SCATTERING FOR SYMBOLIC POTENTIALS OF ORDER ZERO AND MICROLOCAL PROPAGATION NEAR RADIAL POINTS

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ABSTRACT. In this paper, the scattering and spectral theory of $H = \Delta_g + V$ is developed, where Δ_g is the Laplacian with respect to a scattering metric g on a compact manifold X with boundary and $V \in \mathcal{C}^\infty(X)$ is real; this extends our earlier results in the two-dimensional case. Included in this class of operators are perturbations of the Laplacian on Euclidean space by potentials homogeneous of degree zero near infinity. Much of the particular structure of geometric scattering theory can be traced to the occurrence of radial points for the underlying classical system. In this case the radial points correspond precisely to critical points of the restriction, V_0, of V to ∂X and under the additional assumption that V_0 is Morse a functional parameterization of the generalized eigenfunctions is obtained.

The main subtlety of the higher dimensional case arises from additional complexity of the radial points. A normal form near such points obtained by Guillemin and Schaeffer is extended and refined, allowing a microlocal description of the null space of $H - \sigma$ to be given for all but the finite set of 'threshold' values of the energy (meaning when it is a critical value of V_0); additional complications arise at the discrete set of 'effectively resonant' energies. In particular each critical point at which the value of V_0 is less than σ is the source of solutions of $Hu = \sigma u$. The resulting description of the generalized eigenspaces is a rather precise, distributional, formulation of asymptotic completeness. We also derive the closely related L^2 and time-dependent forms of asymptotic completeness, including the absence of L^2 channels associated with the non-minimal critical points. This phenomenon, observed by Herbst and Skibsted, can be attributed to the strictly non-minimal growth of the eigenfunctions arising from these critical points.

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1. Introduction

In this paper, which is a continuation of [4], scattering theory is developed for symbolic potentials of order zero. The general setting is the same as in [4], consisting of a compact manifold with boundary, X, equipped with a scattering metric, g, and a real potential, $V \in \mathcal{C}^\infty(X)$. Recall that such a scattering metric on X is a smooth metric in the interior of X taking the form

$$g = \frac{dx^2}{x^4} + \frac{h}{x^2} \tag{1.1}$$

near the boundary, where x is a boundary defining function and h is a smooth cotensor which restricts to a metric on $\{x = 0\} = \partial X$. This makes the interior, X°, of X a complete manifold which is asymptotically flat and is metrically asymptotic to the large end of a cone, since in terms of the singular normal coordinate $r = x^{-1}$, the leading part of the metric at the boundary takes the form $dr^2 + r^2 h(y, dy)$. In the compactification of X° to X, ∂X corresponds to the set of asymptotic directions of geodesics. In particular, this setting subsumes the case of the standard metric on Euclidean space, or a compactly supported perturbation of it, with a potential which is a classical symbol of order zero, hence not decaying at infinity but rather with leading term which is asymptotically homogeneous of degree zero. The study of the scattering theory for such potentials was initiated by Herbst [9].

Let $V_0 \in \mathcal{C}^\infty(\partial X)$ be the restriction of V to ∂X, and denote by $\mathrm{Cv}(V)$ the set of critical values of V_0. It is shown in [4] that the operator $H = \Delta_g + V$ (where the Laplacian is normalized to be positive) is essentially self-adjoint with continuous spectrum occupying $[\min V_0, \infty)$. There may be discrete spectrum of finite multiplicity in $(-\min_X V, \max V_0]$ with possible accumulation points only at $\mathrm{Cv}(V)$ and then only accumulating from below. To obtain finer results, it is natural to assume, as we do throughout this paper unless otherwise noted, that V_0 is a Morse function, i.e. has only nondegenerate critical points; in particular $\mathrm{Cv}(V)$ is a then finite set; by definition this is the set of *threshold energies,* or *thresholds.*

In the two-dimensional case, considered in [4], the boundary is one-dimensional and so the critical points of V_0 are either minima or maxima. In analyzing the problem in general dimension, we must handle critical points of arbitrary index corresponding to a general nondegenerate Hessian. The classical dynamical system corresponding to the asymptotic behaviour of the operator $H - \sigma$ has *radial points*, two for each critical point of V with critical value less than σ, and the linearization of the flow in the complementary directions has saddle behaviour at non-minimal points. A technical problem arises from the existence of resonances, i.e. integral relations between the eigenvalues of the linearization, for some values of σ and these complicate the reduction of the classical system to a (microlocal) normal form. Indeed in their study of radial points in the setting of classical microlocal analysis, Guillemin and Schaeffer ([3]) exclude these cases. However the closure of the set of resonant energies may have interior, so it is essential to deal with at least most of these cases; one of the main aspects of this work is the microlocal treatment of such resonant radial points.

1.1. **Previous results.** The Euclidean setting described above was first studied by Herbst [9], who showed that any finite energy solution of the time dependent Schrödinger equation, so $u = e^{-itH}f$, can concentrate, in an L^2 sense, asymptotically as $t \to \infty$ only in directions which are critical points of V_0. This was subsequently refined by Herbst and Skibsted, who showed that such concentration can only occur near local minima of V_0. In contrast, solutions of the classical flow can concentrate near any critical point of V_0.

Asymptotic completeness has been studied by Agmon, Cruz and Herbst [1], by Herbst and Skibsted [6], [7], [8] and the present authors in [4]. Agmon, Cruz and Herbst showed asymptotic completeness for sufficiently high energies, while Herbst and Skibsted extended this to all energies except for an explicitly given union of bounded intervals; in the two dimensional case, they showed asymptotic completeness for all energies. These results were obtained by time-dependent methods. On the other hand the principal result of [4] involves a precise description of the generalized eigenspaces of H

$$E^{-\infty}(\sigma) = \{u \in \mathcal{C}^{-\infty}(X); (H-\sigma)u = 0\}; \tag{1.2}$$

note that the space of 'extendible distributions' $\mathcal{C}^{-\infty}(X)$ is the analogue of tempered distributions and reduces to it in case X is the radial compactification of $\mathbb{R}^n$. Thus we are studying all *tempered* eigenfunctions of H. Let us recall these results in more detail.

For any $\sigma \notin \mathrm{Cv}(V)$ the space $E_{\mathrm{pp}}(\sigma)$ of L^2 eigenfunctions is finite dimensional, and reduces to zero except for σ in a discrete (possibly empty) subset of $[\min_X V, \max V_0] \setminus \mathrm{Cv}(V)$. It is always the case that $E_{\mathrm{pp}}(\sigma) \subset \dot{\mathcal{C}}^\infty(X)$ consists of rapidly decreasing functions. Hence $E^{-\infty}_{\mathrm{ess}}(\sigma) \subset E^{-\infty}(\sigma)$, the orthocomplement of $E_{\mathrm{pp}}(\sigma)$, is well defined for $\sigma \notin \mathrm{Cv}(V)$. Furthermore, as shown in the Euclidean case by Herbst in [9], the resolvent, $R(\sigma)$ of H, acting on this orthocomplement, has a limit, $R(\sigma \pm i0)$, on $[\min V_0, \infty) \setminus \mathrm{Cv}(V)$ from above and below. The subspace of 'smooth' eigenfunctions is then defined as

$$E^\infty(\sigma) = \mathrm{Sp}(\sigma)\left(\dot{C}^\infty(X) \ominus E_{\mathrm{pp}}(\sigma)\right) \subset E^{-\infty}(\sigma)$$
$$\mathrm{Sp}(\sigma) \equiv \frac{1}{2\pi i}\big(R(\sigma + i0) - R(\sigma - i0)\big).$$

In fact

$$E^\infty_{\mathrm{ess}}(\sigma) \subset \bigcap_{\epsilon>0} x^{-1/2-\epsilon} L^2(X).$$

An alternative characterization of $E^\infty_{\mathrm{ess}}(\sigma)$ can be given in terms of the *scattering wavefront set* at the boundary of X.

The scattering cotangent bundle, ${}^{\mathrm{sc}}T^*X$, of X is naturally isomorphic to the cotangent bundle over the interior of X, and indeed globally isomorphic to T^*X by a non-natural isomorphism; the natural isomorphism represents both 'compression' and 'rescaling' at the boundary. If (x, y) are local coordinates near a boundary point of X, with x a boundary defining function, then linear coordinates (ν, μ) are defined on the scattering cotangent bundle by requiring that $q \in {}^{\mathrm{sc}}T^*X$ be written as

$$q = -\nu \frac{dx}{x^2} + \sum_i \mu_i \frac{dy_i}{x}, \quad \nu \in \mathbb{R}, \quad \mu \in \mathbb{R}^{n-1}. \tag{1.3}$$

This makes (ν, μ) dual to the basis $(-x^2\partial_x, x\partial_{y_i})$ of vector fields which form an approximately unit length basis, uniformly up to the boundary, for any scattering metric. In Euclidean space, ν is dual to ∂_r and μ_i is dual to the constant-length angular derivative $r^{-1}\partial_{y_i}$. In the analysis of the microlocal aspects of $H - \sigma$, in part for compatibility with [3], it is convenient to multiply $H - \sigma$ by x^{-1}, i.e. to replace it by

$$P = P(\sigma) = x^{-1}(H - \sigma).$$

The classical dynamical system giving the behaviour of particles, asymptotically near ∂X, moving under the influence of the potential corresponds to 'the bicharacteristic vector field,' see (2.3), determined by the *boundary symbol, p*, of P. This vector field is defined on ${}^{\mathrm{sc}}T^*_{\partial X}X$, which is to say on ${}^{\mathrm{sc}}T^*X$ at, and tangent to, the boundary ${}^{\mathrm{sc}}T^*_{\partial X}X = {}^{\mathrm{sc}}T^*X \cap \{x = 0\}$. It has the property that ν is nondecreasing under the flow; we refer to points (y, ν, μ) where $\mu = 0$ as *incoming* if $\nu < 0$ and *outgoing* if $\nu > 0$. What is important in understanding the behaviour of the null space of P, i.e. tempered distributions, u, satisfying $Pu = 0$, is bicharacteristic flow inside $\{p = 0,\, x = 0\}$, a submanifold to which it is tangent. The only critical points of the flow are at points $(y, \nu, 0)$ where y is a critical point of P and $\nu = \pm\sqrt{\sigma - V(y)}$. Thus, the only possible asymptotic escape directions of classical particles under the influence of the potential V are the finite number of critical points $y \in \mathrm{Cv}(V)$. Moreover, only the local minima are stable; the others have unstable directions according to the number of unstable directions as a critical point of $V_0 : \partial X \longrightarrow \mathbb{R}$.

The classical dynamics of p and the quantum dynamics of P are linked via the scattering wavefront set. Let $u \in C^{-\infty}(X)$ be a tempered distribution on X (i.e. in the dual space of $\dot{C}^\infty(X; \Omega)$). The part of the scattering wavefront set, $\mathrm{WF}_{\mathrm{sc}}(u)$, of u lying over the boundary $\{x = 0\}$, which is all that is of interest here, is a closed subset of ${}^{\mathrm{sc}}T^*_{\partial X}X$ which measures the linear oscillations (Fourier modes, in the case of Euclidean space) present in u asymptotically near boundary points; see [12] for the precise definition. We shall also need to use the scattering wavefront set $\mathrm{WF}^s_{\mathrm{sc}}(u)$ with respect to the space $x^s L^2(X)$ which measures the microlocal regions where u fails to be in $x^s L^2(X)$. There is a propagation theorem for the scattering wavefront set in the style of the theorem of Hörmander in the standard setting; if $Pu \in \dot{C}^\infty(X)$, then the scattering wavefront set of u is contained in $\{p = 0\}$ and is invariant under the bicharacteristic flow of P, see [12]. In particular, generalized eigenfunctions of u have scattering wavefront set invariant under the bicharacteristic flow of P. Note that the elliptic part of this statement is already a uniform version of the fact that all solutions are smooth.

In view of this propagation theorem, it is possible to consider where generalized eigenfunctions 'originate'. Let us say that a generalized eigenfunction *originates* at a radial point q, if $q \in \mathrm{WF}_{\mathrm{sc}}(u)$ and if $\mathrm{WF}_{\mathrm{sc}}(u)$ is contained in the forward flowout $\Phi_+(q)$ of q; thus each point in $\mathrm{WF}_{\mathrm{sc}}(u)$ can be reached from q by travelling along curves that are everywhere tangent to the flow and with ν nondecreasing along the curve, so allowing the possibility of passing through radial points, where the flow vanishes, on the way. In Part I of this paper we showed, in the two-dimensional case and provided the eigenvalue σ is a non-threshold value,

- Every L^2 eigenfunction is in $\dot{C}^\infty(X)$.
- Every nontrivial generalized eigenfunction pairing to zero with the L^2 eigenspace fails to be in $x^{-1/2}L^2(X)$.
- There are generalized eigenfunctions originating at each of the incoming radial points in $\{p = 0\}$, i.e. at each critical point of V_0 with value less than σ.
- There are fundamental differences between the behaviour of eigenfunctions near a local minimum and at other critical points. The radial point corresponding to a local minimum is always an isolated point of the scattering wavefront set for some non-trivial eigenfunction. For other critical points, the scattering wavefront set necessarily propagates and in generic situations each nontrivial generalized eigenfunction is singular at some minimal radial point.
- A generalized eigenfunction, u, with an isolated point in its scattering wavefront set, necessarily a radial point corresponding to a local minimum of V_0, has a complete asymptotic expansion there. The expansion is determined by its leading term, which is a Schwartz function of $n-1$ variables. The resulting map extends by continuity to an injective map from $E^\infty_{\text{ess}}(\sigma)$ into $\oplus_q L^2(\mathbb{R}^{n-1})$, where the direct sum is over local minima of V_0 with value less than the energy σ.
- The space $E^0_{\text{ess}}(\sigma)$, consisting of those generalized eigenfunctions which are in $x^{-1/2}L^2$ microlocally near $\{\nu = 0\}$, is a Hilbert space and the map above extends to a unitary isomorphism, $M_+(\sigma)$, from $E^0_{\text{ess}}(\sigma)$ to $\oplus_q L^2(\mathbb{R}^{n-1})$. A similar map $M_-(\sigma)$ can be defined by reversal of sign or complex conjugation and the the scattering matrix for $P = P(\sigma)$ at energy σ may be written
$$S(\sigma) = M_+(\sigma)M_-^{-1}(\sigma).$$

In this paper we extend these results to higher dimensions.

1.2. **Results and structure of the paper.** We treat this problem by microlocal methods. Thus, the 'classical' system, consisting of the bicharacteristic vector field, plays a dominant role. The main step involves reducing this vector field to an appropriate normal form in a neighbourhood of each of its zeroes, which are just the radial points. Nondegeneracy of the critical points of V_0 implies nondegeneracy of the linearization of the bicharacteristic vector field at the corresponding radial points. If there are no resonances, Sternberg's Linearization Theorem, following an argument of Guillemin and Schaeffer, allows the bicharacteristic vector field to be reduced to its linearization by a contact transformation of ${}^{\text{sc}}T^*_{\partial X}X$. At the quantum level this means that conjugation by a (scattering) Fourier integral operator, associated to this contact transformation, microlocally replaces P by an operator with principal symbol in normal form. For this normal form we construct 'test modules' of pseudodifferential operators and analyze the commutators with the transformed operator. Modulo lower order terms, the operator itself becomes a quadratic combination of elements of the test module. Just as in Part I, we use the resulting system of regularity constraints to determine the microlocal structure of the eigenfunctions and ultimately show the existence of asymptotic expansions for eigenfunctions with some additional regularity.

However, the problem of resonances cannot be avoided. Even for a fixed operator and fixed critical point, the closure of the set of values of σ for which resonances occur may have non-empty interior. Such resonances prevent the reduction of the bicharacteristic vector field to its linearization, and hence of the symbol of P to an associated model, although partial reductions are still possible. In general it is necessary to allow many more terms in the model. Fortunately most of these terms are not relevant to the construction of the test modules and to the derivation of the asymptotic expansions. We distinguish between 'effectively nonresonant' energies, where the additional resonant terms are such that the definition of the test modules, now only to finite order, proceeds much as before and the 'effectively resonant' energies, where this is not the case. Ultimately, we analyze the regularity of solutions at all (non-threshold) energies. Near effectively nonresonant energies, smoothness of families of eigenfunctions may still be readily shown. Effectively resonant energies are harder to analyze, but the set of these is shown to be *discrete*. In any case, the space of microlocal eigenfunctions is parameterized at all non-threshold energies. At effectively resonant energies the problems arising from the failure of the direct analogue of Sternberg's linearization are overcome by showing that, to an appropriate finite order, the operator may be reduced to a non-quadratic function of the test module.

In outline, the discussion proceeds as follows. In sections 2 – 4 we study radial points. This is a general microlocal study except that we work under the assumption that the symplectic map associated to the linearization of the flow at each radial point (see Lemma 2.4) has no 4-dimensional irreducible invariant subspaces; this assumption is always fulfilled in the case of our operator $\Delta+V-\sigma$. The main result is Theorem 3.7 in which the operator is microlocally conjugated to a linear vector field plus certain 'error terms'. In the nonresonant case the error terms can be made to vanish identically, while in the effectively nonresonant case the error terms have a good property with respect to a test module of pseudodifferential operators, namely they can be expressed as a positive power x^ϵ, $\epsilon > 0$ times a power of the module. In the effectively resonant case this is no longer possible and we must allow 'genuinely' resonant terms, but the set of effectively resonant energies is discrete in the parameter σ in all dimensions.

We then turn in sections 5 – 7 to studying microlocal eigenfunctions which are microlocally outgoing at a given radial point q. The main result here is Theorem 6.7 (or Theorem 7.3 in the effectively resonant case) which gives a parameterization of such microlocal eigenfunctions. For a minimal radial point, they are parameterized by $\mathcal{S}(\mathbb{R}^{n-1})$, Schwartz functions of $n-1$ variables, for a maximal radial point they are parameterized by formal power series in $n-1$ variables, and in the intermediate case of a saddle point with k positive directions, they are parameterized by formal power series in $n-1-k$ variables with values in $\mathcal{S}(\mathbb{R}^k)$. In all cases, the parameterizing data appear explicitly in the asymptotic expansion of the eigenfunction at the critical point.

We next investigate in sections 8 and 9 the manner in which the various radial points interact, and prove, in Theorem 9.2, a 'microlocal Morse decomposition.' This shows that for each non-threshold energy σ there are genuine eigenfunctions (as opposed to microlocal eigenfunctions) in $E^\infty_{\mathrm{ess}}(\sigma)$ associated to each energy-permissible critical point.

Then we turn in sections 10 and 11 to the spectral decomposition of P and prove several versions of asymptotic completeness. First this is established at a fixed, non-threshold energy; see Theorem 10.1 which shows that the natural map from $E^0_{\mathrm{ess}}(\sigma)$ to the leading term in its asymptotic expansion (i.e. to its parameterizing data) is unitary. Next we prove a form valid uniformly over an interval of the spectrum, Theorem 10.10. In section 11 a time-dependent formulation is derived, as Theorem 11.3. This is based on the behaviour at large times of solutions of the time-dependent Schrödinger equation $D_t u = Pu$ and is subsequently used to derive a result of Herbst and Skibsted's on the absence of L^2-channels corresponding to non-minimal critical points (Corollary 11.5).

1.3. **Notation.**

Notation	**Description/definition of notation**	**Reference**
V_0	restriction of V to ∂X	
$\mathrm{Cv}(V)$	set of critical values of V_0	
${}^{\mathrm{sc}}T^*X$	scattering cotangent bundle over X	(1.3)
${}^{\mathrm{sc}}T^*_{\partial X}X$	restriction of ${}^{\mathrm{sc}}T^*X$ to ∂X	(1.3)
x	boundary defining function of X s.t. (1.1) holds	
y	coordinates on ∂X	
(ν, μ)	fibre coordinates on ${}^{\mathrm{sc}}T^*X$	(1.3)
$y = (y', y'', y''')$	decomposition of y variable	(2.11)
$\mu = (\mu', \mu'', \mu''')$	dual decomposition of μ variable	(2.11)
r'_i, r''_j, r'''_k	eigenvalues of the contact map A	(2.11)
Y''_j	$y''_j / x^{r''_j}$	(5.23)
Y'''_k	$y'''_k / x^{1/2}$	(5.23)
Δ	(positive) Laplacian with respect to g	
P	$x^{-1}(\Delta + V - \sigma)$	Sec. 2
H	$\Delta + V$	
$R(\sigma)$	resolvent of H, $(H - \sigma)^{-1}$	
$R(\sigma \pm i0)$	limit of resolvent on real axis from above/below	
$\tilde{V}$	modified potential	Lem. 8.5
$\tilde{R}(\sigma)$	resolvent of modified potential $(\Delta + \tilde{V} - \sigma)^{-1}$	
$L^2_{\mathrm{sc}}(X)$	L^2 space with respect to Riemannian density of g	
$H^{m,0}_{\mathrm{sc}}(X)$	Sobolev space; image of $L^2_{\mathrm{sc}}(X)$ under $(1+\Delta)^{-m/2}$	
$H^{m,l}_{\mathrm{sc}}(X)$	$x^l H^{m,0}_{\mathrm{sc}}(X)$	
$\Psi^{m,0}_{\mathrm{sc}}(X)$	scattering pseudodiff. ops. of differential order m	
$\Psi^{m,l}_{\mathrm{sc}}(X)$	$x^l \Psi^{m,0}_{\mathrm{sc}}(X)$; maps $H^{m',l'}_{\mathrm{sc}}(X)$ to $H^{m'-m,l'+l}_{\mathrm{sc}}(X)$	
$\sigma_{\partial,l}(A)$	boundary symbol of $A \in \Psi^{m,l}(X)$; $\mathcal{C}^\infty$ fn. on ${}^{\mathrm{sc}}T^*_{\partial X}X$	
$\sigma_\partial(A)$	$\sigma_{\partial,0}(A)$	
$\mathrm{WF}_{\mathrm{sc}}(u)$	scattering wavefront set of u; closed subset of ${}^{\mathrm{sc}}T^*_{\partial X}X$	
$\mathrm{WF}^{m,l}_{\mathrm{sc}}(u)$	scattering wavefront set with respect to $H^{m,l}_{\mathrm{sc}}$	
${}^{\mathrm{sc}}H_p$	scattering Hamilton vector field	Sec. 2
$\Phi_+(q)$	forward flowout from $q \in {}^{\mathrm{sc}}T^*_{\partial X}X$	Sec. 1.1
radial point	point in ${}^{\mathrm{sc}}T^*_{\partial X}X$ where p and ${}^{\mathrm{sc}}H_p$ vanish	Sec. 2
$\mathrm{RP}_\pm(\sigma)$	set of radial points of $H - \sigma$ where $\pm\nu > 0$	
$\mathrm{Min}_+(\sigma)$	subset of $\mathrm{RP}_+(\sigma)$ associated to local minima of V_0	

$\leq$	partial order on $\mathrm{RP}_+(\sigma)$ compatible with Φ_+	Def. 8.3
$\tilde{E}_{\mathrm{mic},+}(O,P)$	microlocal solutions of $Pu=0$ in the set O	(4.1)
$E_{\mathrm{mic},+}(q,\sigma)$	microlocal solutions of $(H-\sigma)u=0$ near q	(4.4)
$E^s_{\mathrm{ess}}(\sigma)$	space of generalized σ-eigenfunctions of H	(9.1)
$E^s(\Gamma,\sigma)$	subset of $u\in E^s_{\mathrm{ess}}(\sigma)$ with $\mathrm{WF}_{\mathrm{sc}}(u)\cap\mathrm{RP}_+(\sigma)\subset\Gamma$	(9.5)
$E^s_{\mathrm{Min},+}(\sigma)$	$E^s(\Gamma,\sigma)$, with $\Gamma=\mathrm{Min}_+(\sigma)$	
$\mathcal{M}$	test module	Sec. 5
$I^{(s)}_{\mathrm{sc}}(O,\mathcal{M})$	space of iteratively-regular functions w. r. t. $\mathcal{M}$	(5.9)
τ	rescaled time variable; $\tau=xt$	Sec. 11
X_{Sch}	$X\times\overline{\mathbb{R}}_\tau$	(11.2)

2. Radial points

If X is a compact n-dimensional manifold with smooth boundary and $P\in\Psi^{*,-1}_{\mathrm{sc}}(X)$ (for example, $P=x^{-1}(\Delta+V-\sigma)$), then the boundary part of its principal symbol, $p=\sigma_\partial(P)$, is a $\mathcal{C}^\infty$ function on ${}^{\mathrm{sc}}T^*_{\partial X}X$. In this, and the next, section we consider radial points of a general real-valued function, $p\in\mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X)$, with only occasional references to the particular case, $p=|\zeta|^2+V_0-\sigma$, of direct interest in this paper. If (x,y) are local coordinates on X, with x being a boundary defining function, then recall from (1.3) that this determines dual coordinates (ν,μ) on the scattering cotangent bundle. The objective is to find a symplectic change of coordinates in which the form of p is simplified. In this section we consider the simplification of p up to second order, in a sense made precise below.

The basic non-degeneracy assumption we make is that

$$p=0 \text{ implies } dp\neq 0; \tag{2.1}$$

this excludes true 'thresholds' which however do occur for our problem, when 0 is a critical value of V_0. It follows directly from (2.1) that the boundary part of the characteristic variety

$$\Sigma=\{q\in{}^{\mathrm{sc}}T^*_{\partial X}X;p(q)=0\}\text{ is smooth;}$$

we shall assume that it is compact, corresponding to the ellipticity of P. We may extend p to a $\mathcal{C}^\infty$ function on ${}^{\mathrm{sc}}T^*X$, still denoted by p. Over the interior ${}^{\mathrm{sc}}T^*_{X^\circ}X$ is naturally identified with T^*X°, which is a symplectic manifold with canonical symplectic form ω. Near the boundary, expressed in terms of sc-dual coordinates,

$$\omega=d\left(-\nu\frac{dx}{x^2}+\sum_i\mu_i\frac{dy_i}{x}\right)=(-d\nu+\sum_i\mu_i\frac{dy_i}{x})\wedge\frac{dx}{x^2}+\sum_i d\mu_i\wedge\frac{dy_i}{x}. \tag{2.2}$$

Consider the Hamilton vector field, $H_{x^{-1}p}$, of $x^{-1}p$, which we shall denote ${}^{\mathrm{sc}}H_p$, fixed by the identity $\omega(\cdot,H_p)=dp$. Then ${}^{\mathrm{sc}}H_p$ extends to a vector field on ${}^{\mathrm{sc}}T^*X$ tangent to its boundary, so ${}^{\mathrm{sc}}H_p\in\mathcal{V}_{\mathrm{b}}({}^{\mathrm{sc}}T^*X)$. At the boundary ${}^{\mathrm{sc}}H_p$, as an element of $\mathcal{V}_{\mathrm{b}}({}^{\mathrm{sc}}T^*X)$, is independent of the extension of p. We denote the restriction of ${}^{\mathrm{sc}}H_p$ (as a vector field) to ${}^{\mathrm{sc}}T^*_{\partial X}X$ by W, so $W\in\mathcal{V}({}^{\mathrm{sc}}T^*_{\partial X}X)$. Explicitly in local coordinates

$$\begin{aligned}{}^{\mathrm{sc}}H_p=&-(\partial_\nu p)(x\partial_x+\mu\cdot\partial_\mu)+(x\partial_x p-p+\mu\cdot\partial_\mu p)\partial_\nu\\&+\sum_j\left(\partial_{\mu_j}p\,\partial_{y_j}-\partial_{y_j}p\,\partial_{\mu_j}\right)+x\mathcal{V}_{\mathrm{b}}({}^{\mathrm{sc}}T^*X);\end{aligned} \tag{2.3}$$

since p is smooth up to the boundary, $x\partial_x p = 0$ at ${}^{\mathrm{sc}}T^*_{\partial X}X$. Thus,

$$W = -(\partial_\nu p)\mu \cdot \partial_\mu + (\mu \cdot \partial_\mu p - p)\partial_\nu + \sum_j \left(\partial_{\mu_j} p \, \partial_{y_j} - \partial_{y_j} p \, \partial_{\mu_j}\right). \tag{2.4}$$

Alternatively W may be described in terms of the contact structure on ${}^{\mathrm{sc}}T^*_{\partial X}X$ given by $\alpha = \omega(\cdot, x^2\partial_x)$. This contact structure is well-defined, i.e. α is fixed up to a positive smooth multiple. In terms of scattering coordinates

$$\alpha = -d\nu + \mu \cdot dy.$$

Then W is the Legendre vector field of p, determined by

$$d\alpha(., W) + \gamma\alpha = dp, \ \alpha(W) = p \tag{2.5}$$

for some function γ. It follows that W is tangent to Σ, since $dp(W) = \gamma\alpha(W) = \gamma p = 0$ at any point at which p vanishes.

At a point in Σ at which dp and α are linearly independent, p (or the underlying operator) is, by definition, of principal type. Conversely, *radial points* are those at which dp and α are linearly dependent; from (2.5) and the nondegeneracy of α this is equivalent to the vanishing of W, $W(q) = 0$. Thus, at a radial point, $dp = \lambda\alpha$, $\lambda = \gamma(q)$, and it follows from (2.5) that $\lambda = -\partial_\nu p$ and from (2.1) that $\lambda \neq 0$. We may choose coordinates in the base such that $\mu = 0$ at q and then $\alpha = -d\nu$ and $dp = -\lambda d\nu$ at q.

Definition 2.1. A radial point $q \in \Sigma$ for a real-valued function $p \in \mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X)$ satisfying (2.1) is said to be *non-degenerate* if the vector field W, restricted to $\Sigma = \{p = 0\}$, has a non-degenerate zero at q. Note that this implies that a non-degenerate radial point is necessarily isolated in the set of radial points.

The vector field W vanishes at a radial point q, hence its linearization is well defined as linear map, A' on $T_q{}^{\mathrm{sc}}T^*_{\partial X}X$, (later we will use the transpose, A, as a map on differentials)

$$A'v = [V, W](q), \tag{2.6}$$

for any smooth vector field V with $V(q) = v$; it is independent of the choice of extension and can also be written in terms of the Lie derivative

$$A'v = -\mathcal{L}_W V(q). \tag{2.7}$$

Since $Wp = \gamma p$, A' preserves the subspace $T_q\Sigma$. Since α is normal to it, the restriction of $d\alpha$ to $T_q\Sigma$ is a symplectic 2-form, ω_q.

