence, when the magnetic field admits a unique and nondegenerate minimum, we are able to reduce the spectral analysis of the low-lying eigenvalues to a one-dimensional  $\hbar$ -pseudodifferential operator whose Weyl's symbol admits an asymptotic expansion in powers of  $\hbar^{\frac{1}{2}}$ .

### 1. Introduction

**1A. Motivation and context.** The analysis of the magnetic Laplacian  $(-i\hbar\nabla - A)^2$  in the semiclassical limit  $\hbar \rightarrow 0$  has been the object of many developments in the last twenty years. The existence of the discrete spectrum for this operator, together with the analysis of the eigenvalues, is related to the notion of a “magnetic bottle”, or quantum confinement by a pure magnetic field, and has important applications in physics. Moreover, motivated by investigations of the third critical field in Ginzburg–Landau theory for superconductivity, there has been great attention focused on estimates of the lowest eigenvalue. In the last decade, it appears that the spectral analysis of the magnetic Laplacian has acquired a life of its own. For a story and discussions about the subject, the reader is referred to the recent reviews [Fournais and Helffer 2010; Helffer and Kordyukov 2014; Raymond 2016].

In contrast to the wealth of studies exploring the semiclassical approximations of the Schrödinger operator  $-\hbar^2\Delta + V$ , the *classical* picture associated with the Hamiltonian  $\|p - A(q)\|^2$  has almost never been investigated to describe the *semiclassical* bound states (i.e., the eigenfunctions of low energy) of the magnetic Laplacian. The paper [Raymond and Vŭ Ngọc 2015] is to our knowledge the first rigorous work in this direction. In that paper, which deals with the two-dimensional case, the notion of magnetic drift, well known to physicists, is cast in a symplectic framework, and using a semiclassical Birkhoff normal form (see, for instance, [Vŭ Ngọc 2006; 2009; Charles and Vŭ Ngọc 2008]) it becomes possible to describe all the eigenvalues of order  $\mathcal{O}(\hbar)$ . Independently, the asymptotic expansion of a smaller set of eigenvalues was established in [Helffer and Kordyukov 2011; 2015] through different methods which act directly on the quantum side: explicit unitary transforms and a Grushin-like reduction are used to reduce the two-dimensional operator to an effective one-dimensional operator.

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The three-dimensional case happens to be much harder. The only known results in this case that provide a full asymptotic expansion of a given eigenvalue concern toy models where the confinement is obtained by a boundary carrying a Neumann condition on a half-space [Raymond 2012] or on a wedge in [Popoff and Raymond 2013]. In the case of smooth confinement without boundary, a construction of quasimodes by Helffer and Kordyukov [2013] suggests what the expansions of the low-lying eigenvalues could be. But, as was expected by Colin de Verdière [1996] in his list of open questions, extending the symplectic and microlocal techniques to the three-dimensional case contains an intrinsic difficulty in the fact that the symplectic form cannot be nondegenerate on the characteristic hypersurface. The goal of our paper is to answer this question by fully carrying out this strategy. After averaging the cyclotron motion, the effect of the degeneracy of the symplectic form can be observed on the fact that the reduced operator is only partially elliptic. Hence, the key ingredient will be a separation of scales via the introduction of a new semiclassical parameter for only one part of the variables. These semiclassical scales are reminiscent of the three scales that have been exhibited in the classical picture in the large field limit; see [Benettin and Sempio 1994; Cheverry 2015]. They are also related to the Born–Oppenheimer-type of approximation in quantum mechanics (see, for instance, [Born and Oppenheimer 1927; Martinez 2007]). In fact, in a partially semiclassical context and under generic assumptions, a full asymptotic expansion of the first magnetic eigenvalues (and the corresponding WKB expansions) has been recently established in any dimension in the paper by Bonnaillie-Noël, Hérau and Raymond [Bonnaillie-Noël et al. 2016].

**1B. Magnetic geometry.** Let us now describe the geometry of the problem. The configuration space is

$$\mathbb{R}^3 = \{q_1 e_1 + q_2 e_2 + q_3 e_3 \mid q_j \in \mathbb{R}, j = 1, 2, 3\},$$

where  $(e_j)_{j=1,2,3}$  is the canonical basis of  $\mathbb{R}^3$ . The phase space is

$$\mathbb{R}^6 = \{(q, p) \in \mathbb{R}^3 \times \mathbb{R}^3\}$$

and we endow it with the canonical 2-form

$$\omega_0 = dp_1 \wedge dq_1 + dp_2 \wedge dq_2 + dp_3 \wedge dq_3. \quad (1-1)$$

We will use the standard Euclidean scalar product  $\langle \cdot, \cdot \rangle$  on  $\mathbb{R}^3$  and  $\|\cdot\|$ , the associated norm. In particular, we can rewrite  $\omega_0$  as

$$\omega_0((u_1, u_2), (v_1, v_2)) = \langle v_1, u_2 \rangle - \langle v_2, u_1 \rangle \quad \forall u_1, u_2, v_1, v_2 \in \mathbb{R}^3.$$

The main object of this paper is the magnetic Hamiltonian, defined for all  $(q, p) \in \mathbb{R}^6$  by

$$H(q, p) = \|p - A(q)\|^2, \quad (1-2)$$

where  $A \in \mathcal{C}^\infty(\mathbb{R}^3, \mathbb{R}^3)$ .

Let us now introduce the magnetic field. The vector field  $A = (A_1, A_2, A_3)$  is associated (via the Euclidean structure) with the 1-form

$$\alpha = A_1 dq_1 + A_2 dq_2 + A_3 dq_3$$

and its exterior derivative is a 2-form, called the magnetic 2-form and expressed as

$$d\alpha = (\partial_1 A_2 - \partial_2 A_1)dq_1 \wedge dq_2 + (\partial_1 A_3 - \partial_3 A_1)dq_1 \wedge dq_3 + (\partial_2 A_3 - \partial_3 A_2)dq_2 \wedge dq_3.$$

The form  $d\alpha$  may be identified with a vector field. If we let

$$\mathbf{B} = \nabla \times \mathbf{A} = (\partial_2 A_3 - \partial_3 A_2, \partial_3 A_1 - \partial_1 A_3, \partial_1 A_2 - \partial_2 A_1) = (B_1, B_2, B_3),$$

then we can write

$$d\alpha = B_3 dq_1 \wedge dq_2 - B_2 dq_1 \wedge dq_3 + B_1 dq_2 \wedge dq_3. \quad (1-3)$$

The vector field  $\mathbf{B}$  is called the magnetic field. Notice that we can express the 2-form  $d\alpha$  thanks to the magnetic matrix

$$M_{\mathbf{B}} = \begin{pmatrix} 0 & B_3 & -B_2 \\ -B_3 & 0 & B_1 \\ B_2 & -B_1 & 0 \end{pmatrix}.$$

Indeed we have

$$d\alpha(U, V) = \langle U, M_{\mathbf{B}} V \rangle = \langle U, V \times \mathbf{B} \rangle = [U, V, \mathbf{B}] \quad \forall (U, V) \in \mathbb{R}^3 \times \mathbb{R}^3, \quad (1-4)$$

where  $[\cdot, \cdot, \cdot]$  is the canonical mixed product on  $\mathbb{R}^3$ . We note that  $\mathbf{B}$  belongs to the kernels of  $M_{\mathbf{B}}$  and  $d\alpha$ .

An important role will be played by the characteristic hypersurface

$$\Sigma = H^{-1}(0),$$

which is the submanifold defined by the parametrization

$$\mathbb{R}^3 \ni q \mapsto j(q) := (q, \mathbf{A}(q)) \in \mathbb{R}^3 \times \mathbb{R}^3.$$

We may notice the relation between  $\Sigma$ , the symplectic structure and the magnetic field given by

$$j^* \omega_0 = d\alpha, \quad (1-5)$$

where  $d\alpha$  is defined in (1-3).

**1C. Confinement assumptions and discrete spectrum.** This paper is devoted to the semiclassical analysis of the discrete spectrum of the magnetic Laplacian  $\mathcal{L}_{\hbar, \mathbf{A}} := (-i\hbar \nabla_q - \mathbf{A}(q))^2$ , which is the semiclassical Weyl quantization of  $H$  (see (2-1)). This means that we will consider that  $\hbar$  belongs to  $(0, \hbar_0)$  with  $\hbar_0$  small enough.

If  $\mathcal{L}$  is a self-adjoint operator, we denote its spectrum by  $\mathfrak{s}(\mathcal{L})$ . The discrete spectrum of  $\mathcal{L}$  consists of the isolated eigenvalues with finite multiplicity. The essential spectrum is by definition the complement in  $\mathfrak{s}(\mathcal{L})$  of the discrete spectrum and is denoted by  $\mathfrak{s}_{\text{ess}}(\mathcal{L})$ . It is empty when  $\mathcal{L}$  has compact resolvent.

It is known (see, for example, [Avron et al. 1978]) that  $\mathcal{L}_{\hbar, \mathbf{A}}$  is essentially self-adjoint and we always consider with the same notation its self-adjoint extension.

Let us recall the assumptions under which the discrete spectrum actually exists. In two dimensions, with a nonvanishing magnetic field, a standard estimate (see [Avron et al. 1978; Cycon et al. 1987]) gives

$$\hbar \int_{\mathbb{R}^2} |B(q)| |u(q)|^2 dq \leq \langle \mathcal{L}_{\hbar, \mathbf{A}} u \mid u \rangle \quad \forall u \in C_0^\infty(\mathbb{R}^2). \tag{1-6}$$

This implies that, as  $B(q) \rightarrow +\infty$ , the magnetic Laplacian has compact resolvent. Except in special cases when some components of the magnetic field have constant sign, this doesn't hold anymore in higher dimensions (see [Dufresnoy 1983]). One can give examples where  $|B(q)| \rightarrow +\infty$  and the operator doesn't have a compact resolvent. We should impose a control of the oscillations of  $\mathbf{B}$  at infinity. Under this condition, we get an estimate similar to (1-6) at the price of a small loss. When there exists a constant  $C > 0$  such that

$$\|\nabla \mathbf{B}(q)\| \leq C(1 + b(q)) \quad \forall q \in \mathbb{R}^3, \tag{1-7}$$

and  $b(q) := \|\mathbf{B}(q)\|$  tends to  $+\infty$ , one can show again that the magnetic Laplacian has compact resolvent [Helffer and Mohamed 1996].

In the semiclassical context, we would like to consider the case of  $\mathbb{R}^3$  and, in addition to (1-7), a confining assumption which allows the presence of the essential spectrum above a certain threshold. More precisely:

**Assumption 1.1.** We assume that (1-7) holds and

$$b(q) \geq b_0 := \inf_{q \in \mathbb{R}^3} b(q) > 0. \tag{1-8}$$

Under Assumption 1.1, it is proven in [Helffer and Mohamed 1996, Theorem 3.1] that there exist  $h_0 > 0$  and  $C_0 > 0$  such that, for all  $\hbar \in (0, h_0)$ ,

$$\hbar(1 - C_0 \hbar^{\frac{1}{4}}) \int_{\mathbb{R}^3} b(q) |u(q)|^2 dq \leq \langle \mathcal{L}_{\hbar, \mathbf{A}} u \mid u \rangle \quad \forall u \in C_0^\infty(\mathbb{R}^3). \tag{1-9}$$

In this case, if we do not assume that  $b(q) \rightarrow +\infty$ , the spectrum is not necessarily discrete, but using this inequality and Persson's theorem [1960], we obtain that the bottom of the essential spectrum is asymptotically above  $\hbar b_1$ , where

$$b_1 := \liminf_{|q| \rightarrow +\infty} b(q).$$

More precisely, under Assumption 1.1, there exist  $h_0 > 0$  and  $C_0 > 0$  such that, for all  $\hbar \in (0, h_0)$ ,

$$\mathfrak{s}_{\text{ess}}(\mathcal{L}_{\hbar, \mathbf{A}}) \subset [\hbar b_1(1 - C_0 \hbar^{\frac{1}{4}}), +\infty). \tag{1-10}$$

**Assumption 1.2.** We assume that

$$0 < b_0 < b_1. \tag{1-11}$$

Moreover, we will assume that there exists a point  $q_0 \in \mathbb{R}^3$  and  $\varepsilon > 0$ ,  $\tilde{\beta}_0 \in (b_0, b_1)$  such that

$$\{b(q) \leq \tilde{\beta}_0\} \subset D(q_0, \varepsilon), \tag{1-12}$$

where  $D(q_0, \varepsilon)$  is the Euclidean ball centered at  $q_0$  and of radius  $\varepsilon$ . For the rest of the article we let  $\beta_0 \in (b_0, \tilde{\beta}_0)$ . Without loss of generality, we can assume that  $q_0 = 0$  and that  $A(0) = 0$  (which can be obtained with a change of gauge).

Note that Assumption 1.2 implies that the minimal value of  $b$  is attained inside  $D(q_0, \varepsilon)$ .

Throughout this paper, we will strengthen the assumptions on the nature of the point  $q_0$ . At some stage of our investigation,  $q_0$  will be the unique minimum of  $b$ . Note in particular that (1-12) is satisfied as soon as  $b$  admits a unique and nondegenerate minimum.

**1D. Informal description of the results.** Let us now informally walk through the main results of this paper. We will assume (as precisely formulated in (1-11)–(1-12)) that the magnetic field does not vanish and is confining.

Of course, for eigenvalues of order  $\mathcal{O}(\hbar)$ , the corresponding eigenfunctions are microlocalized in the semiclassical sense near the characteristic manifold  $\Sigma$  (see, for instance, [Robert 1987; Zworski 2012]). Moreover, the confinement assumption implies that the eigenfunctions of  $\mathcal{L}_{\hbar, A}$  associated with eigenvalues less than  $\beta_0 \hbar$  enjoy localization estimates à la Agmon. Therefore we will be reduced to investigating the magnetic geometry locally in space near a point  $q_0 = 0 \in \mathbb{R}^3$  belonging to the confinement region and which, for notational simplicity, we may assume to be the origin.

Then, in a neighborhood of  $(0, A(0)) \in \Sigma$ , there exist symplectic coordinates  $(x_1, \xi_1, x_2, \xi_2, x_3, \xi_3)$  such that  $\Sigma = \{x_1 = \xi_1 = \xi_3 = 0\}$  and  $(0, A(0))$  has coordinates  $0 \in \mathbb{R}^6$ . Hence  $\Sigma$  is parametrized by  $(x_2, \xi_2, x_3)$ .

**1D1. First Birkhoff form.** In these coordinates suited for the magnetic geometry, it is possible to perform a semiclassical Birkhoff normal form and microlocally unitarily conjugate  $\mathcal{L}_{\hbar, A}$  to a first normal form  $\mathcal{N}_{\hbar} = \text{Op}_{\hbar}^w(N_{\hbar})$  with an operator-valued symbol  $N_{\hbar}$  depending on  $(x_2, \xi_2, x_3, \xi_3)$  in the form

$$N_{\hbar} = \xi_3^2 + b(x_2, \xi_2, x_3)\mathcal{I}_{\hbar} + f^*(\hbar, \mathcal{I}_{\hbar}, x_2, \xi_2, x_3, \xi_3) + \mathcal{O}(|\mathcal{I}_{\hbar}|^{\infty}, |\xi_3|^{\infty}),$$

where  $\mathcal{I}_{\hbar} = \hbar^2 D_{x_1}^2 + x_1^2$  is the first encountered harmonic oscillator and where  $(\hbar, I, x_2, \xi_2, x_3, \xi_3) \mapsto f^*(\hbar, I, x_2, \xi_2, x_3, \xi_3)$  satisfies, for  $I \in (0, I_0)$ ,

$$|f^*(\hbar, I, x_2, \xi_2, x_3, \xi_3)| \leq C(|I|^{\frac{3}{2}} + |\xi_3|^3 + \hbar^{\frac{3}{2}}).$$

Since we wish to describe the spectrum in a spectral window containing at least the lowest eigenvalues, we are led to replace  $\mathcal{I}_{\hbar}$  by its lowest eigenvalue  $\hbar$  and thus, we are reduced to the two-dimensional pseudodifferential operator  $\mathcal{N}_{\hbar}^{[1]} = \text{Op}_{\hbar}^w(N_{\hbar}^{[1]})$ , where

$$N_{\hbar}^{[1]} = \xi_3^2 + b(x_2, \xi_2, x_3)\hbar + f^*(\hbar, \hbar, x_2, \xi_2, x_3, \xi_3) + \mathcal{O}(\hbar^{\infty}, |\xi_3|^{\infty}).$$

**1D2. Second Birkhoff form.** If we want to continue the normalization, we shall assume a new nondegeneracy condition (the first one was the positivity of  $b$ ).

