Traveling waves for a quasilinear wave equation

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TRAVELING WAVES FOR A QUASILINEAR WAVE EQUATION

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Abstract. We consider a 2+1 dimensional wave equation appearing in the context of polarized waves for the nonlinear Maxwell equations. The equation is quasilinear in the time derivatives and involves two material functions \( V \) and \( \Gamma \). We prove the existence of traveling waves which are periodic in the direction of propagation and localized in the direction orthogonal to the propagation direction. Depending on the nature of the nonlinearity coefficient \( \Gamma \) we distinguish between two cases: (a) \( \Gamma \in L^\infty \) being regular and (b) \( \Gamma = \gamma \delta_0 \) being a multiple of the delta potential at zero. For both cases we use bifurcation theory to prove the existence of nontrivial small-amplitude solutions. One can regard our results as a persistence result which shows that guided modes known for linear wave-guide geometries survive in the presence of a nonlinear constitutive law. Our main theorems are derived under a set of conditions on the linear wave operator. They are subsidised by explicit examples for the coefficients \( V \) in front of the (linear) second time derivative for which our results hold.

1. Introduction

Of concern is the following 2+1 dimensional quasilinear wave equation

\[
- \Delta u + c_t^2 \left( V(\lambda, y)u + \Gamma(y)u^3 \right) = 0, \tag{1.1}
\]

which appears in the context of polarized waves for the nonlinear Maxwell equations. Here, \( u = u(t, x, y) \) is the unknown depending on time \( t \in \mathbb{R}_+ \) and the two spatial variables \( x, y \). We assume \( u \) to be periodic in \( x \)-direction and localized in \( y \)-direction. In what follows, we denote by \( \mathbb{T} \) the one dimensional flat \( 2\pi \)-periodic torus, so that \( (x, y) \in \mathbb{T} \times \mathbb{R} \). The potentials \( V(\lambda, \cdot) \) and \( \Gamma \) depend only on \( y \) and incorporate material properties. Here, \( \lambda \in \mathbb{R} \) is a parameter. The function \( \Gamma \) might be a bounded function (referred to as regular \( \Gamma \)) or a multiple of a delta potential at \( y = 0 \) (referred to as distributional \( \Gamma \)).

To motivate our interest in (1.1), let us explain how it appears in the context of electromagnetics. Recall that the Maxwell equations in the absence of charges and currents are given by

\[
\begin{align*}
\nabla \cdot \mathbf{D} &= 0, \\
\nabla \times \mathbf{E} &= -\partial_t \mathbf{B}, \\
\nabla \cdot \mathbf{B} &= 0, \\
\n\nabla \times \mathbf{H} &= \partial_t \mathbf{D}, \\
\mathbf{D} &= \varepsilon_0 \mathbf{E} + \mathbf{P} \mathbf{E}, \\
\mathbf{B} &= \mu_0 \mathbf{H}.
\end{align*}
\]

The modeling of the underlying material is done by making assumptions on the form of the polarization field \( \mathbf{P} \). Here, we assume that \( \mathbf{P} \) depends instantaneously on the electric field \( \mathbf{E} \) as follows

\[
\mathbf{P}(\mathbf{E}) = \varepsilon_0 \chi_1(\mathbf{x}) \mathbf{E} + \varepsilon_0 \chi_3(\mathbf{x}) |\mathbf{E}|^2 \mathbf{E},
\]

with \( \mathbf{x} = (x, y, z) \in \mathbb{R}^3 \), cf. [1], Section 2.3. For simplicity we take \( \chi_1, \chi_3 \) as given scalar functions instead of the more general matrix/tensor structure of these quantities. The values \( \varepsilon_0, \mu_0 \) are constant such that \( c^2 = (\varepsilon_0 \mu_0)^{-1} \) and \( c \) is the speed of light in vacuum. By direct calculations from Maxwell’s equations one obtains the second-order quasilinear wave-type equation for the electric field

\[
0 = \nabla \times \nabla \times \mathbf{E} + c_t^2 \left( V(\mathbf{x}) \mathbf{E} + \Gamma(\mathbf{x}) |\mathbf{E}|^2 \mathbf{E} \right), \tag{1.2}
\]

where \( V(\mathbf{x}) = \mu_0 \varepsilon_0 (1 + \chi_1(\mathbf{x})) \) and \( \Gamma(\mathbf{x}) = \mu_0 \varepsilon_0 \chi_3(\mathbf{x}) \). The magnetic induction \( \mathbf{B} \) can be retrieved from \( \nabla \times \mathbf{E} = -\partial_t \mathbf{B} \) by time-integration and it will satisfy \( \nabla \cdot \mathbf{B} = 0 \) provided it does so at time \( t = 0 \). By assumption the magnetic field is given by \( \mathbf{H} = \frac{1}{\mu_0} \mathbf{B} \) and it satisfies \( \nabla \times \mathbf{H} = \partial_t \mathbf{D} \). It remains to check that the displacement field \( \mathbf{D} \) satisfies the Gauss law \( \nabla \cdot \mathbf{D} = 0 \) in the absence of external charges. This follows directly from the constitutive equation \( \mathbf{D} = \varepsilon_0 (1 + \chi_1(\mathbf{x})) \mathbf{E} + \varepsilon_0 \chi_3(\mathbf{x}) |\mathbf{E}|^2 \mathbf{E} \) and the assumption of the polarized form of the electric field

\[
\mathbf{E}(\mathbf{x}, t) = (0, 0, u(t, x, y))^T.
\]
If we assume additionally that $V(x) = V(y)$ and $\Gamma(x) = \Gamma(y)$ then the quasilinear vectorial wave-type equation (1.2) turns into the scalar equation (1.1) for $u = u(t, x, y)$.

We study the existence of traveling wave solutions of (1.1) propagating in $x$-direction for certain classes of potentials $V$. More precisely, we consider potentials of the form

$$V(\lambda, y) = \lambda V_0(y) + V_1(y), \quad \lambda \in \mathbb{R},$$

where $V_0 \in L^\infty(\mathbb{R})$ and $V_1$ is a distribution (e.g. a $\delta$-potential). If

$$u(t, x, y) = \Phi(x - t, y)$$

is a traveling wave solution of (1.1), propagating in $x$-direction with wave speed $v = 1$, then $\Phi : \mathbb{T} \times \mathbb{R} \to \mathbb{R}$ satisfies

$$-\Phi_{yy} - (1 - \lambda V_0(y) - V_1(y))\Phi_{xx} + \Gamma(y)(\Phi^3)_{xx} = 0. \quad (1.4)$$

The parameter $\lambda \in \mathbb{R}$ will serve as a bifurcation parameter. One might ask why we introduced $\lambda$ as a bifurcation parameter in the form $V(\lambda, y) = \lambda V_0(y) + V_1(y)$ and not in the more intuitive form $V(\lambda, y) = \lambda(V_0(y) + V_1(y))$ – the latter giving $\sqrt{\lambda}$ the meaning of the propagation speed of the traveling wave. The reason lies in the distributional character of $V_1$. The choice of the underlying function spaces for our analysis allows to formulate a (suitably defined, cf. Lemma 4.3) bounded inverse of $\tilde{L}_\lambda$, which is a slightly modified version of the wave operator $L_\lambda = -\partial^2_y - (1 - \lambda V_0(y) - V_1(y))\partial^2_x$. Extending the multiplication with $\lambda$ also to the distributional part $V_1$ causes a difficulties when differentiating with respect to $\lambda$, cf. Remark 4.5.