Lemma 2.2. *At a non-degenerate radial point for p, where $dp = \lambda\alpha$, the linearization is such that*

$$S = A' - \frac{1}{2}\lambda \,\mathrm{Id} \in \mathfrak{sp}(2(n-1))$$

is in the Lie algebra of the symplectic group with respect to ω_q :

$$\omega_q(Sv_1, v_2) + \omega_q(v_1, Sv_2) = 0, \ \forall \ v_1, v_2 \in T_q\Sigma.$$

Proof. Observe that (2.5) implies that

$$L_W\alpha = (d\alpha)(W, \cdot) + d(\alpha(W)) = \gamma\alpha. \tag{2.8}$$

For two vector smooth vector fields V_i, defined near q,

$$\begin{aligned} W(d\alpha(V_1, V_2)) &= L_W(d\alpha(V_1, V_2)) \\ &= (L_W d\alpha)(V_1, V_2) + d\alpha(L_W V_1, V_2) + d\alpha(V_1, L_W V_2). \end{aligned} \tag{2.9}$$

The left side vanishes at q so using (2.7)

$$\omega_q(A'v_1, v_2) + \omega_q(v_1, A'v_2) = \lambda\omega_q(v_1, v_2)\ \forall\ v_1, v_2 \in T_q\Sigma. \tag{2.10}$$

□

It follows from Lemma 2.2, see for example [3], that A' is decomposable into invariant subspaces of dimension 2 and 4, with eigenvalues on the two-dimensional subspaces of the form λr, $\lambda(1-r)$, $r \leq 1/2$ real or $\lambda(1/2+ia)$, $\lambda(1/2-ia)$, with $a > 0$.

While the eigenvalue λ of dx does not affect the normal form of p, it has a major influence on the structure of microlocal solutions. Note that if $\lambda > 0$, then x is increasing along bicharacteristics of p in the interior of ${}^{\mathrm{sc}}T^*X$, i.e. the bicharacteristics leave the boundary, i.e. 'come in from infinity' if ∂X is removed, while if $\lambda < 0$, the bicharacteristics approach the boundary, i.e. 'go out to infinity'. Correspondingly we make the following definition.

Definition 2.3. We say that a non-degenerate radial point q for p with $dp(q) = \lambda\alpha(q)$ is outgoing if $\lambda < 0$, and we say that it is incoming if $\lambda > 0$.

For $p = |\zeta|^2 + V_0 - \sigma$, we have $\lambda = -\partial_\nu p = -2\nu$. Hence, radial points are outgoing for $\nu > 0$ and incoming for $\nu < 0$ in this case. We next discuss the form the linearization takes for $p = |\zeta|^2 + V_0 - \sigma$.

Lemma 2.4. *For the function $p = |\zeta|^2 + V_0 - \sigma$ with V_0 Morse, the radial points are all nondegenerate and the linear operator S associated with each has only two-dimensional invariant symplectic subspaces.*

Remark 2.5. In view of the non-occurrence of non-decomposable invariant subspaces of dimension 4 in this case we will exclude them from further discussion below.

Proof. Choose Riemannian normal coordinates y_j on ∂X, so the metric function h satisfies $h - |\mu|^2 = \mathcal{O}(|y|^2)$. Since the Hessian of $V|_{\partial X}$ is a symmetric matrix, it can be diagonalized by a linear change of coordinates on ∂X, given by a matrix in $\mathrm{SO}(n-1)$, which thus preserves the form of the metric. It follows that for each j, $(dy_j, d\mu_j)$ is an invariant subspace of A. □

Let $\mathcal{I}$ denote the ideal of $\mathcal{C}^\infty$ functions on ${}^{\mathrm{sc}}T^*_{\partial X}X$ vanishing at a given radial point, q. The linearization of W then acts on $T^*_q\left({}^{\mathrm{sc}}T^*_{\partial X}X\right) = \mathcal{I}/\mathcal{I}^2$; $dp(q)$, or equivalently α_q, is necessarily an eigenvector of A with eigenvalue 0. Similarly, ${}^{\mathrm{sc}}H_p$ defines a linear map $\tilde{A}$ on $T^*_q\left({}^{\mathrm{sc}}T^*X\right)$. Since $dp(q) = -\lambda d\nu$, $\tilde{A}$ preserves the conormal line, $\operatorname{span} dx$ and the eigenvalue of $\tilde{A}$ corresponding to the eigenvector dx is λ. Thus $\tilde{A}$ acts on the quotient

$$T^*_q\left({}^{\mathrm{sc}}T^*_{\partial X}X\right) \equiv T^*_q\left({}^{\mathrm{sc}}T^*X\right) / \operatorname{span} dx,$$

and this action clearly reduces to A.

By Darboux's theorem we may make a local contact diffeomorphism of ${}^{\mathrm{sc}}T^*_{\partial X}X$ and arrange that $q = (0,0,0)$. Thus, as a module over $\mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X)$ in terms of multiplication of functions, $\mathcal{I}$ is generated by ν, y_j and the μ_j, for $j = 1, \ldots, n-1$. Thus in general we have the following possibilities for the two-dimensional invariant subspaces of A.

(i) There are two independent real eigenvectors with eigenvalues in $\lambda(\mathbb{R}\backslash[0,1])$.

(ii) There are two independent real eigenvectors with eigenvalues in $\lambda(0,1)$.
(iii) There are no real eigenvectors and two complex eigenvectors with eigenvalues in $\lambda(\frac{1}{2}+i(\mathbb{R}\setminus\{0\}))$.
(iv) There is only one non-zero real eigenvector with eigenvalue $\frac{1}{2}\lambda$.

Case (iv) was called the 'Hessian threshold' case in Part I. In all cases the sum of the two (generalized) eigenvalues is λ.

Lemma 2.6. *By making a change of contact coordinates near a radial point q for $p \in \mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X)$ for which the linearization has neither a Hessian threshold subspace,* (iv)*, nor any non-decomposable 4-dimensional invariant subspace, coordinates y and μ, decomposed as $y = (y', y'', y''')$ and $\mu = (\mu', \mu'', \mu''')$, may be introduced so that*

(i)
$$(y', \mu') = (y_1, \dots, y_{s-1}, \mu_1, \dots, \mu_{s-1}) \tag{2.11}$$
where $e'_j = dy'_j$, $f'_j = d\mu'_j$ are eigenvectors of A with eigenvalues $\lambda r'_j$, $\lambda(1-r'_j)$, $j = 1, \dots, s-1$ with $r'_j < 0$ real and negative.

(ii) *$(y'', \mu'') = (y_s, \dots, y_{m-1}, \mu_s, \dots, \mu_{m-1})$ where $e''_j = dy''_j$, $f''_j = d\mu''_j$ are eigenvectors with eigenvalues $\lambda r''_j$, $\lambda(1-r''_j)$, $j = s, \dots, m-1$ where $0 < r''_j \le 1/2$ is real and positive.*

(iii) *$(y''', \mu''') = (y_m, \dots, y_{n-1}, \mu_m, \dots, \mu_{n-1})$, where some complex combination of e'''_j, f'''_j, of dy'''_j and $d\mu'''_j$, $m \le j \le n-1$, are eigenvectors with eigenvalues $\lambda r'''_j$ and $\lambda(1-r'''_j)$ with $r'''_j = 1/2 + i\beta'''_j$, $\beta'''_j > 0$.*

Thus if we set $e = (e', e'', e''')$, $f = (f', f'', f''')$ the eigenvectors of A are $d\nu, e_j$ and f_j, with respective eigenvalues $0, \lambda r_j$ and $\lambda(1-r_j)$; we will take the coordinates so that the r_j are ordered by their real parts.

In coordinates in which the eigenspaces take this form it can be seen directly that
$$p = -\nu + \sum_{j=1}^{m-1} r_j y_j \mu_j + \sum_{j=m}^{n-1} Q_j(y_j, \mu_j) + \nu e_1 + e_2 \tag{2.12}$$
the Q_j, are homogeneous polynomials of degree 2, e_1 vanishes at least linearly and e_2 to third order.

Remark 2.7. For the function $p = |\zeta|^2 + V_0 - \sigma$ with V_0 Morse, the eigenvalues of A at a radial point q are easily calculated in the coordinates used in the proof of Lemma 2.4. Indeed, since the 2-dimensional invariant subspaces decouple, the results of [4] can be used. The eigenvalues corresponding to the 2-dimensional subspace in which the eigenvalue of the Hessian is $2a_j$ are thus
$$\lambda\left(\frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{a_j}{\sigma - V_0(0)}}\right), \text{ where } \lambda = -2\nu(q).$$

3. Microlocal normal form

We will reduce $P(\sigma) = x^{-1}(\Delta + V - \sigma)$ to a model form by conjugation with a Fourier integral operator e^{iB}, where $B \in \Psi^{*,-1}_{\mathrm{sc}}(X)$ has real principal symbol, so $P' = e^{-iB}Pe^{iB} \in \Psi^{*,-1}_{\mathrm{sc}}(X)$. Under a local version of the Fourier transform this is equivalent to the conjugation of a pseudodifferential operator, in the usual sense, by the Fourier integral operator obtained by exponentiation of a pseudodifferential operator of first order, with real principal symbol; see [14]. In particular $H_{\tilde b}$ (where $\tilde b = \sigma(B)$) is a smooth vector field on ${}^{\mathrm{sc}}T^*X$ tangent to its boundary and by Egorov's theorem, $\sigma(P')$ is the pull-back of $\sigma(P)$ by the flow of the vector field $H_{\tilde b}$ at time 1.

In fact, we only need to put the principal and subprincipal symbols of P into model form, and the latter needs to be done only along the 'flow-out', i.e. the unstable manifold, of q, which can be done via conjugation by a function; this is accomplished in Lemma 6.1. The model form of the subprincipal symbol only plays a role in the polyhomogeneous, as opposed to just conormal, analysis, which is the reason it is postponed to Section 6.

Thus, in this section we only put the principal symbol of P into a normal form p_{norm}. For this purpose, we only need to construct the principal symbol $\sigma(B)$ of B as in the first paragraph. This in turn can be be written as $x^{-1}\tilde b$, $\tilde b \in \mathcal{C}^\infty({}^{\mathrm{sc}}T^*X)$, so we only need to construct a function b on ${}^{\mathrm{sc}}T^*_{\partial X}X$ such that the pull-back $\Phi^* p$ of p by the time 1 flow Φ of $H_{x^{-1}\tilde b}$ is the desired model form p_{norm}, where $\tilde b$ is some extension of b to ${}^{\mathrm{sc}}T^*X$; this property is independent of the chosen extension. Thus *any* B with $\sigma(B) = \tilde b$ will conjugate P to an operator with principal symbol p_{norm}. This construction is accomplished in two steps, following Guillemin and Schaeffer [3] in the non-resonant setting. First we construct the Taylor series of b at $q = (0,0,0)$, which puts p into a model form modulo terms vanishing to infinite order at q. Next, we remove this error *along the unstable manifold* of q by modifying an argument due to Nelson [15].

Rather than using powers of $\mathcal{I}$ to filter $\mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X)$ in the construction of the Taylor series of b, we proceed as in [3] and assign degree 1 to y and μ but degree two to ν in local coordinates as discussed above. Thus, let $\mathfrak{h}^j$ denote the space of functions

$$\mathfrak{h}^j = \sum_{2a+|\beta|+|\gamma|-2=j} \nu^a y^\beta \mu^\gamma \mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X)$$

Note that this is well-defined, independently of our choice of local coordinates, since $-d\nu$ is the contact form α at q, so ν is well-defined up to quadratic terms. The Poisson bracket preserves this filtration of $\mathcal{I}$ in the following sense. If $\tilde a$, $\tilde b$ are some smooth extensions to ${}^{\mathrm{sc}}T^*X$ of elements $a \in \mathfrak{h}^i$, $b \in \mathfrak{h}^j$ then

$$x^{-1}\tilde c = \{x^{-1}\tilde a, x^{-1}\tilde b\} \Longrightarrow c = \tilde c|_{{}^{\mathrm{sc}}T^*_{\partial X}X} \in \mathfrak{h}^{i+j}.$$

When this holds we write $c = \{\{a,b\}\}$; explicitly,

$$\{\{a,b\}\} = W_a(b) + \frac{\partial a}{\partial \nu} b - \frac{\partial b}{\partial \nu} a, \tag{3.1}$$

with W given by (2.4). Thus

$$\{\{.,.\}\} : \mathfrak{h}^i \times \mathfrak{h}^j \mapsto \mathfrak{h}^{i+j}. \tag{3.2}$$

We then consider the quotient

$$\mathfrak{g}^j = \mathfrak{h}^j / \mathfrak{h}^{j+1},$$

so the bracket $\{\{.,.\}\}$ descends to

$$\mathfrak{g}^i \times \mathfrak{g}^j \to \mathfrak{g}^{i+j}.$$

Remark 3.1. These statements remain true with $\mathfrak{h}^j$ replaced by $\mathcal{I}^j$. However, note that $p = -\nu$ in $\mathcal{I}/\mathcal{I}^2$, since $dp = -d\nu$ at q, but it is *not true* that $p = -\nu$ in $\mathfrak{g}^0$. In fact, p is given by (3.3) below in $\mathfrak{g}^0$.

Using contact coordinates as discussed above, $\mathfrak{g}^j$ may be freely identified with the space of homogeneous functions of ν, y, μ of degree $j+2$ where the degree of ν is 2. Now let p_0 be the part of p of homogeneity degree two, so from (2.12)

$$p_0 = -\nu + \sum_{j=1}^{m-1} r_j y_j \mu_j + \sum_{j=m}^{n-1} Q_j(y_j, \mu_j),\ p - p_0 \in \mathfrak{h}^1. \tag{3.3}$$

If we take $b \in \mathfrak{h}^l$, $l \geq 1$ and let Φ be the time 1 flow of $H_{x^{-1}b}$ then

$$x\Phi^*(x^{-1}p) = p + \{\{p, b\}\} = p + \{\{p_0, b\}\},\ \text{modulo } \mathfrak{h}^{l+1}. \tag{3.4}$$

This allows us to remove higher order term in the Taylor series of the symbol successively provided we can solve the 'homological equation'

$$\{\{p_0, b\}\} = e \in \mathfrak{h}^l,\ \text{modulo } \mathfrak{h}^{l+1}.$$

This we need to consider the range of this linear map; its eigenfunctions are easily found from the eigenfunctions of the linearization of ${}^{\mathrm{sc}}H_p$.

Lemma 3.2. *The (equivalence classes of the) monomials $p_0^a e^\beta f^\gamma$ with $2a + |\beta| + |\gamma| = l + 2$ satisfy*

$$\begin{gathered}\{\{p_0, p_0^a e^\beta f^\gamma\}\} = R_{a,\beta,\gamma} p_0^a e^\beta f^\gamma \text{ with eigenvalue} \\ R_{a,\beta,\gamma} = \lambda \left(a - 1 + \sum_{j=1}^{n-1} \beta_j r_j + \sum_{j=1}^{n-1} \gamma_j (1 - r_j) \right)\end{gathered} \tag{3.5}$$

and give a basis of eigenvectors for $\{\{p_0, .\}\}$ acting on $\mathfrak{g}^l$.

Proof. Taking into account the eigenvalues and eigenvectors of A, all eigenvalues and eigenvectors of $\{\{p_0, .\}\}$ can be calculated iteratively using the derivation property of the original Poisson bracket. This implies

$$\begin{aligned}\{\{p_0, ab\}\} &= x\{x^{-1}p_0, x(x^{-1}a)(x^{-1}b)\} \\ &= x^{-1}\{x^{-1}p_0, x\}ab + x\{x^{-1}p_0, x^{-1}a\}b + xa\{x^{-1}p_0, x^{-1}b\} \\ &= \lambda ab + \{\{p_0, a\}\}b + a\{\{p_0, b\}\},\end{aligned} \tag{3.6}$$

where each term within $\{.,.\}$ really uses a $\mathcal{C}^\infty$ extensions of the a, b, p_0 to ${}^{\mathrm{sc}}T^*X$, followed by evaluation of the bracket and then restriction to ${}^{\mathrm{sc}}T^*_{\partial X}X$. Since

$$\{\{p_0, a\}\} = x\{x^{-1}p_0, x^{-1}a\} = x\{x^{-1}p_0, x^{-1}\}a + \{x^{-1}p_0, a\} = -\lambda a + \{x^{-1}p_0, a\},$$

on $\mathfrak{g}^{-1}$ the eigenvectors of $\{\{p_0, .\}\}$ are the eigenvectors e_j and f_j of A with eigenvalues $-\lambda + \lambda r_j$ and $-\lambda + \lambda(1 - r_j)$. Moreover, in $\mathfrak{g}^0$, p_0 is an eigenvector of $\{\{p_0, .\}\}$ with eigenvalue 0. Thus, e_j, f_j and p_0 satisfy the claim of the lemma. Since the other generators of $\mathfrak{g}^0$, as well as generators of $\mathfrak{g}^j$, $j \geq 1$, can be written as a products of the e_j, f_j and p_0, the conclusion of the lemma follows by induction. □

Definition 3.3. We call the multiindices in the set

$$I = \{(\alpha, \beta); R_{0,\beta,\gamma} = 0 \text{ and } |\alpha| + |\beta| \geq 3\}, \tag{3.7}$$

with $R_{a,\beta,\gamma}$ given by (3.5), *resonant*.

Conjugation therefore allows us to remove, by iteration, all terms except those with indices in I. Expanding p_0^a using (3.3) we deduce the following.

Proposition 3.4. *If P is as above and the leading term of $p = \sigma_{\partial,-1}(P)$ is given by* (3.3) *near a given radial point q then there exists a local contact diffeomorphism Φ near q such that*

$$e^{-1}\Phi^* p = -\nu + \sum_{j=1}^{m} r_j y_j \mu_j + \sum_{j=m+1}^{n-1} Q_j(y_j,\mu_j) + \sum_I c_{\alpha,\beta} e^\alpha f^\beta \text{ modulo } \mathcal{I}^\infty = \mathfrak{h}^\infty \text{ at } q \tag{3.8}$$

with e smooth, $e(q) = 1$ and I given by (3.7)*.*

Proof. The Taylor series of Φ and e at q can be constructed inductively over the filtration $\mathfrak{h}^j$ as indicated above. At the jth stage, the terms of weighted homogeneity j can be removed from p except for those in the null space of $\{\{p_0,\cdot\}\}$, i.e. the resonant terms with $R_{a,\alpha,\beta} = 0$. For those with $a > 0$, i.e. with at least one factor of p_0, can be removed by adding a term of the appropriate homogeneity to e. This leads to (3.8) in the sense of formal power series. However, by use of Borel's Lemma a local contact diffeomorphism and elliptic factor can be found giving (3.8). □

Now a small extension of Nelson's proof of the Sternberg linearization theorem can be used to remove the infinite order vanishing error along the unstable manifold, i.e. at $\nu = 0$, $\mu = 0$, $y'' = 0$, $y''' = 0$.

Proposition 3.5. *Suppose that X and X_0 are $\mathcal{C}^\infty$ vector fields on $\mathbb{R}^N$ with $X - X_0$ vanishing to infinite order at* 0*. Suppose also that they are both linear outside a compact set and equal there to their common linearization, $DX(0)$, at* 0 *which is assumed to have no pure imaginary eigenvalue. Let $U(t)$, $U_0(t)$ be the flows generated by X and X_0. If E is a linear submanifold invariant under X_0 such that*

$$\lim_{t\to\infty} U_0(t)x = 0 \ \forall\ x \in E \tag{3.9}$$

then for all $j = 0, 1, 2, \ldots$ and $x \in E$

$$\lim_{t\to\infty} D^j(U(-t)U_0(t))x \tag{3.10}$$

exists, and is continuous in $x \in E$, and

$$W_- x = \lim_{t\to\infty} U(-t)U_0(t)x,\ x \in E$$

has a $\mathcal{C}^\infty$ extension, G, to $\mathbb{R}^N$ which is the identity to infinite order at 0 *and such that $(G^{-1})_* X = X_0$ to infinite order along E in a neighbourhood of* 0*.*

Remark 3.6. Note that the derivatives D^j in (3.10) refer to the ambient space $\mathbb{R}^N$, and *not* merely to E. This is useful in producing the Taylor series of G for the last part of the conclusion.

Proof. We follow the proof of Theorem 8 in [15]. Indeed, if X_0 was assumed to be linear then Nelson's theorem would apply directly. In fact, dropping this assumption has little effect on the proof; the main difference is that a little more work is required to show the exponential contraction property, (3.11) below.

Since the real part of every eigenvalue of $DX(0)$ is non-zero, $\mathbb{R}^N = E_+ \oplus E_-$ where E_+, resp. E_-, is the direct sum of the generalized eigenspaces of $DX(0)$ with eigenvalues with positive, resp. negative, real parts. Since E is invariant under X_0, and hence under $DX(0)$, necessarily $E \subset E_-$. We actually apply the theorem with

$E = E_-$, but, as in Nelson's discussion, the more general case is useful for the inductive argument for the derivatives.

Let e_j denote a basis of E_- consisting of generalized eigenvectors of $DX(0)$ with corresponding eigenvalue σ_j; we shall consider the e_j as differentials of linear functions f_j on $\mathbb{R}^N$. For $x \in \mathbb{R}^N$, let $x(t) = U_0(t)x$, $F_j(t) = f_j(x(t))$. Then $\frac{dF_j}{dt}|_{t=t_0} = (X_0 f_j)(x(t_0))$ where

$$X_0 f_j(y) = DX(0) f_j(y) + \mathcal{O}(\|y\|^2).$$

Moreover, for $y \in E_-$, $\|y\|^2 \leq C_1 \sum_j f_j^2$ for some $C_1 > 0$. So, setting $\rho = \sum f_j^2$, we deduce that

$$X_0 \rho(y) = \sum_j 2\sigma_j f_j^2(y) + \mathcal{O}(\rho(y)^{3/2}),$$

hence with $R(t) = \rho(x(t))$, $c_0 \in (\sup \sigma_j, 0)$, there exists $\delta > 0$ such that for $\|R(t)\| \leq \delta$,

$$\frac{dR}{dt} - 2c_0 R \leq 0,$$

and hence $R(t) \leq e^{-2c_0 t}\|x\|$ for $t \geq 0$, $\|r(x)\| \leq \delta$, $x \in E_-$. A corresponding estimate also holds outside a compact set, as X_0 is given by $DX(0)$ there, so a patching argument and (3.9) yield the estimate $R(t) \leq C_0 e^{-2c_0 t}\|x\|$ for all $x \in E_-$. Since $R(t)^{1/2}$ is equivalent to $\|.\|$, we deduce that there are constants C, $c > 0$ such that

$$\|U_0(t)x\| \leq Ce^{-ct}\|x\| \ \forall\ x \in E \text{ and } t \geq 0. \tag{3.11}$$

For the remainder of the argument we can follow Nelson's proof even more closely. Thus, let κ be a Lipschitz constant for X and X_0, and choose m such that $cm > \kappa$. Note that there exists $c_0 > 0$ such that for all $x \in \mathbb{R}^N$,

$$\|X_1(x)\| \leq c_0 \|x\|^m. \tag{3.12}$$

For $t_1 \geq t_2 \geq 0$, $t_1 = t_2 + t$, $x \in E$,

$$\begin{aligned} I = \|U(-t_1)U_0(t_1)x - U(-t_2)U_0(t_2)x\| &= \|U(-t_2)\left(U(-t)U_0(t) - \mathrm{Id}\right)U_0(t_2)x\| \\ &\leq e^{\kappa t_2}\|(U(-t)U_0(t) - \mathrm{Id})U_0(t_2)x\| \end{aligned}$$

by the Lipschitz condition (see [15, Theorem 5]). But with $X = X_0 + X_1$, by [15, Proof of Theorem 6, (5)]

$$\|U(-t)U_0(t)y - y\| \leq \int_0^t e^{\kappa s}\|X_1(U_0(s)y)\|\, ds.$$

Applying this with $y = U_0(t_2)x$, we deduce that

$$I \leq e^{\kappa t_2}\int_0^t e^{\kappa s}\|X_1(U_0(s+t_2)x)\|\, ds. \tag{3.13}$$

Thus, by (3.12) and (3.11),

$$\begin{aligned} I &\leq e^{\kappa t_2}\int_0^t e^{\kappa s} c_0 C^m e^{-cm(s+t_2)}\|x\|^m\, ds \\ &\leq e^{\kappa t_2}\int_0^\infty e^{\kappa s} c_0 C^m e^{-cm(s+t_2)}\|x\|^m\, ds = \frac{c_0 C^m e^{-(cm-\kappa)t_2}\|x\|^m}{cm-\kappa}. \end{aligned}$$

Letting $t_2 \to \infty$ shows that $W_- x = \lim_{t\to\infty} U(-t)U_0(t)x$ exists, with convergence uniform on compact sets, hence W_- is continuous in $x \in E$. Moreover, applying the estimate with $t_2 = 0$ shows that $W_-(x) - x = \mathcal{O}(\|x\|^m)$. Since m is arbitrary, as long as it is sufficiently large, this shows that W_- is the identity to infinite order at 0, provided it is smooth, as we proceed to show.

Smoothness can be seen by a similar argument. Namely, first consider the first derivatives, or rather the 1-jet. Thus, we work on $\mathbb{R}^N \oplus \mathcal{L}(\mathbb{R}^N)$. Let (x, ξ) denote the components with respect to this decomposition. These evolve under the flow $U'(t)$, resp. $U_0'(t)$, given by

$$X'(x,\xi) = (X(x), DX(x)\cdot\xi),\ \ X_0'(x,\xi) = (X_0(x), DX_0(x)\cdot\xi),$$

where $DX(x)$ and ξ are considered as elements of $\mathcal{L}(\mathbb{R}^N)$, and $\cdot$ is composition of operators. These vector fields are globally Lipschitz with Lipschitz constant κ' even though they are *not* linear outside a compact subset of $\mathbb{R}^N \oplus \mathcal{L}(\mathbb{R}^N)$ due to the dependence of DX on x. Thus,

$$\|U_0'(t)(x,\xi)\| \leq e^{\kappa' t}\|(x,\xi)\|, \tag{3.14}$$

see [15, Theorem 5]. So (3.13) still applies, with X_1 replaced by X_1', κ replaced by κ', etc. Now choose m such that $cm > 2\kappa'$. Then

$$\|X_1'(y,\eta)\| \leq c_0'\|y\|^m\|(y,\eta)\|, \tag{3.15}$$

so by (3.11) and (3.14),

$$\begin{aligned} I &\leq e^{\kappa' t_2}\int_0^t e^{\kappa' s} c_0' C^m e^{-cm(s+t_2)}\|x\|^m e^{\kappa'(s+t_2)}\|(x,\xi)\|\,ds \\ &\leq e^{\kappa' t_2}\int_0^\infty e^{\kappa' s} c_0' C^m e^{-cm(s+t_2)}\|x\|^m e^{\kappa'(s+t_2)}\|(x,\xi)\|\,ds \\ &= \frac{c_0' C^m e^{-(cm-2\kappa')t_2}\|x\|^m}{cm-2\kappa'}. \end{aligned}$$

Thus, $\lim_{t\to\infty} U'(-t)U_0'(t)x$ exists, with convergence uniform on compact sets, so the limit depends continuously on (x,ξ) for $x \in E$.

The higher derivatives can be handled similarly. The resulting Taylor series about E can be summed asymptotically, giving G: this part of the argument of Nelson is unchanged. □

Next we apply this general result to the symbol p. Following Lemma 2.6, when resonances occur we cannot remove all error terms even in the sense of formal power series. Consequently we do not attempt to get a full normal form in a neighbourhood of the critical point, but only along the submanifold

$$S = \{\nu = 0,\ y'' = 0,\ y''' = 0,\ \mu = 0\}, \tag{3.16}$$

which is the unstable manifold for W_0. After reduction to normal form, errors which are polynomial in the normal directions to S will remain. For later purposes, we divide these into two parts. An 'effectively resonant' error term is a polynomial containing only resonant terms of the form

$$r_{\mathrm{er}} = \sum_{\alpha', |\beta'|=1} c_{\alpha'\beta'}(e')^{\alpha'}(f')^{\beta'} + \sum_{\alpha'',\beta''} c_{\alpha''\beta''}(e'')^{\alpha''}(f'')^{\beta''}. \tag{3.17}$$

Notice that there are only a finite number of terms which can occur here at a given critical point since in the first sum β' is restricted to be degree one and $r_j' < 0$ for all j, while in the second r_j'' and $1 - r_j''$ have the same sign; since $1 - r_j'' > 1/2$ it follows that $|\beta''| \leq 1$ in the second sum as well. Let $\mathcal{J}_S$ denote the ideal of $\mathcal{C}^\infty$ functions on ${}^{\mathrm{sc}}T^*_{\partial X}X$ which vanish on S and set

$$I'' = \left\{(\alpha'', \beta''); \sum_{j=s}^{m-1} r''_j \alpha''_j + (1 - r''_j)\beta''_j \in (1, 2)\right\}. \tag{3.18}$$

An 'effectively nonresonant' error term is an element of $\mathcal{J}_S$ of the form

$$\begin{gathered} r_{\mathrm{enr}} = \sum_{j=1}^{s} h_j f'_j + \sum_{(\alpha'',\beta'')\in I''} h''_{\alpha'',\beta''} e^{\alpha''} f^{\beta''} + \sum_{j,k} h'''_{jk} e'''_j f'''_k \\ h_j \in \mathcal{J}_S,\ j = 0, 1, \ldots, s,\ h''_{\alpha'',\beta''} \in \mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X),\ (\alpha'', \beta'') \in I'', \\ h'''_{jk} \in \mathcal{J}_S,\ j, k = m, \ldots, n-1. \end{gathered} \tag{3.19}$$

Theorem 3.7. *Using the notation of Lemma 2.6 for coordinates near a radial point of q of p there is a local contact diffeomorphism Φ from a neighbourhood of $(0, 0, \ldots, 0)$ to a neighbourhood of q such that $\Phi^* p = e p_{\mathrm{norm}}$ with $e(q) = 1$ such that*

$$p_{\mathrm{norm}} = -\nu + \sum_j r_j y_j \mu_j + \sum_{j=m}^{n-1} Q_j(y_j, \mu_j) + r_{\mathrm{enr}} + r_{\mathrm{er}}, \tag{3.20}$$

with r_{enr} of the form (3.19) *and r_{er} of the form* (3.17)*; in addition at a non-resonant critical point, i.e. if $I = \emptyset$, then we may take $r_{\mathrm{enr}} = r_{\mathrm{er}} = 0$ near q.*

Remark 3.8. If F is a Fourier integral operator with canonical relation Φ then $\tilde{E}\tilde{P} = F^{-1}PF$, with $\tilde{E}$ elliptic at q, satisfies $\sigma_{\partial,-1}(\tilde{P}) = p_{\mathrm{norm}}$.