Now we assume that, for any  $(x_2, \xi_2)$  in a neighborhood of  $(0, 0)$ , the function  $x_3 \mapsto b(x_2, \xi_2, x_3)$  admits a unique and nondegenerate minimum denoted by  $s(x_2, \xi_2)$ . Then, by using a new symplectic

transformation in order to center the analysis at the partial minimum  $s(x_2, \xi_2)$ , we get a new operator  $\underline{N}_\hbar^{[1]}$  whose Weyl symbol is in the form

$$\underline{N}_\hbar^{[1]} = v^2(x_2, \xi_2)(\xi_3^2 + \hbar x_3^2) + \hbar b(x_2, \xi_2, s(x_2, \xi_2)) + \text{remainders},$$

with

$$v(x_2, \xi_2) = \left(\frac{1}{2} \partial_3^2 b(x_2, \xi_2, s(x_2, \xi_2))\right)^{\frac{1}{4}} \tag{1-13}$$

and where the remainders have been properly normalized to be at least formal perturbations of the second harmonic oscillator  $\xi_3^2 + \hbar x_3^2$ . Since the frequency of this oscillator is  $\hbar^{-\frac{1}{2}}$  in the classical picture, we are naturally led to introduce the new semiclassical parameter

$$h = \hbar^{\frac{1}{2}}$$

and the new impulsion

$$\xi = \hbar^{\frac{1}{2}} \tilde{\xi}$$

so that

$$\text{Op}_\hbar^w(\xi_3^2 + \hbar x_3^2) = h^2 \text{Op}_h^w(\tilde{\xi}_3^2 + x_3^2).$$

We therefore get the  $h$ -symbol of  $\underline{N}_\hbar^{[1]}$ ,

$$\underline{N}_h^{[1]} = h^2 v^2(x_2, h\tilde{\xi}_2)(\tilde{\xi}_3^2 + x_3^2) + h^2 b(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + \text{remainders}.$$

We can again perform a Birkhoff analysis in the space of formal series given by  $\mathcal{E} = \mathcal{F}[[x_3, \tilde{\xi}_3, h]]$ , where  $\mathcal{F}$  is a space of symbols in the form  $c(h, x_2, h\tilde{\xi}_2)$ . We get the new operator  $\mathfrak{M}_h = \text{Op}_h^w(M_h)$ , with

$$M_h = h^2 b(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + h^2 \mathcal{J}_h \text{Op}_h^w v^2(x_2, h\tilde{\xi}_2) + h^2 g^*(h, \mathcal{J}_h, x_2, h\tilde{\xi}_2) + \text{remainders},$$

where  $\mathcal{J}_h = \text{Op}_h^w(\tilde{\xi}_3^2 + x_3^2)$  and  $g^*(h, J, x_2, \xi_2)$  is of order three with respect to  $(J^{\frac{1}{2}}, h^{\frac{1}{2}})$ . Motivated again by the perspective of describing the low-lying eigenvalues, we replace  $\mathcal{J}_h$  by  $h$  and rewrite the symbol with the old semiclassical parameter  $\hbar$  to get the operator  $\mathcal{M}_\hbar^{[1]} = \text{Op}_\hbar^w(M_\hbar^{[1]}) = \text{Op}_\hbar^w(M_\hbar^{[1]})$ , with

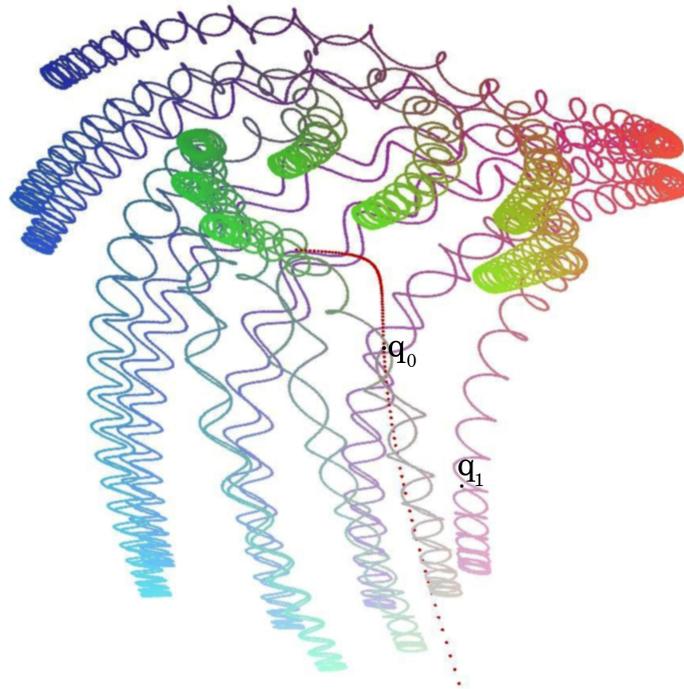
$$M_\hbar^{[1]} = \hbar b(x_2, \xi_2, s(x_2, \xi_2)) + \hbar^{\frac{3}{2}} v^2(x_2, \xi_2) + \hbar g^*(\hbar^{\frac{1}{2}}, \hbar^{\frac{1}{2}}, x_2, \xi_2) + \text{remainders}. \tag{1-14}$$

**1D3. Third Birkhoff form.** The last generic assumption is the uniqueness and nondegeneracy of the minimum of the new ‘‘principal’’ symbol

$$(x_2, \xi_2) \mapsto b(x_2, \xi_2, s(x_2, \xi_2))$$

that implies that  $b$  admits a unique and nondegenerate minimum at  $(0, 0, 0)$ . Up to an  $\hbar^{\frac{1}{2}}$ -dependent translation in the phase space and a rotation, we are essentially reduced to a standard Birkhoff normal form with respect to the third harmonic oscillator  $\mathcal{K}_\hbar = \hbar^2 D_{x_2}^2 + x_2^2$ .

Note that all our normal forms may be used to describe the classical dynamics of a charged particle in a confining magnetic field (see Figure 1).



**Figure 1.** The dashed line represents the integral curve of the confining magnetic field  $\mathbf{B} = \text{curl}\mathbf{A}$  through  $q_0 = (0.5, 0.6, 0.7)$  for  $\mathbf{B}(x, y, z) = (\frac{1}{2}y, \frac{1}{2}z, \sqrt{1+x^2})$  and the full line represents the projection in the  $q$ -space of the Hamiltonian trajectory with initial condition  $(q_0, p_0)$  (with  $p_0 = (-0.6, 0.01, 0.2)$ ) ending at  $(q_1, p_1)$ . The motion is easier to follow on a video: see <http://tinyurl.com/3DMagneticFlow>.

**1D4. Microlocalization.** Of course, at each step, we will have to provide accurate microlocal estimates of the eigenfunctions of the different operators to get a good control of the different remainders. In a first approximation, we will get localizations at the scales  $x_1, \xi_1, \xi_3 \sim \hbar^\delta$  ( $\delta > 0$  is small enough) and  $x_2, \xi_2, x_3 \sim 1$ . In a second approximation, we will get  $x_3, \xi_3 \sim \hbar^\delta$ . In the final step, we will refine the localization by  $x_2, \xi_2 \sim \hbar^\delta$ .

**1E. A semiclassical eigenvalue estimate.** Let us already state one of the consequences of our investigation. It will follow from the third normal form that we have a complete description of the spectrum below the threshold  $b_0\hbar + 3v^2(0, 0)\hbar^{\frac{3}{2}}$ . This description is reminiscent of the results à la Bohr–Sommerfeld of [Helffer and Robert 1984; Helffer and Sjöstrand 1989, Appendix B] (see also [Helffer and Kordyukov 2015, Remark 1.4]) obtained in the case of one-dimensional semiclassical operators.

**Theorem 1.3.** Assume that  $b$  admits a unique and nondegenerate minimum at  $q_0$ . Define

$$\sigma = \frac{\text{Hess}_{q_0} b(\mathbf{B}(q_0), \mathbf{B}(q_0))}{2b_0^2}, \quad \theta = \sqrt{\frac{\det \text{Hess}_{q_0} b}{\text{Hess}_{q_0} b(\mathbf{B}(q_0), \mathbf{B}(q_0))}}. \tag{1-15}$$

There exists a function  $k^* \in C_0^\infty(\mathbb{R}^2)$  with arbitrarily small compact support, and

$$k^*(\hbar^{\frac{1}{2}}, Z) = \mathcal{O}((\hbar + |Z|)^{\frac{3}{2}})$$

when  $(\hbar, Z) \rightarrow (0, 0)$ , such that the following holds:

For all  $c \in (0, 3)$ , the spectrum of  $\mathcal{L}_{\hbar, A}$  below  $b_0\hbar + c\sigma^{\frac{1}{2}}\hbar^{\frac{3}{2}}$  coincides modulo  $\mathcal{O}(\hbar^\infty)$  with the spectrum of the operator  $\mathcal{F}_\hbar$  acting on  $L^2(\mathbb{R}_x)$  given by

$$\mathcal{F}_\hbar = b_0\hbar + \sigma^{\frac{1}{2}}\hbar^{\frac{3}{2}} - \frac{\zeta}{2\theta}\hbar^2 + \hbar\left(\frac{1}{2}\theta\mathcal{K}_\hbar + k^*(\hbar^{\frac{1}{2}}, \mathcal{K}_\hbar)\right), \quad \mathcal{K}_\hbar = \hbar^2 D_x^2 + x^2,$$

with some constant  $\zeta$ .

**Remark 1.4.** The constant  $\zeta$  in Theorem 1.3 is given by the formula

$$\zeta = \|\nabla v^2(0, 0)\|^2,$$

where the function  $v$  is given in (1-13). Observe also that  $\sigma = v^4(0, 0)$ .

**Corollary 1.5.** Under the hypothesis of Theorem 1.3, let  $(\lambda_m(\hbar))_{m \geq 1}$  be the nondecreasing sequence of the eigenvalues of  $\mathcal{L}_{\hbar, A}$ . For any  $c \in (0, 3)$ , let

$$N_{\hbar, c} := \{m \in \mathbb{N}^* \mid \lambda_m(\hbar) \leq \hbar b_0 + c\sigma^{\frac{1}{2}}\hbar^{\frac{3}{2}}\}.$$

Then the cardinal of  $N_{\hbar, c}$  is of order  $\hbar^{-\frac{1}{2}}$ , and there exist  $v_1, v_2 \in \mathbb{R}$  and  $\hbar_0 > 0$  such that

$$\lambda_m(\hbar) = \hbar b_0 + \sigma^{\frac{1}{2}}\hbar^{\frac{3}{2}} + \left[\theta\left(m - \frac{1}{2}\right) - \frac{\zeta}{2\theta}\right]\hbar^2 + v_1\left(m - \frac{1}{2}\right)\hbar^{\frac{5}{2}} + v_2\left(m - \frac{1}{2}\right)^2\hbar^3 + \mathcal{O}(\hbar^{\frac{5}{2}})$$

uniformly for  $\hbar \in (0, \hbar_0)$  and  $m \in N_{\hbar, c}$ .

In particular, the splitting between two consecutive eigenvalues satisfies

$$\lambda_{m+1}(\hbar) - \lambda_m(\hbar) = \theta\hbar^2 + \mathcal{O}(\hbar^{\frac{5}{2}}).$$

*Proof.* If the support of  $k^*$  is small enough, the hypothesis  $k^*(\hbar^{\frac{1}{2}}, Z) = \mathcal{O}((\hbar + |Z|)^{\frac{3}{2}})$  implies that, when  $\hbar$  is small enough,

$$(1 + \eta)\mathcal{K}_\hbar \geq \mathcal{K}_\hbar + \frac{2}{\theta}k^*(\hbar^{\frac{1}{2}}, \mathcal{K}_\hbar) \geq (1 - \eta)\mathcal{K}_\hbar$$

for some small  $\eta > 0$ . Therefore, since the eigenvalues of  $\mathcal{K}_\hbar$  are  $(2m - 1)\hbar$ ,  $m \in \mathbb{N}^*$ , the variational principle implies that the number of eigenvalues of  $\mathcal{K}_\hbar + (2/\theta)k^*(\hbar^{\frac{1}{2}}, \mathcal{K}_\hbar)$  below a threshold  $C_\hbar$  belongs to

$$\left[\frac{1}{2}\left(\frac{C_\hbar}{\hbar(1 + \eta)} + 1\right), \frac{1}{2}\left(\frac{C_\hbar}{\hbar(1 - \eta)} + 1\right)\right].$$

Taking  $C_\hbar = (2/\theta)(c - 1)\sigma^{\frac{1}{2}}\hbar^{\frac{1}{2}} + (\zeta/\theta^2)\hbar$ , and applying the theorem, we obtain the estimate for the cardinal of  $N_{\hbar, c}$ . The corresponding eigenvalues of  $\mathcal{L}_{\hbar, A}$  are of the form

$$\lambda_m(\hbar) = \hbar b_0 + \sigma^{\frac{1}{2}}\hbar^{\frac{3}{2}} - \frac{\zeta}{2\theta}\hbar^2 + \hbar\left[\theta\left(m - \frac{1}{2}\right)\hbar + k^*(\hbar^{\frac{1}{2}}, 2m - 1)\right] + \mathcal{O}(\hbar^\infty),$$

with  $(2m - 1)\hbar \leq C_{\hbar}/(1 - \eta)$ . Therefore there exists a constant  $\tilde{C} > 0$ , independent of  $\hbar$ , such that all  $m \in \mathbb{N}_{\hbar,c}$  satisfy the inequality  $(2m - 1)\hbar \leq \tilde{C}\hbar^{\frac{1}{2}}$ . Writing

$$k^*(\hbar^{\frac{1}{2}}, Z) = c_0\hbar^{\frac{3}{2}} + v_1\hbar^{\frac{1}{2}}\left(\frac{1}{2}Z\right) + c_1\hbar^2 + v_2\left(\frac{1}{2}Z\right)^2 + v_3\hbar Z + \hbar^{\frac{1}{2}}\mathcal{O}(h + |Z|)^2 + \mathcal{O}(Z^3),$$

we see that, for  $m \in \mathbb{N}_{\hbar,c}$ ,

$$k^*(\hbar^{\frac{1}{2}}, (2m - 1)\hbar) = v_1\hbar^{\frac{3}{2}}\left(m - \frac{1}{2}\right) + v_2\hbar^2\left(m - \frac{1}{2}\right)^2 + \mathcal{O}(\hbar^{\frac{3}{2}}),$$

which gives the result. □

**Remark 1.6.** An upper bound of  $\lambda_m(\hbar)$  for fixed  $\hbar$ -independent  $m$  with remainder in  $\mathcal{O}(\hbar^{\frac{9}{4}})$  was obtained in [Helffer and Kordyukov 2013] through a quasimodes construction involving powers of  $\hbar^{\frac{1}{4}}$ . To the authors' knowledge, Corollary 1.5 gives the most accurate description of magnetic eigenvalues in three dimensions, in such a large spectral window. Note also that the nondegeneracy assumption on the norm of  $\mathbf{B}$  is not purely technical. Indeed, at the quantum level, it appears through microlocal reductions matching with the splitting of the Hamiltonian dynamics into three scales: the cyclotron motion around field lines, the center-guide oscillation along the field lines, and the oscillation within the space of field lines.

**1F. Organization of the paper.** The paper is organized as follows. In Section 2, we state our main results. Section 3 is devoted to the investigation of the first normal form (see Theorem 2.1 and Corollary 2.4). In Section 4 we analyze the second normal form (see Theorems 2.8 and 2.11 and Corollaries 2.9 and 2.13). Section 5 is devoted to the third normal form (see Theorem 2.15 and Corollary 2.16).

### 2. Statements of the main results

We recall (see [Dimassi and Sjöstrand 1999, Chapter 7]) that a function  $m : \mathbb{R}^d \rightarrow [0, \infty)$  is an order function if there exist constants  $N_0, C_0 > 0$  such that

$$m(X) \leq C_0 \langle X - Y \rangle^{N_0} m(Y)$$

for any  $X, Y \in \mathbb{R}^d$ . The symbol class  $S(m)$  is the space of smooth  $\hbar$ -dependent functions  $a_{\hbar} : \mathbb{R}^d \rightarrow \mathbb{C}$  such that, for all  $\alpha \in \mathbb{N}^d$ ,

$$|\partial_x^\alpha a_{\hbar}(x)| \leq C_\alpha m(x) \quad \forall \hbar \in (0, 1].$$

Throughout this paper, we assume that the components of the vector potential  $\mathbf{A}$  belong to a symbol class  $S(m)$ . Note that this implies that  $\mathbf{B} \in S(m)$ , and conversely, if  $\mathbf{B} \in S(m)$ , then there exist a potential  $A$  and another order function  $m'$  such that  $\mathbf{A} \in S(m')$ . Moreover, the magnetic Hamiltonian  $H(x, \xi) = \|\xi - \mathbf{A}(x)\|^2$  belongs to  $S(m'')$  for an order function  $m''$  on  $\mathbb{R}^6$ .

We will work with the Weyl quantization; for a classical symbol  $a_{\hbar} = a(x, \xi; \hbar) \in S(m)$ , it is defined as

$$\text{Op}_{\hbar}^w a \psi(x) = \frac{1}{(2\pi\hbar)^d} \int_{\mathbb{R}^{2d}} e^{i(x-y, \xi)/\hbar} a\left(\frac{x+y}{2}, \xi\right) \psi(y) dy d\xi \quad \forall \psi \in \mathcal{S}(\mathbb{R}^d). \quad (2-1)$$

The Weyl quantization of  $H$  is the magnetic Laplacian  $\mathcal{L}_{\hbar, \mathbf{A}} = (-i\hbar\nabla - \mathbf{A})^2$ .