Throughout the paper, a function $u$ is called a traveling wave solution of (1.1) if $u$ takes the form (1.3) and $\Phi$ is a solution of (1.4), which is periodic in its first and localized in its second component.

We investigate the existence of nontrivial solutions $\Phi_{\lambda}$ of (1.4) corresponding to the parameter $\lambda$ under certain assumptions on the potential $V$; thereby providing the existence a nontrivial traveling wave solution $u_\lambda$ of (1.1). We apply bifurcation theory for the parameter $\lambda$ to find nontrivial solutions of (1.4). Our aim is to analyze the existence of nontrivial solutions in a way as general as possible, finding key properties of associate linear operators, which guarantee the existence of solutions via bifurcation theory. Eventually, we provide examples of specific potentials $V$ for which these properties can be verified. In particular, the following cases are under consideration:

(P1) **$V$ is a $\delta$–potential on a positive background**, that is $V$ is a distribution of the form

$$V(\lambda, y) = \lambda + \alpha \delta_0(y).$$

(P2) **$V$ is a $\delta$–potential on a step background**, that is $V$ is a distribution of the form

$$V(\lambda, y) = \lambda 1_{|y| \geq b} + \beta 1_{|y| < b} + \alpha \delta_0(y).$$

Concerning the nonlinear potential $\Gamma$ we distinguish between regular $\Gamma$, that is $\Gamma \in L^\infty(\mathbb{R})$, and distributional $\Gamma$, that is $\Gamma = \gamma \delta_0$. The main results for regular $\Gamma$ are shown in Section 2.1 and for distributional $\Gamma$ in Section 2.2.

Let us also comment on related work. Problem (1.1) has been considered in [17] where spatially localized traveling wave solutions of the 1+1-dimensional quasi-linear Maxwell model were investigated. The authors assume that $V(y)$ is a periodic arrangement of delta potentials. Using a multiple scale ansatz in fast and slow time, the field profile is expanded into infinitely many modes which are quasiperiodic in time (time-periodic both in the fast and slow time variables). Using local bifurcation methods the authors solve a related system which is homotopically linked to the Maxwell problem written as any infinite coupled system. It is not clear if the local bifurcation connects the related system and the Maxwell problem but numerical results support the existence of spatially localized traveling waves. In [7] and [9] another approximation (including error-estimates) of a version of (1.1) with periodic coefficients by finitely many coupled modes near band edges has been performed both analytically and numerically.

In the studies of the nonlinear Maxwell-system (1.2), often monochromatic waves $E(x) = U(x)e^{i\omega t} + c.c.$ are considered. Since a typical cubic nonlinearity generates higher harmonics, they either need to be neglected (leading to an error), or the constitutive equation for $D$ is replaced by a time-averaged nonlinearity $D = \varepsilon_0(1 + \chi_1(x))E + \varepsilon_0\chi_3(x)\frac{1}{\tau} \int_0^\tau |E|^2 dt E$, cf. [19, 20, 21, 14, 2, 8, 16] and particularly the two survey papers [3, 15]. In contrast to the previously cited works, our approach is genuinely polychromatic and does not rely on time-averaged material laws. In our solution ansatz we allow for harmonics of arbitrary order and we treat (1.1) without any approximation. Recently in [12] a similar approach was taken and spatially localized, time-periodic
solution of (1.1) were obtained via variational methods. The result of the present paper and [12] are complementary in the following sense: (a) in [12] only distributional $\Gamma$ is considered whereas in the present paper we also allow for regular $\Gamma \in L^\infty$; (b) in the case of distributional $\Gamma$, [12] only treats $V \in L^2$ whereas in the present paper we always have a delta potential contributing to $V$. Variational methods as in [12] have the advantage of producing solutions which may be far away from the trivial solution whereas local bifurcation methods as in the present paper produce solutions in the vicinity of zero. On the other hand, the local bifurcation method leads to more precise information about the actual shape of the bifurcating branch of solutions.

**Outline of the paper.** We close the introduction with a brief outline of the paper. In Section 2, we collect our main results. In Theorem 2.3 and Theorem 2.10 we provide a set of conditions on the linear wave operator guaranteeing the existence of nontrivial traveling wave solutions of (1.1) for regular and distributional $\Gamma$, respectively. Subsequently, we present in Corollary 2.5, Corollary 2.6, and Corollary 2.13, Corollary 2.14 particular examples in the form of (P1) and (P2) for regular and distributional $\Gamma$. In Section 3 we fix some notation. The remaining sections 4–7 are devoted to the proofs of our main results. To be more precise, in Section 4 we prove the existence result in Theorem 2.3 for regular $\Gamma$ followed by the proofs of Corollary 2.5 and Corollary 2.6 in Section 5, which provide specific examples. Similarly, we prove in Section 6 the existence result in Theorem 2.10 for distributional $\Gamma$ and finalize our studies in Section 7 with the proofs of Corollary 2.13 and Corollary 2.14 on specific examples in the case of distributional $\Gamma$. In the appendix we collect auxiliary results.

## 2. Main results

We are looking for solutions of (1.4) of the form

$$\Phi(x, y; \lambda) = \sum_{k \in \mathbb{N}} \phi_k(y; \lambda) \sin(kx).$$

(2.1)

Our analysis is going to be divided into two parts separating the case when $\Gamma$ is regular in the sense that $\Gamma \in L^\infty(\mathbb{R})$ and the case when $\Gamma$ is distributional and takes the extreme form of a $\delta$-potential. This is essentially due to the fact that in the former case we are concerned with a nonlinear equation on the domain $\mathbb{T} \times \mathbb{R}$, while in case of $\Gamma$ being a $\delta$-potential the problem can be viewed as a linear equation on $\mathbb{T} \times \mathbb{R}\setminus\{0\}$ – which can be solved separately – equipped with a nonlinear boundary condition at $x = 0$ induced by the delta potential.