Remark 3.9. Is will be seen below, of the two error terms, only r_{er} has any effect on the leading asymptotics of microlocal solutions. The construction below shows that modulo $\mathcal{I}^\infty$, r_{enr} may be chosen to consist of resonant terms only, i.e. to be an asymptotic sum of resonant terms. However, this plays no role in the paper; all the relevant information is contained in the statement of the theorem.

Remark 3.10. Any term $\nu^a \mu^\beta y^\gamma$ with $a + |\beta| \geq 2$ and $a \neq 0$, or with $|\beta| \geq 3$ can be included in r_{er} or r_{enr}. The same is true for any term with $|\beta| \geq 2$ such that $\beta_j \neq 0$ for some j with $\operatorname{Re} r_j \neq \frac{1}{2}$. In particular, if $\operatorname{Re} r_j \neq \frac{1}{2}$ for any j, the only terms which need to be removed have $a + |\beta| \leq 1$. The conjugating Fourier integral operator can therefore also be arranged to have such terms only and thus to be of the form e^{iB}, with $B = Z + (f/x)$ where Z is a vector field on X tangent to its boundary and f is smooth function on X. Correspondingly, the normal form may be achieved by conjugation of P by an oscillatory function, $e^{if/x}$, followed by pull-back by a local diffeomorphism of X, i.e. a change of coordinates. However, if $\operatorname{Re} r_j = \frac{1}{2}$ for some j, some quadratic terms in μ would also need to be removed for the model form, but since they play a role analogous to r_{er}, the arguments of Section 5, giving conormality, are unaffected, and only the polyhomogeneous statements of Section 6 would need alterations. However, the contact diffeomorphism (i.e. FIO conjugation) approach we present here is both more unified and more concise.

Proof. First we apply Proposition 3.4. Next we need to show that r_{er} as in (3.17) and r_{enr} as in (3.17) can be chosen to have Taylor series at 0 given exactly by the error term in (3.8).

So, consider a monomial $\nu^a e^\alpha f^\beta$ with $(a,\alpha,\beta)\in I$. If $\alpha'''\neq 0$ then $\beta'''\neq 0$ since $\operatorname{Im} r_j''' > 0$, and only the eigenvalues of f_j''' have negative imaginary parts, and conversely. In addition, $2a+|\alpha|+|\beta|\geq 3$ implies that a monomial with $\alpha'''\neq 0$ or $\beta'''\neq 0$ has the form $\nu^a e^{\tilde\alpha} f^{\tilde\beta} e_j''' f_k'''$ for some j,k with $2a+|\tilde\alpha|+|\tilde\beta|\geq 1$ and

$$\operatorname{Re}(a+\sum r_l\tilde\alpha_l+\sum(1-r_l)\tilde\beta_l)=0.$$

Since $\operatorname{Re}(1-r_l)>0$ for all l and $\operatorname{Re} r_l>0$ for $l\geq s$, while $r_l<0$ for $l\leq s-1$, we must have $\tilde\alpha'\neq 0$ (i.e. $\tilde\alpha_l\neq 0$ for some $l\leq s-1$) and correspondingly $a+|\tilde\alpha''|+|\tilde\alpha'''|+|\tilde\beta|>0$. Due to the latter, $\nu^a e^{\tilde\alpha} f^{\tilde\beta}$ vanishes on S, so the terms with $\alpha'''\neq 0$ or $\beta'''\neq 0$ appear in r_{enr}.

So we may assume that $\alpha'''=\beta'''=0$. If $a\neq 0$, the monomial is of the form $\nu^{\tilde a} e^{\tilde\alpha} f^{\tilde\beta}\nu$, $\tilde a=a-1$, $2\tilde a+|\tilde\alpha|+|\tilde\beta|\geq 1$ with

$$\tilde a+\sum r_j\tilde\alpha_j+\sum(1-r_j)\tilde\beta_j=0.$$

Arguing as in the previous paragraph we deduce that the terms with $a\neq 0$ also appear in r_{enr}.

So we may now assume that $a=0$, $\alpha'''=\beta'''=0$. If $\beta'\neq 0$, the monomial is of the form $\nu^a e^{\tilde\alpha} f^{\tilde\beta} f_j$ for some j, and $2a+|\tilde\alpha|+|\tilde\beta|\geq 2$,

$$a+\sum r_l\tilde\alpha_l+\sum(1-r_l)\tilde\beta_l=r_j<0.$$

We can still conclude that $\tilde\alpha'\neq 0$, but it is not automatic ath $a+|\tilde\alpha''|+|\tilde\beta|>0$. However, if $a+|\tilde\alpha''|+|\tilde\beta|>0$ then $\nu^a e^{\tilde\alpha} f^{\tilde\beta} f_j$ is again included in r_{enr}, while if $a+|\tilde\alpha''|+|\tilde\beta|=0$, then the monomial is included in r_{er}.

Finally then, we may assume that $a=0$, $\beta'=0$, $\alpha'''=\beta'''=0$. Since $r_j'<0$ for all $j=1,\ldots,s-1$

$$\sum(r_j''\alpha_j''+(1-r_j'')\beta_j'')\geq\sum r_j'\alpha_j'+\sum(r_j''\alpha_j''+(1-r_j'')\beta_j'')=1.$$

Moreover, the equality holds if and only if $\alpha'=0$, in which case this term is included in r_{er}. The terms with $\alpha'\neq 0$ can be included in $h''_{\tilde\alpha'',\tilde\beta''} e^{\tilde\alpha''} f^{\tilde\beta''}$ for some $\tilde\alpha''\leq\alpha''$, $\tilde\beta''\leq\beta''$, chosen by reducing α'' and/or β'' to make

$$\sum(r_j''\tilde\alpha_j''+(1-r_j'')\tilde\beta_j'')\in(1,2).$$

This can be done since r_j'', $1-r_j''\in(0,1)$.

It follows that p can be conjugated to the form

$$-\nu+\sum_j r_j y_j\mu_j+\sum_{j=m}^{n-1} Q_j(y_j,\mu_j)+r_{\mathrm{enr}}+r_{\mathrm{er}}+r_\infty, \tag{3.21}$$

where $r_{\mathrm{enr}}, r_{\mathrm{er}}$ are as in (3.19), (3.17), with both vanishing if q is non-resonant, and r_∞ vanishes to infinite order at $(0,0,0)$. Thus, it remains to show that we can remove the r_∞ term in a neighbourhood of the origin.

To do this we apply Proposition 3.5. Let X' be the Legendre vector field of (3.21), and let X_1' be the Legendre vector field of r_∞, while $X_0'=X'-X_1'$. Let $\tilde X$ be the linear vector field with differential equal to $DX(0)$, let χ be identically 1 near 0, and let $X=\chi X'+(1-\chi)\tilde X$, etc. Let E be the subspace S of $\mathbb{R}^{2n-1}$, defined by (3.16). Then Proposition 3.5 is applicable, and G given by it may be chosen as a contact diffeomorphism since $U(t)$, $U_0(t)$ are such, see [3, Section 3, Theorem 4]. □

We also need a parameter-dependent version of this theorem. Namely, suppose that p depends smoothly on a parameter σ, can we make the normal form depend smoothly on σ as well? This problem can be approached in at least two different ways. One can consider σ simply as a parameter, so $p \in \mathcal{C}^\infty((\partial^{\mathrm{sc}}T^*X) \times I) = \mathcal{C}^\infty(({}^{\mathrm{sc}}T^*_{\partial X}X) \times I)$ and then try to carry out the reduction to normal form uniformly. Alternatively, one identify p with the function p' on the larger space $\partial^{\mathrm{sc}}T^*(X \times I)$ arising by the pull-back under the natural projection

$$p' = \pi^* p,\ \pi : {}^{\mathrm{sc}}T^*_{\partial X \times I}(X \times I) \to ({}^{\mathrm{sc}}T^*_{\partial X}X) \times I$$

and then carry out the reduction to a model on the larger space. Whilst the second approach may be more natural from a geometric stance, we will adopt the first, since it is closer to the point of view of spectral theory of [4]. Clearly the difficulty in obtaining a uniform normal form is particularly acute near a value of σ at which the effectively resonant terms do not vanish. Fortunately in the case of central interest here, and in other cases too, the set of points at which such problems arise is discrete.

Lemma 3.11. *If $P = P(\sigma) = x^{-1}(\Delta + V - \sigma)$, $q = q(\sigma)$ is a radial point of P lying over the critical point $\pi(q)$ of V_0 and $I(\sigma))$ is the set* (3.7) *for $p(\sigma)$ then*

(3.22)
$$\mathcal{R}_{\mathrm{er},q} = \big\{\sigma \in (V_0(\pi(q)), +\infty);\ \textit{either}\ \exists\ (0,(\alpha',0),(\beta',0)) \in I(\sigma)\ \textit{with}\ |\beta'| = 1 \\ \textit{or}\ \exists\ (0,(0,\alpha''),(0,\beta'')) \in I(\sigma)\big\}$$

is discrete in $(V_0(\pi(q)), +\infty)$.

Remark 3.12. It follows that if $K \subset (V_0(\pi(q)), +\infty)$ is compact then $K \cap \mathcal{R}_{\mathrm{er},q}$ is finite. Thus, to prove properties such as asymptotic completeness, one can ignore all effectively resonant $\sigma \in K$.

Proof. Let K be a compact subset of $(V_0(\pi(q)), +\infty)$. The set $K \cap \mathcal{R}_{\mathrm{er},q}$ of effectively resonant energies in K is the the union of zeros of a finite number of analytic functions (none of which are identically zero). Indeed, from Theorem 3.7, $\mathcal{R}_{\mathrm{er},q}$ is given by the union of the set of zeros of the countable collection of functions

$$-1 + \sum_{j=s}^{m-1} \alpha''_j r''_j(\sigma) + \beta''_j(1 - r''_j(\sigma)), \quad -1 + (1 - r_k) + \sum_{j=1}^{s-1} \alpha'_j r'_j(\sigma)$$

as $k = 1, \ldots, s-1$, while α', α'', β'' are multiindices. But if $c > 0$ is large enough then $c^{-1} > |r_j(\sigma)| > c$ for all j and for all $\sigma \in K$ as K is compact and the r_j do not vanish there. Correspondingly, for $|\alpha'| > \frac{2}{c^2}$,

$$-1 + (1 - r_k) + \sum_{j=1}^{s-1} \alpha'_j r'_j(\sigma) < -r_k - |\alpha'|c < -c^{-1},$$

and analogously for $|\alpha''| + |\beta''| > \frac{2}{c}$,

$$-1 + \sum_{j=s}^{m-1} \alpha''_j r''_j(\sigma) + \beta''_j(1 - r''_j(\sigma)) > -1 + (|\alpha''| + |\beta''|)c > 1.$$

Thus, there are only a finite number of these analytic functions that may vanish in K, as claimed. □

For a given critical point, consider an open interval $O \subset (V_0(\pi(q)), +\infty) \setminus \mathcal{R}_{\mathrm{er},q}$. Apart from the coefficients h_j, $h''_{\alpha'',\beta''}$, etc., in (3.19) the only part of the model form depending on σ is

$$I''(\sigma) = \{(\alpha'', \beta'');\ \sum_{j=s}^{m-1} r''_j(\sigma)\alpha''_j + (1 - r''_j(\sigma))\beta''_j \in (1, 2)\}.$$

We note that on compact subsets K of O, there is a $c > 0$ such that $r''_j(\sigma) > c$ for $\sigma \in K$, and then for $|\alpha''| + |\beta''| > 2c^{-1}$,

$$\sigma_{\alpha''\beta''}(\sigma) = \sum_{j=s}^{m-1} r''_j(\sigma)\alpha''_j + (1 - r''_j(\sigma))\beta''_j > 2,$$

so if we let

$$J_K = \cup_{\sigma\in K} I''(\sigma),$$

then J_K is a finite set of multiindices. For each multiindex (α'', β'') we let

$$O_{\alpha'',\beta''} = \sigma^{-1}_{\alpha''\beta''}((1, 2)), \tag{3.23}$$

which is thus an open subset of O.

For the parameter dependent version of the Theorem 3.7 we introduce

$$\mathcal{S} = \{(y, \nu, \mu, \sigma); \nu = 0,\ y'' = 0,\ y''' = 0,\ \mu = 0,\ \sigma \in O\}, \tag{3.24}$$

in place of S (3.16).

Theorem 3.13. *Suppose that $p \in \mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X \times O)$, $O \subset (V_0(\pi(q)), +\infty) \setminus \mathcal{R}_{\mathrm{er},q}$ is open, that the symplectic map S induced by the linearization A' of p at $q(\sigma)$ (see Lemma 2.2) can be smoothly decomposed (as a function of $\sigma \in O$) into two-dimensional invariant symplectic subspaces and that there exists $c > 0$ such that $r''_j(\sigma) > c$ for $\sigma \in O$ then $\Phi(\sigma)$ and $F(\sigma)$ can be chosen smoothly in σ so that $p_{\mathrm{norm}}(\sigma) = \sigma_1(\tilde{P}(\sigma))$, $\tilde{P}(\sigma) = F(\sigma)^{-1}P(\sigma)F(\sigma)$, is of the form in Theorem 3.7, with the sum over I'' replaced by a locally finite sum (the sum is over J_K over compact subsets $K \subset O$,) the h_j, etc., in* (3.19) *depending smoothly on σ, i.e. they are in $\mathcal{C}^\infty({}^{\mathrm{sc}}T^*_{\partial X}X \times O)$, vanishing at $\mathcal{S}$ as in Theorem 3.7, and $h''_{\alpha''\beta''}$ supported in ${}^{\mathrm{sc}}T^*_{\partial X}X \times O_{\alpha''\beta''}$ in terms of* (3.23).

Remark 3.14. For $P = x^{-1}(\Delta + V - \sigma)$ the conditions of the theorem are satisfied for any bounded $O = I$ disjoint from the discrete set of effectively resonant σ, since in local coordinates (y, μ) on $\Sigma(\sigma)$, the eigenspaces of S are independent of σ as shown in the proof of Lemma 2.4, and the r''_j are bounded below by Remark 2.7.

Proof. Since the invariant subspaces depend smoothly on σ by assumption, so do the eigenvalues of the linearization, and there is smooth family of local contact diffeomorphisms, i.e. coordinate changes, under which $p(\sigma)$ takes the form (2.12), i.e.

$$p(\sigma) = -\nu + \sum_{j=1}^{m-1} r_j(\sigma)y_j\mu_j + \sum_{j=m}^{n-1} Q_j(\sigma, y_j, \mu_j) + \nu e_1 + e_2 \tag{3.25}$$

the $Q_j(\sigma, .)$, are homogeneous polynomials of degree 2, e_1 vanishes at least linearly and e_2 to third order, all depending smoothly on σ.

For the rest of the argument it is convenient to reduce the size of the parameter set O as follows. For $\sigma \in O$, let

$$\begin{aligned}\hat{O}(\sigma) = &\bigcap\{O_{\alpha'',\beta''} = \sigma^{-1}_{\alpha'',\beta''}((1,2)) :\ \sigma_{\alpha'',\beta''}(\sigma) \in (1,2)\}\cap \\ &\bigcap\{\sigma^{-1}_{\alpha'',\beta''}((-\infty,1)) :\ \sigma_{\alpha'',\beta''}(\sigma) \in (-\infty,1)\},\end{aligned} \tag{3.26}$$

an open set (as it is a finite intersection of open sets) that includes σ. Thus, $\{\hat{O}(\sigma) :\ \sigma \in O\}$ is an open cover of O. We take a locally finite subcover and a subordinate partition of unity. It suffices now to show the theorem for each element $\hat{O}(\sigma_0)$ of the subcover in place of O, for we can then paste together the models p_{norm} we thus obtain using the partition of unity. Thus, we may assume that $O = \hat{O}(\sigma_0)$ for some $\sigma_0 \in O$, and prove the theorem with the sum over I'' replaced by a sum over $I''(\sigma_0)$. Hence, on O, for any (α'', β'') either

a) $\sigma_{\alpha''\beta''}(\sigma_0) > 1$, and then for some $(\tilde{\alpha}'', \tilde{\beta}'') \in I''(\sigma_0)$, $(\alpha'', \beta'') \geq (\tilde{\alpha}'', \tilde{\beta}'')$ (reduce $|\alpha''| + |\beta''|$ until $\sigma_{\tilde{\alpha}'',\tilde{\beta}''} \in (1, 2)$ – this will happen as $r_j \in (0, 1/2)$) hence $\sigma_{\alpha''\beta''}(\sigma) \geq \sigma_{\tilde{\alpha}''\tilde{\beta}''}(\sigma) > 1$ for all $\sigma \in O$ by the definition of $\hat{O}(\sigma_0)$, or
b) $\sigma_{\alpha''\beta''}(\sigma_0) < 1$, and then $\sigma_{\alpha''\beta''}(\sigma) < 1$ for all $\sigma \in O$ by the definition of $\hat{O}(\sigma_0)$.

In order to make $\Phi(\sigma)$ smooth in σ, we slightly modify the construction of the local contact diffeomorphism $\Phi_1(\sigma)$ in Proposition 3.4 so that for any given σ we do not necessarily remove every term we can (i.e. which are non-resonant for that particular σ). Namely, we choose the set I' of multiindices (a, α, β) *which we do not remove by* $\Phi_1(\sigma)$ so that I' is independent of σ, and such that I' contains every multiindex which is resonant for *some* $\sigma \in O$, i.e. $I' \supset \cup_{\sigma\in O} I(\sigma)$, with $I(\sigma)$ denoting the set of multiindices corresponding to resonant terms for $p(\sigma)$, as in Proposition 3.4. With any such choice of I', the local contact diffeomorphism of Proposition 3.4, $\Phi_1(\sigma)$, can be chosen smoothly in σ such that $\Phi_1^* p$ is of the form

$$-\nu + \sum_{j=1}^{m} r_j(\sigma) y_j \mu_j + \sum_{j=m+1}^{n-1} Q_j(\sigma, y_j, \mu_j) + \sum_{I'} c_{a\alpha\beta}(\sigma) \nu^a e^\alpha f^\beta \text{ modulo } \mathcal{I}^\infty = \mathfrak{h}^\infty \text{ at } q,$$

with $c_{a\alpha\beta}$ depending smoothly on σ.

The requirement $I' \supset \cup_{\sigma\in O} I(\sigma)$ means that for $(a, \alpha, \beta) \notin I'$, $R_{a,\alpha,\beta}(\sigma)$ must not vanish for $\sigma \in O$. Here we recall that $R_{a,\alpha,\beta}(\sigma)$ is the eigenvalue of $\{\{p_0, .\}\}$ defined by (3.5), namely

$$R_{a,\alpha,\beta}(\sigma) = \lambda \left(a - 1 + \sum_{j=1}^{n-1} \alpha_j r_j(\sigma) + \sum_{j=1}^{n-1} \beta_j (1 - r_j(\sigma)) \right) \tag{3.27}$$

Keeping this in mind, we choose I' by defining its complement $(I')^c$ to consist of multiindices (a, α, β) with $2a + |\alpha| + |\beta| \geq 3$ such that either

(i) $a + |\beta'| = 1$ and $\alpha'' = 0$, $\alpha''' = 0$, $\beta'' = 0$, $\beta''' = 0$, or
(ii) $|\alpha'''| \geq 1$, $\beta''' = 0$, or
(iii) $|\beta'''| \geq 1$, $\alpha''' = 0$, or
(iv) $a = 0$, $\beta' = 0$, $|\alpha'''| + |\beta'''| = 2$, $\alpha'' = 0$, $\beta'' = 0$, or
(v) $a = 0$, $\beta' = 0$, $\alpha''' = \beta''' = 0$, $\sigma_{\alpha''\beta''}(\sigma) < 1$ (for one, hence all, $\sigma \in O$, as remarked above).

We next show that multiindices in $(I')^c$ are indeed non-resonant. In cases (ii)–(iii), $\operatorname{Im} R_{a,\alpha,\beta}(\sigma) \neq 0$ since the imaginary part of all terms in (3.27) (with nonzero imaginary part) has the same sign, and there is at least one term with non-zero imaginary part, so (a, α, β) is non-resonant.

In case (v), the non-resonance follows from

$$\lambda^{-1} R_{a,\alpha,\beta}(\sigma) \leq -1 + \sigma_{\alpha''\beta''}(\sigma) < 0,$$

since $\lambda^{-1} R_{a,\alpha,\beta}(\sigma) = -1 + \sigma_{\alpha''\beta''}(\sigma) + \sum_{j=1}^{s-1} \alpha_j r_j$, and each term in the last summation is non-positive.

In case (i), if $a = 1$, $\beta' = 0$ then $\lambda^{-1} R_{a,\alpha,\beta}(\sigma) = \sum_{j=1}^{s-1} r_j \alpha_j < 0$ since $|\alpha'| \geq 1$ due to $2a + |\alpha| + |\beta| \geq 3$. Also in case (i), if $a = 0$, $|\beta'| = 1$, with say $\beta_l = 1$, then

$$\lambda^{-1} R_{a,\alpha,\beta}(\sigma) = -r_l + \sum_{j=1}^{s-1} \alpha_j r_j$$

which may not vanish for then (a, α, β) would be effectively resonant – it would correspond to one of the terms in the first summation in (3.17).

Finally, in case (iv),

$$\lambda^{-1} \operatorname{Re} R_{a,\alpha,\beta}(\sigma) = \sum_{j=1}^{s-1} \alpha_j r_j < 0$$

since $\alpha' \neq 0$ due to $2a + |\alpha| + |\beta| \geq 3$.

Thus, all terms corresponding to multiindices in $(I')^c$ can be removed from $p(\sigma)$ by a local contact diffeomorphism $\Phi_1(\sigma)$ that is $\mathcal{C}^\infty$ in σ. So we only need to remark that any term corresponding to a multiindex in I' can be absorbed into $r_{\mathrm{enr}}(\sigma)$. In fact, such a multiindex has either

1) $a + |\beta'| \geq 2$, or
2) $a + |\beta'| = 1$ and $|\alpha''| + |\alpha'''| + |\beta''| + |\beta'''| \geq 1$, or
3) $|\alpha'''| + |\beta'''| \geq 3$ (with neither α''' nor β''' zero), or
4) $a = 0$, $\beta' = 0$, $|\alpha'''| = 1$, $|\beta'''| = 1$, $|\alpha''| + |\beta''| \geq 1$, or
5) $a = 0$, $\beta' = 0$, $\alpha''' = 0$, $\beta''' = 0$, $\sigma_{\alpha''\beta''} > 1$.

The first two cases can be incorporated into the h_0 or h_j terms in (3.19). The third and fourth ones can be incorporated into the h'''_{jk} term. Finally, in the fifth case, any infinite linear combination of these monomials can be written as

$$\sum_{(\tilde{\alpha}'',\tilde{\beta}'') \in I''(\sigma_0)} h''_{\tilde{\alpha}'',\tilde{\beta}''} (e'')^{\tilde{\alpha}''} (f'')^{\tilde{\beta}''},$$

as remarked in (i) after (3.26).

We thus obtain

$$-\nu + \sum_j r_j(\sigma) y_j \mu_j + \sum_{j=m}^{n-1} Q_j(y_j, \mu_j) + r_{\mathrm{enr}}(\sigma) + r_\infty,$$

with r_{enr} as in (3.19), and r_∞ vanishes to infinite order at $(0, 0, 0)$. Finally, we can remove the r_∞ term in a neighbourhood of the origin using Proposition 3.5 as in the proof of Theorem 3.7, thus completing the proof of this theorem. □

4. Microlocal solutions

In [4] microlocally outgoing solutions were defined using the global function ν on ${}^{\mathrm{sc}}T^*_{\partial X}X$. This is increasing along W and plays the role of a time function; microlocally incoming and outgoing solution are then determined by requiring the wave front set to lie on one side of a level surface of ν. In the present study of microlocal operators, no such global function is available. However there are always microlocal analogues, denoted here by ρ, defined in appropriate neighbourhodds of a critical point.

Lemma 4.1. *There is a neighbourhood $\mathcal{O}_1$ of q in ${}^{\mathrm{sc}}T^*_{\partial X}X$ and a function $\rho \in \mathcal{C}^\infty(\mathcal{O}_1)$ such that $\mathcal{O}_1$ contains no radial point of P except q, $\rho(q) = 0$, and $W\rho \geq 0$ on $\Sigma \cap \mathcal{O}$ with $W\rho > 0$ on $\Sigma \cap \mathcal{O}_1 \setminus \{q\}$.*

Proof. This follows by considering the linearization of W. Namely, if P is conjugated to the form (2.12), then for outgoing radial points q take $\rho = |y'|^2 - (|y''|^2 + |y'''|^2 + |\mu|^2)$, defined in a coordinate neighbourhood $\mathcal{O}_0$, for incoming radial points take its negative. On Σ, $W\rho \geq c(|y|^2 + |\mu|^2) + h$ for some $c > 0$ and $h \in \mathcal{I}^3$. As (y, μ) form a coordinate system on Σ near q, it follows that $W\rho \geq \frac{c}{2}(|y|^2 + |\mu|^2)$ on a neighbourhood $\mathcal{O}'$ of q in Σ. Now let $\mathcal{O}_1 \subset \mathcal{O}_0$ be such that $\mathcal{O} \cap \Sigma = \mathcal{O}'$. Note that $W\rho(p) = 0$, $p \in \mathcal{O}_1$, implies $p = q$, so there are indeed no other radial points in $\mathcal{O}_1$, finishing the proof. □

Remark 4.2. Below it is convenient to replace $\mathcal{O}_1$ by a smaller neighbourhood $\mathcal{O}$ of q with $\overline{\mathcal{O}} \subset \mathcal{O}_1$, so ρ is defined and increasing on a neighbourhood of $\overline{\mathcal{O}}$.

Consider the structure of the dynamics of W in $\mathcal{O}$. First, ρ is increasing (i.e. 'non-decreasing') along integral curves γ of W, and it is strictly increasing unless γ reduces to q. Moreover, W has no non-trivial periodic orbits and

Lemma 4.3. *Let $\mathcal{O}$ be as in Remark 4.2. If $\gamma : [0, T) \to \mathcal{O}$ or $\gamma : [0, +\infty) \to \mathcal{O}$ is a maximally forward-extended bicharacteristic, then either γ is defined on $[0, +\infty)$ and $\lim_{t\to+\infty} \gamma(t) = q$, or γ is defined on $[0, T)$ and leaves every compact subset K of $\mathcal{O}$, i.e. there is $T_0 < T$ such that for $t > T_0$, $\gamma(t) \notin K$.*

An analogous conclusion holds for maximally backward-extended bicharacteristics.

Proof. If $\gamma : [0, +\infty) \to \mathcal{O}$ then $\lim_{t\to+\infty} \rho(\gamma(t)) = \rho_+$ exists by the monotonicity of ρ, and any sequence $\gamma_k : [0, 1] \to \Sigma$, $\gamma_k(t) = \gamma(t_k + t)$, $t_k \to +\infty$, has a uniformly convergent subsequence, which is then an integral curve $\tilde{\gamma}$ of W in Σ with image in $\overline{\mathcal{O}}$, hence in $\mathcal{O}_1$. Then ρ is constant along this bicharacteristic. But the only bicharacteristic segment in $\mathcal{O}_1$ on which ρ is constant is the one with image $\{q\}$, so $\lim_{t\to+\infty} \gamma(t) = q$. The claim for γ defined on $[0, T)$ is standard. □

As in [4] we make use of open neighbourhoods of the critical points which are well-behaved in terms of W.

Definition 4.4. By a W-balanced neighbourhood of a non-degenerate radial point q we shall mean a neighbourhood, O, of q in ${}^{\mathrm{sc}}T^*_{\partial X}X$ with $\overline{O} \subset \mathcal{O}$ (in which ρ is defined) such that O contains no other radial point, meets $\Sigma(\sigma)$ in a W-convex set (that is, each integral curve of W meets $\Sigma(\sigma)$ in a single interval, possibly empty) and is such that the closure of each integral curve of W in O meets $\rho = \rho(q)$.

The existence of W-balanced neighbourhoods follows as in [4].

If q is a radial point for P and O a W-balanced neighbourhood of q we set

$$\tilde{E}_{\mathrm{mic},+}(O,P) = \big\{u \in \mathcal{C}^{-\infty}(X); O \cap \mathrm{WF}_{\mathrm{sc}}(Pu) = \emptyset, \\ \text{and } \mathrm{WF}_{\mathrm{sc}}(u) \cap O \subset \{\rho \geq \rho(q)\}\big\}, \tag{4.1}$$

with $\tilde{E}_{\mathrm{mic},-}(O,P)$ defined by reversing the inequality.

Lemma 4.5. *If $O \ni q$ is a W-balanced neighbourhood then every $u \in \tilde{E}_{\mathrm{mic},\pm}(O,P)$ satisfies $\mathrm{WF}_{sc}(u) \cap O \subset \Phi_\pm(\{q\})$; furthermore, for $u \in \tilde{E}_{\mathrm{mic},\pm}(O,P)$*

$$\mathrm{WF}_{sc}(u) \cap O = \emptyset \Longleftrightarrow q \notin \mathrm{WF}_{sc}(u).$$

Thus, we could have defined $\tilde{E}_{\mathrm{mic},\pm}(O,P)$ by strengthening the restriction on the wavefront set to $\mathrm{WF}_{\mathrm{sc}}(u) \cap O \subset \Phi_\pm(\{q\})$. With such a definition there is no need for O to be W-balanced; the only relevant bicharacteristics would be those contained in $\Phi_\pm(\{q\})$. Moreover, with this definition ρ does not play any role in the definition, so it is clearly independent of the choice of ρ.

Proof. For the sake of definiteness consider $u \in \tilde{E}_{\mathrm{mic},+}(O,P)$; the other case follows similarly. Suppose $\zeta \in O \setminus \{q\}$. If $\rho(\zeta) < \rho(q)$, then $\zeta \notin \mathrm{WF}_{\mathrm{sc}}(u)$ by the definition of $\tilde{E}_{\mathrm{mic},+}(O,P)$, so we may suppose that $\rho(\zeta) \geq \rho(q)$. Since $q \in \Phi_+(\{q\})$ we may also suppose that $\zeta \neq q$.