**2A. Normal forms and spectral reductions.** Let us introduce our first Birkhoff normal form  $\mathcal{N}_\hbar$ .

**Theorem 2.1.** *If  $B(0) \neq 0$ , there exists a neighborhood of  $(0, A(0))$  endowed with symplectic coordinates  $(x_1, \xi_1, x_2, \xi_2, x_3, \xi_3)$  in which  $\Sigma = \{x_1 = \xi_1 = \xi_3 = 0\}$  and  $(0, A(0))$  has coordinates  $0 \in \mathbb{R}^6$ , and there exist an associated unitary Fourier integral operator  $U_\hbar$  and a smooth function  $f^*(\hbar, Z, x_2, \xi_2, x_3, \xi_3)$  compactly supported with respect to  $Z$  and  $\xi_3$ , whose Taylor series with respect to  $Z, \xi_3, \hbar$  is*

$$\sum_{k \geq 3} \sum_{2\ell + 2m + \beta = k} \hbar^\ell c_{\ell, m, \beta}^*(x_2, \xi_2, x_3) Z^m \xi_3^\beta,$$

such that

$$U_\hbar^* \mathcal{L}_{\hbar, A} U_\hbar = \mathcal{N}_\hbar + \mathcal{R}_\hbar, \tag{2-2}$$

with

$$\mathcal{N}_\hbar = \hbar^2 D_{x_3}^2 + \mathcal{I}_\hbar \text{Op}_\hbar^w b + \text{Op}_\hbar^w f^*(\hbar, \mathcal{I}_\hbar, x_2, \xi_2, x_3, \xi_3),$$

and where

- (a) we have  $\mathcal{I}_\hbar = \hbar^2 D_{x_1}^2 + x_1^2$ ,
- (b) the operator  $\text{Op}_\hbar^w f^*(\hbar, \mathcal{I}_\hbar, x_2, \xi_2, x_3, \xi_3)$  has to be understood as the Weyl quantization of an operator-valued symbol,
- (c) the remainder  $\mathcal{R}_\hbar$  is a pseudodifferential operator such that, in a neighborhood of the origin, the Taylor series of its symbol with respect to  $(x_1, \xi_1, \xi_3, \hbar)$  is 0.

**Remark 2.2.** In Theorem 2.1, the direction of  $B$  considered as a vector field on  $\Sigma$  is  $\partial/\partial x_3$  and the function  $b \in C^\infty(\mathbb{R}^6)$  stands for  $b \circ j_{|\Sigma}^{-1} \circ \pi$ , where  $\pi : \mathbb{R}^6 \rightarrow \Sigma : \pi(x_1, \xi_1, x_2, \xi_2, x_3, \xi_3) = (0, 0, x_2, \xi_2, x_3, 0)$ . In addition, note that the support of  $f^*$  in  $Z$  and  $\xi_3$  may be chosen as small as we want.

**Remark 2.3.** In the context of Weyl’s asymptotics, a close version of this theorem appears in [Ivrii 1998, Chapter 6].

In order to investigate the spectrum of  $\mathcal{L}_{\hbar, A}$  near the low-lying energies, we introduce the pseudodifferential operator

$$\mathcal{N}_\hbar^{[1]} = \hbar^2 D_{x_3}^2 + \hbar \text{Op}_\hbar^w b + \text{Op}_\hbar^w f^*(\hbar, \hbar, x_2, \xi_2, x_3, \xi_3),$$

obtained by replacing  $\mathcal{I}_\hbar$  by  $\hbar$ .

**Corollary 2.4.** *We introduce*

$$\mathcal{N}_\hbar^\# = \text{Op}_\hbar^w (N_\hbar^\#), \tag{2-3}$$

with

$$N_\hbar^\# = \xi_3^2 + \mathcal{I}_\hbar \underline{b}(x_2, \xi_2, x_3) + f^{*, \#}(\hbar, \mathcal{I}_\hbar, x_2, \xi_2, x_3, \xi_3),$$

and where  $\underline{b}$  is a smooth extension of  $b$  away from  $D(0, \varepsilon)$  such that (1-12) still holds and where  $f^{*, \#} = \chi(x_2, \xi_2, x_3) f^*$ , with  $\chi$  a smooth cutoff function that is 1 in a neighborhood of  $D(0, \varepsilon)$ . We also define the operator attached to the first eigenvalue of  $\mathcal{I}_\hbar$ ,

$$\mathcal{N}_\hbar^{[1], \#} = \text{Op}_\hbar^w (N_\hbar^{[1], \#}), \tag{2-4}$$

where  $N_\hbar^{[1], \#} = \xi_3^2 + \hbar \underline{b}(x_2, \xi_2, x_3) + f^{*, \#}(\hbar, \hbar, x_2, \xi_2, x_3, \xi_3)$ .

If  $\varepsilon$  and the support of  $f^*$  are small enough, then we have:

- (a) The spectra of  $\mathcal{L}_{\hbar, A}$  and  $\mathcal{N}_{\hbar}^{\sharp}$  below  $\beta_0 \hbar$  coincide modulo  $\mathcal{O}(\hbar^\infty)$ .
- (b) For all  $c \in (0, \min(3b_0, \beta_0))$ , the spectra of  $\mathcal{L}_{\hbar, A}$  and  $\mathcal{N}_{\hbar}^{[1], \sharp}$  below  $c \hbar$  coincide modulo  $\mathcal{O}(\hbar^\infty)$ .

Let us now state our results concerning the normal form of  $\mathcal{N}_{\hbar}^{[1]}$  (or  $\mathcal{N}_{\hbar}^{[1], \sharp}$ ) under the following assumption.

**Notation 2.5.** If  $f = f(\mathbf{z})$  is a differentiable function, we denote by  $T_{\mathbf{z}} f(\cdot)$  its tangent map at the point  $\mathbf{z}$ . Moreover, if  $f$  is twice differentiable, the second derivative of  $f$  is denoted by  $T_{\mathbf{z}}^2 f(\cdot, \cdot)$ .

**Assumption 2.6.** We assume that  $T_0^2 b(\mathbf{B}(0), \mathbf{B}(0)) > 0$ .

**Remark 2.7.** If the function  $b$  admits a unique and positive minimum at 0 and it is nondegenerate, then Assumption 2.6 is satisfied.

Under Assumption 2.6, we have  $\partial_3 b(0, 0, 0) = 0$  and, in the coordinates  $(x_2, \xi_2, x_3)$  given in Theorem 2.1,

$$\partial_3^2 b(0, 0, 0) > 0. \tag{2-5}$$

It follows from (2-5) and the implicit function theorem that, for small  $x_2$ , there exists a smooth function  $(x_2, \xi_2) \mapsto s(x_2, \xi_2)$ , with  $s(0, 0) = 0$ , such that

$$\partial_3 b(x_2, \xi_2, s(x_2, \xi_2)) = 0. \tag{2-6}$$

The point  $s(x_2, \xi_2)$  is the unique (in a neighborhood of  $(0, 0, 0)$ ) minimum of  $x_3 \mapsto b(x_2, \xi_2, x_3)$ . We define

$$v(x_2, \xi_2) := \left(\frac{1}{2} \partial_3^2 b(x_2, \xi_2, s(x_2, \xi_2))\right)^{\frac{1}{4}}.$$

**Theorem 2.8.** Under Assumption 2.6, there exist a neighborhood  $\mathcal{V}_0$  of 0 and a Fourier integral operator  $V_{\hbar}$  which is microlocally unitary near  $\mathcal{V}_0$  and such that

$$V_{\hbar}^* \mathcal{N}_{\hbar}^{[1]} V_{\hbar} =: \underline{\mathcal{N}}_{\hbar}^{[1]} = \text{Op}_{\hbar}^w(\underline{N}_{\hbar}^{[1]}),$$

where  $\underline{N}_{\hbar}^{[1]} = v^2(x_2, \xi_2)(\xi_3^2 + \hbar x_3^2) + \hbar b(x_2, \xi_2, s(x_2, \xi_2)) + \underline{r}_{\hbar}$  and  $\underline{r}_{\hbar}$  is a semiclassical symbol such that  $\underline{r}_{\hbar} = \mathcal{O}(\hbar x_3^3) + \mathcal{O}(\hbar \xi_3^3) + \mathcal{O}(\xi_3^3) + \mathcal{O}(\hbar^2)$ .

**Corollary 2.9.** Let us introduce

$$\underline{\mathcal{N}}_{\hbar}^{[1], \sharp} = \text{Op}_{\hbar}^w(\underline{N}_{\hbar}^{[1], \sharp}),$$

where  $\underline{N}_{\hbar}^{[1], \sharp} = \underline{v}^2(x_2, \xi_2)(\xi_3^2 + \hbar x_3^2) + \hbar \underline{b}(x_2, \xi_2, s(x_2, \xi_2)) + \underline{r}_{\hbar}^{\sharp}$ , with  $\underline{r}_{\hbar}^{\sharp} = \chi(x_2, \xi_2, x_3, \xi_3) \underline{r}_{\hbar}$ , and where  $\underline{v}$  denotes a smooth and constant (with a positive constant) extension of the function  $v$ .

There exists a constant  $\tilde{c} > 0$  such that, for any cut-off function  $\chi$  equal to 1 on  $D(0, \varepsilon)$  with support in  $D(0, 2\varepsilon)$ , we have:

- (a) The spectra of  $\underline{\mathcal{N}}_{\hbar}^{[1], \sharp}$  and  $\mathcal{N}_{\hbar}^{[1], \sharp}$  below  $(b_0 + \tilde{c}\varepsilon^2)\hbar$  coincide modulo  $\mathcal{O}(\hbar^\infty)$ .
- (b) For all  $c \in (0, \min(3b_0, b_0 + \tilde{c}\varepsilon^2))$ , the spectra of  $\mathcal{L}_{\hbar, A}$  and  $\underline{\mathcal{N}}_{\hbar}^{[1], \sharp}$  below  $c \hbar$  coincide modulo  $\mathcal{O}(\hbar^\infty)$ .

**Notation 2.10** (change of semiclassical parameter). We let  $h = \hbar^{\frac{1}{2}}$  and, if  $A_{\hbar}$  is a semiclassical symbol on  $T^*\mathbb{R}^2$ , admitting a semiclassical expansion in  $\hbar^{\frac{1}{2}}$ , we write

$$\mathcal{A}_{\hbar} := \text{Op}_{\hbar}^w A_{\hbar} = \text{Op}_h^w A_h =: \mathfrak{A}_h,$$

with

$$A_h(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3) = A_{h^2}(x_2, h\tilde{\xi}_2, x_3, h\tilde{\xi}_3).$$

Thus,  $\mathcal{A}_{\hbar}$  and  $\mathfrak{A}_h$  represent the same operator when  $h = \hbar^{\frac{1}{2}}$ , but the former is viewed as an  $\hbar$ -quantization of the symbol  $A_{\hbar}$ , while the latter is an  $h$ -pseudodifferential operator with symbol  $A_h$ . Notice that, if  $A_{\hbar}$  belongs to some class  $S(m)$ , then  $A_h \in S(m)$  as well. This is of course not true the other way around.

**Theorem 2.11.** *Under Assumption 2.6, there exists a unitary operator  $W_h$  as well as a smooth function  $g^*(h, Z, x_2, \xi_2)$ , with compact support as small as we want with respect to  $Z$  and with compact support in  $(x_2, \xi_2)$ , whose Taylor series with respect to  $Z, h$  is*

$$\sum_{2m+2\ell \geq 3} c_{m,\ell}(x_2, \xi_2) Z^m h^\ell,$$

such that

$$W_h^* \mathfrak{U}_h^{[1],\#} W_h =: \mathfrak{M}_h = \text{Op}_h^w (M_h),$$

with

$$M_h = h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + h^2 \mathcal{J}_h \text{Op}_h^w \underline{\nu}^2(x_2, h\tilde{\xi}_2) + h^2 g^*(h, \mathcal{J}_h, x_2, h\tilde{\xi}_2) + h^2 R_h + h^\infty S(1),$$

where

- (a) the operator  $\mathfrak{U}_h^{[1],\#}$  is  $\underline{\mathcal{N}}_h^{[1],\#}$  (but written in the  $h$ -quantization),
- (b) we have let  $\mathcal{J}_h = \text{Op}_h^w (\tilde{\xi}_3^2 + x_3^2)$ ,
- (c) the function  $R_h$  satisfies  $R_h(x_2, h\tilde{\xi}_2, x_3, \tilde{\xi}_3) = \mathcal{O}((x_3, \tilde{\xi}_3)^\infty)$ .

**Remark 2.12.** Note that the support of  $g^*$  with respect to  $Z$  may be chosen as small as we want. Note also that we have used  $\mathfrak{U}_h^{[1],\#}$  instead of  $\mathfrak{U}_h^{[1]}$ : since  $W_h$  is exactly unitary, we get a direct comparison of the spectra.

**Corollary 2.13.** *We introduce*

$$\mathfrak{M}_h^\# = \text{Op}_h^w (M_h^\#),$$

with

$$M_h^\# = h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + h^2 \mathcal{J}_h \underline{\nu}^2(x_2, h\tilde{\xi}_2) + h^2 g^*(h, \mathcal{J}_h, x_2, h\tilde{\xi}_2).$$

We also define

$$\mathfrak{M}_h^{[1],\#} = \text{Op}_h^w (M_h^{[1],\#}),$$

with

$$M_h^{[1],\#} = h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + h^3 \underline{\nu}^2(x_2, h\tilde{\xi}_2) + h^2 g^*(h, h, x_2, h\tilde{\xi}_2).$$

If  $\varepsilon$  and the support of  $g^*$  are small enough, we have:

- (a) For all  $\eta > 0$ , the spectra of  $\mathfrak{M}_h^{[1],\#}$  and  $\mathfrak{M}_h^\#$  below  $b_0h^2 + \mathcal{O}(h^{2+\eta})$  coincide modulo  $\mathcal{O}(h^\infty)$ .
- (b) For  $c \in (0, 3)$ , the spectra of  $\mathfrak{M}_h^\#$  and  $\mathfrak{M}_h^{[1],\#}$  below  $b_0h^2 + c\sigma^{\frac{1}{2}}h^3$  coincide modulo  $\mathcal{O}(h^\infty)$ .
- (c) If  $c \in (0, 3)$ , the spectra of  $\mathcal{L}_{\hbar,A}$  and  $\mathcal{M}_h^{[1],\#} = \mathfrak{M}_h^{[1],\#}$  below  $b_0\hbar + c\sigma^{\frac{1}{2}}\hbar^{\frac{3}{2}}$  coincide modulo  $\mathcal{O}(\hbar^\infty)$ .

Finally, we can perform a last Birkhoff normal form for the operator  $\mathcal{M}_h^{[1],\#}$  as soon as  $(x_2, \xi_2) \mapsto \underline{b}(x_2, \xi_2, s(x_2, \xi_2))$  admits a unique and nondegenerate minimum at  $(0, 0)$ . Under this additional assumption,  $b$  admits a unique and nondegenerate minimum at  $(0, 0, 0)$ .

Therefore we will use the following stronger assumption.

**Assumption 2.14.** The function  $b$  admits a unique and positive minimum at 0 and it is nondegenerate.

**Theorem 2.15.** Under Assumption 2.14, there exists a unitary  $\hbar$ -Fourier integral operator  $Q_{\hbar^{1/2}}$  whose phase admits an expansion in powers of  $\hbar^{\frac{1}{2}}$  such that

$$Q_{\hbar^{1/2}}^* \mathcal{M}_h^{[1],\#} Q_{\hbar^{1/2}} = \mathcal{F}_\hbar + \mathcal{G}_\hbar,$$

where

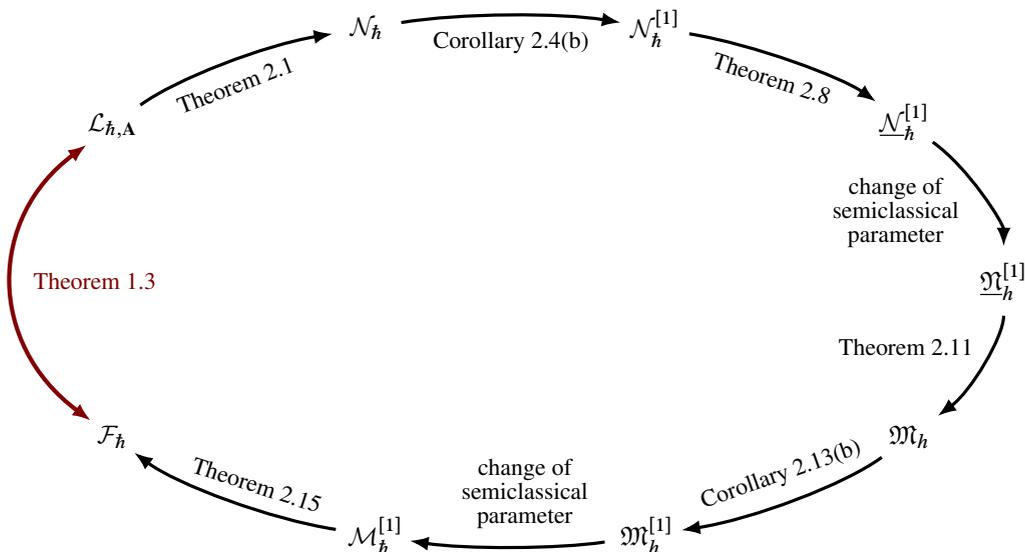
- (a)  $\mathcal{F}_\hbar$  is defined in Theorem 1.3,
- (b) the remainder is in the form  $\mathcal{G}_\hbar = \text{Op}_\hbar^w(G_\hbar)$ , with  $G_\hbar = \hbar\mathcal{O}(|z_2|^\infty)$ .

**Corollary 2.16.** If  $\varepsilon$  and the support of  $k^*$  are small enough, we have:

- (a) For all  $\eta \in (0, \frac{1}{2})$ , the spectra of  $\mathcal{M}_h^{[1],\#}$  and  $\mathcal{F}_\hbar$  below  $b_0\hbar + \mathcal{O}(\hbar^{1+\eta})$  coincide modulo  $\mathcal{O}(\hbar^\infty)$ .
- (b) For all  $c \in (0, 3)$ , the spectra of  $\mathcal{L}_{\hbar,A}$  and  $\mathcal{F}_\hbar$  below  $b_0\hbar + c\sigma^{\frac{1}{2}}\hbar^{\frac{3}{2}}$  coincide modulo  $\mathcal{O}(\hbar^\infty)$ .

**Remark 2.17.** Since the spectral analysis of  $\mathcal{F}_\hbar$  is straightforward, Corollary 2.16(b) implies Theorem 1.3.

The next sections are devoted to the proofs of our main results.