### 2.1. Main result for regular $\Gamma$.

Let us start with the definition of a weak solution of (1.4) in the case when $\Gamma \in L^\infty(\mathbb{R})$.

**Definition 2.1** (Weak solution in the case of regular $\Gamma$). We say that $\Phi \in H^2(\mathbb{T}; L^2(\mathbb{R})) \cap H^1(\mathbb{T}; H^1(\mathbb{R}))$ is a weak solution of (1.4) if and only if

$$\int_{\mathbb{T}} \int_{\mathbb{R}} \Phi_y \psi_y - (1 - \lambda V_0(y)) \Phi_{xx} \psi \, dy \, dx - \int_{\mathbb{T}} \langle V_1(\cdot) \Phi_x(\cdot, \cdot), \psi_x(\cdot, \cdot) \rangle \, dx + \int_{\mathbb{T}} \int_{\mathbb{R}} (\Phi^3)_{xx} \psi \, dy \, dx = 0$$

for any $\psi \in H^1(\mathbb{T}; H^1(\mathbb{R}))$. Here, $\langle \cdot, \cdot \rangle$ is the dual pairing between $H^{-1}(\mathbb{R})$ and $H^1(\mathbb{R})$.

**Remark 2.2.**

(a) We consider $V_1$ as a bounded linear operator from $H^1(\mathbb{R})$ into $H^{-1}(\mathbb{R})$. When $V_1 = \delta_0$ this means that for $f, g \in H^1(\mathbb{R})$ we have $\langle V_1 f, g \rangle = f(0)g(0)$, i.e., since $f \in C(\mathbb{R})$ it multiplies $\delta_0$ and generates $f(0)\delta_0$ as a distribution acting on $g$.

(b) Clearly $\Phi_{xx} \in L^2(\mathbb{T} \times \mathbb{R})$. We shall see in Section 4 (cf. (4.8), (4.9) in Lemma 4.4) that also $\Phi \in L^\infty(\mathbb{T} \times \mathbb{R})$ and $\Phi_x \in L^4(\mathbb{T} \times \mathbb{R})$ so that $(\Phi^3)_{xx} = 3\Phi^2 \Phi_{xx} + 6\Phi \Phi_x^2 \in L^2(\mathbb{T} \times \mathbb{R})$.

If $\Gamma \in L^\infty(\mathbb{R})$, the ansatz in (2.1) allows us to reduce the problem of finding nontrivial solutions of (1.4) to studying spectral properties of the family of linear wave operators

$$L^k_\lambda := -\frac{d^2}{dy^2} + k^2(1 - \lambda V_0(y) - V_1(y)) \quad \text{for} \quad k \in \mathbb{N}.$$

We prove the following theorem:
Theorem 2.3 (Existence of traveling waves for regular $\Gamma$). Assume that $\Gamma \in L^\infty(\mathbb{R})$, the potential $V$ is given by

$$V(\lambda, y) = \lambda V_0(y) + V_1(y)$$

and

(L0) $V_0 \in L^\infty(\mathbb{R})$ and $V_1 : H^{-1}(\mathbb{R}) \to H^{-1}(\mathbb{R})$ is bounded;

(L1) for every fixed $k \in \mathbb{N}$ and $\lambda \in \mathbb{R}$ the operator $L_k^\lambda : D(L_k^\lambda) \subseteq L^2(\mathbb{R}) \to L^2(\mathbb{R})$ is self-adjoint;

(L2) there exists a wavenumber $k_* \in \mathbb{N}$, a value $\lambda_* \in \mathbb{R}$, and an open interval $I_{\lambda_*} \subseteq \mathbb{R}$ containing $\lambda_*$ such that zero is an isolated simple eigenvalue of $L_{k_*}$ and $0 \in \rho(L_{k_*})$ for any $(k, \lambda) \in \mathbb{N} \times I_{\lambda_*}$ with $(k, \lambda) \neq (k_*, \lambda_*);

(L3) if $L_k^\lambda \phi = f$ for some $f \in L^2(\mathbb{R})$, then

$$\|\phi\|_{L^2(\mathbb{R})} \leq \frac{1}{k^\beta} \|f\|_{L^2(\mathbb{R})} \quad \text{and} \quad \|\phi\|_{L^2(\mathbb{R})} \leq \frac{1}{k^\beta} \|f\|_{L^2(\mathbb{R})}$$

uniformly for $\lambda \in I_{\lambda_*}$ and $k \in \mathbb{N}$ sufficiently large.

If in addition $V_0$ satisfies the transversality condition

$$\langle V_0 \phi^*, \phi^* \rangle_{L^2(\mathbb{R})} \neq 0, \quad (2.2)$$

where $\phi^*$ spans the one-dimensional kernel of $L_{k_*}$, then there exists $\varepsilon_0 > 0$ and a smooth curve through $(0, \lambda_*)$,

$$\{(\Phi(\varepsilon), \lambda(\varepsilon)) \mid |\varepsilon| < \varepsilon_0 \} \subset (H^2(\mathbb{T}; L^2(\mathbb{R})) \cap H^1(\mathbb{R}; H^1(\mathbb{R}))) \times I_{\lambda_*},$$

of nontrivial solutions of (1.4) with

$$\Phi(0) = 0, \quad D_\lambda \Phi(0)(x, y) = \phi^*(y) \sin(k_* x),$$

$$\lambda(0) = \lambda_*, \quad \lambda'(0) = 0, \quad \lambda''(0) = \frac{3}{2} \int_{\mathbb{R}} V_0(y)(\phi^*)^2(y) \, dy.$$
2.2. Main result for distributional $\Gamma$. Again, we start with the definition of a weak solution of (1.4), but now in the case when $\Gamma$ is given by a $\delta$-potential. We assume that the function $V_1 = W + \alpha \delta_0$ splits into a regular part $W$ and the distributional part $\alpha \delta_0$ so that $V = \lambda V_0 + W + \alpha \delta_0$, where $V_0, W \in L^\infty(\mathbb{R})$ and $\Gamma = \gamma \delta_0$.

**Definition 2.8** (Weak solution in the case of distributional $\Gamma$). We say that $\Phi \in H^2(T; L^2(\mathbb{R})) \cap H^1(T; H^1(\mathbb{R})) \cap C(\mathbb{R}; H^2(T))$ is a weak solution of (1.4) if and only if

$$\int_T \int_\mathbb{R} \Phi_y \Psi_y = (1 - \lambda V_0 - W(y)) \Phi_{xx} \Psi_T dy dx + \int_T (\alpha \Phi_{xx}(x, 0) + \gamma(\Phi^3)_{xx}(x, 0)) \Psi_T(x, 0) dx = 0$$

for any $\Psi \in H^1(T; H^1(\mathbb{R}))$.