Let $\gamma : \mathbb{R} \to \Sigma$ be the bicharacteristic through ζ with $\gamma(0) = \zeta$. As O is W-convex, and $\mathrm{WF}_{\mathrm{sc}}(Pu) \cap O = \emptyset$, the analogue here of Hörmander's theorem on the propagation of singularities shows that

$$\zeta \in \mathrm{WF}_{\mathrm{sc}}(u) \Rightarrow \gamma(\mathbb{R}) \cap O \subset \mathrm{WF}_{\mathrm{sc}}(u).$$

As O is W-balanced, there exists $\zeta' \in \overline{\gamma(\mathbb{R})} \cap O$ such that $\rho(\zeta') = \rho(q)$. If $\rho(\zeta) = \rho(q) = 0$, we may assume that $\zeta' = \zeta$. From this assumption, and the fact that ρ is increasing along the segment of γ in $\mathcal{O}$, and O is W-convex, we conclude that $\zeta' \in \overline{\gamma((-\infty, 0])} \cap O$.

If $\zeta' = \gamma(t_0)$ for some $t_0 \in \mathbb{R}$, then for $t < t_0$, $\rho(\gamma(t)) < \rho(\gamma(t_0)) = \rho(q)$, and for sufficiently small $|t - t_0|$, $\gamma(t) \in O$ as O is open. Thus, $\gamma(t) \notin \mathrm{WF}_{\mathrm{sc}}(u)$ by the definition of $\tilde{E}_{\mathrm{mic},+}(O,P)$, and hence we deduce that $\zeta \notin \mathrm{WF}_{\mathrm{sc}}(u)$.

On the other hand, if $\zeta' \notin \gamma(\mathbb{R})$, then as O is open $\gamma(t_k) \in O$ for a sequence $t_k \to -\infty$, and as O is W-convex, $\gamma|_{(-\infty,0]} \subset O$. Then, again from the propagation of singularities and Lemma 4.3, $\zeta' = q$. □

We may consider $\tilde{E}_{\mathrm{mic},\pm}(O,P)$ as a space of microfunctions, $E_{\mathrm{mic},+}(q,P)$, by identifying elements which differ by functions with wavefront set not meeting O:

$$E_{\mathrm{mic},\pm}(q,P) = \tilde{E}_{\mathrm{mic},\pm}(O,P)/\{u \in \mathcal{C}^{-\infty}(X); \mathrm{WF}_{\mathrm{sc}}(u) \cap O = \emptyset\}.$$

The result is then independent of the choice of O, as we show presently.

If O_1 and O_2 are two W-balanced neighbourhoods of q then

$$O_1 \subset O_2 \Longrightarrow \tilde{E}_{\mathrm{mic},\pm}(O_2,P) \subset \tilde{E}_{\mathrm{mic},\pm}(O_1,P). \tag{4.2}$$

Since $\{u \in \mathcal{C}^{-\infty}(X); \mathrm{WF}_{\mathrm{sc}}(u) \cap O = \emptyset\} \subset \tilde{E}_{\mathrm{mic},\pm}(O,P)$ for all O and this linear space decreases with O, the inclusions (4.2) induce similar maps on the quotients

$$\begin{gathered} E_{\mathrm{mic},\pm}(O,P) = \tilde{E}_{\mathrm{mic},\pm}(O,P)/\{u \in \mathcal{C}^{-\infty}(X); \mathrm{WF}_{\mathrm{sc}}(u) \cap O = \emptyset\}, \\ O_1 \subset O_2 \Longrightarrow E_{\mathrm{mic},\pm}(O_2,P) \longrightarrow E_{\mathrm{mic},\pm}(O_1,P). \end{gathered} \tag{4.3}$$

Lemma 4.6. *Provided O_i, for $i = 1, 2$, are W-balanced neighbourhoods of q, the map in* (4.3) *is an isomorphism.*

Proof. We work with $E_{\mathrm{mic},+}$ for the sake of definiteness.

The map in (4.3) is injective since any element u of its kernel has a representative $\tilde{u} \in \tilde{E}_{\mathrm{mic},+}(O_2, \sigma)$ which satisfies $q \notin \mathrm{WF}_{\mathrm{sc}}(\tilde{u})$, hence $\mathrm{WF}_{\mathrm{sc}}(\tilde{u}) \cap O_2 = \emptyset$ by Lemma 4.5, so $u = 0$ in $E_{\mathrm{mic},+}(O_2, \sigma)$.

The surjectivity follows from Hörmander's existence theorem in the real principal type region [10]. First, note that

$$R = \inf\{\rho(p) : \ p \in \Phi_+(\{q\}) \cap (\mathcal{O} \setminus O_1)\} > 0 = \rho(q)$$

since in $\mathcal{O}$, ρ is increasing along integral curves of W, and strictly increasing away from q. Let U be a neighbourhood of $\Phi_+(\{q\}) \cap \overline{O_1}$ such that $\overline{U} \subset \mathcal{O}$, and $\rho > R_0 = R/2$ on $U \setminus O_1$. Let $A \in \Psi_{\mathrm{sc}}^{-\infty,0}(\mathcal{O})$ be such that $\mathrm{WF}'_{\mathrm{sc}}(\mathrm{Id} - A) \cap \overline{O_1} \cap \Phi_+(\{q\}) = \emptyset$ and $\mathrm{WF}'_{\mathrm{sc}}(A) \subset U$. Thus, $\mathrm{WF}_{\mathrm{sc}}(Au) \subset U$ and $\mathrm{WF}_{\mathrm{sc}}(PAu) \subset U \setminus O_1$, so in particular $\rho > R_0$ on $\mathrm{WF}_{\mathrm{sc}}(PAu)$. We have thus found an element, namely $\tilde{u} = Au$, of the equivalence class of u with wave front set in $\mathcal{O}$ and such that $\rho > R_0 > 0 = \rho(q)$ on the wave front set of the 'error', $P\tilde{u}$.

We now note that the forward bicharacteristic segments from $U \setminus O_1$ inside $\mathcal{O}$ leave $\overline{O_2}$ by the remark after Lemma 4.1; since $\overline{O_2} \setminus O_1$ is compact, there is an upper bound $T > 0$ for when this happens. Thus, Hörmander's existence theorem allows us to solve $Pv = P\tilde{u}$ on O_2 with $\mathrm{WF}_{\mathrm{sc}}(v)$ a subset of the forward bicharacteristic segments emanating from $U \setminus \overline{O_1}$. Then $u' = \tilde{u} - v$ satisfies $\mathrm{WF}_{\mathrm{sc}}(u') \subset \mathcal{O} \cap \{\rho \geq 0 = \rho(q)\}$, $\mathrm{WF}_{\mathrm{sc}}(Pu') \cap O_2 = \emptyset$, so $u' \in E_{\mathrm{mic},+}(O_2, P)$, and $q \notin \mathrm{WF}_{\mathrm{sc}}(u' - u)$. Thus $\mathrm{WF}_{\mathrm{sc}}(u' - u) \cap O_1 = \emptyset$, hence u and u' are equivalent in $\tilde{E}_{\mathrm{mic},+}(O_1, P)$. This shows surjectivity. □

It follows from this Lemma that the quotient space $E_{\mathrm{mic},\pm}(q, P)$ in (4.3) is well-defined, as the notation already indicates, and each element is determined by the behaviour microlocally 'at' q. When P is the operator $x^{-1}(\Delta + V - \sigma)$, then we will denote this space

$$E_{\mathrm{mic},\pm}(q, \sigma). \tag{4.4}$$

Definition 4.7. By a *microlocally outgoing solution* to $Pu = 0$ at a radial point q we shall mean either an element of $\tilde{E}_{\mathrm{mic},+}(q, P)$ or of $E_{\mathrm{mic},+}(q, P)$.

5. Test Modules

Following [4], we use test modules of pseudodifferential operators to analyze the regularity of microlocally incoming solutions near radial points. This involves microlocalizing near the critical point with errors which are well placed relative to the flow.

Definition 5.1. An element $Q \in \Psi_{\mathrm{sc}}^{*,0}(X)$ is a *forward microlocalizer* in a neighbourhood $O \ni q$ of a radial point $q \in {}^{\mathrm{sc}}T^*_{\partial X}X$ for $P \in \Psi_{\mathrm{sc}}^{*,-1}(X)$ if it is elliptic at q and there exist B, $F \in \Psi_{\mathrm{sc}}^{0,0}(O)$ and $G \in \Psi_{\mathrm{sc}}^{0,1}(X)$ such that

$$i[Q^*Q, P] = (B^*B + G) + F \ \text{and} \ \mathrm{WF}'_{\mathrm{sc}}(F) \cap \Phi_+(\{q\}) = \emptyset. \tag{5.1}$$

Using the normal form established earlier we can show that such forward microlocalizers exist under our standing assumption that

$$\text{the linearization has neither a Hessian threshold subspace, (iv),}\\ \text{nor any non-decomposable 4-dimensional invariant subspace.} \tag{5.2}$$

Proposition 5.2. *A forward microlocalizer exists in any neighbourhood of any non-degenerate radial point* $q \in {}^{\mathrm{sc}}T^*_{\partial X}X$ *for* $P \in \Psi^{*,-1}_{\mathrm{sc}}(X)$ *at which the linearization satisfies* (5.2).

Proof. Since the conditions (5.1) are microlocal and invariant under conjugation with an elliptic Fourier integral operator, it suffices to consider the model form in Theorem 3.7 which holds under the same conditions (5.2).

Let $R = |\mu'|^2 + |y''|^2 + |y'''|^2 + |\mu''|^2 + |\mu'''|^2$, and

$$S = \{\tilde{p} = 0,\ R = 0\},$$

so S is the flow-out of q. We shall choose $Q \in \Psi^{-\infty,0}_{\mathrm{sc}}(X)$ such that

$$\sigma_\partial(Q) = q = \chi_1(|y'|^2)\chi_2(R)\psi(\tilde{p}), \tag{5.3}$$

where $\chi_1,\ \chi_2,\ \psi \in \mathcal{C}^\infty_c(\mathbb{R})$, $\chi_1,\ \chi_2 \geq 0$ are supported near 0, ψ is supported near 0, $\chi_1,\ \chi_2 \equiv 1$ near 0 and $\chi_1' \leq 0$ in $[0,\infty)$. Choosing all supports sufficiently small ensures that $Q \in \Psi^{-\infty,0}_{\mathrm{sc}}(O)$. Note that $\operatorname{supp} d(\chi_2 \circ R) \cap S = \emptyset$. On the other hand,

$$ {}^{\mathrm{sc}}H_p\chi_1(\sum_j (y_j')^2) = 2\sum_j y_j'(\ {}^{\mathrm{sc}}H_p y_j')\chi_1'(|y'|^2) = 2\lambda y_j'(r_j' y_j' + h_j)\chi_1'(|y'|^2), \tag{5.4}$$

with h_j vanishing quadratically at q. Moreover, on $\operatorname{supp}\chi_1' \circ (|.|^2)$, y' is bounded away from 0. Since $r_j' < 0$, $-\sum_j r_j'(y_j')^2 > 0$ on $\operatorname{supp}\chi_1' \circ (|.|^2)$. The error terms h_j can be estimated in terms of $|y'|^2$, R and $\tilde{p}^2$, so, given any $C > 0$, there exists $\delta > 0$ such that the $-\sum_j y_j'(r_j'y_j' + h_j) > 0$ if $\operatorname{supp}\chi_1 \subset (-\delta,\delta)$, $R/|y'|^2 < C$ and $|\tilde{p}|/|y'| < C$. In particular, taking $C = 2$, $-\sum_j y_j'(r_j'y_j' + h_j) > 0$ on $S \cap \operatorname{supp}\chi_1' \circ (|.|^2)$, for $R = \tilde{p} = 0$ on S. Thus (5.1) is satisfied (with B appropriately specified, microsupported near S), provided that χ_1 is chosen so that $(-\chi_1\chi_1')^{1/2}$ is smooth.

More explicitly, letting $\chi \in \mathcal{C}^\infty_c(\mathbb{R})$ be supported in $(-1,1)$ be identically equal to 1 in $(-\frac{1}{2},\frac{1}{2})$ with $\chi' \leq 0$ on $[0,\infty)$, $\chi \geq 0$, $\chi_1 = \chi_2 = \psi = \chi(./\delta)$. Indeed, for any choice of $\delta \in (0,1)$, $|y'|^2 \geq \delta/2$ on $\operatorname{supp}\chi_1' \circ |.|^2$, hence $R/|y'|^2 < 2$, $|\tilde{p}|/|y'| < 2$ on $\operatorname{supp} q \cap \operatorname{supp}\chi_1' \circ |.|^2$. With $C = 2$, choosing $\delta \in (0,1)$ as above, we can write

$$\begin{gathered}\sigma_\partial(i[Q^*Q,P]) = -\ {}^{\mathrm{sc}}H_p q^2 = -4\lambda\tilde{b}^2 + \tilde{f},\\ \tilde{b} = (\sum_j y_j'(r_j'y_j' + h_j)\chi_1'(|y'|^2)\chi_1(|y'|^2))^{1/2}\chi_2(R)\psi(\tilde{p}),\ \operatorname{supp}\tilde{f} \cap S = \emptyset,\end{gathered} \tag{5.5}$$

which finishes the proof since $\lambda < 0$ for an outgoing radial point. □

A test module in an open set $O \subset {}^{\mathrm{sc}}T^*_{\partial X}X$ is, by definition, a linear subspace $\mathcal{M} \subset \Psi^{*,-1}_{\mathrm{sc}}(X)$ consisting of operators microsupported in O which contains and is a module over $\Psi^{*,0}_{\mathrm{sc}}(X)$, is closed under commutators, and is algebraically finitely generated. To deduce regularity results we need extra conditions relating the module to the operator P.

Definition 5.3. If $P \in \Psi^{*,-1}_{\mathrm{sc}}(X)$ has real principal symbol near a non-degenerate outgoing radial point q then a test module $\mathcal{M}$ is said to be P-positive at q if it is supported in a W-balanced neighbourhood of q and

(i) $\mathcal{M}$ is generated by $A_0 = \mathrm{Id}$, $A_1, \dots, A_N = P$ over $\Psi_{\mathrm{sc}}^{*,0}(X)$,
(ii) for $1 \le i \le N-1$, $0 \le j \le N$ there exists $C_{ij} \in \Psi_{\mathrm{sc}}^{*,0}(X)$, such that

$$i[A_i, x\tilde{P}] = \sum_{j=0}^{N} xC_{ij}A_j \tag{5.6}$$

where $\sigma_\partial(C_{ij})(\tilde{q}) = 0$, for all $0 \neq j < i$, and $\operatorname{Re}\sigma_\partial(C_{jj})(\tilde{q}) \ge 0$.

As shown in [4], microlocal regularity of solutions of a pseudodifferential equation can be deduced by combining such a P-positive test module with a microlocalizing operator as discussed above. We recall and slightly modify this result.

Proposition 5.4. *(Essentially Proposition 6.7 of [4]). Suppose that $P \in \Psi_{\mathrm{sc}}^{*,-1}(X)$ has real principal symbol, q is a non-degenerate outgoing radial point for P,*

$$\sigma_{\partial,1}(xP - (xP)^*)(q) = 0, \tag{5.7}$$

$\mathcal{M}$ is a P-positive test module at q, $Q \in \Psi_{\mathrm{sc}}^{*,0}(X)$ is a forward microlocalizer for P at q and for some $s < -\frac{1}{2}$, $u \in H_{sc}^{\infty,s}(X)$ satisfies

$$\mathrm{WF}_{sc}(u) \cap O \subset \Phi_+(\{q\}) \text{ and } Pu \in \dot{C}^\infty(X), \tag{5.8}$$

then $u \in I_{\mathrm{sc}}^{(s)}(O', \mathcal{M})$ where O' is the elliptic set of Q.

Proof. As already noted this is essentially Proposition 6.7 of [4]; there are some small differences to be noted. In [4], the condition in (5.6) was $j > i$; here we changed to $j < i$ for a more convenient ordering. Since the labelling is arbitrary, this does not affect the proof of the Proposition.

Also, in [4] the proposition was stated for the 0th order operators such as $\Delta + V - \sigma$, which are formally self-adjoint with respect to a scattering metric. This explains the appearance of xP both in (5.7) and in (5.6) here, even though in the applications below, $[A_i, x]$ could be absorbed in the C_{i0} term. In particular, $s < -1/2$ in (5.8) arises from a pairing argument that uses the formal self-adjointness of xP, modulo terms that can be estimated by $[x^s A^\alpha, xP]$, $s > 0$, A^α a product of the A_j.

Also, in [4] the proposition is proved for (5.7) is replaced by $(xP) = (xP)^*$, but (5.7) is sufficient for all arguments in [4] to go through, for $B = (xP) - (xP)^*$ would contribute error terms of the form $x^s A^\alpha B$ with $\sigma_{\partial,1}(B)(q) = 0$, which can thus be handled exactly the same way as the C_{jj} term in (5.6).

In fact (5.7) can always be arranged for any $P_0 \in \Psi_{\mathrm{sc}}^{*,-1}(X)$ with a non-degenerate radial point and real principal symbol. Indeed, we only need to conjugate by x^k giving

$$P = x^k P_0 x^{-k},\ k = \frac{-\sigma_{\partial,1}(B)(q)}{2i\lambda} \in \mathbb{R}$$

satisfies (5.7); here $dp|_q = \lambda\alpha|_q$, with α the contact form. Microlocal solutions $P_0u_0 = 0$, correspond to microlocal solutions $Pu = 0$ via $u = x^k u_0$, so $u \in H_{\mathrm{sc}}^{\infty,s}(X)$ is replaced by $u_0 \in H_{\mathrm{sc}}^{\infty,s-k}(X)$. □

Thus, iterative regularity with respect to the module essentially reduces to showing that the positive commutator estimates (5.6) hold. For each critical point q satisfying (5.2) a suitable (essentially maximal) module is constructed below, so microlocally outgoing solutions to $Pu = 0$ have iterative regularity under the module; that is, that

$$u \in I_{\mathrm{sc}}^{(s)}(O, \mathcal{M}) = \{u; \mathcal{M}^m u \subset H_{\mathrm{sc}}^{\infty,s}(X) \text{ for all } m\}. \tag{5.9}$$

The test modules are elliptic off the forward flow out $\Phi_+(q)$ which is an isotropic submanifold of Σ. Thus, it is natural to expect that u is some sort of an isotropic distribution. In fact the flow out (in the model setting just the submanifold S) has non-standard homogeneity structure, so these distributions are more reasonably called 'anisotropic'.

First we construct a test module for the model operator when there are no resonant terms. Thus, we can assume that the principal symbol is

$$p_0 = -\nu + \sum_{j=1}^{m-1} r_j y_j \mu_j + \sum_{j=m}^{n-1} Q_j(y_j, \mu_j).$$

Then let $\mathcal{M}$ be the test module generated by Id and operators with principal symbols

$$x^{-1} f'_j, \quad x^{-r''_j} e''_j, \quad x^{-(1-r''_j)} f''_j, \quad x^{-1/2} e'''_j, \quad x^{-1/2} f'''_j \quad \text{and} \quad x^{-1} p_0 \tag{5.10}$$

over $\Psi^{*,0}_{\mathrm{sc}}(X)$.

Note that the order of the generators is given by the negative of the normalized eigenvalue (i.e. the eigenvalue in Lemma 2.6 divided by λ) subject to the conditions that if the order would be < -1, it is adjusted to -1, and if it would be > 0, it is omitted. The latter restrictions conform to our definition of a test module, in which all terms of order 0 are included and there are no terms of order less than -1. These orders can be seen to be optimal (i.e. most negative) by a principal symbol calculation) of the commutator with A in which the corresponding eigenvalue arises.

Lemma 5.5. *Suppose P is nonresonant at q. Then the module $\mathcal{M}$ generated by* (5.10) *is closed under commutators and satisfies condition* (5.6).

Proof. It suffices to check the commutators of generators to show that $\mathcal{M}$ is closed. In view of (2.3) (applied with a in place of p), $\{a, b\} = {}^{\mathrm{sc}}H_a b$, this can be easily done. Property (5.6) follows readily from (3.1). Indeed, we have the stronger property

$$i[A_i, P(\sigma)] = c_i A_i + G_i,\ G_i \in \Psi^{*,0}(X),\ \mathrm{Re}\, c_i \geq 0$$

where A_i is any of the generators of $\mathcal{M}$ listed in (5.10). □

Remark 5.6. We may take generators of $\mathcal{M}$ to be the operators

$$\begin{gathered} D_{y'_j},\ x^{-r''_j} y''_j,\ x^{r''_j} D_{y''_j},\ x^{-1/2} y'''_j,\ x^{1/2} D_{y'''_j} \text{ and} \\ x D_x + \sum_{j=1}^{m-1} r_j y_j D_{y_j} + \sum_{j=m}^{n-1} Q_j(x^{-1/2} y_j, x^{1/2} D_{y_j}). \end{gathered} \tag{5.11}$$

Combining this with Proposition 5.4 proves that, in the nonresonant case, if u is a microlocal solution at q, and if $\mathrm{WF}^s_{\mathrm{sc}}(u)$ is a subset of the W-flowout of q, then $u \in I^{(s)}_{\mathrm{sc}}(O, \mathcal{M})$ for all $s < -1/2$.

The discrepancy between the 'resonance order' of polynomials in $\nu^a e^\beta f^\gamma$, given by $a + \sum_j \beta_j r_j + \sum_k \gamma_k (1 - r_k)$ and the 'module order' given by the sum of the orders of the corresponding module elements is closely related to arguments which allow us to most resonant terms as 'effectively nonresonant'. To give an explicit example, take a resonant term of the form $y'_i \mu'_j (y'')^{\beta''}$, corresponding to a term like $x^{-1} y'_i (y'')^{\beta''} (x D_{y'_j})$ in P. Resonance requires that $r'_i + (1 - r'_j) + \sum_k \beta''_k r''_k = 1$ and

$|\beta''| > 0$. In the module, this corresponds to a product of module elements *times a power* x^ϵ *with* $\epsilon > 0$, since we can write it

$$x^\epsilon y_i' \prod_k (x^{-r_k''} y_k'')^{\beta_k''} D_{y_i'}, \quad \epsilon = \sum_k \beta_k'' r_k'' > 0.$$

Since, by Proposition 5.4, the eigenfunction u remains in $x^s L^2(X)$, for all $s < -1/2$, under application of products of elements of $\mathcal{M}$, this term applied to u gains us a factor x^ϵ, and therefore it can be treated as an error term in determining the asymptotic expansion of u; see the proof of Theorem 6.7. Only the terms where the module order is equal to the resonance order affect the expansion of u to leading order, and it is these we have labelled as 'effectively resonant'.

Next we consider the general resonant case. To do so, we need to enlarge the module $\mathcal{M}$ so that certain products of the generators of $\mathcal{M}$, such as those in the resonant terms of Theorem 3.7, are also included in the larger module $\widetilde{\mathcal{M}}$. For a simple example, see section 8 of Part I. It is convenient to replace P_0 by xD_x as the last generator of $\mathcal{M}$ listed in (5.11), though this is not necessary; all arguments below can be easily modified if this is not done. Let us denote the generators of $\mathcal{M}$ by

$$A_0 = \mathrm{Id}, A_1 = x^{-s_1} B_1, \ldots, A_{N-1} = x^{-s_{N-1}} B_{N-1},\ A_N = xD_x = x^{-1} B_N, \quad s_i = -\operatorname{order}(A_i),\ B_i \in \Psi_{\mathrm{sc}}^{-\infty,0}(O). \tag{5.12}$$

Note that for each $i = 1, \ldots, N$, $d\sigma_{\partial,0}(B_i)$ is an eigenvector of the linearization of W; we denote the eigenvalue by σ_i. Thus,

$$s_i = \min(1, \sigma_i) > 0 \text{ for } i = 1, \ldots, N.$$

For any multiindex $\alpha \in \mathbb{N}^N$ (with $\mathbb{N} = \{1, 2, \ldots\}$) let

$$s(\alpha) = \min(\sum s_i \alpha_i, 1),\ \tilde{s}(\alpha) = \sum_i s_i \alpha_i - s(\alpha) = \max(0, \sum_i s_i \alpha_i - 1),$$

and let

$$A^\alpha = A_1^{\alpha_1} A_2^{\alpha_2} \ldots A_N^{\alpha_N}.$$

Let e_i be the multiindex $e_i = (0, \ldots, 0, 1, 0, \ldots, 0)$, where the 1 is in the ith slot, if $i = 1, \ldots, N$, and let $e_0 = (0, \ldots, 0)$.

To deal with resonant terms, we define a module $\mathcal{M}_k$ generated (over $\Psi_{\mathrm{sc}}^{-\infty,0}(O)$) by the operators

$$x^{\tilde{s}(\alpha)} A^\alpha \in \Psi_{\mathrm{sc}}^{-\infty,-s(\alpha)}(O),\ |\alpha| \le k. \tag{5.13}$$

Note that $\alpha = 0$ gives Id as one of the generators. Thus, the order of the generators in (5.13) is 'truncated' so that it is always between 0 and -1; in particular $\mathcal{M}_k \subset \Psi_{\mathrm{sc}}^{-\infty,-1}(O)$. Since in computations below we want to think of $\Psi_{\mathrm{sc}}^{-\infty,0}(O)$ as the submodule of $\mathcal{M}_k$ consisting of trivial elements, it is convenient to work modulo such terms, so we use what is essentially the principal symbol equivalence relation on $\mathcal{M}_k$ where $P \sim Q$ if $P - Q \in \Psi_{\mathrm{sc}}^{-\infty,0}(O)$.

While it appears that the ordering in the factors in the product A^α matters, this is not the case. Indeed, if σ is a permutation of $\{1, \ldots, |\alpha|\}$, and $j : \{1, \ldots, |\alpha|\} \mapsto \{1, \ldots, N\}$ which takes α_m-times the value m, $m = 1, \ldots, N$, then

$$x^{\tilde{s}(\alpha)} A_{j(1)} \ldots A_{j(|\alpha|)} \sim x^{\tilde{s}(\alpha)} A_{j(\sigma(1))} \ldots A_{j(\sigma(|\alpha|))},$$

for this is clear if σ interchanges n and $n+1$, as

$$x^{\tilde{s}(\alpha)}A_{j(1)}\dots A_{j(n-1)}[A_{j(n)},A_{j(n+1)}]A_{j(n+2)}\dots A_{j(|\alpha|)} \\ \in \Psi_{\mathrm{sc}}^{-\infty,\tilde{s}(\alpha)+1-\sum s_i\alpha_i}(O)\subset\Psi_{\mathrm{sc}}^{-\infty,0}(O)$$

since $\tilde{s}(\alpha)+1-\sum_i s_i\alpha_i=1-s(\alpha)\geq 0$.

In addition, for $Q\in\Psi_{\mathrm{sc}}^{-\infty,0}(O)$,

$$x^{\tilde{s}(\alpha)}QA_{j(1)}\dots A_{j(|\alpha|)}\sim x^{\tilde{s}(\alpha)}A_{j(1)}\dots A_{j(m)}QA_{j(m+1)}\dots A_{j(|\alpha|)}.$$

Similarly, one can shift powers of x from in front of the product to in between factors, so in fact the generators can be written equivalently, modulo $\Psi_{\mathrm{sc}}^{-\infty,0}(O)$, as

$$x^{s(\alpha)}B^\alpha\in\Psi_{\mathrm{sc}}^{-\infty,-s(\alpha)}(O),\ |\alpha|\leq k, \tag{5.14}$$

where $B^\alpha=B_1^{\alpha_1}\dots B_N^{\alpha_N}$.

Moreover, there is an integer J such that $\mathcal{M}_k=\mathcal{M}_J$ if $k\geq J$; indeed this is true for any $J\geq 2(r_s'')^{-1}$, where r_s'' is the smallest positive eigenvalue of the operator in Lemma 2.4 (or $J\geq 4$ if no eigenvalue lies in $(0,\frac{1}{2}]$), since then adding new elements to the product simply has the effect of multiplying by an element of $\Psi_{\mathrm{sc}}^{*,0}(X)$.

In particular, note that the generators in (5.13) or (5.14) are usually not linearly independent: some B_{α_j} may be absorbable into a $\Psi_{\mathrm{sc}}^{*,0}(O)$ factor without affecting $s(\alpha)$. We could easily give a linearly independent (over $\Psi_{\mathrm{sc}}^{*,0}(O)$) subset of the generators, but this is of no importance here.

Suppose that $\tilde{P}$, the normal operator for $P(\sigma)$ at q, contains resonant terms. Then Lemma 5.5 is replaced by

Lemma 5.7. *Let $>$ be a total order on multiindices α satisfying*

(i) $|\alpha'|>|\alpha|$ *implies* $\alpha'>\alpha$*;*
(ii) $|\alpha'|=|\alpha|$ *and* $\sum_k s_k\alpha_k'>\sum_k s_k\alpha_k$ *imply* $\alpha'>\alpha$*;*
(iii) $|\alpha'|=|\alpha|=1$*,* $\alpha'=e_i$*,* $\alpha=e_j$*,* $s_i=s_j=1$*,* $\sigma_i>\sigma_j$ *imply that* $\alpha'>\alpha$*.*

With the corresponding ordering of the generators $x^{-\tilde{s}(\alpha)}A^\alpha$, the module $\mathcal{M}_J$ is a test module for $\tilde{P}$ at q satisfying (5.6).

Remark 5.8. (ii) and (iii) could be replaced by (ii)': $|\alpha'|=|\alpha|$ and $\sum_k\sigma_k\alpha_k'>\sum_k\sigma_k\alpha_k$ imply $\alpha'>\alpha$, which would simplify the statement of the lemma. However, the proof is slightly simpler with the present statement. Note that (ii)+(iii) is not equivalent to (ii)', i.e. the ordering of the generators may be different, but either ordering gives (5.6).