### 3. First Birkhoff normal form

We assume that  $\mathbf{B}(0) \neq 0$  so that in some neighborhood  $\Omega$  of 0 the magnetic field does not vanish. Up to a rotation in  $\mathbb{R}^3$  (extended to a symplectic transformation in  $\mathbb{R}^6$ ) we may assume that  $\mathbf{B}(0) = \|\mathbf{B}(0)\|e_3$ . In this neighborhood, we may define the unit vector

$$\mathbf{b} = \frac{\mathbf{B}}{\|\mathbf{B}\|} \quad (3-1)$$

and find vectors  $\mathbf{c}$  and  $\mathbf{d}$  depending smoothly on  $q$  such that  $(\mathbf{b}, \mathbf{c}, \mathbf{d})$  is a direct orthonormal basis.

#### 3A. Symplectic coordinates.

**3A1. Straightening the magnetic vector field.** Let  $\widehat{\Omega}$  be a small neighborhood of  $0 \in \mathbb{R}^2$ . We consider the form  $d\alpha$  and we would like to find a diffeomorphism  $\chi$ , defined on  $\widehat{\Omega}$ , such that  $\chi^*(d\alpha) = d\hat{q}_1 \wedge d\hat{q}_2$ , where we use the notation  $\chi(\hat{q}) = q$ . First, it is easy to find a local diffeomorphism  $\varphi$  such that

$$\partial_3\varphi(\tilde{q}) = \mathbf{b}(\varphi(\tilde{q}))$$

and  $\varphi(\tilde{q}_1, \tilde{q}_2, 0) = (\tilde{q}_1, \tilde{q}_2, 0)$ . This is just the standard straightening lemma for the nonvanishing vector field  $\mathbf{b}$ .

The vector  $e_3$  is in the kernel of  $\varphi^*(d\alpha)$ , which implies that we have  $\varphi^*(d\alpha) = f(\tilde{q})d\tilde{q}_1 \wedge d\tilde{q}_2$  for some smooth function  $f$ .

But since the form  $\varphi^*(d\alpha)$  is closed,  $f$  does not depend on  $\tilde{q}_3$ . It is then easy to find another diffeomorphism  $\psi$ , corresponding to the change of variables

$$\hat{q} = \psi(\tilde{q}) = (\psi_1(\tilde{q}_1, \tilde{q}_2), \psi_2(\tilde{q}_1, \tilde{q}_2), \tilde{q}_3),$$

such that

$$\psi^*(\varphi^*(d\alpha)) = d\hat{q}_1 \wedge d\hat{q}_2.$$

We let  $\chi = \varphi \circ \psi$  and we notice that

$$\chi^*(d\alpha) = d\hat{q}_1 \wedge d\hat{q}_2, \quad \partial_3\chi(\hat{q}) = \mathbf{b}(\chi(\hat{q})). \quad (3-2)$$

**Remark 3.1.** It follows from (3-2) and (1-4) that  $\det T\chi = \|\mathbf{B}\|^{-1}$ .

**3A2. Symplectic coordinates.** Let us consider the new parametrization of  $\Sigma$  given by

$$\begin{aligned} \iota: \widehat{\Omega} &\rightarrow \Sigma, \\ \hat{q} &\mapsto (\chi(\hat{q}), A_1(\chi(\hat{q})), A_2(\chi(\hat{q})), A_3(\chi(\hat{q}))), \end{aligned}$$

which gives a basis  $(f_1, f_2, f_3)$  of  $T\Sigma$ ,

$$f_j = (T\chi(e_j), TA \circ T\chi(e_j)), \quad j = 1, 2, 3.$$

Using (1-5), and the fact that  $f_3$  is in the kernel of  $d\alpha$ , we find  $\omega_0(f_j, f_3) = 0$ ,  $j = 1, 2$ . Finally,  $\omega_0(f_1, f_2) = d\alpha(T\chi e_1, T\chi e_2) = \chi^*(d\alpha)(e_1, e_2) = 1$ .

The following vectors of  $\mathbb{R}^3 \times \mathbb{R}^3$  form a basis of the symplectic orthogonal of  $T_{\iota(\hat{q})}\Sigma$ :

$$\begin{aligned} \mathbf{f}_4 &= \|\mathbf{B}\|^{-\frac{1}{2}}(\mathbf{c}, ({}^tT_{\chi(\hat{q})}\mathbf{A})\mathbf{c}), \\ \mathbf{f}_5 &= \|\mathbf{B}\|^{-\frac{1}{2}}(\mathbf{d}, ({}^tT_{\chi(\hat{q})}\mathbf{A})\mathbf{d}), \end{aligned} \tag{3-3}$$

so that

$$\omega_0(\mathbf{f}_4, \mathbf{f}_5) = -1.$$

We let  $\mathbf{f}_6 = (0, \mathbf{b}) + \rho_1 \mathbf{f}_1 + \rho_2 \mathbf{f}_2$ , where  $\rho_1$  and  $\rho_2$  are determined so that  $\omega_0(\mathbf{f}_j, \mathbf{f}_6) = 0$  for  $j = 1, 2$ . We notice that  $\omega_0(\mathbf{f}_j, \mathbf{f}_6) = 0$  for  $j = 4, 5$  and  $\omega_0(\mathbf{f}_3, \mathbf{f}_6) = -1$ .

**3A3. Diagonalizing the Hessian.** We recall that

$$H(q, p) = \|p - \mathbf{A}(q)\|^2$$

so that, at a critical point  $p = \mathbf{A}(q)$ , the Hessian is

$$T^2H((U_1, V_1), (U_2, V_2)) = 2\langle V_1 - T_q\mathbf{A}(U_1), V_2 - T_q\mathbf{A}(U_2) \rangle.$$

Let us notice that

$$\begin{aligned} T^2H(\mathbf{f}_4, \mathbf{f}_5) &= 2\|\mathbf{B}\|^{-1}\langle \mathbf{B} \times \mathbf{c}, \mathbf{B} \times \mathbf{d} \rangle = 0, \\ T^2H(\mathbf{f}_4, \mathbf{f}_6) &= 2\langle \mathbf{B} \times \mathbf{c}, \mathbf{b} \rangle = 0, \\ T^2H(\mathbf{f}_5, \mathbf{f}_6) &= 2\langle \mathbf{B} \times \mathbf{d}, \mathbf{b} \rangle = 0. \end{aligned}$$

The Hessian, restricted to the symplectic orthogonal of  $T_{\iota(\hat{q})}\Sigma$ , is diagonal in the basis  $(\mathbf{f}_4, \mathbf{f}_5, \mathbf{f}_6)$ . Moreover we have

$$T^2H(\mathbf{f}_4, \mathbf{f}_4) = d^2H(\mathbf{f}_5, \mathbf{f}_5) = 2\|\mathbf{B}\|^{-1}\|\mathbf{B} \times \mathbf{c}\|^2 = 2\|\mathbf{B}\|^{-1}\|\mathbf{B} \times \mathbf{d}\|^2 = 2\|\mathbf{B}\|.$$

Finally we have

$$T^2H(\mathbf{f}_6, \mathbf{f}_6) = 2.$$

Now we consider the local diffeomorphism

$$(x, \xi) \mapsto \iota(x_2, \xi_2, x_3) + x_1 \mathbf{f}_4(x_2, \xi_2, x_3) + \xi_1 \mathbf{f}_5(x_2, \xi_2, x_3) + \xi_3 \mathbf{f}_6(x_2, \xi_2, x_3).$$

The Jacobian of this map is a symplectic matrix on  $\Sigma$ . We may apply the Moser–Weinstein argument (see [Weinstein 1971]) to make this map locally symplectic near  $\Sigma$  modulo a change of variable which is tangent to the identity.

Near  $\Sigma$ , in these new coordinates, the Hamiltonian  $H$  admits the expansion

$$\hat{H} = H^0 + \mathcal{O}(|x_1|^3 + |\xi_1|^3 + |\xi_3|^3), \tag{3-4}$$

where  $\hat{H}$  denotes  $H$  in the coordinates  $(x_1, x_2, x_3, \xi_1, \xi_2, \xi_3)$ , and with

$$H^0 = \xi_3^2 + b(x_2, \xi_2, x_3)(x_1^2 + \xi_1^2), \quad b = \|\mathbf{B}(x_2, \xi_2, x_3)\|. \tag{3-5}$$

**3B. Semiclassical Birkhoff normal form.**

**3B1. Birkhoff procedure in formal series.** Let us consider the space  $\mathcal{E}$  of formal power series in  $(x_1, \xi_1, \xi_3, \hbar)$  with coefficients smoothly depending on  $\tilde{x} = (x_2, \xi_2, x_3)$ :

$$\mathcal{E} = C_{x_2, \xi_2, x_3}^\infty[[x_1, \xi_1, \xi_3, \hbar]].$$

We endow  $\mathcal{E}$  with the semiclassical Moyal product (with respect to all variables  $(x_1, x_2, x_3, \xi_1, \xi_2, \xi_3)$ ) denoted by  $\star$  and the commutator of two series  $\kappa_1$  and  $\kappa_2$  is defined as

$$[\kappa_1, \kappa_2] = \kappa_1 \star \kappa_2 - \kappa_2 \star \kappa_1.$$

The degree of  $x_1^{\alpha_1} \xi_1^{\alpha_2} \xi_3^\beta \hbar^\ell = z_1^\alpha \xi_3^\beta \hbar^\ell$  is  $\alpha_1 + \alpha_2 + \beta + 2\ell = |\alpha| + \beta + 2\ell$ . The space of monomials of degree  $N$  is denoted  $\mathcal{D}_N$ , and  $\mathcal{O}_N$  is the space of formal series with valuation at least  $N$ . For any  $\tau, \gamma \in \mathcal{E}$ , we define  $\text{ad}_\tau \gamma = [\tau, \gamma]$ .

**Proposition 3.2.** *Given  $\gamma \in \mathcal{O}_3$ , there exist formal power series  $\tau, \kappa \in \mathcal{O}_3$  such that*

$$e^{i\hbar^{-1} \text{ad}_\tau} (H^0 + \gamma) = H^0 + \kappa,$$

with  $[\kappa, |z_1|^2] = 0$ .

*Proof.* Let  $N \geq 1$ . Assume that we have, for  $\tau_N \in \mathcal{O}_3$ ,

$$e^{i\hbar^{-1} \text{ad}_{\tau_N}} (H^0 + \gamma) = H^0 + K_3 + \dots + K_{N+1} + R_{N+2} + \mathcal{O}_{N+3},$$

with  $K_i \in \mathcal{D}_i$ ,  $[K_i, |z_1|^2] = 0$  and  $R_{N+2} \in \mathcal{D}_{N+2}$ .

Let  $\tau' \in \mathcal{D}_{N+2}$ . Then we have

$$e^{i\hbar^{-1} \text{ad}_{\tau_N + \tau'}} (H^0 + \gamma) = H^0 + K_3 + \dots + K_{N+1} + K_{N+2} + \mathcal{O}_{N+3},$$

with  $K_{N+2} \in \mathcal{D}_{N+2}$  such that

$$K_{N+2} = R_{N+2} + i\hbar^{-1} \text{ad}_{\tau'} H^0 + \mathcal{O}_{N+3}.$$

Let us temporarily admit that (see Lemma 3.3 below)

$$i\hbar^{-1} \text{ad}_{\tau'} H^0 = i\hbar^{-1} b \text{ad}_{\tau'} |z_1|^2 + \mathcal{O}_{N+3}.$$

We obtain

$$K_{N+2} = R_{N+2} + b \text{ad}_{\tau'} |z_1|^2,$$

which we rewrite as

$$R_{N+2} = K_{N+2} + i\hbar^{-1} b \text{ad}_{|z_1|^2} \tau' = K_{N+2} + b\{|z_1|^2, \tau'\}.$$

Since  $b(\tilde{x}) \neq 0$ , we deduce the existence of  $\tau'$  and  $K_{N+2}$  such that  $K_{N+2}$  commutes with  $|z_1|^2$ . □

**Lemma 3.3.** *For  $\tau' \in \mathcal{D}_{N+2}$ , we have*

$$i\hbar^{-1} \text{ad}_{\tau'} H^0 = i\hbar^{-1} b \text{ad}_{\tau'} |z_1|^2 + \mathcal{O}_{N+3}.$$

*Proof.* We observe that

$$i\hbar^{-1} \operatorname{ad}_{\tau'} H^0 = i\hbar^{-1} \operatorname{ad}_{\tau'} \xi_3^2 + i\hbar^{-1} \operatorname{ad}_{\tau'} (b(\tilde{x})|z_1|^2).$$

Let us write

$$\tau' = \sum_{|\alpha|+\beta+2l=N+2} a_{\alpha,\beta,l}(\tilde{x}) z_1^\alpha \xi_3^\beta \hbar^l.$$

Then, for the first term, we have

$$i\hbar^{-1} \operatorname{ad}_{\tau'} \xi_3^2 = \{\tau', \xi_3^2\} = -2\xi_3 \frac{\partial \tau'}{\partial x_3} = -2 \sum_{|\alpha|+\beta+2\ell=N+2} \frac{\partial a_{\alpha,\beta,\ell}}{\partial x_3}(\tilde{x}) z_1^\alpha \xi_3^{\beta+1} \hbar^\ell \in \mathcal{O}_{N+3}.$$

We also have

$$\begin{aligned} i\hbar^{-1}(\operatorname{ad}_{\tau'} b(\tilde{x})) &= \{\tau', b\} + \hbar^2 \mathcal{O}_N = \frac{\partial \tau'}{\partial \xi_3} \frac{\partial b}{\partial x_3} + \frac{\partial \tau'}{\partial \xi_2} \frac{\partial b}{\partial x_2} - \frac{\partial \tau'}{\partial x_2} \frac{\partial b}{\partial \xi_2} + \mathcal{O}_{N+1} \\ &= \sum_{|\alpha|+\beta+2\ell=N+2} \beta a(\tilde{x}) \frac{\partial b}{\partial x_3} z_1^\alpha |z_1|^2 \xi_3^{\beta-1} \hbar^\ell + \mathcal{O}_{N+1} \in \mathcal{O}_{N+1}. \end{aligned}$$

Therefore, for the second term, we get

$$\begin{aligned} i\hbar^{-1} \operatorname{ad}_{\tau'} (b(\tilde{x})|z_1|^2) &= i\hbar^{-1}(\operatorname{ad}_{\tau'} b(\tilde{x}))|z_1|^2 + i\hbar^{-1} b(\tilde{x}) \operatorname{ad}_{\tau'} |z_1|^2 \\ &= i\hbar^{-1} b(\tilde{x}) \operatorname{ad}_{\tau'} |z_1|^2 + \mathcal{O}_{N+3}, \end{aligned}$$

which completes the proof of the lemma. □

**3B2. Quantizing the formal procedure.** Let us now prove Theorem 2.1. Using (3-4) and applying the Egorov theorem (see [Robert 1987; Zworski 2012] or Theorem A.2), we can find a unitary Fourier integral operator  $U_\hbar$  such that

$$U_\hbar^* \mathcal{L}_{\hbar,A} U_\hbar = C_0 \hbar + \operatorname{Op}_\hbar^w(H^0) + \operatorname{Op}_\hbar^w(r_\hbar),$$

where the Taylor series (with respect to  $x_1, \xi_1, \xi_3, \hbar$ ) of  $r_\hbar$  satisfies  $r_\hbar^T = \gamma \in \mathcal{O}_3$  and  $C_0$  is the value at the origin of the subprincipal symbol of  $U_\hbar^* \mathcal{L}_{\hbar,A} U_\hbar$ . One can choose  $U_\hbar$  such that the subprincipal symbol is preserved by conjugation,<sup>1</sup> which implies  $C_0 = 0$ . Applying Proposition 3.2, we obtain  $\tau$  and  $\kappa$  in  $\mathcal{O}_3$  such that

$$e^{i\hbar^{-1} \operatorname{ad}_\tau} (H^0 + \gamma) = H^0 + \kappa,$$

with  $[\kappa, |z_1|^2] = 0$ .

We can introduce a smooth symbol  $a_\hbar$  with compact support such that we have  $a_\hbar^T = \tau$  in a neighborhood of the origin. By Proposition 3.2 and Theorem A.4, we obtain that the operator

$$e^{i\hbar^{-1} \operatorname{Op}_\hbar^w(a_\hbar)} (\operatorname{Op}_\hbar^w(H^0) + \operatorname{Op}_\hbar^w(r_\hbar)) e^{-i\hbar^{-1} \operatorname{Op}_\hbar^w(a_\hbar)}$$

---

<sup>1</sup>This is sometimes called the *improved Egorov theorem*. It was first discovered by Weinstein [1975] in the homogeneous setting. For the semiclassical case, see, for instance, [Helffer and Sjöstrand 1989, Appendix A].

is a pseudodifferential operator such that the formal Taylor series of its symbol is  $H^0 + \kappa$ . In this application of Theorem A.4, we have used the filtration  $\mathcal{O}_j$  defined in Section 3B1. Since  $\kappa$  commutes with  $|z_1|^2$ , we can write it as a formal series in  $|z_1|^2$ :

$$\kappa = \sum_{k \geq 3} \sum_{2\ell + 2m + \beta = k} \hbar^\ell c_{\ell,m}(x_2, \xi_2, x_3) |z_1|^{2m} \xi_3^\beta.$$

This formal series can be reordered by using monomials  $(|z_1|^2)^{*m}$ :

$$\kappa = \sum_{k \geq 3} \sum_{2\ell + 2m + \beta = k} \hbar^\ell c_{\ell,m}^*(x_2, \xi_2, x_3) (|z_1|^2)^{*m} \xi_3^\beta.$$

Thanks to the Borel lemma, we may find a smooth function  $f^*(\hbar, I, x_2, \xi_2, x_3, \xi_3)$ , with compact support as small as we want with respect to  $\hbar, I$  and  $\xi_3$ , such that its Taylor series with respect to  $\hbar, I, \xi_3$  is

$$\sum_{k \geq 3} \sum_{2\ell + 2m + \beta = k} \hbar^\ell c_{\ell,m}^*(x_2, \xi_2, x_3) I^m \xi_3^\beta.$$

This achieves the proof of Theorem 2.1.