**Remark 2.9.** Clearly $\Phi_{xx}(\cdot, 0) \in L^2(T)$ and $\Phi(\cdot, 0), \Phi_x(\cdot, 0) \in L^\infty(\mathbb{T})$ so that $(\Phi^3(\cdot, 0))_{xx} = 3\Phi(\cdot, 0)\Phi_x(\cdot, 0)_{xx} + 6\Phi(\cdot, 0)\Phi_x(\cdot, 0)^2 \in L^2(T)$. Moreover, $\Psi \in H^1(T; H^1(\mathbb{R})) \subset H^1(T \times \mathbb{R})$ has an $L^2$-trace at $y = 0$.

Note that (1.4) can be written as a linear partial differential equation on $T \times \mathbb{R} \setminus \{0\}$ equipped with a nonlinear boundary condition on $T$:

$$\begin{cases}
-\Phi_y y - (1 - \lambda V_0 - W) \Phi_{xx} = 0, \\
\Phi(x, 0^+) - \Phi(x, 0^-) = \tilde{c}_\alpha (\alpha \Phi + \gamma \Phi^3) (x, 0), 
\end{cases} 
(x, y) \in T \times \mathbb{R} \setminus \{0\}, 
(2.5)
$$

As before let

$$L^\lambda_k := -\frac{d^2}{dy^2} + \kappa^2 (1 - \lambda V_0(y) - W(y) - \alpha \delta_0(y))$$

be a family of linear wave operators and set

$$L^\lambda_{0,k} := -\frac{d^2}{dy^2} + \kappa^2 (1 - \lambda V_0(y) - W(y))$$

to be the regular part of $L^\lambda_k$. We prove the following theorem:

**Theorem 2.10** (Existence of traveling wave for distributional $\Gamma$). Assume that $\Gamma = \gamma \delta_0$, the potential $V$ is given by

$$V(\lambda, y) = \lambda V_0(y) + W(y) + \alpha \delta_0(y),$$

and

(\hat{L}0) $V_0, W \in L^\infty(\mathbb{R})$ are even;  
(\hat{L}1) there exists an interval $I \subset \mathbb{R}$ such that for every fixed $k \in \mathbb{N}$ and $\lambda \in I$ the operator $L^\lambda_{0,k} : H^2(\mathbb{R}) \subset L^2(\mathbb{R}) \rightarrow L^2(\mathbb{R})$ satisfies $\phi \in \rho(L^\lambda_{0,k})$;  
(\hat{L}2) there exists a wavenumber $k_\lambda \in \mathbb{N}$, a value $\lambda_\lambda \in \mathbb{R}$, and an open interval $I_{\lambda_\lambda} \subset I \subset \mathbb{R}$ containing $\lambda_\lambda$ such that zero is an isolated simple eigenvalue of $L^\lambda_{0,k_\lambda}$ and $0 \in \rho(L^\lambda_{0,k})$ for any $(k, \lambda) \in \mathbb{N} \times I_{\lambda_\lambda}$ with $(k, \lambda) \neq (k_\lambda, \lambda_\lambda)$;  
(\hat{L}3) there exist $C > 0$ such that $\| \phi_k(\cdot; \lambda) \|_{L^2(0, \infty)} \leq C$ uniformly for $\lambda \in I_{\lambda_\lambda}, k \in \mathbb{N}$, and where $\phi_k \in H^2(0, \infty)$ satisfies

$$L^\lambda_{0,k} \phi_k(y; \lambda) = 0 \text{ on } (0, \infty) \text{ with } \phi_k(0; \lambda) = 1.$$  

If in addition $V_0$ satisfies the transversality condition

$$\langle V_0 \phi^*, \phi^* \rangle_{L^2(\mathbb{R})} \neq 0,$$

where $\phi^*$ spans the one-dimensional kernel of $L^\lambda_{0,k_\lambda}$, then there exists $\epsilon_0 > 0$ and a smooth curve through $(0, \lambda_\lambda)$

$$\{(\Phi(\varepsilon), \lambda(\varepsilon)) \mid |\varepsilon| < \epsilon_0 \} \subset (H^2(T; L^2(\mathbb{R})) \cap H^1(T; H^1(\mathbb{R})) \cap \Phi(\cdot, 0) \in H^2(T)) \times I_{\lambda_\lambda}$$

of nontrivial solutions of (1.4) with

$$\Phi(0) = 0, \quad D_x \Phi(0)(x, y) = \phi^*(y) \sin(k_\lambda x),$$

$$\gamma \lambda(0) = \lambda_\lambda, \quad \tilde{\lambda}(0) = 0, \quad \tilde{\lambda}(0) = -\frac{3\gamma}{4k_\lambda V_0(y)(\phi^*)^2(y)} dy.$$

**Remark 2.11.** The transversality condition (2.6) is trivially satisfied if $V_0 \geq 0$, $\neq 0$ or $V_0 \leq 0$, $\neq 0$.

---

1The existence and the properties of the functions $\phi_k$ are detailed in Remark 6.1.
Remark 2.12. We can formulate (L2) entirely in terms of the ansatz-functions \( \phi_k(\lambda) \) defined in (L3). To this end notice that \( \sigma_{ess}(L_{0,\alpha}^k) = \sigma_{ess}(L_{1,\alpha}^k) \), cf. Lemma A.5. Since \( 0 \not\in \sigma(L_{0,\alpha}^k) \) by assumption (L1) it is clear that \( 0 \in \sigma(L_{1,\alpha}^k) \) is characterized by zero being an eigenvalue of \( L_{1,\alpha}^k \). Moreover, the solutions of \( V_0, W \), means that \( \phi_k(\lambda) \) is up to scalar multiples the unique candidate for the eigenfunction and has to satisfy
\[
2\phi_k^\prime(0+; \lambda) + k^2 \alpha = 0.
\]
Here \( 2\phi_k^\prime(0+; \lambda) \) is the jump of the first derivative of the even function \( \phi_k(\lambda) \) at \( y = 0 \). Based on this characterization of zero belonging to the spectrum of \( L_{1,\alpha}^k \) we can replace (L2) by
\[
(L2) \quad \text{there exists a wavenumber } k_* \in \mathbb{N}, \lambda_* > 0, \text{ and an open interval } I_{\lambda_*} \subset \mathbb{R}^+ \text{ containing } \lambda_* \text{ such that}
\]
\[
2\phi_k^\prime(0+; \lambda) + k^2 \alpha = 0
\]
if and only if \( (k, \lambda) = (k_*, \lambda_*) \) for any \( k \in \mathbb{N} \) and \( \lambda \in I_{\lambda_*} \).