Proof. We first observe that $\mathcal{M}_J$ is closed under commutators. Indeed, not only is $\mathcal{M}$ closed under commutators, but the commutators $[A_i,A_j]$ can be written as $\sum_{l=0}^N C_lA_l$ with $C_l\in\Psi_{\mathrm{sc}}^{-\infty,0}(X)$ and $C_l=0$ unless $s_l\leq s_i+s_j-1$. Expanding

$$[x^{\tilde{s}(\alpha)}Q_\alpha A^\alpha,x^{\tilde{s}(\beta)}Q_\beta A^\beta],\ Q_\alpha,Q_\beta\in\Psi_{\mathrm{sc}}^{-\infty,0}(O),$$

and ignoring momentarily the commutators with powers of x and with Q_α and Q_β, gives a sum of terms of the form

$$x^{\tilde{s}(\alpha)+\tilde{s}(\beta)}Q_\alpha Q_\beta A^{\alpha'}A^{\beta'}[A_i,A_j]A^{\alpha''}A^{\beta''}$$

with $\alpha=\alpha'+\alpha''+e_i$, and similarly for β. Substituting in $[A_i,A_j]=\sum_{l=0}^N C_lA_l$ shows that this is an element of the module and is indeed equivalent, modulo

$\Psi_{\mathrm{sc}}^{-\infty,0}(O)$, to

$$\sum_{l:s_l\le s_i+s_j-1}\left(C_l x^{\tilde s(\alpha)+\tilde s(\beta)-\tilde s(\gamma^{(l)})}\right)x^{\tilde s(\gamma^{(l)})}A^{\gamma^{(l)}},\tag{5.15}$$
$$\gamma^{(l)}=\alpha'+\alpha''+\beta'+\beta''+e_l=\alpha+\beta-e_i-e_j+e_l,$$

provided that

$$\tilde s(\gamma^{(l)})\le\tilde s(\alpha)+\tilde s(\beta).\tag{5.16}$$

But $\tilde s(\alpha)+\tilde s(\beta)\ge(\sum s_i\alpha_i-1)+(\sum s_i\beta_i-1)=\sum s_i\gamma_i^{(l)}+s_i+s_j-s_l-2\ge\sum s_i\gamma_i^{(l)}-1$ as $s_i+s_j-s_l\ge 1$. Moreover, $\tilde s(\alpha)+\tilde s(\beta)\ge 0$, so

$$\tilde s(\alpha)+\tilde s(\beta)\ge\max(\sum s_k\gamma_k^{(l)}-1,0)=\tilde s(\gamma^{(l)}),$$

proving (5.16).

The commutators

$$x^{\tilde s(\beta)}Q_\beta[x^{\tilde s(\alpha)}Q_\alpha,A^\beta]A^\alpha,\ x^{\tilde s(\alpha)}Q_\alpha[A^\alpha,x^{\tilde s(\beta)}Q_\beta]A^\beta\tag{5.17}$$

also lie in $\mathcal{M}_J$. Indeed, $[A_i,x^\rho Q]=x^{\rho-s_i+1}Q'$ for some $Q'\in\Psi_{\mathrm{sc}}^{-\infty,0}(O)$, so they are sums of terms of the form $x^{\tilde s(\alpha)+\tilde s(\beta)-s_i+1}Q'A^\gamma$ with $\gamma=\alpha+\beta-e_i$. Now,

$$\tilde s(\gamma)\le\tilde s(\alpha)+\tilde s(\beta)-s_i+1$$

since $\tilde s(\alpha)+\tilde s(\beta)-s_i+1\ge 0$ as $1\ge s_i$ as well as $\tilde s(\alpha)+\tilde s(\beta)-s_i+1\ge(\sum_k s_k\alpha_k-1)+(\sum_k s_k\beta_k-1)-s_i+1=\sum_k s_k\gamma_k-1$, so $\tilde s(\alpha)+\tilde s(\beta)-s_i+1\ge\max(\sum_k s_k\gamma_k-1,0)=\tilde s(\gamma)$ indeed, proving that (5.17) is in $\mathcal{M}_J$. The commutators

$$[x^{\tilde s(\alpha)}Q_\alpha,x^{\tilde s(\beta)}Q_\beta]A^\alpha A^\beta\tag{5.18}$$

can be shown to lie in $\mathcal{M}_J$ by a similar argument, this time using $\gamma=\alpha+\beta$, and $\tilde s(\gamma)\le\tilde s(\alpha)+\tilde s(\beta)+1$. Thus, we conclude that $[x^{\tilde s(\alpha)}Q_\alpha A^\alpha,x^{\tilde s(\beta)}Q_\beta A^\beta]\in\mathcal{M}_J$, and hence $\mathcal{M}_J=\mathcal{M}_{J+1}=\dots$ is closed under commutators.

Modulo $\Psi_{\mathrm{sc}}^{-\infty,0}(O)$, $x^{\tilde s(\gamma^{(l)}))}A^{\gamma^{(l)}}$ may be replaced by $x^{-s(\gamma^{(l)})}B^{\gamma^{(l)}}$. If $|\gamma^{(l)}|>J$ in (5.15), then this is written in terms of one of the generators listed in (5.14) (or equivalently, modulo $\Psi_{\mathrm{sc}}^{-\infty,0}(O)$, in (5.13)), only after some of the factors in $B^{\gamma^{(l)}}$, which we may always take from $B_lB^{\beta'}B^{\beta''}$, are moved to the front and are incorporated in C_l, i.e. they are simply regarded as 0th order operators and C_l is replaced by $\tilde C_l=C_lB_lB^{\beta'}B^{\beta''}$. Notice the principal symbol of $\tilde C_l$ always vanishes at q in this case. Analogous conclusions hold for the terms in (5.17) and (5.18).

On the other hand, if $|\gamma^{(l)}|\le J$, then $x^{\tilde s(\gamma^{(l)})}A^{\gamma^{(l)}}$ is one of the generators in (5.13), and $|\gamma^{(l)}|=|\alpha|+|\beta|-1$ if $l\ge 1$, and $|\gamma^{(l)}|=|\alpha|+|\beta|-2$ if $l=0$. Moreover, if $\sum_k s_k\beta_k>1$ then

$$\sum_k s_k\gamma_k^{(l)}=\sum_k s_k\alpha_k+\sum_k s_k\beta_k-s_i-s_j+s_l\ge\sum_k s_k\alpha_k+\sum_k s_k\beta_k-1>\sum_k s_k\alpha_k.\tag{5.19}$$

For the terms in (5.17) and (5.18), if $|\gamma|\le J$, we always get $|\gamma|\ge|\alpha|+|\beta|-1$ since $\gamma=\alpha+\beta$ or $\gamma=\alpha+\beta-e_i$ for some i.

Now we turn to (5.6). First, with $\tilde P$ replaced by P_0, (5.6) is certainly satisfied, exactly as in the non-resonant case, since the $\sigma_{\partial,0}(B^\alpha)$ are eigenvectors of the linearization of W with eigenvalue given in Section 3. Thus,

$$i[A^\alpha,x^{-1}P_0]\sum_\gamma C'_\gamma A^\gamma,\ C'_\gamma\in\Psi_{\mathrm{sc}}^{-\infty,0}(O),\tag{5.20}$$

with $\sigma_{\partial,0}(C'_\gamma(q)) = 0$ if $\alpha \neq \gamma$ and $\operatorname{Re}\sigma_{\partial,0}(C'_\alpha(q)) \geq 0$. So it remains to show that it also holds for the resonant terms. If $x^{-s(\beta)}Q_\beta B^\beta$ is a resonant term, then $s(\beta) = 1$. Moreover,

(i) if $|\beta| = 1$, then $x^{-1}Q_\beta B^\beta = \sum_{\mu'}(y')^{\mu'}D_{y'_k}$ for some μ' and some k; in particular it is a summand of r_{er};
(ii) if $|\beta| = 2$, then either $x^{-1}Q_\beta B^\beta = B_j D_{y'_k}$ for some $j > 0, k$, or $x^{-1}Q_\beta B^\beta$ is associated to the sum over I'' in (3.19); in either case $\sum s_k\beta_k > 1$.

We claim that for a resonant term $x^{-s(\beta)}Q_\beta B^\beta$,

$$[x^{-s(\alpha)}B^\alpha, x^{-s(\beta)}Q_\beta B^\beta] \sim \sum_\gamma \tilde{C}_\gamma x^{-s(\gamma)}B^\gamma,\ \tilde{C}_\gamma \in \Psi_{\text{sc}}^{-\infty,0}(X), \tag{5.21}$$

and each term on the right hand side has the following property:

(i) Either $\sigma_{\partial,0}(\tilde{C}_\gamma)(q) = 0$,
(ii) or $|\gamma| > |\alpha|$,
(iii) or $|\gamma| = |\alpha|$, $\sum_k s_k\gamma_k > \sum_k s_k\alpha_k$,
(iv) or $|\gamma| = |\alpha| = 1$, $\gamma = e_k$, $\alpha = e_j$, $s_j = s_k = 1$ and $\sigma_k > \sigma_j$.

Indeed, if $|\beta| \geq 3$, then either (i) or (ii) holds, depending on whether any factors A_k had to be cancelled to write the commutator in terms of the generators in (5.13). If $|\beta| = 2$, then $\sum s_k\beta_k > 1$. Thus, again, either (i) or (ii) holds, or $|\gamma| = |\alpha|$ and $\sum_k s_k\gamma_k > \sum_k s_k\alpha_k$ by (5.19), so (iii) holds. Finally, if $|\beta| = 1$, then $x^{-1}Q_\beta B^\beta = \sum_{\mu'}(y')^{\mu'}D_{y'_k}$ for some μ' and some k. Since $r_1 \leq r_2 \leq \ldots \leq r_{s-1} < 0$, and the resonance condition is $\sum_{l=1}^{s-1}\mu'_l r_l + (1 - r_k) = 1$ with $|\mu'| + 1 \geq 3$, we immediately deduce that $\mu'_l = 0$ for $l \leq k$. Thus, not only do powers of x commute with $x^{-1}Q_\beta B^\beta$, but all A_i commute with $D_{y'_k}$ and $[A_i, (y')^{\mu'}] = 0$ unless $A_i = D_{y'_j}$ and $\mu'_j \neq 0$ for some j, which in turn implies that $j > k$, so $1 - r_k > 1 - r_j$, hence (iv) holds. This completes the proof of (5.21).

By the assumption on the ordering of the multiindices α, we deduce that for all resonant terms $x^{-s(\beta)}B^\beta$,

$$i[A^\alpha, x^{-s(\beta)}B^\beta] = \sum_\gamma C_\gamma A^\gamma,\ C_\gamma \in \Psi_{\text{sc}}^{-\infty,0}(O),$$

and either $\sigma_{\partial,0}(C_\gamma)(q) = 0$, or $\gamma > \alpha$. Combining this with (5.20), we deduce that $\mathcal{M}_J$ satisfies (5.6). This establishes the lemma. □

Corollary 5.9. *Let $\mathcal{M} = \mathcal{M}_J$ be as in the previous lemma. Suppose that*

$$s < -\frac{1}{2},\quad u \in H_{sc}^{\infty,s}(X),\ \tilde{P}u \in \dot{C}^\infty(X) \text{ and } \mathrm{WF}_{sc}(u) \cap O \subset \Phi_+(\{q\}). \tag{5.22}$$

Then $u \in I_{\text{sc}}^{(s)}(O, \mathcal{M})$.

Regularity with respect to $\mathcal{M}$ can be understood more geometrically as follows. Suppose $\delta > 0$ is sufficiently small so that (x, y', y'', y'') define local coordinates on the region U given by $0 \leq x < \delta$, $|y_j| < \delta$ for all j. Let

$$\Phi : U^\circ \to \mathbb{R}^n_+,\ \Phi(x, y', y'', y''') = (x, y', Y'', Y'''),\ Y''_j = \frac{y''_j}{x^{r_j}},\ Y'''_j = \frac{y'''_j}{x^{1/2}}. \tag{5.23}$$

Thus, Φ is a diffeomorphism onto its range $\Phi(U^\circ)$ with

$$\Phi^{-1}(x, y', Y'', Y''') = (x, y'_j, x^{r_j}Y''_j, x^{1/2}Y''').$$

Note that $\overline{\Phi(U^\circ)}$ is not compact; Y'' and Y''' are 'global' variables. Thus Φ^{-1} is actually continuous on $\overline{\Phi(U^\circ)}$ since $r''_j > 0$. Thus, Φ is a blow-up and Φ^{-1} is a somewhat singular blow-down map. In the coordinates (x, y', Y'', Y''') the Riemannian density takes the form

$$ax^{-n-1}\,dx\,dy = ax^{-n+\sum r''_j+(n-m)/2-1}\,dx\,dy'\,dY''\,dY''',$$

$a > 0$, $a \in \mathcal{C}^\infty(X)$. We thus conclude that (for O small) $u \in I^{(s)}_{\mathrm{sc}}(O, \mathcal{M})$ if and only if for any $Q \in \Psi^{-\infty,0}_{\mathrm{sc}}(O)$ with Schwartz kernel supported in $U \times U$, its microlocalization Qu satisfies

$$\begin{aligned}(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D^{\beta'}_{y'} D^{\beta''}_{Y''} D^{\beta'''}_{Y'''} Qu \\ \in x^{s+n/2-\sum r''_j/2-(n-m)/4} L^2(x^{-1}\,dx\,dy'\,dY''\,dY'''),\end{aligned} \tag{5.24}$$

for every a, β, γ'' and γ''', i.e. if and only if microlocally u is conormal in (x, y') with values in Schwartz functions in (Y'', Y'''), with the weight given by $s + n/2 - \sum r''_j/2 - (n - m)/4$.

We also recall that for conormal functions, the L^2 and the L^∞ spaces are very close, namely they are included in each other with a loss of x^ϵ. Thus, $u \in I^{(s)}_{\mathrm{sc}}(O, \mathcal{M})$ implies that

$$\begin{aligned}(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D^{\beta'}_{y'} D^{\beta''}_{Y''} D^{\beta'''}_{Y'''} Qu \\ \in x^{s+n/2-\sum r''_j/2-(n-m)/4-\epsilon} L^\infty(x^{-1}\,dx\,dy'\,dY''\,dY'''),\end{aligned}$$

for every $\epsilon > 0$.

6. Effectively nonresonant operators

We now assume that the normal form p_{norm} for $\sigma_1(P(\sigma))$ at q is such that the term r_{er} vanishes. If this is true, we shall call p_{norm} *effectively nonresonant*, and σ an *effectively nonresonant energy* for q. The significance of the notion of effective resonance in general is that the form of the asymptotics of microlocally outgoing solutions of $Pu = f$, $f \in \dot{\mathcal{C}}^\infty(X)$, is independent of r_{enr}; only r_{er} changes this form slightly. Moreover, effective non-resonance is a more typical condition than non-resonance. For the actual Hamiltonian we are interested in, $P(\sigma) = x^{-1}(\Delta+V-\sigma)$, the set of the effectively resonant energies, i.e. the set of energies σ at which $P(\sigma)$ is effectively resonant at some radial point, is discrete, as shown in Lemma 3.11, while the closure of the set of resonant energies may have nonempty interior! Nonetheless, we shall treat both effectively resonant and effectively nonresonant energies in this paper. We deal with the effectively nonresonant case in this section and treat the effectively resonant case in the following section. In both cases, it is convenient to put P, and not only its principal symbol, to model form. This is accomplished in the following lemma.

Lemma 6.1. *Let $\tilde{P}$ be as in Theorem 3.7. $\tilde{P}$ can be conjugated by a smooth function to the form*

$$\begin{aligned}P_{\mathrm{norm}} &= xD_x + \sum_{j=1}^{m-1} r_j y_j D_{y_j} + \sum_{j=m}^{n-1} Q_j(x^{-1/2}y_j, x^{1/2}D_{y_j}) + R_{\mathrm{er}} + b + R \\ R_{\mathrm{er}} &= \sum_{j=1}^{s-1} \mathcal{P}_j(y')D_{y_j} + \sum_{j=s}^{m-1} \mathcal{P}_j(y'')D_{y_j} + \mathcal{P}_0(y''),\end{aligned} \tag{6.1}$$

where b is a constant, Q_j is a real elliptic homogeneous quadratic polynomial (i.e. a harmonic oscillator), $\mathcal{P}_j$ and $\mathcal{P}_0$ are homogeneous polynomials of degree r_j resp. 1, when y_k is assigned degree r_k, and $R \in x^\epsilon(\mathcal{M})^j$ for some $j \in \mathbb{N}$ and $\epsilon > 0$. In addition, for $s \leq j \leq m-1$, $\mathcal{P}_j$ is actually a polynomial in $y_s, \ldots, y_{j-1}$ (i.e. is independent of $y_j, \ldots, y_{m-1}$) without constant or linear terms, while for $j \leq s-1$, $\mathcal{P}_j$ is a polynomial in $y_{j+1}, \ldots, y_{s-1}$.

We call P_{norm} a normal form *of P. If p_{norm} is effectively non-resonant then $R_{\mathrm{er}} = 0$.*

Remark 6.2. Note that $Q_j(x^{-1/2}y_j, x^{1/2}D_{y_j})$ is not completely well-defined since Q_j is a homogeneous quadratic polynomial, and y_j and D_{y_j} do not commute. However, any two choices for the quantization Q_j differ by a constant multiple of the commutator $[x^{-1/2}y_j, x^{1/2}D_{y_j}] = [y_j, D_{y_j}]$, hence by a constant.

In particular, with the notation of the previous section, $Q_j(Y_j, D_{Y_j})$ may be arranged to be self-adjoint with respect to dY_j, by symmetrizing if necessary, which changes Q_j at most by a constant.

Proof. With the notation of Lemma 5.7, any effectively resonant monomial gives rise to a term of the form $x^{-1}Q_\beta B^\beta$ with $\sum_k s_k\beta_k = 1$, while the effectively non-resonant terms are of the form $x^{-1}Q_\beta B^\beta$ with $\sum_k s_k\beta_k > 1$. This is indeed the key point in categorizing resonant terms as effectively resonant or nonresonant; see the proof of Theorem 6.7. But if $\epsilon = \sum s_k\beta_k - 1 > 0$, we can rewrite $x^{-1}Q_\beta B^\beta \sim x^\epsilon Q_\beta A^\beta$ (i.e. the difference of the two sides is in $\Psi_{\mathrm{sc}}^{-\infty,0}(X)$), and $Q_\beta A^\beta \in \mathcal{M}^{|\beta|}$. Since there are only finitely many effectively non-resonant terms in (3.19), we deduce that any $\tilde{P}$ with $\sigma_1(\tilde{P}) = p_{\mathrm{norm}}$ may be written

$$\tilde{P} = xD_x + \sum_{j=1}^{m-1} r_j y_j D_{y_j} + \sum_{j=m}^{n-1} Q_j(x^{-1/2}y_j, x^{1/2}D_{y_j}) + R_{\mathrm{er}} + B + \tilde{R}, \tag{6.2}$$

where R_{er} is as in (6.1), $\tilde{R} \in x^\epsilon\mathcal{M}_J$ for some $\epsilon > 0$, and $B \in \Psi_{\mathrm{sc}}^{*,0}(X)$. Note that $\mathcal{P}_j$ and $\mathcal{P}_0$ are polynomials, and the homogeneity claim is the meaning of the resonance condition Proposition 3.4. For $s \leq j \leq m-1$, $\mathcal{P}_j$ is independent of $y_j, \ldots, y_{m-1}$ since $0 < r_s \leq r_{s+1} \leq \ldots \leq r_{m-1}$; y_j itself cannot appear in $\mathcal{P}_j$ due to the restriction $2a + |\beta| + |\gamma| \geq 3$ in Proposition 3.4. Similarly, for $j \leq s-1$, $\mathcal{P}_j$ is independent of $y_1, \ldots, y_j$ as $r_1 \leq r_2 \leq \ldots \leq r_{s-1} < 0$. This also shows that the polynomials $\mathcal{P}_j$, $j \neq 0$, have no constant or linear terms.

Let B have symbol $b(\nu, y, \mu)$. Modulo terms in $x^\epsilon\mathcal{M}^j$, this can be reduced to the symbol $b'(0, (y', 0, 0), 0)$. Finally, by conjugating P_{norm} by a function $e^{if(y')}$, we can remove the y'-dependence of b'. Indeed, the Taylor series of f can be constructed iteratively. Let $\mathcal{I}'$ denote the ideal of functions of y' that vanish at 0. Conjugating $\tilde{P}$ by e^{if} produces the terms $\sum_{j=1}^{s-1} r_j' y_j' D_{y_j'} f$, as well as terms from R_{er}, which map $(\mathcal{I}')^k \to (\mathcal{I}')^{k+1}$. For $k \geq 1$, $f \mapsto \sum_{j=1}^{s-1} r_j' y_j' \partial_{y_j'} f$ defines a linear map on $(\mathcal{I}')^k$, $k \geq 1$, with all eigenvalues negative since $r_j' < 0$ for $j = 1, \ldots, s-1$. Thus, this map is invertible, and this shows that $b' - b'(0)$ can be conjugated away in Taylor series. Then it is straightforward to check that the infinite order vanishing error can also be removed. □

Later in this section we show that if p_{norm} is effectively non-resonant, the form of the leading asymptotics of microlocally outgoing solutions for (6.1) and for the completely explicit operator

$$P_0 = xD_x + \sum_{j=1}^{m-1} r_j y_j D_{y_j} + \sum_{j=m}^{n-1} Q_j(x^{-\frac12} y_j, x^{\frac12} D_{y_j}) + b, \quad b \text{ constant} \tag{6.3}$$

are the same, if $R \in x^{1+\epsilon}\mathcal{M}^j$ for some $\epsilon > 0$, i.e. R is indeed an 'error term'. An analogous conclusion holds in the effectively resonant case, with R_{er} included in the right hand side of (6.3).

First, however, we study the asymptotics of approximate solutions of $P_0 u = 0$. The constant b simply introduces a power x^{-ib} into the asymptotics, as can be seen by conjugation of P_0 by x^{-ib}. Here it is convenient to have the asymptotics for the ultimately relevant case, where the operator xP is self-adjoint, stated explicitly, so we assume that xP_0 is formally self-adjoint on $L^2_{\mathrm{sc}}(X)$, which amounts to

$$\operatorname{Im} b = \frac{n-1}{2} - \frac12 \Big(\sum_{j=1}^{s-1} r'_j + \sum_{j=s}^{m-1} r''_j\Big) - \frac{n-m}{2}, \tag{6.4}$$

provided that we have already made Q_j self-adjoint as stated in Remark 6.2. Note that $\frac{n-m}{2} = \sum_{j=m}^{n-1} \operatorname{Re} r'''_j$.

For convenience, we separate the case where q is a source/sink of W, hence of the contact vector field of P_0. Recall from the previous section that

$$Y''_j = x^{-r''_j} y''_j, \quad Y''' = x^{-1/2} y''', \tag{6.5}$$

and define the exponents

$$\tilde b = b - i\frac{n-m}{4}, \ a_{\beta'} = -\sum_{j=1}^{s-1} r_j \beta'_j - i\tilde b. \tag{6.6}$$

Notice that $\operatorname{Re} a_{\beta'} \to \infty$ as $|\beta'| \to \infty$.

Proposition 6.3. *Suppose that the radial point q is a source/sink of W, and (6.4) holds. Suppose that $u \in I^{(s)}(O, \mathcal{M})$, and $P_0 u \in I^{(s')}(O, \mathcal{M})$ where $s < -1/2 < s'$. Then u takes the form*

$$u = \sum_k x^{-i\tilde b - i\sigma_k} w_k(Y'') v_k(Y''') + u' \tag{6.7}$$

where the sum is over $k \in \mathbb{N}$, $v_k(Y)$ is an L^2-normalized eigenfunction of the harmonic oscillator

$$\sum_{j=m}^{n-1} \tilde Q_j(Y_j, D_{Y_j}),\ \tilde Q_j(Y_j, D_{Y_j}) = Q_j(Y_j, D_{Y_j}) - \frac14 (Y_j D_{Y_j} + D_{Y_j} Y_j),\ Y_j = \frac{y_j}{x^{1/2}}, \tag{6.8}$$

with eigenvalue σ_k, w_k are Schwartz functions with each seminorm rapidly decreasing in k, and $u' \in I^{(s'-\epsilon)}(O, \mathcal{M})$ for every $\epsilon > 0$.

Conversely, given any sequence w_k that are Schwartz functions in Y'' with each seminorm rapidly decreasing in k, and given any $f \in I^{(s')}_{\mathrm{sc}}(O, \mathcal{M})$, there exists $u \in \cap_{s<-1/2} I^{(s)}_{\mathrm{sc}}(O, \mathcal{M})$ of the form (6.7) with $\mathrm{WF}_{sc}(P_0 u - f) \cap O = \emptyset$.

Remark 6.4. The result is true if we only assume $s < s'$. However, if $s \geq -1/2$, we can replace s by $\tilde s > -1/2$, apply the proposition with $\tilde s$ in place of s, and then use $u \in I^{(s)}_{\mathrm{sc}}(O, \mathcal{M})$ to show that each w_k vanishes. On the other hand, if $s' \geq -1/2$, the proof of the proposition shows that $u \in I_{\mathrm{sc}}^{(s)}(O,\mathcal{M})$ implies $u \in I_{\mathrm{sc}}^{(s'-\epsilon)}(O,\mathcal{M})$ for every $\epsilon > 0$.

Proposition 6.5. *Suppose that q is a saddle point of W, and (6.4) holds. Suppose $u \in I^{(s)}(O,\mathcal{M})$, and $P_0 u \in I^{(s')}(O,\mathcal{M})$ for some $s < s' < \infty$. Then u takes the form*

$$u = \sum_{\beta',k} x^{a_{\beta'} - i\sigma_k} (y')^{\beta'} w_{\beta',k}(Y'') v_k(Y''') + u' \tag{6.9}$$

where the sum is over $k \in \mathbb{N}$ and a finite set of multiindices β', $v_k(Y)$ and σ_k are as above, $w_{\beta',k}$ are Schwartz functions with each seminorm rapidly decreasing in k, and $u' \in I^{(s'-\epsilon)}(O,\mathcal{M})$ for every $\epsilon > 0$.

Conversely, given any sequence of Schwartz functions $w_{\beta',k}$, finite in β' with each seminorm rapidly decreasing in k, and any $f \in I_{\mathrm{sc}}^{(s')}(O,\mathcal{M})$ there exists $u \in \cap_{s<-1/2} I_{\mathrm{sc}}^{(s)}(O,\mathcal{M})$ of the form (6.9) with $\mathrm{WF}_{sc}(P_0 u - f) \cap O = \emptyset$.

Remark 6.6. As shown later, $x^2 D_x$ gives rise to the terms in $\tilde{Q} - Q$ after the change of variables $(x, y_j) \mapsto (x, \frac{y_j}{x^{1/2}})$. If Q_j is self-adjoint on $L^2(\mathbb{R}, dY_j)$ then $\tilde{Q}_j$ has the same property.

Also, with

$$B = \frac{n-1}{2} - \frac{1}{2}\sum_j r_j'' - \frac{n-m}{4},$$

the (β',k) summand in (6.9) is in $I_{\mathrm{sc}}^{(\mathrm{Re}\, a_{\beta'} - B - \frac{1}{2} - \epsilon)}(O,\mathcal{M})$ for every $\epsilon > 0$. We show below that $\mathrm{Im}\,\tilde{b} = B + d$, $d = -\frac{1}{2}\sum r_j' > 0$, so the (β',k) summand is in $I_{\mathrm{sc}}^{(d - \sum r_j \beta_j' - \frac{1}{2} - \epsilon)}(O,\mathcal{M})$ for every $\epsilon > 0$, and in view of the rapid decay in k, the same is true after the k summation. Thus, for u as in (6.9), $u \in I_{\mathrm{sc}}^{(d-\frac{1}{2}-\epsilon)}(O,\mathcal{M})$ provided $s' > d - \frac{1}{2}$, i.e. decays x^d faster than the microlocal solutions at sources/sinks of W.

Proof of Proposition 6.3. Suppose that $P_0 u = f \in I^{(s')}(O,\mathcal{M})$ for some $s' > -1/2$. Let O' be a W-balanced neighbourhood of q with $\overline{O'} \subset O$, and let $Q \in \Psi_{\mathrm{sc}}^{-\infty,0}(X)$ satisfy $\mathrm{WF}'_{\mathrm{sc}}(Q) \subset O$ (i.e. $Q \in \Psi_{\mathrm{sc}}^{-\infty,0}(O)$) and $\mathrm{WF}'_{\mathrm{sc}}(\mathrm{Id} - Q) \cap \overline{O'} = \emptyset$, with Schwartz kernel supported in $U \times U$,

$$U = \{0 \le x < \delta,\ |y_j| < \delta \text{ for all } j\}.$$

(See (5.23) for the definition of the diffeomorphism Φ, the coordinates Y_j, etc.) Then, as noted in (5.24), by the definition of $I_{\mathrm{sc}}^{(s)}(O,\mathcal{M})$, $\tilde{u} = Qu$ satisfies

$$(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D_{Y''}^{\beta''} D_{Y'''}^{\beta'''} \tilde{u} \in x^s L^2_{\mathrm{sc}}(X)$$

for all a, β'', β''', γ'' and γ'''. Note that $\tilde{u}$ is a microlocalization of u since $\mathrm{WF}_{\mathrm{sc}}(u - Qu) \subset \mathrm{WF}'_{\mathrm{sc}}(\mathrm{Id} - Q)$, so $\mathrm{WF}_{\mathrm{sc}}(u - Qu) \cap O' = \emptyset$. Moreover,

$$P_0(Qu) = QP_0 u + [P_0, Q]u = Qf + f',\ \ f' \in \dot{\mathcal{C}}^\infty(X),$$

since $\mathrm{WF}_{\mathrm{sc}}(u) \cap O \subset \{q\}$, while $\mathrm{WF}'_{\mathrm{sc}}([P_0,Q]) \subset \mathrm{WF}'_{\mathrm{sc}}(Q) \cap \mathrm{WF}'_{\mathrm{sc}}(\mathrm{Id} - Q) \subset O \setminus \overline{O'}$, so $\mathrm{WF}_{\mathrm{sc}}(u) \cap \mathrm{WF}'_{\mathrm{sc}}([P_0,Q]) = \emptyset$. Thus, with $\tilde{f} = Qf + f'$,

$$\begin{aligned} &P_0 \tilde{u} = \tilde{f}, \\ &(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D_{Y''}^{\beta''} D_{Y'''}^{\beta'''} \tilde{f} \in x^{s'} L^2_{\mathrm{sc}}(X), \end{aligned} \tag{6.10}$$

for all a, β'', β''', γ'' and γ'''.