**3C. Spectral reduction to the first normal form.** This section is devoted to the proof of Corollary 2.4.

**3C1. Numbers of eigenvalues.**

**Lemma 3.4.** *Under Assumption 1.2, there exists  $h_0 > 0$  and  $\varepsilon_0 > 0$  such that, for all  $\hbar \in (0, h_0)$ , the essential spectrum of  $\mathcal{N}_\hbar^\sharp$  admits the lower bound*

$$\inf \mathfrak{s}_{\text{ess}}(\mathcal{N}_\hbar^\sharp) \geq (\beta_0 + \varepsilon_0)\hbar.$$

*Proof.* By using the assumption, we may consider a smooth function  $\chi$  with compact support and  $\varepsilon_0 > 0$  such that

$$\xi_3^2 + b(x_2, \xi_2, x_3) + \chi(x_2, x_3, \xi_2, \xi_3) \geq \beta_0 + 2\varepsilon_0.$$

Then, given  $\eta \in (0, 1)$  and estimating the second term in (2-3) by using that the support of  $f^*$  is chosen small enough and the semiclassical Calderon–Vaillancourt theorem, we notice that, for  $\hbar$  small enough,

$$\mathcal{N}_\hbar^\sharp \geq (1 - \eta) \text{Op}_\hbar^w(\xi_3^2 + |z_1|^2 b(x_2, \xi_2, x_3)). \tag{3-6}$$

Since the essential spectrum is invariant by (relatively) compact perturbations, we have

$$\mathfrak{s}_{\text{ess}}(\mathcal{N}_\hbar^\sharp + (1 - \eta)\hbar \text{Op}_\hbar^w \chi(x_2, x_3, \xi_2, \xi_3)) = \mathfrak{s}_{\text{ess}}(\mathcal{N}_\hbar^\sharp).$$

Hence

$$\inf \mathfrak{s}_{\text{ess}}(\mathcal{N}_\hbar^\sharp) \geq \inf \mathfrak{s}(\mathcal{N}_\hbar^\sharp + (1 - \eta)\hbar \text{Op}_\hbar^w \chi(x_2, x_3, \xi_2, \xi_3)).$$

In order to bound the right-hand side from below, we write

$$\begin{aligned} \mathcal{N}_\hbar^\sharp + (1 - \eta)\hbar \text{Op}_\hbar^w \chi(x_2, x_3, \xi_2, \xi_3) &\geq (1 - \eta) \text{Op}_\hbar^w(\xi_3^2 + |z_1|^2 b(x_2, \xi_2, x_3)) + (1 - \eta)\hbar \text{Op}_\hbar^w \chi(x_2, x_3, \xi_2, \xi_3) \\ &\geq \hbar(1 - \eta) \text{Op}_\hbar^w(\xi_3^2 + b(x_2, \xi_2, x_3) + \chi(x_2, x_3, \xi_2, \xi_3)) \\ &\geq \hbar(1 - \eta)(\beta_0 + 2\varepsilon_0 - C\hbar), \end{aligned}$$

where we have used the semiclassical Gårding inequality. Taking  $\eta$  and then  $\hbar$  small enough, this concludes the proof.  $\square$

By using the Hilbertian decomposition given by the Hermite functions  $(e_{k,\hbar})_{k \geq 1}$  associated with  $\mathcal{I}_\hbar$ , we notice that

$$\mathcal{N}_\hbar^\# = \bigoplus_{k \geq 1} \mathcal{N}_\hbar^{[k],\#},$$

where

$$\mathcal{N}_\hbar^{[k],\#} = \hbar^2 D_{x_3}^2 + (2k - 1)\hbar \text{Op}_\hbar^w b + \text{Op}_\hbar^w f^{*,\#}(\hbar, (2k - 1)\hbar, x_2, \xi_2, x_3, \xi_3) \tag{3-7}$$

acting on  $L^2(\mathbb{R}^2)$ .

**Lemma 3.5.** *For all  $\eta \in (0, 1)$ , there exist  $C > 0$  and  $h_0 > 0$  such that, for all  $k \geq 1$  and  $\hbar \in (0, h_0)$ , we have  $\inf \mathfrak{s}(\mathcal{N}_\hbar^{[k],\#}) \geq (1 - 2\eta)b_0(2k - 1)\hbar$ .*

*Proof.* Applying (3-6) to  $\psi(x_1, x_2, x_3) = \varphi(x_2, x_3)e_{k,\hbar}(x_1)$ , we infer that

$$\langle \mathcal{N}_\hbar^{[k],\#} \varphi, \varphi \rangle \geq (2k - 1)\hbar(1 - \eta) \langle \text{Op}_\hbar^w(b)\varphi, \varphi \rangle.$$

With the Gårding inequality, we get

$$\langle \text{Op}_\hbar^w(b)\varphi, \varphi \rangle \geq (b_0 - C\hbar)\|\varphi\|^2,$$

and the conclusion follows by the min-max principle.  $\square$

We immediately deduce the following proposition.

**Proposition 3.6.** *We have the following descriptions of the low-lying spectrum of  $\mathcal{N}_\hbar^\#$ .*

- (a) *There exist  $\hbar_0 > 0$  and  $K \in \mathbb{N}$  such that, for  $\hbar \in (0, \hbar_0)$ , the spectrum of  $\mathcal{N}_\hbar^\#$  lying below  $\beta_0\hbar$  is contained in the union  $\bigcup_{k=1}^K \text{sp}(\mathcal{N}_\hbar^{[k],\#})$ .*
- (b) *If  $c \in (0, \min(3b_0, \beta_0))$ , then there exists  $\hbar_0 > 0$  such that for all  $\hbar \in (0, \hbar_0)$  the eigenvalues of  $\mathcal{N}_\hbar^\#$  lying below  $c\hbar$  coincide with the eigenvalues of  $\mathcal{N}_\hbar^{[1],\#}$  below  $c\hbar$ .*

**Notation 3.7.** If  $\mathcal{L}$  is a self-adjoint operator and  $E < \inf \mathfrak{s}_{\text{ess}}(\mathcal{L})$ , we denote by  $N(\mathcal{L}, E)$  the number of eigenvalues of  $\mathcal{L}$  lying in  $(-\infty, E)$ .

We deduce the following proposition.

**Corollary 3.8.** *Under assumption (1-11), we have*

$$N(\mathcal{L}_{\hbar,A}, \beta_0\hbar) = \mathcal{O}(\hbar^{-\frac{3}{2}}), \quad N(\mathcal{N}_\hbar^\#, \beta_0\hbar) = \mathcal{O}(\hbar^{-2}).$$

*Proof.* To get the first estimate, we use the Lieb–Thirring inequalities (which provide an upper bound on the number of eigenvalues in dimension three) and the diamagnetic inequality (see [Raymond and Vũ Ngọc 2015] and (1-9)). To get the second estimate, we use the first point in Proposition 3.6. Moreover, given  $\eta \in (0, 1)$ , by using  $\hbar \in (0, 1)$  we infer

$$\langle \mathcal{N}_\hbar^{[k],\#} \psi, \psi \rangle \geq (1 - \eta)\hbar \langle \text{Op}_\hbar^w(\xi_3^2 + b(x_2, \xi_2, x_3))\psi, \psi \rangle.$$

Note that the last inequality is very rough. By the min-max principle, we deduce that

$$N(\mathcal{N}_\hbar^{[k],\sharp}, \beta_0 \hbar) \leq N(\text{Op}_\hbar^w(\xi_3^2 + b(x_2, \xi_2, x_3)), (1 - \eta)^{-1} \beta_0).$$

Then, we conclude by using the Weyl asymptotics and our confinement assumption:

$$N(\text{Op}_\hbar^w(\xi_3^2 + b(x_2, \xi_2, x_3)), (1 - \eta)^{-1} \beta_0) = \mathcal{O}(\hbar^{-2}). \quad \square$$

Since  $\mathcal{N}_\hbar^\sharp$  commutes with  $\mathcal{I}_\hbar$ , we also deduce the following corollary.

**Corollary 3.9.** *For any eigenvalue  $\lambda$  of  $\mathcal{N}_\hbar^\sharp$  such that  $\lambda \leq \beta_0 \hbar$ , we may consider an orthonormal eigenbasis of the space  $\ker(\mathcal{N}_\hbar^\sharp - \lambda)$  formed with functions in the form  $e_{k,\hbar}(x_1)\varphi_\hbar(x_2, x_3)$  with  $k \in \{1, \dots, K\}$ . Moreover, we have  $\mathbb{1}_{(-\infty, \beta_0 \hbar)}(\mathcal{N}_\hbar^\sharp) = \mathcal{O}(\hbar^{-2})$  and each eigenfunction associated with  $\lambda \leq \beta_0 \hbar$  is a linear combination of at most  $\mathcal{O}(\hbar^{-2})$  such tensor products.*

**3C2. Microlocalization estimates.** The following proposition follows from the same lines as in dimension two (see [Helffer and Mohamed 1996, Theorem 2.1]).

**Proposition 3.10.** *Under Assumptions 1.1 and 1.2, for any  $\varepsilon > 0$ , there exist  $C(\varepsilon) > 0$  and  $h_0(\varepsilon) > 0$  such that, for any eigenpair  $(\lambda, \psi)$  of  $\mathcal{L}_{\hbar,A}$  with  $\lambda \leq \beta_0 \hbar$ , we have for  $\hbar \in (0, h_0(\varepsilon))$ ,*

$$\int_{\mathbb{R}^3} e^{2(1-\varepsilon)\phi(q)/\hbar^{\frac{1}{2}}} |\psi|^2 \, dq \leq C(\varepsilon) \exp(\varepsilon \hbar^{-\frac{1}{2}}) \|\psi\|^2,$$

$$\mathcal{Q}_{\hbar,A}(e^{(1-\varepsilon)\phi(q)/\hbar^{\frac{1}{2}}} \psi) \leq C(\varepsilon) \exp(\varepsilon \hbar^{-\frac{1}{2}}) \|\psi\|^2,$$

where  $\phi$  is the distance to the bounded set  $\{\|\mathbf{B}(q)\| \leq \beta_0\}$  for the Agmon metric  $(\|\mathbf{B}(q)\| - \beta_0)_+ g$ , with  $g$  the standard metric.

**Proposition 3.11.** *Under Assumptions 1.1 and 1.2, we consider  $0 < b_0 < \beta_0 < b_1$  and there exist  $C > 0$  and  $\hbar_0 > 0$  such that, for any eigenpair  $(\lambda, \psi)$  of  $\mathcal{L}_{\hbar,A}$  with  $\lambda \leq \beta_0 \hbar$ , we have for  $\hbar \in (0, \hbar_0)$  and  $\delta \in (0, \frac{1}{2})$ ,*

$$\psi = \chi_0(\hbar^{-2\delta} \mathcal{L}_{\hbar,A}) \chi_1(q) \psi + \mathcal{O}(\hbar^\infty) \|\psi\|,$$

where  $\chi_0$  is a cutoff function compactly supported in the ball of center 0 and radius 1 and where  $\chi_1$  is a compactly supported smooth cutoff function that is 1 in an open neighborhood of  $\{\|\mathbf{B}(q)\| \leq \beta_0\}$ .

Let us now investigate the microlocalization of the eigenfunctions of  $\mathcal{N}_\hbar^\sharp$ .

**Proposition 3.12.** *Let  $\chi$  be a smooth cutoff function that is 0 on  $\{b \leq \beta_0\}$  and 1 on the set  $\{b \geq \beta_0 + \varepsilon\}$ . If  $\lambda$  is an eigenvalue of  $\mathcal{N}_\hbar^\sharp$  such that  $\lambda \leq \beta_0 \hbar$  and if  $\psi$  is an associated eigenfunction, then we have*

$$\text{Op}_\hbar^w(\chi(x_2, \xi_2, x_3))\psi = \mathcal{O}(\hbar^\infty) \|\psi\|.$$

*Proof.* Due to Corollary 3.9, it is sufficient to prove the estimate for a function in the form  $\psi(x_1, x_2, x_3) = e_{k,\hbar}(x_1)\varphi(x_2, x_3)$ , where  $k$  lies in  $\{1, \dots, K\}$  and we have

$$\mathcal{N}_\hbar^\sharp \psi = \lambda \psi, \quad \text{or equivalently} \quad \mathcal{N}_\hbar^{[k],\sharp} \varphi = \lambda \varphi,$$

where we recall (3-7). Then, we write

$$\mathcal{N}_h^{[k],\#} \text{Op}_h^w(\chi)\varphi = \lambda \text{Op}_h^w(\chi)\varphi + [\mathcal{N}_h^{[k],\#}, \text{Op}_h^w(\chi)]\varphi$$

and it follows that

$$\langle \mathcal{N}_h^{[k],\#} \text{Op}_h^w(\chi)\varphi, \text{Op}_h^w(\chi)\varphi \rangle = \lambda \|\text{Op}_h^w(\chi)\varphi\|^2 + \langle [\mathcal{N}_h^{[k],\#}, \text{Op}_h^w(\chi)]\varphi, \text{Op}_h^w(\chi)\varphi \rangle. \tag{3-8}$$

Rough pseudodifferential estimates imply that there exist  $C > 0, \hbar_0 > 0$  such that, for all  $\hbar \in (0, \hbar_0)$ ,

$$\begin{aligned} & | \langle [\mathcal{N}_h^{[k],\#}, \text{Op}_h^w(\chi)]\varphi, \text{Op}_h^w(\chi)\varphi \rangle | \\ & \leq C \hbar^2 \|\text{Op}_h^w(\underline{\chi})\varphi\|^2 + C \hbar \|\text{Op}_h^w(\underline{\chi})\varphi\|^2 + C \hbar \langle \text{Op}_h^w(\partial_3 \chi)\varphi, \text{Op}_h^w(\xi_3) \text{Op}_h^w(\chi)\varphi \rangle. \end{aligned} \tag{3-9}$$

Combining (3-9) and (3-8), we get

$$\|\text{Op}_h^w(\xi_3) \text{Op}_h^w(\chi)\varphi\| \leq C \hbar^{\frac{1}{2}} \|\text{Op}_h^w(\underline{\chi})\varphi\|, \tag{3-10}$$

where  $\underline{\chi}$  is a smooth cutoff function living on a slightly larger support than  $\chi$ . By using (3-10), we can improve the commutator estimate

$$| \langle [\mathcal{N}_h^{[k],\#}, \text{Op}_h^w(\chi)]\varphi, \text{Op}_h^w(\chi)\varphi \rangle | \leq C \hbar^{\frac{3}{2}} \|\text{Op}_h^w(\underline{\chi})\varphi\|^2.$$

We infer that, there exist  $C > 0, \hbar_0 > 0$  such that for  $\hbar \in (0, \hbar_0)$ ,

$$\langle \mathcal{N}_h^{[k],\#} \text{Op}_h^w(\chi)\varphi, \text{Op}_h^w(\chi)\varphi \rangle \leq \beta_0 \hbar \|\text{Op}_h^w(\chi)\varphi\|^2 + C \hbar^{\frac{3}{2}} \|\text{Op}_h^w(\underline{\chi})\varphi\|^2.$$

By using the semiclassical Gårding inequality and the support of  $\chi$ , we get

$$\langle \mathcal{N}_h^{[k],\#} \text{Op}_h^w(\chi)\varphi, \text{Op}_h^w(\chi)\varphi \rangle \geq (\beta_0 + \varepsilon_0) \hbar \|\text{Op}_h^w(\chi)\varphi\|^2$$

and we deduce

$$\|\text{Op}_h^w(\chi)\varphi\|^2 \leq C \hbar^{\frac{1}{2}} \|\text{Op}_h^w(\underline{\chi})\varphi\|^2.$$

The conclusion follows by a standard iteration argument. □

The following proposition is concerned with the microlocalization with respect to  $\xi_3$ .

**Proposition 3.13.** *Let  $\chi_0$  be a smooth cutoff function that is 0 in a neighborhood of 0 and let  $\delta \in (0, \frac{1}{2})$ . If  $\lambda$  is an eigenvalue of  $\mathcal{N}_h^\#$  such that  $\lambda \leq \beta_0 \hbar$  and if  $\psi$  is an associated eigenfunction, then we have*

$$\text{Op}_h^w(\chi_0(\hbar^{-\delta} \xi_3))\psi = \mathcal{O}(\hbar^\infty) \|\psi\|.$$

*Proof.* We write again  $\psi(x_1, x_2, x_3) = e_{k,\hbar}(x_1)\varphi(x_2, x_3)$  with  $k \in \{1, \dots, K\}$  and we have  $\mathcal{N}_h^{[k],\#}\varphi = \lambda\varphi$ . We use again the formula (3-8) with  $\chi_0(\hbar^{-\delta} \xi_3)$ . We get the commutator estimate

$$| \langle [\mathcal{N}_h^{[k],\#}, \text{Op}_h^w(\chi_0(\hbar^{-\delta} \xi_3))]\varphi, \text{Op}_h^w(\chi_0(\hbar^{-\delta} \xi_3))\varphi \rangle | \leq C \hbar^{\frac{3}{2}-\delta} \|\text{Op}_h^w(\underline{\chi}_0(\hbar^{-\delta} \xi_3))\varphi\|^2.$$

We have

$$\text{Op}_h^w((\hbar^{-\delta} \xi_3)^2 \chi_0^2(\hbar^{-\delta} \xi_3)) = \text{Op}_{\hbar^{1-\delta}}^w(\xi_3^2 \chi_0^2(\xi_3)),$$

so that, with the Gårding inequality,

$$\langle \text{Op}_h^w((\hbar^{-\delta}\xi_3)^2\chi_0^2(\hbar^{-\delta}\xi_3))\varphi, \varphi \rangle \geq (1 - C\hbar^{1-\delta})\|\varphi\|^2.$$

We infer

$$(\hbar^{2\delta}(1 - C\hbar^{1-\delta}) - \beta_0\hbar)\|\text{Op}_h^w(\chi_0(\hbar^{-\delta}\xi_3))\varphi\|^2 \leq C\hbar^{\frac{3}{2}-\delta}\|\text{Op}_h^w(\chi_0(\hbar^{-\delta}\xi_3))\varphi\|^2. \quad \square$$

Using  $\text{Op}_h^w f^*(\hbar, \mathcal{I}_h, x_2, \xi_2, x_3, \xi_3) = \text{Op}_h^w f(\hbar, |z_1|^2, x_2, \xi_2, x_3, \xi_3)$ , we deduce the following in the same way.