In Section 6 we prove Theorem 2.10. Claiming periodicity in one spatial direction and evenness in the transverse direction we make a Fourier ansatz of the form
\[
\Phi(x, y; \lambda) = \sum_{k \in \mathbb{N}} \phi_k(\lambda) \phi_k(\lambda y) \sin(kx),
\]
where \( \phi_k \) are the decaying functions from assumption (L3). In particular, the ansatz (2.7) solves the linear differential equation in (2.5) and thus reduces the problem of finding nontrivial solutions of (1.4) to the following family of algebraic equations
\[
2\phi_k^\prime(0+; \lambda) + k^2 \alpha = -k^2 \left( \alpha \phi_k(\lambda) - \frac{1}{4} \gamma (a(\lambda) * a(\lambda) * a(\lambda))_{\lambda} \right)
\]
for all \( k \in \mathbb{N} \).

In the spirit of Section 4, we show that if conditions (L0) – (L3) are satisfied, then the nonlinear equation (2.8) has a non-trivial solution \( (a_k(\lambda))_{k \in \mathbb{Z}} \) with \( a_k(\lambda) = -a_{-k}(\lambda) \) and the decay property
\[
(k^2 a_k(\lambda))_{k \in \mathbb{Z}} \in l^2(\mathbb{R});
\]
thereby providing a solution of (1.4) in the form of (2.7). Here, \( l^2(\mathbb{R}) \) denotes the space of \( l^2 \)-summable sequences in \( \mathbb{R}^\mathbb{Z} \). Condition (L1) guarantees the existence of the family of even ansatz-functions \( (\phi_k)_{k \in \mathbb{N}} \) with \( \phi_k(0; \lambda) = 1 \). Condition (L2) assures that there exists \( k_* \in \mathbb{N}, \lambda_* \in \mathbb{R} \) and an interval \( I_{\lambda_*} \subset \mathbb{R} \) including \( \lambda_* \) such that the linearization of (2.8), given by the multiplication operator
\[
A_{\lambda_*}^k := 2\phi_k^\prime(0+; \lambda) + k^2 \alpha,
\]
has a one-dimensional kernel if \( (k, \lambda) = (k_*, \lambda_*) \), that is \( A_{\lambda_*}^{k(*)} = 0 \); and \( A_{\lambda_*}^k \neq 0 \) for all \( (k, \lambda) \in \mathbb{N} \times I_{\lambda_*} \) with \( (k, \lambda) \neq (k_*, \lambda_*) \). This is a necessary bifurcation condition. After we have proved Theorem 2.10, we investigate the specific cases, when \( V \) is a potential of the form as in (P1) and (P2). The former being a \( \delta \)-potential on a constant background, while the latter is a \( \delta \)-potential on the background of a step function. In both cases the \( \delta \)-potential part in \( V \) is essential, guaranteeing sufficient decay properties of the sequence \( (a_k(\lambda))_{k \in \mathbb{N}} \). In particular, we prove the following corollaries:

Corollary 2.13 (Case P1, distributional \( \Gamma \)). Assume that \( \Gamma = \gamma \delta_0 \) and \( V(\lambda, y) = \lambda + \alpha \delta_0(y) \). If \( k_* \in \mathbb{N} \) and \( \lambda_* < 1 \) are given and \( \alpha > 0 \) is determined from
\[
\alpha = \frac{2\sqrt{1-\lambda_*}}{k_*}
\]
then the assumptions in Theorem 2.10 are satisfied with
\[
\phi^\ast(y) = e^{-k_* \sqrt{1-\lambda_*}|y|}
\]
and
\[
\Phi(0) = 0, \quad D_y \Phi(0)(x, y) = e^{-k_* \sqrt{1-\lambda_*}|y|} \sin(k_* x),
\]
\[
\lambda(0) = \lambda_*, \quad \dot{\lambda}(0) = -\gamma k_* \sqrt{1-\lambda_*}.
\]
Moreover, the solutions \( \Phi(\varepsilon) \) take the form
\[
\Phi(\varepsilon)(x, y) = \sum_{k \in \mathbb{N}} a_k(\varepsilon) e^{-k \sqrt{1-\lambda_\varepsilon}|y|} \sin(kx).
\]
Corollary 2.14 (Case P2, distributional Γ). Let \( \Gamma \in L^\infty(\mathbb{R}) \) and \( V(\lambda, y) = \lambda I_{|y| \geq b} + \beta I_{|y| < b} + \alpha \delta_0(y) \). Suppose furthermore that \( k_a \in \mathbb{N} \) and \( \lambda_0 < 1 \) are given. If

- (Case \( \beta > 1 \)) \( b, \alpha > 0 \) are determined from
  \[
  b = \frac{\pi}{\sqrt{b - 1}}, \quad \alpha = 2 \sqrt{1 - \lambda_0}
  \]
- (Case \( \beta < 1 \)) \( b > 0 \) is given and \( \alpha > 0 \) is determined from
  \[
  \alpha = 2 \sqrt{1 - \beta} \cdot \sqrt{\frac{1 - \beta \sinh(k_a \sqrt{1 - \beta}) + \sqrt{1 - \lambda_0 \cosh(k_a \sqrt{1 - \beta})}}{1 - \beta \cosh(k_a \sqrt{1 - \beta}) + \sqrt{1 - \lambda_0 \sinh(k_a \sqrt{1 - \beta})}}}
  \]
- (Case \( \beta = 1 \)) \( b > 0 \) is given and \( \alpha > 0 \) is determined from
  \[
  \alpha = \frac{2 \sqrt{1 - \lambda_0}}{k_a (1 + \sqrt{1 - \lambda_0} k_a b)}
  \]

then in all three cases the assumptions in Theorem 2.10 are satisfied.

Remark 2.15. Details on the construction of \( \phi^* \) in Corollary 2.14, the functions \( \phi_k \) and the form of the solutions \( \Phi(z,x,y) = \sum_{k \in \mathbb{N}} a_k(z) \phi_k(y;\lambda) \sin(kx) \) can be taken from Section 7.2.

3. Notation

If \( f \) and \( g \) are elements in an ordered Banach space, we write \( f \preceq g \) (\( f \succeq g \)) if there exists a constant \( c > 0 \) such that \( f \leq cg \) (\( f \geq cg \)). Moreover, the notation \( f \approx g \) is used whenever \( f \preceq g \) and \( f \succeq g \). We write \( c = c(p_1, p_2, \ldots) > 0 \) if we want to emphasize that the constant \( c > 0 \) depends on the parameters \( p_1, p_2, \ldots \).