To prove first part of the proposition, it thus suffices to show that, with the notation of (6.7),

$$\tilde{u} = \sum_k x^{-i\tilde{b}-i\sigma_k} w_k(Y'')v_k(Y''') + u'. \tag{6.11}$$

Writing the operator P_0 in the coordinates x, Y'', Y''' we have

$$P_0 = xD_x|_Y + \sum_j \tilde{Q}_j(Y_j''', D_{Y_j'''}) + \tilde{b} \tag{6.12}$$

with $\tilde{b} = b - i\frac{n-m}{4}$ as in (6.6). Formal self-adjointness of xP_0, i.e. (6.4), requires that

$$\operatorname{Im} \tilde{b} = \frac{n-1}{2} - \frac{1}{2}\sum_j r_j'' - \frac{n-m}{4} \equiv B. \tag{6.13}$$

As already remarked, (6.10), which states that $\tilde{f}$ is conormal in x, and Schwartz in Y'', Y''', and belongs to $x^{s'}L^2(dxdy/x^{n+1})$, or in terms of the Y coordinates, to $x^{s'+n/2-\sum r_j''/2-(n-m)/4}\ L^2(dxdY/x)$, implies (by conormality) that

$$\tilde{f} \in x^{s'+1/2+B-\epsilon}L^\infty$$

for every $\epsilon > 0$, where B is defined by (6.13). More precisely, for all a, β, γ'' and γ''',

$$(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D_{Y''}^{\beta''} D_{Y'''}^{\beta'''}\tilde{f} \in x^{s'+1/2+B-\epsilon}L^\infty$$

for every $\epsilon > 0$. Conversely these conditions imply that $\tilde{f}$ satisfies (6.10) with s' replaced by $s' - \epsilon$ for every $\epsilon > 0$.

Writing $\tilde{f}$ in the form

$$\tilde{f}(x, Y'', Y''') = \sum_k f_k(x, Y'')v_k(Y'''),$$

where f_k is conormal in x, Schwartz in Y'', with each seminorm rapidly decreasing in k, a particular solution to $P_0\tilde{u} = \tilde{f}$, is given by

$$\begin{aligned} \tilde{u} &= \sum_k u_k(x, Y'')v_k(Y'''), \\ u_k &= -ix^{-i\tilde{b}-i\sigma_k}\int_0^x f_k(t, Y'')t^{i\tilde{b}+i\sigma_k}\,\frac{dt}{t}. \end{aligned} \tag{6.14}$$

Since $s' + 1/2 > 0$, this integral is convergent and it is not hard to see that $\tilde{u} \in I^{(s'-\epsilon)}(O, \mathcal{M})$ for every $\epsilon > 0$.

On the other hand, the general solution to $P_0\tilde{u} = 0$ with $\tilde{u}$ Schwartz in Y'' and Y''' is given by

$$\tilde{u} = \sum_k x^{-i\tilde{b}-i\sigma_k} w_k(Y'')v_k(Y'''), \tag{6.15}$$

where w_k have the property that each seminorm is rapidly decreasing in k. Since any solution is the sum of the particular solution (6.14) and some homogeneous solution, the first half of the proposition follows.

In fact, the second half also follows by defining

$$\tilde{u} = \sum_k u_k(x, Y'')v_k(Y''') + \sum_k x^{-i\tilde{b}-i\sigma_k} w_k(Y'')v_k(Y'''),$$

with u_k as in (6.14). Multiplying by a cutoff function $\phi \in \mathcal{C}^\infty(X)$ which is identically 1 near $(0,0,\dots,0)$, we deduce that $u = \phi\tilde{u}$ satisfies all requirements. $\square$

Proof of Proposition 6.5. We use a similar argument to prove this proposition. Let O', Q, etc., be as in the previous proof. With $\tilde{u} = Qu$, as noted in (5.24),

$$(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D_{y'}^{\beta'} D_{Y''}^{\beta''} D_{Y'''}^{\beta'''}\tilde{u} \in x^s L^2_{\mathrm{sc}}(X), \tag{6.16}$$

for all a, β, γ'' and γ'''. One of the main differences with the proof of Proposition 6.3 is that microlocalization introduces a non-trivial error, i.e. $P_0\tilde{u}$ is not globally well-behaved (not as good as f was microlocally). However, the error is supported away from $y' = 0$. Indeed, now $\mathrm{WF}_{\mathrm{sc}}(u) \cap O \subset S$, and

$$\tilde{f} = P_0\tilde{u} = Qf + f',\ \ f' = [P_0, Q]u.$$

Here $\mathrm{WF}'_{\mathrm{sc}}([P_0,Q]) \cap S \subset \{|y'| > \delta_0\}$ for some $\delta_0 > 0$, so $f' \in I^{(s)}_{\mathrm{sc}}(O, \mathcal{M})$ in fact satisfies

$$(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D_{y'}^{\beta'} D_{Y''}^{\beta''} D_{Y'''}^{\beta'''} f' \in x^s L^2_{\mathrm{sc}}(X)$$

for all a, β', β'' and β''', γ'' and γ''', with the improved conclusion

$$\phi(y')(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D_{y'}^{\beta'} D_{Y''}^{\beta''} D_{Y'''}^{\beta'''} f' \in \dot{\mathcal{C}}^\infty(X)$$

if ϕ is supported in $|y'| < \delta_0$. Correspondingly,

$$\phi(y')(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D_{y'}^{\beta'} D_{Y''}^{\beta''} D_{Y'''}^{\beta'''} \tilde{f} \in x^{s'} L^2_{\mathrm{sc}}(X). \tag{6.17}$$

The operator P_0 in the coordinates x, y', Y'', Y''' now takes the form

$$P_0 = xD_x|_{y',Y'',Y'''} + \sum_j r'_j y'_j D_{y'_j} + \sum_j \tilde{Q}_j(Y'''_j, D_{Y'''_j}) + \tilde{b}, \tag{6.18}$$

with $\tilde{b} = b - i\frac{n-m}{4}$ as in (6.6). Again, (6.17) implies that $\tilde{f}$ is conormal in x, smooth in y', and Schwartz in Y'', Y''', and belongs to $x^{s'+1/2+B-\epsilon}L^\infty$ for every $\epsilon > 0$, where B is defined by (6.13), in the precise sense that for all a, β, γ'' and γ''',

$$\phi(y')(Y'')^{\gamma''}(Y''')^{\gamma'''}(xD_x)^a D_{Y''}^{\beta''} D_{Y'''}^{\beta'''} \tilde{f} \in x^{s'+1/2+B-\epsilon}L^\infty$$

for every $\epsilon > 0$. However, now formal self-adjointness of xP_0 requires that

$$\operatorname{Im}\tilde{b} = B + d, \quad d = -\frac{1}{2}\sum_j r'_j > 0, \tag{6.19}$$

so there is a discrepancy of d compared with the previous proposition. Write $\tilde{f}$ in the form

$$\tilde{f}(x, Y'', Y''') = \sum_k f_k(x, y', Y'')v_k(Y'''),$$

where f_k is conormal in x, smooth in y', and Schwartz in Y'' with seminorms rapidly decreasing in k.

We start by describing solutions of the homogeneous equation $P_0\tilde{u} = 0$ in U which in addition satisfy (6.16). Decomposing $\tilde{u}$ in terms of the v_k, and factoring out a power of x for convenience, i.e. writing $\tilde{u} = \sum_k x^{-i\tilde{b}-i\sigma_k}u_k(x, y', Y'')v_k(Y''')$, we see that the coefficients u_k satisfy

$$(x\partial_x|_{y',Y'',Y'''} + \sum_j r'_j y'_j \partial_{y'_j})u_k = 0.$$

Since $\tilde{u}$ is smooth in the interior of U, $P_0\tilde{u} = 0$ amounts to demanding that u_k be constant along each integral curve segment of the vector field $x\partial_x + \sum_j r'_j y'_j \partial_{y'_j}$, with the value of $\tilde{u}$ depending smoothly on the choice of the integral curve. (We remark that U is convex for this vector field; $|y'|$ is increasing as $x \to 0$.) Thus, we in fact have $u_k(x, y', Y'') = \hat{u}_k(Y', Y'')$ with $\hat{u}_k$ smooth in Y' and Schwartz in Y''. Here $Y'_j = y'_j / x^{r'_j}$; note that $r'_j < 0$. Expanding $\hat{u}_k$ in Taylor series around $Y' = 0$ to order N, we see that

$$u_k(x, y', Y'') - \sum_{|\beta'| \le N-1} x^{-\sum_j r'_j \beta'_j} (y')^{\beta'} w_{\beta',k}(Y'')$$

is a finite sum of terms of the form $x^{-\sum_j r'_j \beta'_j} (y')^{\beta'} \hat{u}_{k,\beta'}(Y', Y'')$ with $\hat{u}_{k,\beta'}$ smooth (Schwartz in Y'''), where the sum runs over β' with $|\beta'| = N$. Thus, given any s'' (e.g. $s'' = s'$), we can choose N sufficiently large so that this difference lies in $I^{(s'')}_{\mathrm{sc}}(O, \mathcal{M})$, which means it is ignorable for our purposes. Thus, the general solution to $P_0\tilde{u} = 0$ in U which satisfies (6.16) is given by

$$\tilde{u} = \sum_{\beta',k} x^{a_{\beta'} - i\sigma_k} (y')^{\beta'} w_{\beta',k}(Y'') v_k(Y'''), \tag{6.20}$$

modulo any $I^{(s'')}_{\mathrm{sc}}(O, \mathcal{M})$ (where the sum is understood as a finite one, due to the remark above), where the seminorms of $w_{\beta',k}$ are rapidly decreasing in k for each β'.

In expressing a particular solution $\tilde{u}$ of $P_0\tilde{u} = f$ in terms of f, we need to integrate along integral curves of the vector field $x\partial_x + \sum_j r'_j y'_j \partial_{y'_j}$, and since $r'_j < 0$, $|y'| \to \infty$ as $x \to 0$ along integral curves (unless $y' = 0$); in fact $|y'|$ is increasing as $x \to 0$ as mentioned above. So we cannot integrate down to $x = 0$. Instead we fix an $x_0 > 0$ and use the formula

$$\begin{aligned} u_k(x, y', Y'') &= (\frac{x}{x_0})^{-i\tilde{b} - i\sigma_k} u_k(x_0, (\frac{x}{x_0})^{-r'_j} y'_j, Y'') \\ &+ i x^{-i\tilde{b} - i\sigma_k} \int_{x_0}^{x} f_k(t, (\frac{x}{t})^{-r'_j} y'_j, Y'') t^{i\tilde{b} + i\sigma_k} \, \frac{dt}{t}. \end{aligned} \tag{6.21}$$

Notice that $u_k(x_\sharp, y'_\sharp, Y''_\sharp)$ depends only on f_k evaluated at points (x, y', Y'') with $|y'| \le |y'_\sharp|$. Thus, (6.17) can be used to deduce properties of u_k, hence of $\tilde{u}$, in $|y'| < \delta_0$.

If $s' < -1/2 + d$, then (6.21) gives $\phi(y')\tilde{u} \in I^{(s'-\epsilon)}(O, \mathcal{M})$ for every $\epsilon > 0$, with ϕ as in (6.17). If $s' \ge -1/2 + d$, then $\phi(y')\tilde{u} \in I^{(-1/2+d-\epsilon)}(O, \mathcal{M})$ for every $\epsilon > 0$. However, we claim that is actually a sum of terms solving the homogeneous equation, plus a function in $I^{(s'-\epsilon)}(O, \mathcal{M})$ for every $\epsilon > 0$. For simplicity we show this only in the case that $-1/2 + d < s' < -1/2 + d + |r'_{s-1}|$. Then we observe that $(x/x_0)^{-i\tilde{b} - i\sigma_k} \tilde{u}(x_0, 0, Y'')$ is a solution of the homogeneous equation, while the difference

$$\begin{aligned} &(\frac{x}{x_0})^{-i\tilde{b} - i\sigma_k} \tilde{u}(x_0, (\frac{x}{x_0})^{-r'_j} y'_j, Y'') - (\frac{x}{x_0})^{-i\tilde{b} - i\sigma_k} \tilde{u}(x_0, 0, Y'') \\ &= \sum_j (\frac{x}{x_0})^{-r'_j} \int_0^1 y'_j \partial_{y'_j} \big(\tilde{u}(x_0, \tau (\frac{x}{x_0})^{-r'_j} y'_j, Y'') \big) \, d\tau \end{aligned}$$

has decay at least $x^{-r'_{s-1}}$ better, hence yields a term in $I^{(s'-\epsilon)}(O,\mathcal{M})$ for every $\epsilon>0$. Similarly, if we replace $f_k(t,(\frac{x}{t})^{-r'_j}y'_j,Y'')$ in the integral by $f_k(t,0,Y'')$ then we get a homogeneous term, while the difference gives a term in $I^{(s'-\epsilon)}(O,\mathcal{M})$ for every $\epsilon>0$. The argument can be repeated, removing more and more terms in the Taylor series for $\tilde u$ and $\tilde f$, for larger values of s'. Since any solution is the sum of the particular solution above and the general solution, the first half of the proposition follows with O replaced by a smaller neighbourhood O'' of q. However, we recover the original statement by using the real principal type parametrix construction of Duistermaat and Hörmander [2].

The second half can be proved as in the previous proposition. Fix some $x_0>0$, and let u_k be given by the second term on the right hand side of (6.21), and let $\hat u=\sum_k u_k(x,Y'')v_k(Y''')$. Then $P_0\hat u=f$, and as shown above, $\hat u$ has the form

$$\hat u=\sum_{\beta',k}x^{a_{\beta'}-i\sigma_k}(y')^{\beta'}\hat w_{\beta',k}(Y'')v_k(Y''')+\hat u', \tag{6.22}$$

with $\hat u'\in I^{(s'-\epsilon)}_{\mathrm{sc}}(O,\mathcal{M})$ for all $\epsilon>0$. Then with

$$\tilde u=\sum_k u_k(x,Y'')v_k(Y''')+\sum_{\beta',k}x^{a_{\beta'}-i\sigma_k}(w_{\beta',k}(Y'')-\hat w_{\beta',k}(Y''))v_k(Y'''),$$

$u=\phi\tilde u$, $\phi\in\mathcal{C}^\infty(X)$ identically 1 near $(0,\dots,0)$, u satisfies all requirements. □

These results on the explicit normal form P_0 then allow us to parameterize microlocally outgoing solutions for every effectively nonresonant critical point.

Theorem 6.7. *Suppose that $P(\sigma)$ is effectively nonresonant at q, with normal form P_{norm} near q as in Lemma 6.1, and* (6.4) *holds.*

(i) *If in addition q is a source/sink of W, then any microlocally outgoing solution u of P_{norm} has the form* (6.7)*, and conversely given any Schwartz sequence of Schwartz functions w_k there is a microlocally outgoing solution u of P_{norm} which has the form* (6.7). *Thus, microlocal solutions at a source/sink of W are parameterized by Schwartz functions of the variables (Y'',Y''').*

(ii) *If q is a saddle point of W, then all microlocally outgoing solutions are in $x^{-1/2+\epsilon}L^2$ for some $\epsilon>0$. For each monomial $(y')^\beta$ in the variables y', each $k\in\mathbb{N}$ and each Schwartz function $w(Y'')$ there is a microlocally outgoing solution of the form*

$$u=\sum_k x^{a_{\beta'}-i\sigma_k}(y')^{\beta'}w(Y'')v_k(Y''')+u', \tag{6.23}$$

where u' is in a strictly faster decaying weighted L^2 space than u, and every microlocally outgoing solution is a sum of such solutions, with the $w=w_{k,\beta'}$ rapidly decreasing as $k\to\infty$ in every seminorm.

Proof. First, $P_{\mathrm{norm}}=P_0+R$, $R\in x^\epsilon\mathcal{M}^j$, $\epsilon>0$. Thus, if O is a neighbourhood of q as above, $\mathrm{WF}_{\mathrm{sc}}(P_{\mathrm{norm}}u)\cap O=\emptyset$, then $u\in I^{(s)}_{\mathrm{sc}}(O,\mathcal{M})$ for all $s<-1/2$, so $Ru\in I^{(s')}_{\mathrm{sc}}(O,\mathcal{M})$ for some $s'>1/2$. Hence $P_0u=P_{\mathrm{norm}}u-Ru\in I^{(s')}_{\mathrm{sc}}(O,\mathcal{M})$.

If q is a source/sink of W, then Proposition 6.3 is applicable, and we deduce that u is microlocally of the form (6.7). Moreover, if q is a source/sink of W, then given any Schwartz sequence of Schwartz functions w_k, let $u_0\in\cap_{s<-1/2}I^{(s)}_{\mathrm{sc}}(O,\mathcal{M})$ be of the form (6.7) with $P_0 u_0 \in \dot{\mathcal{C}}^\infty(X)$. We construct $u_k \in \cap_{r<-1/2-k\epsilon} I_{\mathrm{sc}}^{(r)}(O,\mathcal{M})$, $k \geq 1$, inductively so that $P_0 u_k + R u_{k-1} \in \dot{\mathcal{C}}^\infty(X)$ for $k \geq 1$; this can be done by the second half of Proposition 6.3. Asymptotically summing $\sum_k u_k$ to some $u \in \cap_{s<-1/2} I_{\mathrm{sc}}^{(s)}(O,\mathcal{M})$ gives a microlocally outgoing solution with the prescribed asymptotics, completing the proof of the theorem in this case.

If q is a saddle point of W, we apply Proposition 6.5 with $s' > -1/2$ as in the first paragraph of the proof. If $\epsilon' > 0$ is sufficiently small, all of the terms in (6.9) are in $I_{\mathrm{sc}}^{(-1/2+\epsilon')}(O,\mathcal{M})$ proving the first claim. To show the next, let $u_0 = x^{a_{\beta'} - i\sigma_k}(y')^{\beta'} w(Y'')v_k(Y''')$, so $P_0 u_0 = 0$ and $u_0 \in I_{\mathrm{sc}}^{(s)}(O,\mathcal{M})$ for any $s < -1/2 + d$. We construct u_k inductively as above, using Proposition 6.5, to obtain u. □

Remark 6.8. From (6.7) or (6.25) it is not hard to derive the asymptotic expansion of eigenfunctions of the original operator $\Delta + V - \sigma$; we need only apply the Fourier integral operator F^{-1} to these expansions. In the case of a radial point $q \in \mathrm{Min}_+(\sigma)$, the expansion takes the form

(6.24)
$$u = e^{i\Phi(y)/x} \sum_k x^{-i\tilde{b} - i\sigma_k} w_k(Y'')v_k(Y''') + u',\ u' \in I^{-\frac{1}{2}+\epsilon}(O,\mathcal{M}) \text{ for some } \epsilon > 0$$

where Φ is a smooth function (it parameterizes the Legendrian submanifold which is the image of the zero section under the canonical relation of F^{-1}). For a given σ, only a finite number of terms in the Taylor series for Φ are relevant. Similarly in the case of radial points $q \in \mathrm{RP}_+(\sigma) \setminus \mathrm{Min}_+(\sigma)$, the expansion (6.25) takes the form

$$u = e^{i\Phi(y)/x} \sum_k x^{a_{\beta'} - i\sigma_k}(y')^{\beta'} w(Y'')v_k(Y''') + u', \tag{6.25}$$

with Φ smooth. Again it parameterizes the image of the zero section under the canonical relation of F^{-1}. In this case, the value of Φ on the unstable manifold $\{y'' = y''' = 0\}$ is essential, but only a finite number of terms in the Taylor series for Φ about this unstable manifold are relevant.

These expansions were obtained directly in Part I (i.e. without going via a normal form) in the two dimensional case.

7. Effectively resonant operators

If P is effectively resonant, the simple expressions (6.7) and (6.9) need to be replaced by a slightly more complicated one in which positive integral powers of $\log x$ also appear. Essentially, instead of powers, or Schwartz functions, of $\frac{y_j}{x^{r_j}}$, we also get factors of $\log x$ in the expressions for the Y_l.

Now we define a change of coordinates inductively that simplifies the vector field

$$V = (xD_x) + \sum_{j=1}^{m-1} (r_j y_j + \mathcal{P}_j(y_s, \ldots, y_{j-1}))D_{y_j} \tag{7.1}$$

that appears in (6.1) as the combinations of the linear terms $\sum r_j y_j D_{y_j}$ and the effectively resonant vector fields in R_{er}. (Note that $r_j y_j$ and $\mathcal{P}_j(y_s, \ldots, y_{j-1})$ are both homogeneous of degree r_j.) We do this in two steps to clarify the argument, first only dealing with the y'' terms, i.e. $j = s, \ldots, m-1$.

The coordinates Y_j, $j = s, \ldots, m-1$, are a modification of the coordinates $\frac{y_j}{x^{r_j}}$ that appear in (6.5), so that $Y_j - \frac{y_j}{x^{r_j}}$ are polynomials $\mathcal{P}_j^\sharp$ in $Y_s, \ldots, Y_{j-1}, t = \log x$. Thus, we let

$$Y_s = \frac{y_s}{x^{r_s}},\ \mathcal{P}_s^\sharp = 0,\ \bar{Y}_s(Y_s, \log x) = Y_s + \mathcal{P}_s^\sharp(\log x)$$

and provided that $Y_s, \ldots, Y_{j-1}$, $\mathcal{P}_s^\sharp, \ldots, \mathcal{P}_{j-1}^\sharp$ have been defined, we let

$$\begin{aligned}
&\mathcal{P}_j^\sharp(Y_s, \ldots, Y_{j-1}, t) = \int_0^t \mathcal{P}_j(\bar{Y}_s(Y_s, t'), \ldots, \bar{Y}_{j-1}(Y_s, \ldots, Y_{j-1}, t'))\, dt',\\
&Y_j = \frac{y_j}{x^{r_j}} - \mathcal{P}_j^\sharp(Y_s, \ldots, Y_{j-1}, \log x),\\
&\bar{Y}_j = Y_j + \mathcal{P}_j^\sharp(Y_s, \ldots, Y_{j-1}, \log x),\ j = s, \ldots, m-1.
\end{aligned}$$

The point of the construction is that V annihilates Y_j for all j. This can be seen iteratively: for Y_s this is straightforward, and if $VY_s = \ldots = VY_{j-1} = 0$ then (with $\partial_t \mathcal{P}_j^\sharp$ denoting the derivative with respect to the last variable, $t = \log x$)

$$\begin{aligned}
VY_j &= -r_j \frac{y_j}{x^{r_j}} + (r_j y_j + \mathcal{P}_j(y_s, \ldots, y_{j-1}))x^{-r_j} - (\partial_t \mathcal{P}_j^\sharp)(Y_s, \ldots, Y_{j-1}, \log x)\\
&= \mathcal{P}_j(y_s x^{-r_s}, \ldots, y_{j-1} x^{-r_{j-1}}) - \mathcal{P}_j(\bar{Y}_s(Y_s, \log x), \ldots, \bar{Y}_{j-1}(Y_s, \ldots, Y_{j-1}, \log x))\\
&= 0
\end{aligned}$$

in view of the definition of $Y_s, \ldots, Y_{j-1}$ and $\bar{Y}_s, \ldots, \bar{Y}_{j-1}$.

One can deal with the $j = 1, \ldots, s-1$ terms similarly. We define $\mathcal{P}_j^\sharp$, Y_j and $\bar{Y}_j$ inductively as above, starting with Y_{s-1}. Thus, we let

$$Y_{s-1} = \frac{y_{s-1}}{x^{r_{s-1}}},\ \mathcal{P}_{s-1}^\sharp = 0,\ \bar{Y}_{s-1}(Y_{s-1}, \log x) = Y_{s-1} + \mathcal{P}_{s-1}^\sharp(\log x)$$

and provided that $Y_{j+1}, \ldots, Y_{s-1}$, $\mathcal{P}_{j+1}^\sharp, \ldots, \mathcal{P}_{s-1}^\sharp$ have been defined, we let

(7.2)
$$\begin{aligned}
&\mathcal{P}_j^\sharp(Y_{j+1}, \ldots, Y_{s-1}, t) = \int_0^t \mathcal{P}_j(\bar{Y}_{j+1}(Y_{j+1}, \ldots, Y_{s-1}, t'), \ldots, \bar{Y}_{s-1}(Y_{s-1}, t'))\, dt',\\
&Y_j = \frac{y_j}{x^{r_j}} - \mathcal{P}_j^\sharp(Y_{j+1}, \ldots, Y_{s-1}, \log x),\\
&\bar{Y}_j = Y_j + \mathcal{P}_j^\sharp(Y_{j+1}, \ldots, Y_{s-1}, \log x),\ j = 1, \ldots, s-1.
\end{aligned}$$

With these definitions, in the coordinates $X = x, Y_1, \ldots, Y_{m-1}, y_m, \ldots, y_{n-1}$, i.e. (X, Y', Y'', y'''), which correspond to a blow-up of $x = y_s = \ldots = y_{m-1} = 0$, $V = X^2 D_X$.

The zeroth order term is a polynomial $\mathcal{P}_0$ in $y_s, \ldots, y_{m-1}$ which is homogeneous of degree 1 (where y_j has degree r_j). Thus,

$$x^{-1}\mathcal{P}_0(y_s, \ldots, y_{m-1}) = \mathcal{P}_0(\bar{Y}_s(Y_s, \log x), \ldots, \bar{Y}_{m-1}(Y_s, \ldots, Y_{m-1}, \log x)).$$

Let

$$\mathcal{P}_0^\sharp(Y_s, \ldots, Y_{j-1}, t) = \int_0^t \mathcal{P}_0(\bar{Y}_s(Y_s, t'), \ldots, \bar{Y}_{j-1}(Y_s, \ldots, Y_{j-1}, t'))\, dt',$$

which is thus a polynomial in $Y_s, \ldots, Y_{j-1}, t$. Then $e^{i\mathcal{P}_0^\sharp(Y_s, \ldots, Y_{j-1}, \log x)}$ can be used as an integrating factor, conjugating $\tilde{P}$, to remove the zeroth order term in I''.

Finally, to put the quadratic terms in a convenient form, we let

$$Y_j = \frac{y_j}{x^{1/2}},\ j = m, \dots, n-1$$

as before.

Suppose first that $\mathcal{P}_0 = 0$. With our definition of the Y_j, (6.12), resp. (6.18), hold if q is a source/sink, resp. saddle point, of V_0. Thus, the statement and the proof of Proposition 6.3 holds without any changes, while the statement and the proof of Proposition 6.5 hold provided that $x^{a_{\beta'}}(y')^{\beta'}$ is replaced by $x^{-i\tilde{b}}(Y')^{\beta'}$. A minor difference is that slightly more effort is required to show that $|y'|$ decreases on the integral curves of the vector field (7.1) inside $|y'| < \delta_1$ for $\delta_1 > 0$ small. Namely we need to use that, as $\mathcal{P}_j$, $j = 1, \dots, s-1$ have no linear or constant terms by Lemma 6.1, $V|y'|^2 = \sum_{j=1}^{s-1} r_j y_j^2 + \mathcal{O}(|y'|^3) \le r_{s-1}|y'|^2 + \mathcal{O}(|y'|^3)$, $r_{s-1} < 0$, to conclude that $V|y'|^2 \le 0$ for $|y'| < \delta_1$, $\delta_1 > 0$ small.

In general, with $\tilde{b} = b - i\frac{n-m}{4}$ as in (6.6), (6.12), resp. (6.18), are replaced by

$$P_0 = xD_x|_Y + \sum_j \tilde{Q}_j(Y_j''', D_{Y_j'''}) + \mathcal{P}_0 + \tilde{b}, \tag{7.3}$$

respectively

$$P_0 = xD_x|_{y',Y'',Y'''} + \sum_{j=1}^{s-1}(r_j' y_j' + \mathcal{P}_j)D_{y_j'} + \sum_j \tilde{Q}_j(Y_j''', D_{Y_j'''}) + \mathcal{P}_0 + \tilde{b}. \tag{7.4}$$

Thus,

$$e^{i\mathcal{P}_0^\sharp} P_0 e^{-i\mathcal{P}_0^\sharp} = xD_x|_Y + \sum_j \tilde{Q}_j(Y_j''', D_{Y_j'''}) + \tilde{b}, \tag{7.5}$$

respectively

$$e^{i\mathcal{P}_0^\sharp} P_0 e^{-i\mathcal{P}_0^\sharp} = xD_x|_{y',Y'',Y'''} + \sum_{j=1}^{s-1}(r_j' y_j' + \mathcal{P}_j)D_{y_j'} + \sum_j \tilde{Q}_j(Y_j''', D_{Y_j'''}) + \tilde{b}. \tag{7.6}$$

Since multiplication by $e^{\pm i\mathcal{P}_0^\sharp}$ preserves $I^{(s)}_{\mathrm{sc}}(O,\mathcal{M})$, the rest of the proof of the propositions is applicable with u replaced by $e^{i\mathcal{P}_0^\sharp}u$, $f = P_0 u$ replaced by $e^{i\mathcal{P}_0^\sharp}f$. We thus deduce the following analogues of Propositions 6.3 – 6.5 in the effectively resonant case.

Proposition 7.1. *Suppose that the radial point q is a source/sink of W, and (6.4) holds. Suppose that $u \in I^{(s)}(O,\mathcal{M})$, and $P_0 u \in I^{(s')}(O,\mathcal{M})$ where $s < -1/2 < s'$. Then u takes the form*

$$u = \sum_k x^{-i\tilde{b} - i\sigma_k} e^{-i\mathcal{P}_0^\sharp} w_k(Y'') v_k(Y''') + u' \tag{7.7}$$

where the sum is over $k \in \mathbb{N}$, $v_k(Y)$ is an L^2-normalized eigenfunction of the harmonic oscillator

$$\sum_{j=m}^{n-1} \tilde{Q}_j(Y_j, D_{Y_j}),\ \tilde{Q}_j(Y_j, D_{Y_j}) = Q_j(Y_j, D_{Y_j}) - \frac{1}{4}(Y_j D_{Y_j} + D_{Y_j} Y_j),\ Y_j = \frac{y_j}{x^{1/2}}, \tag{7.8}$$

with eigenvalue σ_k, w_k are Schwartz functions with each seminorm rapidly decreasing in k, and $u' \in I^{(s'-\epsilon)}(O,\mathcal{M})$ for every $\epsilon > 0$.

Conversely, given any sequence w_k that are Schwartz functions in Y'' with each seminorm rapidly decreasing in k, and given any $f \in I^{(s')}_{\mathrm{sc}}(O,\mathcal{M})$, there exists $u \in \cap_{s<-1/2} I^{(s)}_{\mathrm{sc}}(O,\mathcal{M})$ of the form (7.7) *with* $\mathrm{WF}_{sc}(P_0 u - f) \cap O = \emptyset$.