**Proposition 3.14.** *Let  $\chi_1$  be a smooth cutoff function that is 0 in a neighborhood of 0 and let  $\delta \in (0, \frac{1}{2})$ . If  $\lambda$  is an eigenvalue of  $\mathcal{N}_h^\sharp$  such that  $\lambda \leq \beta_0\hbar$  and if  $\psi$  is an associated eigenfunction, then we have*

$$\text{Op}_h^w(\chi_1(\hbar^{-\delta}(x_1, \xi_1)))\psi = \mathcal{O}(\hbar^\infty)\|\psi\|.$$

**Proposition 3.15.** *The spectra of  $\mathcal{L}_{\hbar, A}$  and  $\mathcal{N}_h^\sharp$  below  $\beta_0\hbar$  coincide modulo  $\mathcal{O}(\hbar^\infty)$ .*

*Proof.* We refer to [Raymond and Vŭ Ngŭc 2015, Section 4.3], which contains similar arguments.  $\square$

This proposition provides Corollary 2.4(a). With Proposition 3.6, we deduce point (b).

### 4. Second Birkhoff normal form

**4A. Birkhoff analysis of the first level.** This section is devoted to the proofs of Theorems 2.8 and 2.11.

The goal now is to normalize an  $\hbar$ -pseudodifferential operator  $\mathcal{N}_h^{[1]}$  on  $\mathbb{R}^2$  whose Weyl symbol has the form

$$N_h^{[1]} = \xi_3^2 + \hbar b(x_2, \xi_2, x_3) + r_h(x_2, \xi_2, x_3, \xi_3),$$

where  $r_h$  is a classical symbol with the asymptotic expansion

$$r_h = r_0 + \hbar r_1 + \hbar^2 r_2 + \dots$$

(in the symbol class topology), where each  $r_\ell$  has a formal expansion in  $\xi_3$  of the form

$$r_\ell(x_2, \xi_2, x_3, \xi_3) \sim \sum_{2\ell + \beta \geq 3} c_{\ell, \beta}(x_2, \xi_2, x_3)\xi_3^\beta. \quad (4-1)$$

The leading terms of  $N_h^{[1]}$  are

$$N_h^{[1]} = \xi_3^2 + \hbar b(x_2, \xi_2, x_3) + c_{1,1}(x_2, \xi_2, x_3)\hbar\xi_3 + \mathcal{O}(\hbar\xi_3^2) + \mathcal{O}(\xi_3^3) + \mathcal{O}(\hbar^2). \quad (4-2)$$

**4A1. First normalization of the symbol.** We consider the local change of variables  $\hat{\varphi}(x_2, \xi_2, x_3, \xi_3) = (\hat{x}_2, \hat{\xi}_2, \hat{x}_3, \hat{\xi}_3)$ , where

$$\begin{aligned} \hat{x}_2 &:= x_2 + \xi_3\partial_2 s(x_2, \xi_2), & \hat{x}_3 &:= x_3 - s(x_2, \xi_2), \\ \hat{\xi}_2 &:= \xi_2 + \xi_3\partial_1 s(x_2, \xi_2), & \hat{\xi}_3 &:= \xi_3. \end{aligned} \quad (4-3)$$

It is easy to check that the differential of  $\hat{\varphi}$  is invertible as soon as  $\xi_3$  is small enough. Moreover, we have

$$\hat{\varphi}^*\omega_0 - \omega_0 = \mathcal{O}(|\xi_3|).$$

By the Darboux–Weinstein theorem (see, for instance, [Raymond and Vũ Ngọc 2015, Lemma 2.4]), there exists a local diffeomorphism  $\psi$  such that

$$\psi = \text{Id} + \mathcal{O}(\xi_3^2) \quad \text{and} \quad \psi^* \hat{\varphi}^* \omega_0 = \omega_0. \tag{4-4}$$

Using the improved Egorov theorem, one can find a unitary Fourier integral operator  $V_{\hbar}$  such that the Weyl symbol of  $V_{\hbar}^* \mathcal{N}_{\hbar}^{[1]} V_{\hbar}$  is  $\hat{N}_{\hbar} := N_{\hbar}^{[1]} \circ \hat{\varphi} \circ \psi + \mathcal{O}(\hbar^2)$ . From (4-4), and (4-3), we see that  $\hat{r}_{\hbar} := r_{\hbar} \circ \hat{\varphi} \circ \psi$  is still of the form (4-1), with modified coefficients  $c_{\ell, \beta}$ . Thus, using the new variables and a Taylor expansion in  $\xi_3$ , we get

$$\hat{N}_{\hbar} = \hat{\xi}_3^2 + \hbar b(\hat{x}_2 + \mathcal{O}(\hat{\xi}_3), \hat{\xi}_2 + \mathcal{O}(\hat{\xi}_3), \hat{x}_3 + s(\hat{x}_2 + \mathcal{O}(\hat{\xi}_3), \hat{\xi}_2 + \mathcal{O}(\hat{\xi}_3)) + \mathcal{O}(\hat{\xi}_3^2)) + \mathcal{O}(\hat{\xi}_3^3) + \hat{r}_{\hbar} + \mathcal{O}(\hbar^2)$$

and thus

$$\hat{N}_{\hbar} = \hat{\xi}_3^2 + \hbar b(\hat{x}_2, \hat{\xi}_2, \hat{x}_3 + s(\hat{x}_2, \hat{\xi}_2)) + \hbar \hat{\xi}_3 g(\hat{x}_2, \hat{\xi}_2, \hat{x}_3) + \mathcal{O}(\hbar \hat{\xi}_3^2) + \hat{r}_{\hbar} + \mathcal{O}(\hat{\xi}_3^3) + \mathcal{O}(\hbar^2) \tag{4-5}$$

for some smooth function  $g(\hat{x}_2, \hat{\xi}_2, \hat{x}_3)$ .

Therefore  $\hat{N}_{\hbar}$  has the form

$$\hat{N}_{\hbar} = \hat{\xi}_3^2 + \hbar b(\hat{x}_2, \hat{\xi}_2, \hat{x}_3 + s(\hat{x}_2, \hat{\xi}_2)) + \hat{c}_{1,1}(x_2, \hat{\xi}_2, \hat{x}_3) \hbar \hat{\xi}_3 + \mathcal{O}(\hbar \hat{\xi}_3^2) + \mathcal{O}(\hat{\xi}_3^3) + \mathcal{O}(\hbar^2).$$

**4A2.** *Where the second harmonic oscillator appears.* We now drop all the hats off the variables. We use a Taylor expansion with respect to  $x_3$ , which, in view of (2-6), yields

$$b(x_2, \xi_2, x_3 + s(x_2, \xi_2)) = b(x_2, \xi_2, s(x_2, \xi_2)) + \frac{1}{2} x_3^2 \partial_3^2 b(x_2, \xi_2, s(x_2, \xi_2)) + \mathcal{O}(x_3^3).$$

We let

$$\nu = \left(\frac{1}{2} \partial_3^2 b(x_2, \xi_2, s(x_2, \xi_2))\right)^{\frac{1}{4}} \quad \text{and} \quad \gamma = \ln \nu. \tag{4-6}$$

We introduce the change of coordinates  $(\check{x}_2, \check{x}_3, \check{\xi}_2, \check{\xi}_3) = C(x_2, x_3, \xi_2, \xi_3)$  defined by

$$\begin{aligned} \check{x}_2 &= x_2 + \frac{\partial \gamma}{\partial \xi_2} x_3 \xi_3, & \check{\xi}_2 &= \xi_2 - \frac{\partial \gamma}{\partial x_2} x_3 \xi_3, \\ \check{x}_3 &= \nu x_3, & \check{\xi}_3 &= \nu^{-1} \xi_3, \end{aligned} \tag{4-7}$$

for which one can check that  $C^* \omega_0 - \omega_0 = \mathcal{O}(x_3 \xi_3) = \mathcal{O}(\xi_3)$ . As before, we can make this local diffeomorphism symplectic by the Darboux–Weinstein theorem, which modifies (4-7) by  $\mathcal{O}(\xi_3^2)$ . In the new variables (which we call  $(x_2, x_3, \xi_2, \xi_3)$  again), the symbol  $\check{N}_{\hbar}$  has the form

$$\begin{aligned} \check{N}_{\hbar} &= \nu^2(x_2, \xi_2)(\xi_3^2 + \hbar x_3^2) + \hbar b(x_2, \xi_2, s(x_2, \xi_2)) + \check{c}_{1,1}(x_2, \xi_2, x_3) \hbar \xi_3 \\ &\quad + \mathcal{O}(\hbar x_3^3) + \mathcal{O}(\hbar \xi_3^2) + \mathcal{O}(\xi_3^3) + \mathcal{O}(\hbar^2) \end{aligned}$$

for some smooth function  $\check{c}_{1,1}(x_2, \xi_2, x_3)$ .

**4A3.** *Normalizing the remainder.* The next step is to get rid of the term  $\check{c}_{1,1}(x_2, \xi_2, x_3)\hbar\xi_3$ . Let

$$a(x_2, \xi_2, x_3) := -\frac{1}{2} \int_0^{x_3} \check{c}_{1,1}(x_2, \xi_2, t) dt.$$

Since  $\check{c}_{1,1}$  is compactly supported,  $a$  is bounded, and one can form the unitary pseudodifferential operator  $\exp(iA)$ , where  $A = \text{Op}_\hbar^w(a)$ . We have

$$\exp(-iA) \text{Op}_\hbar^w(\check{N}_\hbar) \exp(iA) = \text{Op}_\hbar^w(\check{N}_\hbar) + \exp(-iA)[\text{Op}_\hbar^w(\check{N}_\hbar), \exp(iA)].$$

The symbol of  $[\exp(-iA) \text{Op}_\hbar^w(\check{N}_\hbar), \exp(iA)]$  is

$$\frac{\hbar}{i} e^{-ia} \{N, e^{ia}\} + \mathcal{O}(\hbar^2) = \hbar \{\check{N}_\hbar, a\} + \mathcal{O}(\hbar^2) = \hbar \{\check{N}_0, a\} + \mathcal{O}(\hbar^2),$$

where  $\check{N}_0$  is the principal symbol of  $\check{N}_\hbar$ , which satisfies

$$\check{N}_0 = \xi_3^2 + \mathcal{O}(\xi_3^3).$$

Therefore  $\{\check{N}_\hbar, a\} = \{\xi_3^2, a\} + \mathcal{O}(\xi_3^2)$ . Since

$$\{\xi_3^2, a\} = 2\xi_3 \frac{\partial a}{\partial x_3} = -\xi_3 \check{c}_{1,1},$$

we get

$$\exp(-iA) \text{Op}_\hbar^w(\check{N}_\hbar) \exp(iA) = \text{Op}_\hbar^w(\check{N}_\hbar - \hbar\xi_3 \check{c}_{1,1} + \mathcal{O}(\hbar\xi_3^2) + \mathcal{O}(\hbar^2)),$$

which shows that we can remove the coefficient of  $\hbar\xi_3$ . The new operator given by the conjugation formula  $\underline{N}_\hbar^{[1]} = \exp(-iA) \text{Op}_\hbar^w(\check{N}_\hbar) \exp(iA)$  has a symbol of the form

$$\underline{N}_\hbar^{[1]} = \underline{\nu}^2(x_2, \xi_2)(\xi_3^2 + \hbar x_3^2) + \hbar b(x_2, \xi_2, s(x_2, \xi_2)) + \underline{r}_\hbar, \tag{4-8}$$

where  $\underline{r}_\hbar = \mathcal{O}(\hbar x_3^3) + \mathcal{O}(\hbar \xi_3^2) + \mathcal{O}(\xi_3^3) + \mathcal{O}(\hbar^2)$ .

This proves Theorem 2.8.

**4A4.** *The second Birkhoff normal form.* We now want to perform a Birkhoff normal form for  $\underline{N}_\hbar^{[1],\#}$  relative to the “second harmonic oscillator”

$$\underline{\nu}^2(x_2, \xi_2)(\xi_3^2 + \hbar x_3^2).$$

Using Notation 2.10, we introduce the new semiclassical parameter  $h = \hbar^{\frac{1}{2}}$ , and use the relation

$$\text{Op}_\hbar^w(\underline{N}_\hbar^{[1],\#}) = \text{Op}_h^w(\underline{N}_h^{[1],\#}).$$

Thus, let  $\tilde{\xi}_j := \hbar^{-\frac{1}{2}} \xi_j$ . The new symbol  $\underline{N}_h^{[1],\#}$  has the form

$$\underline{N}_h^{[1],\#}(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3) = h^2(\underline{\nu}^2(x_2, h\tilde{\xi}_2)(\tilde{\xi}_3^2 + x_3^2) + \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + h^{-2} \underline{r}_{h^2}^\#(x_2, h\tilde{\xi}_2, x_3, h\tilde{\xi}_3)).$$

We introduce momentarily a new parameter  $\mu$  and define

$$\underline{N}_h^{[1],\#}(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3; \mu) := \underline{\nu}^2(x_2, \mu\tilde{\xi}_2)(\tilde{\xi}_3^2 + x_3^2) + \underline{b}(x_2, \mu\tilde{\xi}_2, s(x_2, \mu\tilde{\xi}_2)) + h^{-2} \underline{r}_{h^2}^\#(x_2, \mu\tilde{\xi}_2, x_3, h\tilde{\xi}_3).$$

Notice that  $\mathbb{N}_h^{[1],\#}(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3; h) = h^{-2} \mathbb{N}_h^{[1],\#}(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3)$ . We define now a space of functions suitable for the Birkhoff normal form in  $(x_3, \tilde{\xi}_3, h)$ . Let us now use the notation of the Appendix introduced in (A-4) in the case when the family of smooth linear maps  $\mathbb{R}^2 \rightarrow \mathbb{R}^2$  is given by

$$\varphi_{\mu, \mathbb{R}^2}(x_2, \tilde{\xi}_2) = (x_2, \mu \tilde{\xi}_2).$$

Let

$$\mathcal{F} := \mathcal{C}(1)_{\mathbb{R}^2},$$

where the index  $\mathbb{R}^2$  means that we consider symbols on  $\mathbb{R}^2$ . More explicitly, we have

$$\mathcal{F} = \{d \text{ s.t. } \exists c \in S(1; [0, 1] \times (0, 1])_{\mathbb{R}^2} \mid d(x_2, \tilde{\xi}_2; \mu, h) = c(\varphi_{\mu, \mathbb{R}^2}(x_2, \tilde{\xi}_2); \mu, h)\}.$$

Then we define

$$\mathcal{E} := \mathcal{F}[[x_3, \tilde{\xi}_3, h]],$$

endowed with the full Poisson bracket

$$\mathcal{E} \times \mathcal{E} \ni (f, g) \mapsto \{f, g\} = \sum_{j=2,3} \frac{\partial f}{\partial \tilde{\xi}_j} \frac{\partial g}{\partial x_j} - \frac{\partial g}{\partial \tilde{\xi}_j} \frac{\partial f}{\partial x_j} \in \mathcal{E},$$

and the corresponding Moyal bracket  $[f, g]$ . We remark that the formal Taylor series of the symbol  $\mathbb{N}_h^{[1],\#}(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3; \mu)$  with respect to  $(x_3, \tilde{\xi}_3, h)$  belongs to  $\mathcal{E}$ . We may apply the semiclassical Birkhoff normal form relative to the main term  $\mathbb{V}^2(x_2, \mu \tilde{\xi}_2)(\tilde{\xi}_3^2 + x_3^2)$  exactly as in Section 3B1 (and also [Raymond and Vũ Ngọc 2015, Proposition 2.7]), where we use the fact that the function

$$(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3; \mu, h) \mapsto (\mathbb{V}^2(x_2, \mu \tilde{\xi}_2))^{-1}$$

belongs to  $\mathcal{E}$  because  $\mathbb{V}^2 > C > 0$  uniformly with respect to  $\mu$ . Let us consider  $\gamma \in \mathcal{E}$ , the formal Taylor expansion of  $h^{-2} r_{h^2}^\#(x_2, \mu \tilde{\xi}_2, x_3, h \tilde{\xi}_3)$  with respect to  $(x_3, \tilde{\xi}_3, h)$ . The series  $\gamma$  is of valuation 3 and we obtain two formal series  $\kappa, \tau \in \mathcal{E}$  of valuation at least 3 such that

$$[\kappa, x_3^2 + \tilde{\xi}_3^2] = 0$$

and

$$e^{ih^{-1} \text{ad}_\tau} (\mathbb{V}^2(x_2, \mu \tilde{\xi}_2)(\tilde{\xi}_3^2 + x_3^2) + \gamma) = \mathbb{V}^2(x_2, \mu \tilde{\xi}_2)(\tilde{\xi}_3^2 + x_3^2) + \kappa.$$

The coefficients of  $\tau$  are in  $S(1)$  and one can find a smooth function  $\tau_h \in S(1)$  with compact support with respect to  $(x_3, \tilde{\xi}_3, h)$  and whose Taylor series in  $(x_3, \tilde{\xi}_3, h)$  is  $\tau$ . By the Borel summation,  $\tau_h$  will actually lie in  $S(m')$  with  $m'(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3) = \langle (x_3, \tilde{\xi}_3) \rangle^{-k}$  for any  $k > 0$ , uniformly for small  $h > 0$  and  $\mu \in [0, 1]$ . Notice that  $\mathbb{N}_h^{[1],\#} \in \mathcal{C}(m)$  with  $m = \langle (x_3, \tilde{\xi}_3) \rangle^2 \geq 1$ , and that  $mm' = \mathcal{O}(1)$ .