In Section 6 we are looking for solutions of an infinite dimensional system of nonlinear algebraic equation. We consider solutions in the sequence spaces related to

\[
\ell^2(\mathbb{R}) := \left\{ a = (a_k)_{k \in \mathbb{Z}} \mid a_k \in \mathbb{R} \text{ for all } k \in \mathbb{Z} \text{ and } \|a\|_{\ell^2(\mathbb{R})}^2 := \sum_{k \in \mathbb{Z}} |a_k|^2 < \infty \right\}.
\]

Eventually, for any \( r \in \mathbb{R} \) we set

\[
h^r(\mathbb{R}) := \left\{ a \in \ell^2(\mathbb{R}) \mid ((1 + |k|)^r a_k)_{k \in \mathbb{Z}} \in \ell^2(\mathbb{R}) \right\},
\]

and equip the space \( h^r(\mathbb{R}) \) with the norm

\[
\|a\|_{h^r(\mathbb{R})}^2 := \sum_{k \in \mathbb{Z}} (1 + |k|)^{2r} |a_k|^2.
\]

We also consider the subspaces

\[
\ell^2_2(\mathbb{R}) := \{ a \in \ell^2(\mathbb{R}) : a_{-k} = -a_k \text{ for } k \in \mathbb{Z} \},
\]

\[
h^r_2(\mathbb{R}) := h^r(\mathbb{R}) \cap \ell^2_2(\mathbb{R}).
\]

Throughout the paper we use the notation \( \langle \cdot, \cdot \rangle_H \) to denote the dual pairing in the Hilbert space \( H \). If \( f, g \in L^2(U) \) are real-valued functions, where \( U \subset \mathbb{R}^n \) is a domain in \( \mathbb{R}^n \), \( n \in \mathbb{N} \), then

\[
\langle f, g \rangle_{L^2(U)} := \int_U f(z)g(z) \, dz
\]

and if \( a, b \in \ell^2(\mathbb{R}) \) then

\[
\langle a, b \rangle_{\ell^2(\mathbb{R})} := \sum_{k \in \mathbb{Z}} a_k b_k.
\]

If \( L : D(L) \subset H \to H \) is a linear operator with domain \( D(L) \), we denote by \( \rho(L) := \{ \lambda \in \mathbb{C} \mid \lambda - L : D(L) \to H \text{ has a bounded inverse} \} \) the resolvent set of \( L \). The spectrum of \( L \) is given by \( \mathbb{C} \setminus \rho(L) \). If \( L \) is self-adjoint, then \( \sigma(L) \subset \mathbb{R} \) and the spectrum of \( L \) can be decomposed as a disjoint union

\[
\sigma(L) = \sigma_{\text{ess}}(L) \cup \sigma_d(L),
\]

where \( \sigma_d \) is the discrete spectrum of \( L \) consisting of isolated eigenvalues of \( \sigma(L) \) of finite multiplicity and \( \sigma_{\text{ess}}(L) = \sigma(L)\setminus\sigma_d(L) \) is the essential spectrum.
This section is devoted to the proof of Theorem 2.3. Subsequently, we affirm in Section 5 that the conditions are fulfilled for special cases where \( V \) takes the form in (P1) or (P2), thereby proving Corollary 2.5 and Corollary 2.6. In the following we restrict ourselves to solutions \( \Phi \) of (1.4) having the form

\[
\Phi(x, y; \lambda) = \sum_{k \in \mathbb{N}} \phi_k(y; \lambda) \sin(kx),
\]

where the \( y \)-dependent Fourier coefficients \( (\phi_k)_{k \in \mathbb{N}} \) are decaying at infinity (suitable function spaces are formulated later). Then, \( \Phi \) is a solution of

\[
- \Phi_{yy} - (1 - \lambda V_0(y) - V_1(y)) \Phi_{xx} + \Gamma(y)(\Phi^3)_{xx} = 0
\]

if and only if

\[
-\phi''_k + k^2(1 - \lambda V_0(y) - V_1(y))\phi_k + \frac{1}{4}k^4\Gamma(y)(\Phi \ast \Phi \ast \Phi)_k = 0 \quad \text{for all } k \in \mathbb{N}.
\]

Note that

\[
-\frac{1}{4} (\Phi \ast \Phi \ast \Phi) \text{ is the } k\text{-th Fourier coefficient of } \Phi^3, \text{ cf. Lemma A.1.}
\]

The Fourier ansatz with respect to \( x \) decomposes the operator

\[
\text{ker} \quad \text{if}
\]

\[
\text{into the sequence of Schrödinger operators } L^k
\]

\[
L^k := -\frac{d^2}{dy^2} + k^2(1 - \lambda V_0(y) - V_1(y)).
\]

Recall that we are working under the assumptions (L0)–(L3) from Theorem 2.3.

**Remark 4.1.**

(i) Notice that a necessary condition for (L3) to hold is that the operator \( L^k \) satisfies the spectral gap property

\[
(-ck^2, ck^2) \subset \rho(L^k) \quad \text{for some constant } c > 0
\]

uniformly in \( \lambda \in I_\ast \) and \( k \in \mathbb{N} \) sufficiently large.

(ii) The domain of \( L^k \) is a subset of \( H^1(\mathbb{R}) \), which is the domain of the quadratic form of \( L^k \). As a vector space, it does not depend on \( \lambda \). However, the graph norm on \( D(L^k) \) is \( \lambda \)-dependent and the embedding \( D(L^k) \subset H^1(\mathbb{R}) \) is locally uniformly bounded with respect to \( \lambda \).

The next lemma extends property (L3) to all values of \( k \in \mathbb{N} \) by adding a projection to \( L^k \) for \( k = k_\ast \). For this purpose let \( \text{ker} L^k = \text{span} \{ \phi_\ast \} \) with \( \| \phi_\ast \|_{L^2(\mathbb{R})} = 1 \). Denote by \( P^k \) the projection mapping

\[
P^k \phi := \langle \phi_\ast, \phi \rangle_{L^2(\mathbb{R})} \phi_\ast \quad \text{for any } \phi \in L^2(\mathbb{R})
\]

and define by \( \tilde{L}^k \) and \( \bar{L}^k \) operators that are similar to those of \( L^k \).

**Lemma 4.2.** Let \( \tilde{L}^k \phi = g \) for some \( g \in L^2(\mathbb{R}) \). Then, by possibly shrinking the interval \( I_\ast \), we have that

\[
\| \phi \|_{L^2(\mathbb{R})} \leq \frac{1}{k^2} \| g \|_{L^2(\mathbb{R})} \quad \text{and} \quad \| \phi' \|_{L^2(\mathbb{R})} \leq \frac{1}{k^2} \| g \|_{L^2(\mathbb{R})}
\]

for all \( k \in \mathbb{N} \) uniformly in \( \lambda \in I_\ast \).