Proposition 7.2. *Suppose that q is a saddle point of W, and* (6.4) *holds. Suppose $u \in I^{(s)}(O,\mathcal{M})$, and $P_0 u \in I^{(s')}(O,\mathcal{M})$ for some $s < s' < \infty$. Then u takes the form*

$$u = \sum_{\beta',k} x^{-i\tilde{b}-i\sigma_k} (Y')^{\beta'} e^{-i\mathcal{P}_0^\sharp} w_{\beta',k}(Y'') v_k(Y''') + u' \tag{7.9}$$

where the sum is over $k \in \mathbb{N}$ and a finite set of multiindices β', $v_k(Y)$ and σ_k are as above, $w_{\beta',k}$ are Schwartz functions with each seminorm rapidly decreasing in k, and $u' \in I^{(s'-\epsilon)}(O,\mathcal{M})$ for every $\epsilon > 0$.

Conversely, given any sequence of Schwartz functions $w_{\beta',k}$, finite in β' with each seminorm rapidly decreasing in k, and any $f \in I^{(s')}_{\mathrm{sc}}(O,\mathcal{M})$ there exists $u \in \cap_{s<-1/2} I^{(s)}_{\mathrm{sc}}(O,\mathcal{M})$ of the form (7.9) *with* $\mathrm{WF}_{sc}(P_0 u - f) \cap O = \emptyset$.

We thus deduce the following analogue of Theorem 6.7, with a similar proof.

Theorem 7.3. *Suppose that $P(\sigma)$ is effectively resonant at q, with normal form P_{norm} near q as in Lemma 6.1, and* (6.4) *holds.*

(i) *If in addition q is a source/sink of W, then any microlocal solution u of P_{norm} has the form* (7.7)*, and conversely given any Schwartz sequence of Schwartz functions w_k there is a microlocally outgoing solution u of P_{norm} which has the form* (7.7)*. Thus, microlocal eigenfunctions at a source/sink are parameterized by Schwartz functions of the variables (Y'', Y''').*

(ii) *If q is a saddle point of W, then all microlocal solutions are in $x^{-1/2+\epsilon}L^2$ for some $\epsilon > 0$. For each monomial in the variables Y', each $k \in \mathbb{N}$ and each Schwartz function $w(Y'')$ there is a microlocally outgoing solution of the form*

$$u = x^{-i\tilde{b}-i\sigma_k} e^{-i\mathcal{P}_0^\sharp} (Y')^{\beta'} w(Y'') v_k(Y''') + u', \tag{7.10}$$

where u' is in a strictly faster decaying weighted L^2 space than u, and every microlocally outgoing solution is a sum of such solutions, with the $w = w_{k,\beta'}$ rapidly decreasing as $k \to \infty$ in every seminorm.

8. From microlocal to approximate eigenfunctions

We are interested in the structure of (global) eigenfunctions of $\Delta + V$. While in the first half of the paper a rather general element $P \in \Psi^{*,-1}_{\mathrm{sc}}(X)$ was considered, from now we work with

$$H = \Delta + V \in \Psi^{*,0}_{\mathrm{sc}}(X),\ H(\sigma) = H - \sigma,$$

in particular *the order of H at ∂X is* 0.

In the next section we obtain an iterative description of the 'smooth' eigenfunctions in terms of the microlocal eigenspaces. As the first step, we show that if q is a radial point for $H(\sigma) = H - \sigma$, then elements of $E_{\mathrm{mic},+}(q,\sigma)$, which are the microlocally outgoing eigenfunctions near q, have representatives satisfying $(H-\sigma)u \in \dot{\mathcal{C}}^\infty(X)$, i.e. they extend to approximate eigenfunctions, with $\mathrm{WF}_{\mathrm{sc}}(u)$ a subset of the forward flow-out of q. Stated explicitly this is

Proposition 8.1. *If $q \in \mathrm{RP}_+(\sigma)$ then every element of $E_{\mathrm{mic},+}(q,\sigma)$ has a representative u such that $(H-\sigma)u \in \dot{\mathcal{C}}^\infty(X)$, and $\mathrm{WF}_{sc}(u) \subset \Phi_+(\{q\})$.*

Remark 8.2. From this result it is easy to produce an exact eigenfunction v such that $\mathrm{WF}_{\mathrm{sc}}(v) \cap \{\nu \geq 0\} \subset \Phi_+(\{q\})$; we simply take $v = u - R(\sigma - i0)u$.

The key ingredient of the proof, as in the two-dimensional case studied in [4], is the microlocal solvability of the eigenequation through radial points. To avoid a microlocal construction along the lines of Hörmander [10], we introduce, as in [4], an operator $\tilde{H}$ which arises from H by altering V appropriately. This is chosen to be equal to H near the radial point in question but to have no other radial points in $\mathrm{RP}_+(\sigma)$ at which ν takes a smaller value. One may then assume, in any argument concerning $q \in \mathrm{RP}_+(\sigma)$, that there is no $q' \in \mathrm{RP}_+(\sigma)$ with $\nu(q') < \nu(q)$.

As in [4], we introduce a partial order on $\mathrm{RP}_+(\sigma)$ corresponding to the flow-out under W.

Definition 8.3. If q, $q' \in \mathrm{RP}_+(\sigma)$ we say that $q \leq q'$ if $q' \in \Phi_+(\{q\})$ and $q < q'$ if $q \leq q'$ but $q' \neq q$. A subset $\Gamma \subset \mathrm{RP}_+(\sigma)$ is closed under $\leq$ if, for all $q \in \Gamma$, $\{q' \in \mathrm{RP}_+(\sigma); q \leq q'\} \subset \Gamma$. We call the set $\{q' \in \mathrm{RP}_+(\sigma); q \leq q'\}$ the string generated by q.

Remark 8.4. This partial order relation between two radial points in $\mathrm{RP}_+(\sigma)$ corresponds to the existence of a sequence $q_j \in \mathrm{RP}_+(\sigma)$, $j = 0, \dots, k$, $k \geq 1$, with $q_0 = q$, $q_k = q'$ and such that for every $j = 0, \dots, k-1$, there is a bicharacteristic γ_j with $\lim_{t\to-\infty} \gamma_j = q_j$ and $\lim_{t\to+\infty} \gamma_j = q_{j+1}$.

Lemma 8.5. *Given $\sigma > \min V_0$ and $\tilde{\nu} > 0$, set $K = {V_0}^{-1}((-\infty, \sigma - \tilde{\nu}^2]) \subset \partial X$ then there exists a potential function $\tilde{V} \in \mathcal{C}^\infty(X)$ with $\tilde{V}_0$ Morse such that*

(i) $\tilde{V}_0 \geq V_0$,
(ii) $\tilde{V}_0 = V_0$ *on a neighbourhood of* K,
(iii) *no critical value of* $\tilde{V}$ *lies in the interval* $(\sigma - \tilde{\nu}^2, \sigma]$,
(iv) *if* $\tilde{\Sigma}(\sigma)$ *is the characteristic variety at energy* σ *of* $\tilde{H} = \Delta + \tilde{V}$ *then*

$$\Sigma(\sigma) \cap \{\nu \geq \tilde{\nu}\} = \tilde{\Sigma}(\sigma) \cap \{\nu \geq \tilde{\nu}\} \text{ and} \tag{8.1}$$

(v) $\tilde{H} - \sigma$ *has no* L^2 *null space.*

Proof. Choose a smooth function f on the real line so that $f' > 0$, $f(t) = t$ if $t \leq \sigma - \tilde{\nu}^2$ and $f(t) > \sigma$ for $t \geq \min\{V(q); dV(q) = 0 \text{ and } V(q) > \sigma - \tilde{\nu}^2\} > \sigma - \tilde{\nu}^2$. Then let $\tilde{V} = f \circ V$, so the critical points of V_0 and $\tilde{V}_0$ are the same and are non-degenerate.

On $\Sigma(\sigma) \cap \{\nu \geq \tilde{\nu}\}$, $\nu^2 + |\mu|_y^2 + V_0 = \sigma$, hence $V_0 \leq \sigma - \tilde{\nu}^2$, so $V_0 = \tilde{V}_0$, and therefore $\Sigma(\sigma) \cap \{\nu \geq \tilde{\nu}\} \subset \tilde{\Sigma}(\sigma)$. With the converse direction proved similarly, (i) – (iv) follow. Property (v) can be arranged by a suitable perturbation of $\tilde{V}$ with compact support in the interior. □

These properties of $\tilde{H}$ are exploited in the proof of the following continuation result.

Lemma 8.6 (Lemma 5.5 of [4])**.** *Suppose $u \in \mathcal{C}^{-\infty}(X)$ satisfies*

$$\mathrm{WF}_{sc}(u) \subset \{\nu \geq \nu_1\} \text{ and } \mathrm{WF}_{sc}((H-\sigma)u) \subset \{\nu \geq \nu_2\},$$

for some $0 < \nu_1 < \nu_2$, then there exists $\tilde{u} \in \mathcal{C}^{-\infty}(X)$ with $\mathrm{WF}_{sc}(u - \tilde{u}) \subset \{\nu \geq \nu_2\}$ and $(H-\sigma)\tilde{u} \in \dot{\mathcal{C}}^\infty(X)$.

Proof. We just sketch the proof here; for full details, see [4]. The obvious idea of subtracting $R(\sigma+i0)((H-\sigma)u)$ from u does not quite work, since the forward flow out of other critical points in $\mathrm{RP}_+(\sigma)$ with ν less than $\nu(q)$ may strike q. To avoid this problem, choose $\tilde\nu$ with $\nu_1<\tilde\nu<\nu_2$, sufficiently close to ν_2 so that there are no radial points q with $\nu(q)\in[\tilde\nu,\nu_2)$, and a corresponding $\tilde V$ as in Lemma 8.5. Then consider the function $\tilde R(\sigma+i0)(H-\sigma)Au$, where A vanishes microlocally for $\{\nu\le\tilde\nu\}$ and is equal to the identity microlocally in $\{\nu\ge\nu_2\}$. Since $\tilde V_0$ has no critical points q with $0<\nu(q)<\nu_2$ it follows readily $\tilde u=Au-\tilde R(\sigma+i0)(H-\sigma)Au$ satisfies the desired conditions. □

From this we can readily deduce

Lemma 8.7. *If $q\in\mathrm{RP}_+(\sigma)$ then every element of $E_{\mathrm{mic},+}(q,\sigma)$ has a representative $\tilde u$ such that $(H-\sigma)\tilde u\in\dot{\mathcal C}^\infty(X)$ and $\mathrm{WF}_{sc}(\tilde u)$ is contained in the union of $\Phi_+(\{q\})$ and the $\Phi_+(\{q'\})$ for those $q'\in\mathrm{RP}_+(\sigma)$ with $\nu(q')>\nu(q)$.*

Proof. Let O be a W-balanced neighbourhood of q (see Definition 4.4). Let $A\in\Psi_{\mathrm{sc}}^{-\infty,0}(X)$ be microlocally equal to the identity on $\Phi_+(\{q\})\cap\overline{O}$ and supported in a small neighbourhood of $\Phi_+(\{q\})\cap\overline{O}$. Then there exists $\nu_2>\nu(q)$ such that $\nu>\nu_2$ on $\Phi_+(\{q\})\setminus O$, and $\mathrm{WF}'_{\mathrm{sc}}(A)\setminus O\subset\{\nu\ge\nu_2\}$. Now let u be any representative. Since $\mathrm{WF}_{\mathrm{sc}}(u)\cap O\subset\Phi_+(\{q\})$, $\mathrm{WF}_{\mathrm{sc}}(Au-u)\cap O=\emptyset$. In addition, $\mathrm{WF}_{\mathrm{sc}}(Au)\subset\mathrm{WF}'_{\mathrm{sc}}(A)\cap\mathrm{WF}_{\mathrm{sc}}(u)$, hence $\nu\ge\nu(q)$ on $\mathrm{WF}_{\mathrm{sc}}(Au)$. Moreover, $\mathrm{WF}_{\mathrm{sc}}(Au-u)\cap O=\emptyset$ implies that

$$\mathrm{WF}_{\mathrm{sc}}((H-\sigma)Au)\cap O=\mathrm{WF}_{\mathrm{sc}}((H-\sigma)Au-(H-\sigma)u)\cap O=\emptyset,$$

so $\mathrm{WF}_{\mathrm{sc}}((H-\sigma)Au)\subset\mathrm{WF}'_{\mathrm{sc}}(A)\setminus O$, hence is contained in $\{\nu\ge\nu_2\}$. Thus, by Lemma 8.6, there exists $\tilde u\in C^{-\infty}(X)$ such that $\nu\ge\nu_2$ on $\mathrm{WF}_{\mathrm{sc}}(\tilde u-Au)$ and $(H-\sigma)\tilde u\in\dot{\mathcal C}^\infty(X)$. In particular, $\nu\ge\nu(q)$ in $\mathrm{WF}_{\mathrm{sc}}(\tilde u)$. Moreover, $\nu\ge\nu_2$ on $\mathrm{WF}_{\mathrm{sc}}(\tilde u-u)\cap O$, hence by Lemma 4.5, $\mathrm{WF}_{\mathrm{sc}}(\tilde u-u)\cap O=\emptyset$, so $\tilde u$ and u have the same image in $E_{\mathrm{mic},+}(O,\sigma)$. □

Finally, we can show that each microlocally outgoing eigenfunction is represented by an approximate eigenfunction.

Proof of Proposition 8.1. Let $\tilde u$ be a representative as in Lemma 8.6. If we choose q' from the set

$$\{q'\in\mathrm{RP}_+(\sigma)\cap\mathrm{WF}_{\mathrm{sc}}(\tilde u);\nu(q')>\nu(q),\ q'\notin\Phi_+(\{q\})\},\tag{8.2}$$

with $\nu(q')$ minimal, then, localizing $\tilde u$ near q', gives an element v of $E_{\mathrm{mic},+}(q')$. By subtracting from $\tilde u$ a representative of v given by Lemma 8.7, we remove the wavefront set near q'. Inductively choosing radial points from (8.2) and performing this procedure repeatedly, all wavefront set may be removed from $\tilde u$ except that contained in $\Phi_+(\{q\})$. □

9. Microlocal Morse decomposition

Next we show that global smooth eigenfunctions can, in an appropriate sense, be decomposed into components originating, in the sense of the Introduction, at a single radial point. We do this by defining subspaces of $E^\infty_{\mathrm{ess}}(\sigma)$ corresponding to the location of scattering wavefront set in $\{\nu>0\}$ and showing that suitable quotients of these spaces are isomorphic to the spaces of microlocal eigenfunctions $E^\infty_{\mathrm{mic},+}(q,\sigma)$, $q\in\mathrm{RP}_+(\sigma)$, analyzed in sections 6 and 7. Since each of the spaces

$E^\infty_{\mathrm{mic},+}(q,\sigma)$, $q \in \mathrm{RP}_+(\sigma)$, is non-trivial this shows that each such radial point gives rise to eigenfunctions. However, as noted previously in [6], [7], [8] and [4] in some special cases, there is a qualitative difference between the radial points corresponding to local minima of V_0 and the others. This is expressed by Proposition 10.3 where we show that the eigenfunctions $u \in E^\infty_{\mathrm{Min},+}(\sigma)$ originating only at minimum radial points are dense in $E^0_{\mathrm{ess}}(\sigma)$ (definitions of these spaces are given below).

Recall from [4] the spaces of eigenfunctions of fixed growth

$$E^s_{\mathrm{ess}}(\sigma) = \{u \in E^{-\infty}_{\mathrm{ess}}(\sigma); \mathrm{WF}^{0,s-1/2}_{\mathrm{sc}}(u) \cap \{\nu = 0\} = \emptyset\}. \tag{9.1}$$

This condition is equivalent to requiring that

$$Bu \in x^{s-1/2}L^2(X) \tag{9.2}$$

for some pseudodifferential operator $B \in \Psi^{0,0}_{\mathrm{sc}}(X)$ with boundary symbol which is elliptic on $\Sigma(\sigma) \cap \{\nu = 0\}$ and microsupported in $\{|\nu| < a(\sigma)\}$, where

$$a(\sigma) = \min\{|\nu(q)|; q \in \mathrm{RP}(\sigma)\}.$$

The space $E^0_{\mathrm{ess}}(\sigma)$ is of particular interest. Choose an operator $A \in \Psi^{0,0}_{\mathrm{sc}}(X)$ whose boundary symbol is 0 for $\nu \le -a(\sigma)$ and 1 for $\nu \ge a(\sigma)$. The space $E^0_{\mathrm{ess}}(\sigma)$ is a Hilbert space with norm

$$\|u\|^2_{E^0_{\mathrm{ess}}(\sigma)} = \langle i[H,A]u, u\rangle. \tag{9.3}$$

The positive-definiteness of this form, and its independence of the choice of operator A, was shown in [4], Section 12. An equivalent norm is

$$\|Bu\|_{x^{-1/2}L^2} + \|u\|_{x^{-1/2-\epsilon}L^2} \tag{9.4}$$

where $\epsilon > 0$ and B is as in (9.2); see [4], section 3.

We now define subspaces of $E^s_{\mathrm{ess}}(\sigma)$ depending on the location of the scattering wavefront set inside $\{\nu = 0\}$. Given any $\le$-closed subset Γ of $\mathrm{RP}_+(\sigma)$, we define

$$E^s_{\mathrm{ess}}(\sigma,\Gamma) = \{u \in E^s_{\mathrm{ess}}(\sigma); \mathrm{WF}_{\mathrm{sc}}(u) \cap \mathrm{RP}_+(\sigma) \subset \Gamma\}. \tag{9.5}$$

The set of radial points $q \in \mathrm{RP}_+(\sigma)$ lying above local minima of V is an example of a $\le$-closed subspace and will be denoted $\mathrm{Min}_+(\sigma)$. In this case we use the notation

$$E^s_{\mathrm{Min},+}(\sigma) \equiv E^s_{\mathrm{ess}}(\sigma, \mathrm{Min}_+(\sigma)) = \{u \in E^s_{\mathrm{ess}}(\sigma); \mathrm{WF}_{\mathrm{sc}}(u) \cap \mathrm{RP}_+(\sigma) \subset \mathrm{Min}_+(\sigma)\}$$

to be consistent with [4].

Proposition 9.1. *Suppose that $\Gamma \subset \mathrm{RP}_+(\sigma)$ is $\le$-closed and q is a $\le$-minimal element of Γ. Then with $\Gamma' = \Gamma \setminus \{q\}$*

$$0 \longrightarrow E^\infty_{\mathrm{ess}}(\sigma,\Gamma') \xrightarrow{\ \iota\ } E^\infty_{\mathrm{ess}}(\sigma,\Gamma) \xrightarrow{\ r_q\ } E_{\mathrm{mic},+}(\sigma,q) \longrightarrow 0$$

is a short exact sequence, where ι is the inclusion map and r_q is the microlocal restriction map.

Proof. The injectivity of ι follows from the definitions. The null space of the microlocal restriction map r_q, which can be viewed as restriction to a W-balanced neighbourhood of q, is precisely the subset of $E^\infty_{\mathrm{ess}}(\sigma,\Gamma)$ with wave front set disjoint from $\{q\}$, and this subset is $E^\infty_{\mathrm{ess}}(\sigma,\Gamma')$. Thus it only remains to check the surjectivity of r_q.

We do so first for the strings generated by $q \in \mathrm{RP}_+(\sigma)$. For $q \in \mathrm{Min}_+(\sigma)$, the string just consists of q itself and the result follows trivially. So consider the string $S(q)$ generated by $q \in \mathrm{RP}_+(\sigma) \setminus \mathrm{Min}_+(\sigma)$. By Proposition 8.1 any element of

$E_{\mathrm{mic},+}(q,\sigma)$ has a representative $\tilde{u}$ satisfying $(H-\sigma)\tilde{u} \in \dot{\mathcal{C}}^\infty(X)$ with $\mathrm{WF}_{\mathrm{sc}}(\tilde{u}) \subset \Phi_+(\{q\})$. Then $u = \tilde{u} - R(\sigma - i0)(H-\sigma)\tilde{u} \in E^\infty_{\mathrm{ess}}(\sigma,\Gamma)$, which gives surjectivity in this case.

For any $\leq$-closed set Γ and $\leq$-minimal element q, the string $S(q)$ is contained in Γ, so the surjectivity of r_q follows in general. □

Notice that we can always find a sequence $\emptyset = \Gamma_0 \subset \Gamma_1 \subset \ldots \subset \Gamma_n = \mathrm{RP}_+(\sigma)$, of $\leq$-closed sets with $\Gamma_j \setminus \Gamma_{j-1}$ consisting of a single point q_j which is $\leq$-minimal in Γ_j: we simply order the $q_i \in \mathrm{RP}_+(\sigma)$ so that $\nu(q_1) \geq \nu(q_2) \geq \ldots$, and set $\Gamma_i = \{q_1, \ldots, q_i\}$. Then Proposition 9.1 implies the following

Theorem 9.2. *Suppose that* $\emptyset = \Gamma_0 \subset \Gamma_1 \subset \ldots \subset \Gamma_n = \mathrm{RP}_+(\sigma)$, *is as described in the previous paragraph. Then*

$$\{0\} \longrightarrow E^\infty_{\mathrm{ess}}(\sigma,\Gamma_1) \hookrightarrow \ldots \hookrightarrow E^\infty_{\mathrm{ess}}(\sigma,\Gamma_{n-1}) \hookrightarrow E^\infty_{\mathrm{ess}}(\sigma), \tag{9.6}$$

with

$$E^\infty_{\mathrm{ess}}(\sigma,\Gamma_j)/E^\infty_{\mathrm{ess}}(\sigma,\Gamma_{j-1}) \simeq E_{\mathrm{mic},+}(q_j,\sigma),\ j = 1,2,\ldots,n. \tag{9.7}$$

10. L^2-parameterization of the generalized eigenspaces

Recall from Theorem 6.7, or Theorem 7.3 in the effectively resonant case, that there is a surjective map

$$M_+(\sigma) : E^\infty_{\mathrm{Min},+}(\sigma) \to \oplus_{q\in \mathrm{Min}_+(\sigma)} \mathcal{S}(\mathbb{R}^{n-1}), \quad \sigma \in (\min V_0, \infty) \setminus \mathrm{Cv}(V), \tag{10.1}$$

given by taking $u \in E^\infty_{\mathrm{Min},+}(\sigma)$, microlocally restricting u to a neighbourhood of each q giving $u_q \in E^\infty_{\mathrm{mic},+}(\sigma,q)$ and sending u to the sum of the leading coefficients $\sum_k w_k(Y'')v_k(Y''')$, $(Y'',Y''') \in \mathbb{R}^{n-1}$, of each of the u_q. Since the v_k are normalized eigenfunctions of a harmonic oscillator and the w_k are Schwartz functions of Y'' with seminorms rapidly decreasing in k, the sum is a Schwartz function of (Y'',Y''').

Let us regard $\oplus_q \mathcal{S}(\mathbb{R}^{n-1})$ as a subspace of $\oplus_q L^2(\mathbb{R}^{n-1})$, endowed with the norm

$$\|(w_q)_{q\in\mathrm{Min}_+(\sigma)}\|^2 = \sum_q \sqrt{\sigma - V(\pi(q))} \int_{\mathbb{R}^{n-1}} |w_q(Y)|^2 d\omega_q, \tag{10.2}$$

where ω_q is the measure induced by Riemannian measure, namely the measure $x^{-n+(n-m)/2+\sum_j r''_j} dg$ divided by dx/x and restricted to $x=0$. (It takes the form $dY''\, dY'''$ provided that the y are normal coordinates, centred at the critical point, for the metric $h(0,y,dy)$.)

In this section the following result is proved.

Theorem 10.1. *The map* $M_+(\sigma)$ *in* (10.1) *has a unique extension to an unitary isomorphism*

$$M_+(\sigma) : E^0_{\mathrm{ess}}(\sigma) \to \oplus_{q\in\mathrm{Min}_+(\sigma)} L^2(\mathbb{R}^{n-1}).$$

Remark 10.2. Here, and throughout this section, we take $\sigma \in (\min V_0, \infty) \setminus \mathrm{Cv}(V)$.

To prove the theorem, we establish several intermediate results. First we show

Proposition 10.3. *The space* $E^\infty_{\mathrm{Min},+}(\sigma)$ *is dense in* $E^\infty_{\mathrm{ess}}(\sigma)$ *in the topology of* $E^0_{\mathrm{ess}}(\sigma)$.

Proof. The proof is by induction. We consider a sequence $\Gamma_0 \subset \Gamma_1 \subset \cdots \subset \Gamma_n = \mathrm{RP}_+(\sigma)$ as in the previous section, but with the additional condition that the radial points are ordered so that, among the points with equal values of ν, those corresponding to local minima of V_0 are placed last. We shall prove by induction that

$$E^\infty_{\mathrm{ess}}(\sigma, \Gamma_i \cap \mathrm{Min}_+(\sigma)) \text{ is dense in } E^\infty_{\mathrm{ess}}(\sigma, \Gamma_i) \text{ in the topology of } E^0_{\mathrm{ess}}(\sigma). \tag{10.3}$$

For $i = 1$ there is nothing to prove. Assume that (10.3) is true for $i = k$. Let $\Gamma_{k+1} \setminus \Gamma_k = \{q\}$. If q arises from a local minimum of V_0, then using a microlocal decomposition, any $u \in E^\infty_{\mathrm{ess}}(\sigma, \Gamma_{k+1})$ can be written as the sum of $u_1 \in E^\infty_{\mathrm{ess}}(\sigma, \{q\})$ and $u_2 \in E^\infty_{\mathrm{ess}}(\sigma, \Gamma_k)$. A similar statement is true for $u \in E^\infty_{\mathrm{ess}}(\sigma, \Gamma_{k+1} \cap \mathrm{Min}_+(\sigma))$, which proves (10.3) for $i = k + 1$.

Next suppose that q does not arise from a local minimum of V_0. Then we adapt the argument of Proposition 11.6 of [4] to prove (10.3) for $i = k + 1$. We first make the assumption that σ is not in the point spectrum of H. Using our inductive assumption, it is enough to show that $E^\infty_{\mathrm{ess}}(\sigma, \Gamma_k)$ is dense in $E^\infty_{\mathrm{ess}}(\sigma, \Gamma_{k+1})$. Let $u \in E^\infty_{\mathrm{ess}}(\sigma, \Gamma_{k+1})$. Let $Q \in \Psi^{0,0}_{\mathrm{sc}}(X)$ be microlocally equal to the identity near $\Gamma_k \cap \mathrm{Min}_+(\sigma)$, and microsupported sufficiently close to $\Gamma_k \cap \mathrm{Min}_+(\sigma)$. Then away from $\mathrm{Min}_+(\sigma)$, $u \in x^{-1/2+\epsilon}L^2$ by (ii) of Theorem 6.7 and thus $(H - \sigma)Qu = [H, Q]u \in x^{1/2+\epsilon}L^2$ for some $\epsilon > 0$. This is also true near $\mathrm{Min}_+(\sigma)$ since Q is microlocally the identity there, so we have $(H - \sigma)Qu \in x^{1/2+\epsilon}L^2$ everywhere. This implies that

$$u = Qu - R(\sigma - i0)(H - \sigma)Qu, \tag{10.4}$$

since $v = u - (Qu - R(\sigma - i0)(H - \sigma)Qu)$ satisfies $(H - \sigma)v = 0$ and $v \in x^{-1/2+\epsilon}L^2$ microlocally for $\nu > 0$.

Now choose a modified potential function $\tilde{V}$ as in Lemma 8.5, where we choose $\tilde{\nu}$ larger than $\nu(q)$ but smaller than $\nu(q')$ for every $q' \in \Gamma_k \cap \mathrm{Min}_+(\sigma)$. (This is possible because of the way we ordered the q_i.) Since $\mathrm{WF}_{\mathrm{sc}}(Qu)$ lies in $\{\nu > \tilde{\nu}\}$, we have

$$Qu = \tilde{R}(\sigma + i0)(\tilde{H} - \sigma)Qu. \tag{10.5}$$

Now take $u'_j = \phi(x/r_j)u$, where $\phi \in \mathcal{C}^\infty(\mathbb{R})$, $\phi(t) = 1$ for $t \geq 2$, $\phi(t) = 0$ for $t \leq 1$ and $r_j \to 0$ as $j \to \infty$. Then $u'_j \in \dot{C}^\infty(X)$, and w_j defined by

$$w_j = \tilde{R}(\sigma + i0)(\tilde{H} - \sigma)Qu'_j$$

converge to Qu in $x^{-1/2-\epsilon}L^2$. Our choice of $\tilde{V}$ ensures that

$$\mathrm{WF}_{\mathrm{sc}}(w_j) \cap \mathrm{RP}_+(\sigma) \subset \Gamma_k.$$

Moreover,

$$(H - \sigma)w_j \text{ converges to } (H - \sigma)Qu \text{ in } x^{1/2+\epsilon}L^2. \tag{10.6}$$

Now define

$$u_j = w_j - R(\sigma - i0)(H - \sigma)w_j.$$

Then $u_j \in E^\infty_{\mathrm{ess}}(\sigma, \Gamma_k)$. We claim that $u_j \to u$ in the topology of $E^0_{\mathrm{ess}}(\sigma)$. Certainly, $u_j \to u$ in $x^{-1/2-\epsilon}L^2$. We must also show that $Bu_j \to Bu$ in $x^{-1/2}L^2$, where B is as in (9.2). To do this we write

$$\begin{aligned} Bu_j - Bu &= B\big(w_j - R(\sigma - i0)(H-\sigma)w_j\big) - B\big((\mathrm{Id} - Q)u + Qu\big) \\ &= B\Big(\tilde{R}(\sigma + i0)(\tilde{H} - \sigma)Qu_j' - R(\sigma - i0)(H-\sigma)w_j \\ &\quad + R(\sigma - i0)(H-\sigma)Qu - \tilde{R}(\sigma + i0)(\tilde{H}-\sigma)Qu\Big), \end{aligned}$$

using (10.4) and (10.5), and this goes to zero in $x^{-1/2}L^2$ by (10.6) and propagation of singularities, Theorem 3.1 of [4], as in the proof of [4, Proposition 11.6].