Then, we can apply Theorem A.3 with the family of endomorphisms of  $\mathbb{R}^4$  defined by

$$\varphi_{\mu, \mathbb{R}^4}(x_2, \tilde{\xi}_2, x_3, \tilde{\xi}_3) = (x_2, \mu \tilde{\xi}_2, x_3, \tilde{\xi}_3).$$

Thus, the new operator

$$\mathfrak{M}_h = e^{ih^{-1} \text{Op}_h^w \tau_h} \mathbb{N}_h^{[1],\#} e^{-ih^{-1} \text{Op}_h^w \tau_h}$$

is a pseudodifferential operator whose Weyl symbol belongs to the class  $\mathcal{C}(m)$  modulo  $h^\infty S(1)$  (see the notation of Theorem 2.11). Moreover, thanks to Theorem A.4, its symbol  $M_h$  admits the following Taylor expansion (with respect to  $(x_3, \tilde{\xi}_3, h)$ )

$$\tilde{b}(x_2, \mu\tilde{\xi}_2, s(x_2, \mu\tilde{\xi}_2)) + \underline{v}^2(x_2, \mu\tilde{\xi}_2)(\tilde{\xi}_3^2 + x_3^2) + \kappa.$$

We write  $\kappa = \sum_{m+2\ell \geq 3} c_{m,\ell}(x_2, \mu\tilde{\xi}_2) |\tilde{z}_3|^{*2m} h^\ell$  and we may find a smooth function  $g^*(x_2, \mu\tilde{\xi}_2, Z, h)$  such that its Taylor series with respect to  $Z, h$  is

$$\sum_{2m+2\ell \geq 3} c_{m,\ell}(x_2, \mu\tilde{\xi}_2) Z^m h^\ell.$$

We may now replace  $\mu$  by  $h$ , which achieves the proof of Theorem 2.11.

**4B. Spectral reduction to the second normal form.** This section is devoted to the proof of Corollary 2.13.

**4B1.** From  $\mathcal{N}_h^{[1],\#}$  to  $\underline{\mathcal{N}}_h^{[1],\#}$ . In this section, we prove Corollary 2.9.

**Lemma 4.1.** *We have*

$$N(\mathcal{N}_h^{[1],\#}, \beta_0 h) = \mathcal{O}(h^{-2}), \quad N(\underline{\mathcal{N}}_h^{[1],\#}, \beta_0 h) = \mathcal{O}(h^{-2}).$$

*Proof.* The first estimate comes from Proposition 3.6 and Corollary 3.8. The second estimate can be obtained by the same method as in the proof of Corollary 3.8. □

Let us now summarize the microlocalization properties of the eigenfunctions of  $\underline{\mathcal{N}}_h^{[1],\#}$  in the following proposition.

**Proposition 4.2.** *Let  $\chi_0$  be a smooth cutoff function on  $\mathbb{R}$  that is 0 in a neighborhood of 0 and let  $\delta \in (0, \frac{1}{2})$ . Let  $\chi$  be a smooth cutoff function that is 0 on the bounded set  $\{x_3^2 + \underline{b}(x_2, \xi_2, s(x_2, \xi_2)) \leq \beta_0\}$  and 1 on the set  $\{x_3^2 + \underline{b}(x_2, \xi_2, s(x_2, \xi_2)) \geq \beta_0 + \tilde{\varepsilon}\}$ , with  $\tilde{\varepsilon} > 0$ . If  $\lambda$  is an eigenvalue of  $\underline{\mathcal{N}}_h^{[1],\#}$  such that  $\lambda \leq \beta_0 h$  and if  $\psi$  is an associated eigenfunction, then we have*

$$\text{Op}_h^w(\chi(x_2, \xi_2, x_3))\psi = \mathcal{O}(h^\infty)\|\psi\|,$$

and

$$\text{Op}_h^w(\chi_0(h^{-\delta}\xi_3))\psi = \mathcal{O}(h^\infty)\|\psi\|.$$

*Proof.* The proof follows exactly the same lines as for Propositions 3.12 and 3.13. □

Lemma 4.1 and Proposition 4.2 on the one hand and Propositions 3.12 and 3.13 on the other hand are enough to deduce Corollary 2.9(a) from Theorem 2.8. Part (b) easily follows from Corollary 2.4.

**4B2.** From  $\underline{\mathfrak{M}}_h^{[1],\#}$  to  $\mathfrak{M}_h^\#$ . Let us now prove Corollary 2.13(a). We get the following rough estimate of the number of eigenvalues.

**Lemma 4.3.** *We have*

$$N(\underline{\mathfrak{M}}_h^{[1],\#}, \beta_0 h^2) = N(\mathfrak{M}_h^\#, \beta_0 h^2) = \mathcal{O}(h^{-4}), \tag{4-9}$$

$$N(\mathfrak{M}_h^\#, \beta_0 h^2) = \mathcal{O}(h^{-4}). \tag{4-10}$$

*Proof.* First, we notice that  $\mathfrak{N}_h^{[1],\#}$  and  $\mathfrak{M}_h$  are unitarily equivalent so that (4-9) holds. Then, given  $\eta > 0$  and  $h$  small enough and up to shrinking the support of  $g^*$  and by using the Calderon–Vaillancourt theorem (as in the proof of Lemma 3.4),  $\mathfrak{M}_h^\# \geq \tilde{\mathfrak{M}}_h^\#$  in the sense of quadratic forms, with

$$\tilde{\mathfrak{M}}_h^\# = \text{Op}_h^w(h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2))) + h^2 \mathcal{J}_h \text{Op}_h^w((\underline{v}^2(x_2, h\tilde{\xi}_2)) - \eta).$$

Since  $\underline{v}^2 \geq c > 0$ , we get

$$\begin{aligned} \text{Op}_h^w(h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2))) + h^2 \mathcal{J}_h \text{Op}_h^w((\underline{v}^2(x_2, h\tilde{\xi}_2)) - \eta) \\ \geq \text{Op}_h^w(h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2))) + \frac{1}{2} c h^2 \mathcal{J}_h. \end{aligned}$$

We deduce the upper bound (4-10) by separation of variables and the min-max principle. □

The following proposition deals with the microlocal properties of the eigenfunctions of  $\mathfrak{N}_h^{[1],\#}$ .

**Proposition 4.4.** *Let  $\eta \in (0, 1)$ ,  $\delta \in (0, \frac{1}{2}\eta)$ , and  $C > 0$ . Let  $\chi$  be a smooth cutoff function that is 0 on  $\{\underline{b}(x_2, \xi_2, s(x_2, \xi_2)) \leq \beta_0\}$  and 1 on the set  $\{\underline{b}(x_2, \xi_2, s(x_2, \xi_2)) \geq \beta_0 + \tilde{\varepsilon}\}$ , with  $\tilde{\varepsilon} > 0$ . Let also  $\chi_1$  be a smooth cutoff function on  $\mathbb{R}^2$  that is 0 in a neighborhood of 0.*

*If  $\lambda$  is an eigenvalue of  $\mathfrak{N}_h^{[1],\#}$  such that  $\lambda \leq \beta_0 h^2$  and if  $\psi$  is an associated eigenfunction, we have*

$$\text{Op}_h^w(\chi(x_2, h\tilde{\xi}_2))\psi = \mathcal{O}(h^\infty)\|\psi\| \tag{4-11}$$

*and if  $\lambda$  is an eigenvalue of  $\mathfrak{N}_h^{[1],\#}$  such that  $\lambda \leq b_0 h^2 + C h^{2+\eta}$  and if  $\psi$  is an associated eigenfunction, we have*

$$\text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi = \mathcal{O}(h^\infty)\|\psi\|. \tag{4-12}$$

*Proof.* The estimate (4-11) is a consequence of Proposition 4.2. Then, let us write the symbol of  $\mathfrak{N}_h^{[1],\#}$ ,

$$\underline{\mathfrak{N}}_h^{[1],\#} = h^2 \underline{v}^2(x_2, h\tilde{\xi}_2)(\tilde{\xi}_2^2 + x_3^2) + h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + \underline{r}_{h^2}^\#(x_2, h\tilde{\xi}_2, x_3, h\tilde{\xi}_3).$$

We write

$$\begin{aligned} \langle \underline{\mathfrak{N}}_h^{[1],\#} \text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi, \text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi \rangle \\ = \lambda \|\text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi\|^2 + \langle [\underline{\mathfrak{N}}_h^{[1],\#}, \text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))] \text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi \rangle. \end{aligned}$$

We get

$$\langle [\underline{\mathfrak{N}}_h^{[1],\#}, \text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))] \text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi \rangle \leq C h^3 \|\text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi\|^2,$$

where we have used (4-11). Then, we use that

$$\underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) \geq b_0, \quad \underline{v}^2(x_2, h\tilde{\xi}_2) \geq c_0 > 0, \quad \lambda \leq b_0 h^2 + C h^{2+\eta},$$

and the Gårding inequality to deduce

$$h^2(C h^{2\delta} - C h^\eta) \|\text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi\|^2 \leq C h^3 \|\text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi\|^2.$$

The desired estimate follows by an iteration argument. □

In the same way we can deal with  $\mathfrak{M}_h^\sharp$ .

**Proposition 4.5.** *Let  $\eta \in (0, 1)$ ,  $\delta \in (0, \frac{1}{2}\eta)$ , and  $C > 0$ . Let  $\chi$  be a smooth cutoff function that is 0 on  $\{\underline{b}(x_2, \xi_2, s(x_2, \xi_2)) \leq \beta_0\}$  and 1 on the set  $\{\underline{b}(x_2, \xi_2, s(x_2, \xi_2)) \geq \beta_0 + \tilde{\varepsilon}\}$ , with  $\tilde{\varepsilon} > 0$ . If  $\lambda$  is an eigenvalue of  $\mathfrak{M}_h^\sharp$  such that  $\lambda \leq \beta_0 h^2$  and if  $\psi$  is an associated eigenfunction, we have*

$$\text{Op}_h^w(\chi(x_2, h\tilde{\xi}_2))\psi = \mathcal{O}(h^\infty)\|\psi\| \tag{4-13}$$

and if  $\lambda$  is an eigenvalue of  $\mathfrak{M}_h^\sharp$  such that  $\lambda \leq b_0 h^2 + C h^{2+\eta}$  and if  $\psi$  is an associated eigenfunction, we have

$$\text{Op}_h^w(\chi_1(h^{-\delta}(x_3, \tilde{\xi}_3)))\psi = \mathcal{O}(h^\infty)\|\psi\|. \tag{4-14}$$

*Proof.* In order to get (4-13), it is enough to go back to the representation with semiclassical  $\hbar$ , that is,  $\mathfrak{M}_h^\sharp = \mathcal{M}_h^\sharp$ . Indeed the microlocal estimate follows by the same arguments as in Propositions 3.12 and 3.13. Then, (4-14) follows as in Proposition 4.4.  $\square$

Propositions 4.4 and 4.5 and Theorem 2.11 standardly imply Corollary 2.13(a).

**4B3.** *From  $\mathfrak{M}_h^\sharp$  to  $\mathfrak{M}_h^{[1],\sharp}$ .* Let us now prove Corollary 2.13(b). Note that part (c) is just a reformulation of (b).

Let us consider the Hilbertian decomposition  $\mathfrak{M}_h^\sharp = \bigoplus_{k \geq 1} \mathfrak{M}_h^{[k],\sharp}$ , where the symbol  $M_h^{[k],\sharp}$  of  $\mathfrak{M}_h^{[k],\sharp}$  is

$$h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + (2k - 1)h^3 \underline{v}^2(x_2, h\tilde{\xi}_2) + h^2 g^\star(h, (2k - 1)h, x_2, h\tilde{\xi}_2).$$

There exists  $h_0 > 0$  such that for all  $k \geq 1$  and  $h \in (0, h_0)$ ,

$$\langle \mathfrak{M}_h^{[k],\sharp} \psi, \psi \rangle \geq \langle \text{Op}_h^w(h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + (2k - 1)h^3 (\underline{v}^2(x_2, h\tilde{\xi}_2) - \varepsilon))\psi, \psi \rangle.$$

Since each eigenfunction of  $\mathfrak{M}_h^{[k],\sharp}$  associated with an eigenvalue less than  $\beta_0 h^2$  provides an eigenfunction of  $\mathfrak{M}_h^\sharp$ , we infer that the eigenfunctions of  $\mathfrak{M}_h^{[k],\sharp}$  are uniformly microlocalized in an  $(x_2, \xi_2)$ -neighborhood of  $(0, 0)$  as small as we want. Therefore, on the range of  $\mathbb{1}_{(-\infty, b_0 h^2)}(\mathfrak{M}_h^{[k],\sharp})$ , we have

$$\langle \mathfrak{M}_h^{[k],\sharp} \psi, \psi \rangle \geq \langle \text{Op}_h^w(h^2 \underline{b}(x_2, h\tilde{\xi}_2, s(x_2, h\tilde{\xi}_2)) + (2k - 1)h^3 (\underline{v}^2(0, 0) - 2\varepsilon))\psi, \psi \rangle,$$

and, with the Gårding inequality in the  $\hbar$ -quantization, we get

$$\langle \mathfrak{M}_h^{[k],\sharp} \psi, \psi \rangle \geq \langle \text{Op}_h^w(h^2 b_0 + (2k - 1)h^3 (\underline{v}^2(0, 0) - \varepsilon) - C h^4)\psi, \psi \rangle.$$

This implies Corollary 2.13(b).

### 5. Third Birkhoff normal form

**5A. Birkhoff analysis of the first level.** In this section we prove Theorem 2.15.

We consider  $\mathcal{M}_h^{[1],\sharp} = \text{Op}_h^w(M_h^{[1],\sharp})$ , with

$$M_h^{[1],\sharp} = \hbar \underline{b}(x_2, \xi_2, s(x_2, \xi_2)) + \hbar^{\frac{3}{2}} \underline{v}^2(x_2, \xi_2) + \hbar g^\star(\hbar^{\frac{1}{2}}, \hbar^{\frac{1}{2}}, x_2, \xi_2).$$

By using a Taylor expansion, we get,

$$M_h^{[1],\sharp} = \hbar b_0 + \frac{1}{2} \hbar \text{Hess}_{(0,0)} \underline{b}(x_2, \xi_2, s(x_2, \xi_2)) + \hbar^{\frac{3}{2}} \underline{v}^2(0, 0) + c x_2 \hbar^{\frac{3}{2}} + d \xi_2 \hbar^{\frac{3}{2}} + \hbar \mathcal{O}((\hbar^{\frac{1}{2}}, z_2)^3), \tag{5-1}$$

where  $c = \partial_{x_2} v^2(0, 0)$  and  $d = \partial_{\xi_2} v^2(0, 0)$ , and we have identified the Hessian with its quadratic form in  $(x_2, \xi_2)$ .

Then, there exists a linear symplectic change of variables that diagonalizes the Hessian, so that, if  $L_{\hbar}$  is the associated unitary transform,

$$L_{\hbar}^* \mathcal{M}_{\hbar}^{[1],\#} L_{\hbar} = \text{Op}_{\hbar}^w(\widehat{M}_{\hbar}^{[1],\#}),$$

with

$$\widehat{M}_{\hbar}^{[1],\#} = \hbar b_0 + \frac{1}{2} \hbar \theta (x_2^2 + \xi_2^2) + \hbar^{\frac{3}{2}} v^2(0, 0) + \hat{c} x_2 \hbar^{\frac{3}{2}} + \hat{d} \xi_2 \hbar^{\frac{3}{2}} + \hbar \mathcal{O}((\hbar^{\frac{1}{2}}, z_2)^3),$$

where

$$\theta = \sqrt{\det \text{Hess}_{(0,0)} b(x_2, \xi_2, s(x_2, \xi_2))}.$$

Since  $(\partial_{x_3} b)(x_2, \xi_2, s(x_2, \xi_2)) = 0$  and  $(0, 0)$  is a critical point of  $s$ , we notice that  $\partial_{x_2 x_3}^2 b(0, 0, 0) = \partial_{\xi_2 x_3}^2 b(0, 0, 0) = 0$ . Thus

$$\det \text{Hess}_{(0,0,0)} b(0, 0, 0) = \theta^2 \partial_{x_3}^2 b(0, 0, 0).$$

Using that  $b$  is identified with  $b \circ \chi$  (see Remarks 2.2 and 3.1), this provides the expression given in (1-15).