**Proof.** By Theorem VIII.25 in [18] it follows that the map \( \lambda \mapsto L^k \) is norm-resolvent continuous, that is \( \lambda \mapsto (L^k - i)^{-1} \in \mathcal{L}(L^2(\mathbb{R})) \) is continuous with respect to the operator norm. Let us verify that also \( \tilde{L}^k \) is norm-resolvent convergent to \( \tilde{L}^k \) as \( \lambda \mapsto \lambda_\ast \). Note that \( \text{Id} + P^k \) is a compact perturbation of the identity, injective and hence bijective. Then, for \( \lambda \) close to \( \lambda_\ast \), also \( \text{Id} + P^k \) is bijective. Note that we have the identity

\[
(\tilde{L}^k - i + P^k)^{-1} = \left( (\text{Id} + P^k)(L^k - i)^{-1} \right)^{-1}.
\]
From this we see that
\[
(\tilde{L}_\lambda^k - i)^{-1} = (L_*^k - i)^{-1} \left( 1 + P^k \tilde{L}_\lambda^k \right)^{-1}.
\]
Using the assumption that \( L_*^k \) converges to \( L_*^k \) in the norm resolvent sense, this implies the claim.

Next we show that \( 0 \in \rho(\tilde{L}_\lambda^k) \). Using the assumption that \( \psi \) solves \( \tilde{\phi}_k(x, \cdot) \), we get \( \langle \phi, \tilde{\phi}_k \rangle_{L^2(\mathbb{R})} = 0 \) and hence \( P^k \phi = 0 \). Thus, \( \phi \) also belongs to the kernel of \( L_*^k \), which contradicts \( \langle \phi, \phi^* \rangle_{L^2(\mathbb{R})} = 0 \) and the simplicity of the 0-eigenvalue of \( L_*^k \).

Finally, by (L3) we know that there exists \( k_0 \in \mathbb{N} \) (we assume w.l.o.g. \( k_0 \geq k_* \)) such that (4.4) holds for \( k > k_0 \geq k_* \). This implies that
\[
\inf_{k > k_0} \inf_{|\lambda - \lambda_+| < \delta} \text{dist}(0, \sigma(\tilde{L}_\lambda^k)) > 0.
\]

Now we want to extend this inequality to the remaining values of \( k \in \{1, \ldots, k_0\} \) by possibly diminishing \( \delta \). Thus, let \( k \in \mathbb{N} \) with \( 1 \leq k \leq k_0 \) and assume for contradiction the existence of a sequence \( \lambda_n \to \lambda_+ \) as \( n \to \infty \) such that there exists \( \mu_n \in \sigma(\tilde{L}_\lambda^k) \) with \( \lim_{n \to \infty} \mu_n = 0 \). By norm-resolvent convergence this implies \( 0 \in \sigma(\tilde{L}_\lambda^k) \), which is impossible for \( k \neq k_* \) by (L2) and also impossible for \( k = k_* \) as stated above. This contradiction establishes (4.5) for all \( k \in \mathbb{N} \). Finally, (4.5) shows that the map \( \lambda \mapsto \| (\tilde{L}_\lambda^k)^{-1} \|_{L^2(\mathbb{R}) \to L^2(\mathbb{R})} \) is bounded for \( \lambda \in (\lambda_+ - \delta, \lambda_+ + \delta) \) uniformly for \( k \in \mathbb{N} \). The same holds for \( \lambda \mapsto \| (\tilde{L}_\lambda^k)^{-1} \|_{D(L^\lambda_\lambda) \to D(L^\lambda_\lambda)} \), and due to (ii) in Remark 4.1, also for \( \lambda \mapsto \| (\tilde{L}_\lambda^k)^{-1} \|_{H^1(\mathbb{R}) \to H^1(\mathbb{R})} \). This establishes (4.4) for all \( k \in \mathbb{N} \). \( \square \)

Now, we introduce suitable function spaces and use Lemma 4.2 to reformulate the nonlinear problem (4.1) in a setting, which makes the local bifurcation theorem due to Crandall–Rabinowitz [5] applicable. Set
\[
X := \left\{ \psi \in H^2(\mathbb{T}; L^2(\mathbb{R})) \cap H^1(\mathbb{T}; H^1(\mathbb{R})) \mid \psi(x, y) = \sum_{k \in \mathbb{N}} \phi_k(y) \sin(kx) \right\}
\]
and
\[
Y := \left\{ \psi \in L^2(\mathbb{T}; L^2(\mathbb{R})) \mid \psi(x, y) = \sum_{k \in \mathbb{N}} \phi_k(y) \sin(kx) \right\}.
\]
Moreover, we set
\[
\tilde{L}_\lambda := L_\lambda + P^*,
\]
where \( P^* \) denotes the \( L^2 \)-orthogonal projection onto \( \ker L_*^k \). Recall, that the operator \( L_*^k \) is defined in (4.2). As an immediate consequence of (L0)–(L3), we obtain the following lemma.

**Lemma 4.3.** Assume that (L0)–(L3) holds true and let \( \lambda \in I_{k_*} \). There exists a bounded linear map \( \tilde{L}_\lambda^{-1} : Y \to X \) with the following property: if \( f \in Y \) is given and the function \( \Phi \in X \) solves
\[
\Phi = \tilde{L}_\lambda^{-1} (f + P^* \Phi)
\]
then \( \Phi \) solves
\[
L_\lambda \Phi = f
\]
in the weak sense, that is
\[
\int_{\mathbb{T}} \int_{\mathbb{R}} \Phi(y) \Psi_y(x) - (1 - \lambda V_0(y)) \Phi_x(x) \Psi_y(x) \, dy \, dx - \int_{\mathbb{T}} \int_{\mathbb{R}} \langle V_1(\cdot) \Phi_x(x, \cdot), \Psi_x(x, \cdot) \rangle \, dx = \int_{\mathbb{T}} \int_{\mathbb{R}} f \Psi \, dy \, dx
\]
for any \( \Psi \in X \).