If σ is in the point spectrum of H, then equation (10.4) must be replaced by

$$u = \Pi\Big(Qu - R(\sigma - i0)(H-\sigma)Qu\Big), \tag{10.7}$$

where Π is projection off the L^2 σ-eigenspace. Consequently we must define w_j by $\Pi\tilde{R}(\sigma + i0)(\tilde{H} - \sigma)Qu_j'$, and then the rest of the proof goes through. □

The second intermediate result we need is

Proposition 10.4. *The Hilbert norm* (9.3) *on the subspace* $E^\infty_{\mathrm{Min},+}(\sigma) \subset E^0_{\mathrm{ess}}(\sigma)$ *is given by the formula*

$$\sum_{q \in \mathrm{Min}_+(\sigma)} \sqrt{\sigma - V(\pi(q))} \int_{\mathbb{R}^{n-1}} \big|M^+(q,\sigma)u\big|^2 \, d\omega_q.$$

Proof. The proof is the same as the one dimensional case, which is proved in Proposition 12.6 of [4], so we just give a sketch here.

Let ϕ be as in the proof of Proposition 10.3. Then we can write the natural norm (9.3) on $E^0_{\mathrm{ess}}(\sigma)$ as a limit

$$\lim_{r \to 0} i\langle (H-\sigma)Au, \phi(x/r)u\rangle = \lim_{r\to 0} i\langle Au, [H, \phi(x/r)]u\rangle. \tag{10.8}$$

Since $u \in x^{-1/2-\epsilon}L^2$, the only term in $[H, \phi(x/r)]$ that contributes in the limit is $2(x^2D_x)\phi(x/r)(x^2D_x)$. The cutoff operator A restricts attention to $\{\nu > 0\}$, and the limit vanishes when localized to any region where $u \in x^{-1/2+\epsilon}L^2$, so we can substitute for u a sum of expressions u_q as in (7.9), one for each $q \in \mathrm{Min}_+(\sigma)$. A straightforward computation then gives (10.8). □

Proof of Theorem 10.1. Proposition 10.4 shows that $M_+(\sigma)$ maps $E^\infty_{\mathrm{Min},+}(\sigma)$ into a dense subspace of $\oplus_q L^2(\mathbb{R}^{n-1})$, with the Hilbert norm of $M_+(\sigma)u$, $u \in E^\infty_{\mathrm{Min},+}(\sigma)$, equal to that of u. By Proposition 10.3, $E^\infty_{\mathrm{Min},+}(\sigma)$ is dense in $E^\infty_{\mathrm{ess}}(\sigma)$, and by Corollary 3.13 of [4], $E^\infty_{\mathrm{ess}}(\sigma)$ is dense in $E^0_{\mathrm{ess}}(\sigma)$. The result follows. □

So far we have only considered the microlocal restriction of eigenfunctions near radial points q satisfying $\nu(q) > 0$. For each critical point of V_0, there are two corresponding radial points with opposite signs of ν, and we can equally well consider microlocal restriction near radial points with $\nu(q) < 0$. This leads to an operator

$$M_-(\sigma) : E^0_{\mathrm{ess}}(\sigma) \to \oplus_{q \in \mathrm{Min}_-(\sigma)} L^2(\mathbb{R}^{n-1})$$

and the analogue of Theorem 10.1 holds also for $M_-(\sigma)$.

Definition 10.5. The inverses of $M_\pm(\sigma)$, $P_\pm(\sigma) : \oplus_{q\in \mathrm{Min}_\pm(\sigma)} L^2(\mathbb{R}^{n-1}) \to E^0_{\mathrm{ess}}(\sigma)$ of $M_\pm(\sigma)$ are called the *Poisson operators at energy* σ.

We can identify $\oplus_{q\in\mathrm{Min}_+(\sigma)}L^2(\mathbb{R}^{n-1})$ and $\oplus_{q\in\mathrm{Min}_-(\sigma)}L^2(\mathbb{R}^{n-1})$ in the obvious way, and may therefore assume that the $M_\pm(\sigma)$ have the same range, identified with the domain of $P_\pm(\sigma)$.

Corollary 10.6. *For $\sigma \notin \mathrm{Cv}(V)$, the S-matrix may be identified as the unitary operator $S(\sigma) = M_+(\sigma)P_-(\sigma)$ on $\oplus_{z\in\mathrm{Min}}L^2(\mathbb{R}^{n-1})$.*

Remark 10.7. For $n = 2$, structure of $S(\sigma)$ was described rather precisely in [5] as an anisotropic Fourier integral operator.

Theorem 10.1 is essentially a pointwise version of asymptotic completeness in σ. Integrating gives a version of the usual statement, but we do need uniformity in σ to be able to prove it. For this purpose, as well as for the next section on the time-dependent Schrödinger equation, we prove an extension of Theorem 7.3 that is valid in an interval rather than just at one value. For this purpose, let $I \subset (\min V_0, \infty)$ be a compact interval disjoint from the set of effectively resonant energies, the set of L^2-eigenvalues of H, and $\mathrm{Cv}(V)$. Then for each $\sigma \in I$, the sets $\mathrm{Min}_+(\sigma) \subset \mathrm{RP}_+(\sigma)$ can be identified; we write $\mathrm{Min}_+(I)$ for this set. Each element of $\mathrm{Min}_+(I)$ is thus a continuous family $q(\sigma)$ of minimal radial points, with $q(\sigma) \in \mathrm{Min}_+(\sigma)$.

Proposition 10.8. *Let $I \subset (\min V_0, \infty)$ be as above, and let the $q(\sigma) \in \mathrm{Min}_+(I)$ be an outgoing radial point associated to a minimum point z of V_0, with Y'', Y''' the associated coordinates given by* (5.23)*. For any $h(\sigma, \cdot) \in \mathcal{C}^\infty(I; \mathcal{S}(\overline{\mathbb{R}^{n-1}}))$ there is $\phi \in \dot{\mathcal{C}}^\infty(X)$ such that for every $\sigma \in I$,*

$$\begin{aligned} F_\sigma^{-1}R(\sigma + i0)\phi &= x^{-ib-i\sigma_k} w_k(Y'', \sigma)v_{k,\sigma}(Y''') + u', \\ h(\sigma, Y'', Y''') &= \sum_k w_k(Y'', \sigma)v_{k,\sigma}(Y'''), \end{aligned} \tag{10.9}$$

where $v_{k,\sigma}$ and b are as in Proposition 6.3, and where $u' \in \mathcal{C}^\infty(I; I_{\mathrm{sc}}^{(l)}(X, \mathcal{M}))$ for some $l > -\frac{1}{2}$.

Remark 10.9. The statement $u' \in \mathcal{C}^\infty(I; I_{\mathrm{sc}}^{(l)}(X, \mathcal{M}))$ is meant to underline that this is a global claim, namely $u' \in \mathcal{C}^\infty(I; I_{\mathrm{sc}}^{(l)}(O, \mathcal{M}))$ and that it is $\mathcal{C}^\infty$ with values in $\dot{\mathcal{C}}^\infty(X)$ microlocally away from $\{q(\sigma); \sigma \in I\}$, i.e. for all $A \in \Psi_{\mathrm{sc}}(X)$ with $\mathrm{WF}'_{\mathrm{sc}}(A) \cap \{q(\sigma); \sigma \in I\} = \emptyset$, $Au' \in \mathcal{C}^\infty(I; \dot{\mathcal{C}}^\infty(X))$.

Proof. By the construction of Section 6, for each $\sigma \in I$ there is an approximate microlocally outgoing solution u_σ with $f_\sigma = (H - \sigma)u_\sigma \in \dot{\mathcal{C}}^\infty(X)$ and $F_\sigma^{-1}u_\sigma$ of the same form as the right hand side of (10.9). Indeed, the construction is smooth in σ, in the sense that $(d/d\sigma)^k u \in I^s(O, \mathcal{M})$ for each k and each $s < -1/2$, so that with $f(\sigma, .) = f_\sigma(.)$, we have $f \in \mathcal{C}^\infty(I; \dot{\mathcal{C}}^\infty(X))$. Notice that there is no need to 'globalize' using by Proposition 8.1, since microlocally outgoing solutions over sources/sinks (i.e. minima of V_0) are localized at $q(\sigma)$.

Let $\tilde{f} \in \dot{\mathcal{C}}_c^\infty(\mathbb{C} \times X)$ be an almost analytic extension of f with compact support, so $\overline{\partial}_\sigma f$ vanishes to infinite order at $\mathbb{R} \times X$, and let

$$\phi = \frac{-1}{2\pi i} \int_{\mathbb{C}} R(\sigma)\overline{\partial}_\sigma \tilde{f}\, d\sigma \wedge d\bar{\sigma}.$$

Thus, $\phi \in \dot{\mathcal{C}}^\infty(X)$ since $\overline{\partial}_\sigma \tilde{f}$ vanishes to infinite order on the real axis.

We also claim that (10.9) holds. Indeed, let $\sigma_0 \in \mathbb{R}$, $\chi \in \mathcal{C}_c^\infty(\mathbb{R})$, χ identically 1 near σ_0, let $\tilde{\chi}$ be an almost analytic extension of χ of compact support. Thus, we may write

$$f(\sigma,.) = f(\sigma_0,.)\chi(\sigma) + (\sigma-\sigma_0)g(\sigma,.),\ \ \tilde{f}(\sigma,.) = f(\sigma_0,.)\tilde{\chi}(\sigma) + (\sigma-\sigma_0)\tilde{g}(\sigma,.)$$

with $g \in \dot{\mathcal{C}}_c^\infty(\mathbb{R}\times X)$, $\tilde{g} \in \dot{\mathcal{C}}_c^\infty(\mathbb{C}\times X)$. Then, writing $\sigma - \sigma_0 = (H-\sigma_0) - (H-\sigma)$,

$$\begin{aligned}\phi =& \frac{-1}{2\pi i}\left(\int_{\mathbb{C}} R(\sigma)\overline{\partial}_\sigma\tilde{\chi}\,d\sigma\wedge d\bar{\sigma}\right) f(\sigma_0,.)\\ &- \frac{1}{2\pi i}(H-\sigma_0)\int_{\mathbb{C}} R(\sigma)\overline{\partial}_\sigma\tilde{g}\,d\sigma\wedge d\bar{\sigma} + \frac{1}{2\pi i}\int_{\mathbb{C}} \overline{\partial}_\sigma\tilde{g}\,d\sigma\wedge d\bar{\sigma},\end{aligned}$$

where in the last term is used $(H-\sigma)R(\sigma) = \mathrm{Id}$. Since the last term vanishes (as $\tilde{g}$ is smooth), and the integral in the second term is in $\dot{\mathcal{C}}^\infty(X)$, while the integral in the first term is $\chi(H)$, we deduce that

$$\phi = f_{\sigma_0} + (H-\sigma_0)F_{\sigma_0}$$

for some $F_. \in \dot{\mathcal{C}}^\infty(I\times X)$. Therefore $R(\sigma_0+i0)\phi - R(\sigma_0+i0)f_{\sigma_0} \in \dot{\mathcal{C}}^\infty(X)$, so $R(\sigma_0+i0)\phi$ and $R(\sigma_0+i0)f_{\sigma_0}$ indeed have the same asymptotics. In particular, (10.9) holds for every $\sigma_0 \in \mathbb{R}$. □

Now we state asymptotic completeness in a more standard form.

Theorem 10.10 (Asymptotic completeness)**.** *If $I \subset (\min V_0, \infty)\setminus \mathrm{Cv}(V)$ is compact then*

$$M_+(\cdot)\circ\mathrm{Sp}(\cdot) : \mathrm{Ran}(\Pi_I)\ominus E_{\mathrm{pp}}(I) \to \oplus_{q\in\mathrm{Min}_+(I)} L^2(I\times\mathbb{R}_q^{n-1})$$

is unitary.

Proof. For $f \in \dot{\mathcal{C}}^\infty(X)$ orthogonal to $E_{\mathrm{pp}}(I)$, let

$$u = u(\sigma) = (2\pi i)^{-1}(R(\sigma+i0)f - R(\sigma-i0)f) = \mathrm{Sp}(\sigma)f,$$
$$\text{where } \mathrm{Sp}(\sigma) = (2\pi i)^{-1}(R(\sigma+i0) - R(\sigma-i0))$$

is the spectral measure. The norm of u in $E^0_{\mathrm{ess}}(\sigma)$ is given by $\langle i(H-\sigma)Au, u\rangle$, where A is as in (9.3). Notice that

$$\begin{aligned}2\pi i(H-\sigma)Au - f &= (H-\sigma)A\big(R(\sigma+i0)-R(\sigma-i0)\big)f - (H-\sigma)R(\sigma+i0)f\\ &= (H-\sigma)\Big((A-\mathrm{Id})R(\sigma+i0)f - AR(\sigma-i0)f\Big) = (H-\sigma)v,\quad v\in\dot{\mathcal{C}}^\infty(X),\end{aligned}$$

since

$$\mathrm{WF}'_{\mathrm{sc}}(A)\cap\mathrm{WF}_{\mathrm{sc}}(R(\sigma-i0)f) = \emptyset \text{ and } \mathrm{WF}'_{\mathrm{sc}}(A-\mathrm{Id})\cap\mathrm{WF}_{\mathrm{sc}}(R(\sigma+i0)f) = \emptyset.$$

Hence

$$2\pi\|u\|^2_{E^0_{\mathrm{ess}}(\sigma)} = 2\pi i\langle(H-\sigma)Au,u\rangle = \langle f + (H-\sigma)v, u\rangle = \langle f, \mathrm{Sp}(\sigma)f\rangle.$$

Note that the right hand side is continuous, hence so is the left hand side.

Integrating over σ in I, denoting the spectral projection of H to I by Π_I, and using Proposition 10.4, we deduce that $M_+(\sigma)\,\mathrm{Sp}(\sigma)f$ is continuous with values in L^2 and

$$\|\Pi_I f\|^2 = \int_I \|M_+(\sigma)\,\mathrm{Sp}(\sigma)f\|^2\,d\sigma, \tag{10.10}$$

so $M_+(\cdot) \circ \mathrm{Sp}(\cdot)$ is an isometry on the orthocomplement of the finite dimensional space $E_{\mathrm{pp}}(I)$ in the range of Π_I.

It remains to prove that the range is dense in $\oplus_{q\in\mathrm{Min}} L^2(I \times \mathbb{R}^{n-1})$. Since the set $\mathcal{R}_{\mathrm{er}}$ of effectively resonant values of σ is discrete, it suffices to show that if I is in addition disjoint from $\mathcal{R}_{\mathrm{er}}$, and $h \in \oplus_{q\in\mathrm{Min}} \dot{\mathcal{C}}^\infty(I \times \overline{\mathbb{R}^{n-1}})$ then there is a $f \in \dot{\mathcal{C}}^\infty(X)$ with $M_+(\sigma)\,\mathrm{Sp}(\sigma) f = h(\sigma, .)$. But this was proved in Proposition 10.8, so the proof of the theorem is complete. □

Remark 10.11. We can relate the results of this section more closely with Theorem 9.2 by considering the closure of $E^\infty_{\mathrm{Min},+}(\sigma)$ as a subset of $E^\infty_{\mathrm{ess}}(\sigma)$ in the topology of $E^s_{\mathrm{ess}}(\sigma)$ for varying values of s. We have seen in Proposition 10.3 that $E^\infty_{\mathrm{Min},+}(\sigma)$ is dense, in the topology of $E^0_{\mathrm{ess}}(\sigma)$. In fact the proof of Proposition 10.3 shows that this is true in the topology of $E^s_{\mathrm{ess}}(\sigma)$ for $0 \le s < s_0$, where s_0 is the smallest number such that every $u \in E^\infty_{\mathrm{mic}}(q)$, for every $q \in \mathrm{RP}_+(\sigma) \setminus \mathrm{Min}_+(\sigma)$, is in $x^{-1/2+s_0} L^2$ locally near $\pi(q)$; that s_0 is strictly positive follows from (ii) of Theorem 6.7. By contrast, $E^\infty_{\mathrm{Min},+}(\sigma)$ is closed in the $E^\infty_{\mathrm{ess}}(\sigma)$ topology. What happens as s increases is that the closure of $E^\infty_{\mathrm{Min},+}(\sigma)$ in the $E^s_{\mathrm{ess}}(\sigma)$ topology changes discretely, as s crosses certain values determined by the structure of eigenfunctions at the non-minimal critical points.

One way to understand this is in terms of microlocally *incoming* eigenfunctions at the outgoing radial points, i.e. microlocal eigenfunctions u with scattering wavefront set near q is contained in $\Phi_-(q)$ as opposed to $\Phi_+(q)$. In Part I we showed (in all dimensions) that there are nondegenerate pairings

$$E_{\mathrm{mic},+}(q,\sigma) \times E_{\mathrm{mic},-}(q,\sigma) \to \mathbb{C},$$
$$E^s_{\mathrm{ess}}(\sigma) \times E^{-s}_{\mathrm{ess}}(\sigma) \to \mathbb{C}$$

(Lemma 12.2 and Proposition 12.3 of [4]). The closure of $E^\infty_{\mathrm{Min},+}(\sigma)$, in the topology of $E^s_{\mathrm{ess}}(\sigma)$, may be identified with the annihilator, in $E^\infty_{\mathrm{ess}}(\sigma)$, of the eigenfunctions which are in $E^{-s}_{\mathrm{ess}}(\sigma)$ and have scattering wavefront set contained in

$$\bigcup_{q\in \mathrm{RP}_+(\sigma)\setminus \mathrm{Min}_+(\sigma)} \Phi_-(q) \cup \{\nu < 0\}.$$

This set is trivial for $s < s_0$, and nontrivial for $s > s_0$. The fact that this set of eigenfunctions jumps discretely with s in shown in the two dimensional case in Section 10 of Part I.

11. Long-time asymptotics for the Schrödinger equation

In this final section we deduce the long-time asymptotics for solutions of the initial value problem

$$(D_t + H)u = 0,\ u|_{t=0} = u_0,\ u_0 \in \dot{\mathcal{C}}^\infty(X), \tag{11.1}$$

for a dense set (in $L^2 \ominus E_{\mathrm{pp}}(H)$) of initial data.

Our approach is to use the spectral resolution of u_0 and the functional calculus. In this way, we deduce the long-time asymptotics of u from the asymptotics of generalized eigenfunctions of H using the stationary phase lemma.

We first define the space X_{Sch} on which the asymptotics of the solution u of (11.1) will be described. Let us first choose a globally defined boundary defining function x satisfying (1.1); we can specify, for example, that $x \equiv 1$ outside a collar neighbourhood of ∂X. We then introduce the variable $\tau = tx$, where t is time. Let us compactify the real τ-line $\mathbb{R}$ to an interval $\overline{\mathbb{R}}$ using τ^{-1} as a boundary defining function near $\tau = \infty$, and $-\tau^{-1}$ as a boundary defining function near $\tau = -\infty$. Then we define

$$X_{\mathrm{Sch}} = X \times \overline{\mathbb{R}}_\tau \tag{11.2}$$

Thus X_{Sch} is a compact manifold with corners, with boundary hypersurfaces if (the 'infinity face') at $\tau = \pm\infty$ (or $t = \pm\infty$), naturally diffeomorphic to two copies of X (one at $t = +\infty$, one at $t = -\infty$), and a boundary hypersurface af (the 'asymptotic face') diffeomorphic to $\partial X \times \overline{\mathbb{R}}_\tau$. Notice that at af, every point with $\tau > 0$ corresponds to $t = +\infty$ and every point with $\tau < 0$ corresponds to $t = -\infty$, so this is the place to look for long-time (and large-distance) asymptotics of the Schrödinger wave u. The variable τ has an interpretation of inverse speed; a particle travelling asymptotically radially at speed τ_0^{-1} will end up at af after infinite time at $\tau = \tau_0$.

We now specify a good subset of L^2 initial data u_0, for which the asymptotics as $t \to +\infty$ of the solution, u, to (11.1) are particularly simple. Let $I \subset (\min V_0, \infty)$ be a compact interval disjoint from $\mathrm{Cv}(V)$ and from the set of effectively resonant energies and L^2 eigenvalues of H. Let $(h(\sigma, \cdot))q \in \mathcal{C}^\infty(I; \mathcal{S}(\mathbb{R}^{n-1}))$ be a collection of smooth functions from I into Schwartz functions of $n-1$ variables, one for each $q \in \mathrm{Min}_+(I)$, and let $\phi = \phi(I, h) = \sum_q \phi(I, h_q) \in \dot{C}^\infty(X)$ be the function constructed in Proposition 10.8. Let

$$\mathcal{A}_I = \{\phi(I, h); h(\sigma, \cdot) \in \mathcal{C}^\infty(I; \mathcal{S}(\mathbb{R}^{n-1}))\} \text{ and } \mathcal{A} = \sum_I \mathcal{A}_I$$

be the (algebraic) vector space sum of $\mathcal{A}_I$ over all such I as above. It is clear from Theorem 10.10 that $\mathcal{A}_I$ is dense in $\mathrm{Ran}\,\Pi_I(H) \ominus E_{\mathrm{pp}}(I)$, and hence that $\mathcal{A}$ is dense in $L^2 \ominus E_{\mathrm{pp}}(H) = H_{\mathrm{ac}}(H)$. To give the asymptotics of (11.1) with initial data from $\mathcal{A}$ it suffices to give the asymptotics starting from $u_0 = \phi(I, h)$ for some h as above.

Theorem 11.1. *Suppose that I is disjoint from $\mathrm{Cv}(V)$, the set of effectively resonant energies and the set of L^2-eigenvalues of H, and that $\phi = \phi(I, h) \in \mathcal{A}_I$. Let $u(t, \cdot)$ be the solution of (11.1) with initial data $u_0 = \phi$, regarded as a function on X_{Sch}. Then u has trivial asymptotics at if. Near af $\cap\{\tau > 0\}$, using coordinates $\tau = xt$, x, and (Y'', Y''') defined by (5.23), u takes the form*

(11.3)

$$u(\tau, x, Y'', Y''') = c \sum_{q \in \mathrm{Min}_+(I)} \sum_k \frac{x^{-ib - i\sigma_k + 1/2} e^{i\Psi_q(y,\tau)/x}}{(\sigma - V(z))^{3/4}} w_k(Y'', \sigma(\tau)) v_{k,\sigma(\tau)}(Y''') + u',$$

$$h(\sigma(\tau), Y'', Y''') = \sum_k w_k(Y'', \sigma(\tau)) v_{k,\sigma(\tau)}(Y'''), \quad c = 2e^{i\pi/8},$$

where

$$\sigma(\tau) = V_0(z) + \frac{1}{4\tau^2}, \quad z = \pi(q), \tag{11.4}$$

Ψ is a smooth function of y and τ, h is decomposed as in Proposition 10.8, and u' decays faster than the leading term.

Proof. Let $v(\sigma) = \mathrm{Sp}(\sigma)\phi = (2\pi i)^{-1}(R(\sigma + i0) - R(\sigma - i0))\phi$. Then

$$u(t, \cdot) = \frac{1}{2\pi i} \int_I e^{-it\sigma}(R(\sigma + i0) - R(\sigma - i0))\phi \, d\sigma.$$

Shifting the contour of integration shows that, as $t \to \infty$, $R(\sigma - i0)\phi$ has trivial asymptotics. Hence it is enough to consider

$$u(t, \cdot) = \frac{1}{2\pi i} \int e^{-it\sigma} R(\sigma + i0)\phi \, d\sigma. \tag{11.5}$$

By construction, $F_\sigma^{-1} R(\sigma + i0)\phi$ has asymptotics (10.9) for every σ. Since F_σ is a smooth family of FIOs, it follows that $R(\sigma + i0)\phi$ itself has asymptotics

$$R(\sigma + i0)\phi = e^{i\Phi(y,\sigma)/x} a(Y", Y''', x, \sigma) + v', \tag{11.6}$$

where $v' \in \mathcal{C}^\infty(I; x^l L^2(X))$ for some $l > -1/2$ — see Remark 6.8. Moreover, Φ is a smooth function of σ (it parameterizes the Legendrian submanifold which is the image of the zero section under F_σ), with

$$\Phi(z, \sigma) = \sqrt{\sigma - V_0(z)}, \quad z = \pi(q), \quad q \in \mathrm{Min}_+(\sigma), \tag{11.7}$$

and a in (11.6) is smooth in σ as an element of $I^s(O, \mathcal{M})$ for every $s < -1/2$. Hence we may substitute (11.6) into (11.5) and compute

$$u(t, \cdot) = \frac{1}{2\pi i} \int e^{-it\sigma} \Big(e^{i\Phi(y,\sigma)/x} a(Y", Y''', x, \sigma) + v' \Big) \, d\sigma, \tag{11.8}$$

exploiting the smoothness of Φ and a in σ.

Let $p \in X$ be an interior point. Then $(R(\sigma \pm i0)\phi)(p)$ is a smooth function of σ by Proposition 10.8.

It follows that for a fixed interior point p the integral (11.8) is rapidly decreasing as $t \to \infty$, being the Fourier transform of a smooth, compactly supported function. Hence the asymptotics of u are trivial at if.

To investigate asymptotics at af, where $x \to 0$, we rewrite (11.8) as

(11.9)

$$u(\tau, x, Y'', Y''') = \frac{1}{2\pi i} \int e^{i(-\tau\sigma + \Phi(y,\sigma))/x} \Big(a(Y", Y''', x, \sigma) + v'(Y'', Y''', x, \sigma) \Big) \, d\sigma,$$

and apply stationary phase to the integral. The integrand is rapidly decreasing as $x \to 0$ at points (y, σ) for any y which is not a minimum point of V_0, uniformly in σ, so we may restrict attention to minimum points $z = \pi(q), q \in \mathrm{Min}_+(I)$. There the phase has critical points when $\tau = d_\sigma \Phi(y, \sigma) = \sqrt{\sigma - V_0(z)}/2$, and the second derivative is then $4^{-1}(\sigma - V_0(z))^{-3/2}$, which is nonzero for $\sigma \in I$. The stationary phase lemma then gives (11.3), with $\Psi(y, \tau) = \tau - \Phi(y, \sigma(\tau))$. □

Remark 11.2. Equation (11.4) is just the energy equation 'total energy = potential energy+ kinetic energy' at infinity, since $1/\tau$ is the asymptotic speed. The factor $1/4$ comes from the fact that in writing our Hamiltonian as $\Delta + V$, we have taken the value of mass to be $1/2$ in our units.

We see that solutions of the time dependent Schrödinger equation (at least those with initial data in $\mathcal{A}$) have expansions at af which are equivalent to first spectrally resolving the initial data and looking at the expansion of the corresponding family of generalized eigenfunctions. In view of this, we can recast Theorem 10.10 in time-dependent terms as follows:

Theorem 11.3. *Let u be the solution of the time dependent Schrödinger equation* (11.1) *with initial data u_0. Let b and v_k and $\tilde{Q} = \sum_j \tilde{Q}_j$ be as in Proposition 6.3. The map*

$$\mathcal{A}_I \ni u_0 \mapsto \oplus_{q\in \mathrm{Min}_+(I)} \Big(e^{i\log x\tilde Q} x^{ib} e^{-i\Psi(y,\tau)/x} u(x,\tau,Y'',Y''')\Big)\big|_{x=0}$$

whose existence is guaranteed by Theorem 11.1 extends uniquely by linearity and continuity to a unitary isomorphism

$$L^2 \ominus E_{\mathrm{pp}}(H) \to \oplus_q L^2\big(\mathbb{R}_\tau \times \mathbb{R}^{n-1}_q; \frac{d\tau}{\tau} \otimes \omega_{q,\tau}\big).$$

Here $\omega_{q,\tau}$ *is the measure in* (10.2)*, where* $\tau = \tau(q,\sigma)$ *is given by* (11.4).

Remark 11.4. The operator $e^{i\log x\tilde Q}$ simply removes the factors of $x^{-i\sigma_k}$ in the expansion (11.3), so that we can take a limit as $x \to 0$.

From asymptotic completeness we can also deduce the following result which was recently proved by Herbst and Skibsted, using a direct method involving the uncertainty principle, rather than proceeding via the structure of generalized eigenfunctions as here.

Corollary 11.5 (Absence of L^2 channels at non-minimal critical points)**.** *Let* $\chi \in \mathcal{C}^\infty(X)$ *vanish in a neighbourhood of the local minima of* V_0 *on* ∂X*. Let* u *be the solution of* (11.1) *on* $X \times \mathbb{R}$ *with initial value* $u_0 \in L^2(X)$*. Then*

$$\lim_{t\to\infty} \|\chi u(t,\cdot)\|_{L^2(X)} \to 0. \tag{11.10}$$

Proof. First decompose $u_0 = u_0' + u_0''$, where $u_0' \in E_{\mathrm{pp}}(H)$ and $u_0'' \in L^2 \ominus E_{\mathrm{pp}}(H)$. The solution u' with initial condition u_0' is easily treated, so we consider the solution u'' with initial condition u_0''. Let $\epsilon > 0$ be given. Then by density of $\mathcal{A}$ in $L^2 \ominus E_{\mathrm{pp}}(H)$, we can find $\phi \in \mathcal{A}$, with ϕ equal to a sum of a finite number of $\phi_j(I_j,h_j) \in \mathcal{A}_{I_j}$, such that $\|u_0'' - \phi\|_{L^2} < \epsilon$. Without loss of generality we may assume that all the I_j are disjoint. Let u''' be the solution with initial condition ϕ. By direct calculation from (11.3) we find that

$$\lim_{t\to\infty} \|(1-\chi)u'''(t,\cdot)\|^2_{L^2} = \sum_j \int_I \sqrt{\sigma - V_0(\pi(q))} \|h_j\|^2_{L^2(R^{n-1})}\, d\sigma,$$

which by Theorem 10.10 is equal to $\|\phi\|^2_{L^2}$. But by unitarity of e^{-itH}, we have

$$\|u'''(t,\cdot)\|^2_{L^2} = \|\phi\|^2_{L^2} \text{ for each } t,$$

which implies that

$$\lim_{t\to\infty} \|\chi u'''(t,\cdot)\|^2_{L^2} = 0.$$

So (11.10) is true for ϕ. On the other hand,

$$\limsup_{t\to\infty} \|\chi(u''(t,\cdot) - u'''(t,\cdot))\|_{L^2} \le \epsilon \|\chi\|_{L^\infty},$$

so $\limsup_{t\to\infty} \|\chi u''(t,\cdot)\|_{L^2} \le \epsilon\|\chi\|_{L^\infty}$. Since this is true for every $\epsilon > 0$, the result follows. □

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