Note that  $\hat{c}^2 + \hat{d}^2 = \|(\nabla_{x_2, \xi_2} v^2)(0, 0)\|^2$  since the symplectic transform is in fact a rotation. Moreover, we have

$$\theta(x_2^2 + \xi_2^2) + \hat{c} x_2 \hbar^{\frac{1}{2}} + \hat{d} \xi_2 \hbar^{\frac{1}{2}} = \theta \left( \left( x_2 - \frac{\hat{c} \hbar^{\frac{1}{2}}}{\theta} \right)^2 + \left( \xi_2 - \frac{\hat{d} \hbar^{\frac{1}{2}}}{\theta} \right)^2 \right) - \hbar \frac{\hat{c}^2 + \hat{d}^2}{\theta}.$$

Thus, there exists a unitary transform  $\widehat{U}_{\hbar^{1/2}}$ , which is in fact an  $\hbar$ -Fourier integral operator whose phase admits a Taylor expansion in powers of  $\hbar^{\frac{1}{2}}$ , such that

$$\widehat{U}_{\hbar^{1/2}}^* L_{\hbar}^* \mathcal{M}_{\hbar}^{[1],\#} L_{\hbar} \widehat{U}_{\hbar^{1/2}} =: \underline{F}_{\hbar} = \text{Op}_{\hbar}^w(\underline{F}_{\hbar}),$$

where

$$\underline{F}_{\hbar} = \hbar b_0 + \hbar^{\frac{3}{2}} v^2(0, 0) - \frac{\|(\nabla_{x_2, \xi_2} v^2)(0, 0)\|^2}{2\theta} \hbar^2 + \hbar \left( \frac{1}{2} \theta |z_2|^2 + \mathcal{O}((\hbar^{\frac{1}{2}}, z_2)^3) \right).$$

Now we perform a semiclassical Birkhoff normal form in the space of formal series  $\mathbb{R}[[x_2, \xi_2, \hbar^{\frac{1}{2}}]]$  equipped with the degree such that  $x_2^\ell \xi_2^m \hbar^{\frac{n}{2}}$  is  $\ell + m + n$  and endowed with the Moyal product. Let  $\underline{F}_{\hbar}^T$  be the full Taylor series of  $\underline{F}_{\hbar}$ . We find a formal series  $\tau(x_2, \xi_2, \hbar^{\frac{1}{2}})$  with a valuation at least 3 such that

$$e^{i \hbar^{-1} \text{ad}_{\tau}} \underline{F}_{\hbar}^T = \underline{F}_{\hbar}^T,$$

where  $\underline{F}_{\hbar}^T$  is a formal series of the form

$$\underline{F}_{\hbar}^T = \hbar b_0 + \hbar^{\frac{3}{2}} v^2(0, 0) - \frac{\|(\nabla_{x_2, \xi_2} v^2)(0, 0)\|^2}{2\theta} \hbar^2 + \frac{1}{2} \theta \hbar |z_2|^2 + \hbar k^T(\hbar^{\frac{1}{2}}, |z_2|^2),$$

and  $k^T$  is a formal series in  $\mathbb{R}[[\hbar^{\frac{1}{2}}, |z_2|^2]]$  (and that can be also written as a formal series in Moyal power of  $|z_2|^2$ , say  $(k^T)^*$ ).

Let  $\tilde{\tau}(x_2, \xi_2, \mu)$  be a compactly supported function whose Taylor expansion at  $(0, 0, 0)$  is equal to  $\tau(x_2, \xi_2, \mu)$ . By the Egorov theorem (Theorem A.2), uniformly with respect to the parameter  $\mu$ , we obtain

$$e^{-i \hbar^{-1} \text{Op}_{\hbar}^w(\tilde{\tau})} \text{Op}_{\hbar}^w(\underline{F}_{\mu^2}) e^{i \hbar^{-1} \text{Op}_{\hbar}^w(\tilde{\tau})} =: \text{Op}_{\hbar}^w(\tilde{F}_{\mu})$$

is an  $\hbar$ -pseudodifferential operator depending smoothly on  $\mu$ . Expanding  $\tilde{F}_\mu$  in powers of  $\mu$  in the  $S(1)$  topology, and letting  $\mu = \sqrt{\hbar}$ , we see that  $\tilde{F}_{\sqrt{\hbar}} = F_\hbar + \tilde{G}_\hbar$ , where

$$F_\hbar = \hbar b_0 + \hbar^{\frac{3}{2}} v^2(0, 0) - \frac{\|(\nabla_{x_2, \xi_2} v^2)(0, 0)\|^2}{2\theta} \hbar^2 + \frac{1}{2} \theta \hbar |z_2|^2 + \hbar k(\hbar^{\frac{1}{2}}, |z_2|^2),$$

with  $k$  a smooth function with support as small as desired with respect to its second variable, and  $\tilde{G}_\hbar = \hbar \mathcal{O}(|z_2|^\infty)$ . It remains to notice that  $\text{Op}_\hbar^w(k(\hbar^{\frac{1}{2}}, |z_2|^2))$  can be written as  $k^*(\hbar^{\frac{1}{2}}, \mathcal{K}_\hbar)$  modulo  $\text{Op}_\hbar^w(\mathcal{O}(|z_2|^\infty))$ . This achieves the proof of Theorem 2.15.

**5B. Spectral reduction to the third normal form.** Corollary 2.16 is a consequence of the following lemma and proposition.

**Lemma 5.1.** *We have*

$$N(\mathcal{M}_\hbar^{[1], \#}, \beta_0 \hbar) = \mathcal{O}(\hbar^{-2}), \quad N(\mathcal{F}_\hbar, b_0 \hbar + C \hbar^{1+\eta}) = \mathcal{O}(\hbar^{-1+\eta}).$$

*Proof.* The first estimate follows from Lemma 4.3 and the second one from a comparison with the harmonic oscillator in  $x_2$ . □

The last proposition concerns the microlocalization of the eigenfunctions.

**Proposition 5.2.** *Let  $\eta \in (0, 1)$ ,  $\delta \in (0, \frac{1}{2}\eta)$ , and  $C > 0$ . Let  $\chi$  be a smooth cutoff function that is 0 in a bounded neighborhood of  $(0, 0)$  and 1 outside a bounded neighborhood of  $(0, 0)$ . If  $\lambda$  is an eigenvalue of  $\mathcal{M}_\hbar^{[1], \#}$  or of  $\mathcal{F}_\hbar$  such that  $\lambda \leq b_0 \hbar + C \hbar^{1+\eta}$  and if  $\psi$  is an associated eigenfunction, we have*

$$\text{Op}_\hbar^w(\chi(\hbar^{-\delta}(x_2, \xi_2)))\psi = \mathcal{O}(\hbar^\infty).$$

*Proof.* The proof is similar to that of Proposition 4.4. □

### Appendix: Egorov theorems

We start with the classical result (see, for instance, [Zworski 2012, Theorem 11.1; Robert 1987, Théorème IV.10]).

**Theorem A.1** [Zworski 2012, Theorem 11.1, Remark (ii) on p. 251]. *Let  $P$  and  $Q$  be  $h$ -pseudodifferential operators on  $\mathbb{R}^d$ , with  $P \in \text{Op}_\hbar^w(S(1))$  and  $Q \in \text{Op}_\hbar^w(S(1))$ . Then the operator  $e^{\frac{i}{\hbar}Q} P e^{-\frac{i}{\hbar}Q}$  is a pseudodifferential operator in  $\text{Op}_\hbar^w(S(1))$ , and*

$$e^{\frac{i}{\hbar}Q} P e^{-\frac{i}{\hbar}Q} - \text{Op}_\hbar^w(p \circ \kappa) \in h \text{Op}_\hbar^w(S(1)).$$

*Here  $p$  is the Weyl symbol of  $P$ , and the canonical transformation  $\kappa$  is the time-1 Hamiltonian flow associated with principal symbol of  $Q$ .*

From this classical version of Egorov’s theorem, one can deduce the following refinement that is useful when  $p$  does not belong to  $S(1)$  (as is the case in this paper).

**Theorem A.2.** *Let  $P$  and  $Q$  be  $h$ -pseudodifferential operators on  $\mathbb{R}^d$ , with  $P \in \text{Op}_h^w(S(m))$  and  $Q \in \text{Op}_h^w(S(m'))$ , where  $m$  and  $m'$  are order functions such that*

$$m' = \mathcal{O}(1), \quad mm' = \mathcal{O}(1). \tag{A-1}$$

*Then the operator  $e^{\frac{i}{h}Q} P e^{-\frac{i}{h}Q}$  is a pseudodifferential whose symbol is in  $S(m)$ , and  $e^{\frac{i}{h}Q} P e^{-\frac{i}{h}Q} - \text{Op}_h^w(p \circ \kappa) \in h \text{Op}_h^w(S(1))$ .*

*Proof.* The proof is based on the following observation. In order to compare  $\text{Op}_h^w(p \circ \kappa^t)$  and  $e^{\frac{it}{h}Q} P e^{-\frac{it}{h}Q}$ , we consider the derivative

$$\frac{d}{d\tau} (e^{\frac{i\tau}{h}Q} \text{Op}_h^w(p \circ \kappa^{t-\tau}) e^{-\frac{i\tau}{h}Q}) = e^{\frac{i\tau}{h}Q} \left( \frac{i}{h} [Q, \text{Op}_h^w(p \circ \kappa^{t-\tau})] + \frac{d}{d\tau} \text{Op}_h^w(p \circ \kappa^{t-\tau}) \right) e^{-\frac{i\tau}{h}Q}.$$

From hypothesis (A-1), the term  $[Q, \text{Op}_h^w(p \circ \kappa^{t-\tau})]$  belongs to  $\text{Op}_h^w(S(1))$ ; moreover, if we denote by  $q_0$  the principal symbol of  $Q$ , we have

$$\frac{d}{d\tau} \text{Op}_h^w(p \circ \kappa^{t-\tau}) = -\text{Op}_h^w(\{q_0, p \circ \kappa^{t-\tau}\}),$$

which implies that this term is also in  $\text{Op}_h^w(S(1))$ . By symbolic calculus, we see that

$$\frac{i}{h} [Q, \text{Op}_h^w(p \circ \kappa^{t-\tau})] + \frac{d}{d\tau} \text{Op}_h^w(p \circ \kappa^{t-\tau}) \in h \text{Op}_h^w(S(1)) \tag{A-2}$$

uniformly for  $t, \tau$  in compact sets. It follows by integration from 0 to  $t$  that

$$e^{\frac{it}{h}Q} P e^{-\frac{it}{h}Q} = \text{Op}_h^w(p \circ \kappa^t) + h \int_0^t e^{\frac{is}{h}Q} P_1(s) e^{-\frac{is}{h}Q} ds \tag{A-3}$$

for some  $P_1(s) \in \text{Op}_h^w(S(1))$ , uniformly for  $s \in [0, t]$ . Applying Theorem A.1 to the integrand, we see that  $e^{\frac{it}{h}Q} P e^{-\frac{it}{h}Q} - \text{Op}_h^w(p \circ \kappa^t) \in h \text{Op}_h^w(S(1))$ .  $\square$

In order to quantize the formal Birkhoff procedure of Section 4A4, one needs to consider symbols in a class  $\mathcal{C}$  stable under the Moyal product. For that purpose we first define the families of symbols  $S(m; [0, 1] \times (0, 1])$ , that is, of smooth functions  $a : \mathbb{R}^{2d} \times [0, 1] \times (0, 1] \rightarrow \mathbb{C}$  such that, for any  $\alpha \in \mathbb{N}^{2d}$ , there exists  $C_\alpha$  such that, for all  $(z; \mu, h) \in \mathbb{R}^{2d} \times [0, 1] \times (0, 1]$ ,

$$|\partial_z^\alpha a(z; \mu, h)| \leq C_\alpha m(z)$$

and where  $m$  is an order function on  $\mathbb{R}^{2d}$ . The pair  $(\mu, h)$  is considered as a parameter.

Then, let  $(\varphi_\mu)_{\mu \in [0,1]}$  be a smooth family of linear maps  $\mathbb{R}^{2d} \rightarrow \mathbb{R}^{2d}$  and define the following families of symbols on  $\mathbb{R}^{2d}$  by

$$\mathcal{C}(m) = \{a \in S(m; [0, 1] \times (0, 1]) \mid a(z; \mu, h) = \tilde{a}(\varphi_\mu(z); \mu, h) \text{ with } \tilde{a} \in S(m; [0, 1] \times (0, 1])\}. \tag{A-4}$$

**Theorem A.3.** *Let  $P$  and  $Q$  be  $h$ -pseudodifferential operators on  $\mathbb{R}^d$ , with  $P \in \text{Op}_h^w(\mathcal{C}(m))$  and  $Q \in \text{Op}_h^w(\mathcal{C}(m'))$ , where  $m$  and  $m'$  are order functions such that*

$$m \geq 1, \quad m' = \mathcal{O}(1), \quad mm' = \mathcal{O}(1).$$

*Then  $e^{\frac{i}{h}Q} P e^{-\frac{i}{h}Q} = \tilde{P} + R$ , where  $\tilde{P} \in \text{Op}_h^w(\mathcal{C}(m))$ ,  $R \in h^\infty \text{Op}_h^w(S(1))$ , and with  $\tilde{P} - \text{Op}_h^w(p \circ \kappa) \in h \text{Op}_h^w(\mathcal{C}(1))$ .*

*Proof.* Since  $\varphi_\mu$  is linear, one can see (using, for instance, [Zworski 2012, Theorem 4.17]) that  $\mathcal{C}$  is stable under the formal Moyal product, i.e., for all order functions  $m_1$  and  $m_2$ , we have

$$(\mathcal{C}(m_1)) \star (\mathcal{C}(m_2)) \subset \mathcal{C}(m_1 m_2) + h^\infty S(1).$$

Let  $\kappa$  be the canonical transformation associated with  $Q$ . Then, since  $m \geq 1$ , we have  $p \circ \kappa \in \mathcal{C}(m)$ ; indeed, if we write the Hamiltonian flow of  $Q$  in terms of the variable  $\tilde{z} = \varphi_\mu(z)$ , we see from the linearity of  $\varphi_\mu$  that the components of the transformed vector field belong to  $\mathcal{C}(m')$ . Therefore  $\varphi_\mu \circ \kappa$  is of the form  $\tilde{\kappa}_\mu \circ \varphi_\mu$  for some diffeomorphism  $\tilde{\kappa}_\mu$  depending smoothly on  $\mu$ .

Therefore, both terms in (A-2) belong to  $\text{Op}_h^w(\mathcal{C}(1))$ . Applying this argument inductively in (A-3), we may write, for any  $k > 0$ ,

$$e^{\frac{i}{h}Q} P e^{-\frac{i}{h}Q} - \text{Op}_h^w(p \circ \kappa) - (h\tilde{P}_1 + h^2\tilde{P}_2 + \dots + h^k\tilde{P}_k) \in h^{k+1} \text{Op}_h^w(S(1)),$$

with  $\tilde{P}_j \in \text{Op}_h^w(\mathcal{C}(1))$ . By a Borel summation in  $h$ , parametrized by  $\tilde{z} = \varphi_\mu(z)$ , we can find a symbol  $\hat{P} \in \text{Op}_h^w(\mathcal{C}(1))$  such that we have the asymptotic expansion in  $\text{Op}_h^w(S(1))$

$$\hat{P} \sim h\tilde{P}_1 + h^2\tilde{P}_2 + \dots .$$

We conclude by letting  $\tilde{P} = \text{Op}_h^w(p \circ \kappa) + \hat{P}$ . □

We will also need to examine how the Egorov theorem behaves with respect to taking formal power series of symbols. For this, it is convenient to introduce a filtration of  $S(m)$ .

**Theorem A.4.** *Let  $m$  be an order function on  $\mathbb{R}^{2d}$ , and let  $(\mathcal{O}_j)_{j \in \mathbb{N}}$  be a filtration of  $S(m)$ , i.e.,*

$$\mathcal{O}_0 = S(m), \quad \mathcal{O}_{j+1} \subset \mathcal{O}_j.$$

*Let  $P = \text{Op}_h^w p$  and  $Q = \text{Op}_h^w q$  be  $h$ -pseudodifferential operators on  $\mathbb{R}^d$ , with  $p \in S(m)$  and  $q \in S(m')$ , where  $m'$  is an order function such that  $m'$  and  $mm'$  are bounded.*

*Assume that*

$$\frac{i}{h} \text{ad}_Q(\mathcal{O}_j) \subset \mathcal{O}_{j+1} \quad \forall j \geq 0. \tag{A-5}$$

*Then for any  $k \geq 0$ , the Weyl symbol of the pseudodifferential operator*

$$e^{\frac{i}{h}Q} P e^{-\frac{i}{h}Q} - \sum_{j=0}^k \frac{1}{j!} \left(\frac{i}{h} \text{ad}_Q\right)^j P$$

*belongs to  $\text{Op}_h^w(\mathcal{O}_{k+1})$ . In other words, the series of  $\exp(\frac{i}{h} \text{ad}_Q) P$  converges to  $e^{\frac{i}{h}Q} P e^{-\frac{i}{h}Q}$  for the filtration  $(\mathcal{O}_j)_{j \in \mathbb{N}}$ .*

*Proof.* By the Taylor formula, we can write

$$e^{\frac{i}{h}Q} P e^{-\frac{i}{h}Q} = \sum_{j=0}^k \frac{1}{j!} (\text{ad}_{\frac{i}{h}Q})^j P + \frac{1}{k!} (\text{ad}_{\frac{i}{h}Q})^{k+1} \int_0^1 (1-t)^k e^{\frac{it}{h}Q} P e^{-\frac{it}{h}Q} dt.$$

By Theorem A.2, we see that the integral belongs to  $\text{Op}_h^w(S(m)) = \text{Op}_h^w(\mathcal{O}_0)$ . Therefore, by assumption (A-5), the remainder in the Taylor formula lies in  $\text{Op}_h^w(\mathcal{O}_{k+1})$ . □

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