**Proof.** Let \( \lambda \in I_{k_*} \). For \( g \in Y \) the definition of \( \Phi := \tilde{L}_\lambda^{-1} g \) is given by
\[
\Phi(x, y) = \sum_{k \in \mathbb{N}} \phi_k(y) \sin(kx) \quad \text{with} \quad \phi_k = (\tilde{L}_\lambda^k)^{-1} g_k.
\]
Then Lemma 4.2 implies that \( \Phi \in X \) and that \( \tilde{L}_\lambda^{-1} : Y \to X \) is bounded. Now suppose that \( \Phi \in X \) solves (4.6). Then \( \phi_k = (\tilde{L}_\lambda^k)^{-1} (f_k + P^* \phi_k) \) so that \( \phi_k \in D(\tilde{L}_\lambda^k) = D(L_*^k) \) for all \( k \in \mathbb{N} \). In particular, we know that
\[
L_*^k \phi_k = f_k \quad \text{for all} \quad k \in \mathbb{N}
\]
and thus for $K_0 \in \mathbb{N}$ and $\psi_1, \ldots, \psi_{K_0} \in H^1(\mathbb{R})$ we have

$$\sum_{k=1}^{K_0} \left( \int_{\mathbb{R}} \phi'_k \psi'_k + k^2 (1 - \lambda V_0(y)) dy - \langle V_1 \phi_k, \psi_k \rangle \right) = \sum_{k=1}^{K_0} \int_{\mathbb{R}} f_k \psi_k \, dy.$$ 

Taking the limit $K_0 \to \infty$ in the previous equation will lead to

$$\int_T \int_{\mathbb{R}} \Phi_y \Psi_y - (1 - \lambda V_0(y)) \Phi_x \Psi \, dy \, dx - \int_T \langle V_1(\cdot) \Phi_x(x, \cdot), \Psi (x, \cdot) \rangle \, dx = \int_T \int_{\mathbb{R}} f \Psi \, dy \, dx$$

for any $\Psi \in X$ due to the following estimates:

$$\int_T \int_{\mathbb{R}} |\Phi_y \Psi_y| \, dy \, dx \leq \sum_{k \in \mathbb{N}} \| \Phi' \|_{L^2(\mathbb{R})} \| \psi'_k \|_{L^2(\mathbb{R})} \leq \| \Phi \|_{L^2(T, H^1(\mathbb{R}))} \| \Psi \|_{L^2(T, H^2(\mathbb{R}))},$$

$$\int_T \int_{\mathbb{R}} |V_0(y) \Phi_{xx} \Psi| \, dy \, dx \leq \sum_{k \in \mathbb{N}} \| V_0 \|_{L^\infty(\mathbb{R})} k^2 \| \phi''_k \|_{L^2(\mathbb{R})} \| \psi_k \|_{L^2(\mathbb{R})} \leq \| V_0 \|_{L^\infty(\mathbb{R})} \| \Phi \|_{H^2(T, L^2(\mathbb{R}))} \| \Psi \|_{L^2(T, L^2(\mathbb{R}))},$$

$$\int_T \int_{\mathbb{R}} |\langle V_1(\cdot) \Phi_x(x, \cdot), \Psi (x, \cdot) \rangle| \, dx \leq \sum_{k \in \mathbb{N}} \| V_1 \|_{H^1(\mathbb{R})} \| \phi_k \|_{H^1(\mathbb{R})} \| \psi_k \|_{H^1(\mathbb{R})} \leq \| V_1 \|_{H^1(\mathbb{R})} \| \Phi \|_{H^1(T, H^1(\mathbb{R}))} \| \Psi \|_{H^1(T, H^1(\mathbb{R}))},$$

$$\int_T \int_{\mathbb{R}} |f \Psi| \, dy \, dx \leq \sum_{k \in \mathbb{N}} \| f_k \|_{L^2(\mathbb{R})} \| \psi_k \|_{L^2(\mathbb{R})} \leq \| f \|_{L^2(T, L^2(\mathbb{R}))} \| \Psi \|_{L^2(T, L^2(\mathbb{R}))}.$$
Let us briefly describe the difficulty that arises when one considers the bifurcation problem for distributional potential $V$, i.e., we are missing a half-derivative in the regularity gain.

As above, we would expect to have $F$ as a calculation in the case where $\Phi \in L^\infty$, and due to the Gagliardo–Nirenberg inequality, cf. (4.9).

Finally, the formula in (i) shows that $D_0F(\lambda, x)$ is a compact perturbation of the identity, and hence Fredholm of index zero. Let us compute the kernel of $D_0F(\lambda, x)$.

By the Gagliardo–Nirenberg inequality, we obtain that

$$\left( \int_T \left| \frac{d}{dy} \right|^4 dy \right)^{\frac{1}{4}} \leq C \left( \sum_{k \in \mathbb{N}} k^2 \left| \phi_k \right|^2_{L^2(\mathbb{R})} \right)^{\frac{1}{2}} \left( \sum_{k \in \mathbb{N}} k^4 \left| \phi_k \right|^2_{L^2(\mathbb{R})} \right)^{\frac{1}{2}} \left( \sum_{k \in \mathbb{N}} k^{-3/2} \right)^{\frac{1}{2}}$$

(4.9)

Hence, for $\Phi \in X$ we have $(\Phi^3)_{xx} = 3\Phi^2\Phi_{xx} + 6\Phi\Phi_x^2 \in L^2(\mathbb{T}, L^2(\mathbb{R})) \subset Y$ and thus the mapping properties of $F$ are proved.

The differentiability properties of $F$ with respect to $\Phi$ also follow in a similar way from $\Phi \in L^\infty(\mathbb{T} \times \mathbb{R})$ and $\Phi_x \in L^4(\mathbb{T} \times \mathbb{R})$, as (4.8) and (4.9) that the first/second derivatives of $F$ with respect to $\Phi$ exist, are bounded linear/bilinear operators and contain terms of the form $\text{abc}_{xx}$ or $\text{abc}_{cx}$ where $a, b, c \in X$. Based on the estimates

$$\int_T \int_\mathbb{R} |ab_x c_x|^2 dy dx \leq \|a\|_{L^4(\mathbb{T} \times \mathbb{R})}^2 \|b\|_{L^4(\mathbb{T} \times \mathbb{R})}^2 \|c_x\|_{L^4(\mathbb{T} \times \mathbb{R})}^2,$$

we find in view of (4.8) and (4.9) the first/second derivatives of $F$ with respect to $\Phi$ exist, are bounded linear/bilinear operators from $X$ to $Y$, and depend continuously on $\Phi$ and $x$. Due to the cubic nature of the nonlinearity, differentiability of $F$ of order higher than two with respect to $\Phi$ is independent of $\Phi$.

The differentiability properties of $F$ with respect to $\lambda$ follow from

$$\frac{d}{d\lambda} L^{-1}_\lambda = -L^{-1}_\lambda \frac{d}{d\lambda} \tilde{L}^{-1}_\lambda = -\tilde{L}^{-1}_\lambda V_0 \tilde{c}_2 \tilde{L}^{-1}_\lambda$$

(4.10)

and due to $\tilde{L}^{-1}_\lambda: Y \to X$ and $V_0 \tilde{c}_2 : X \to Y$, we see that the resulting operator on the right-hand side of (4.10) is indeed a bounded linear map from $Y \to X$. Moreover, (4.10) explains the formula for $D_0^2F(0, \lambda)$ in (ii).

Finally, the formula in (i) shows that $D_0F(\lambda, x)$ is a compact perturbation of the identity, and hence Fredholm of index zero. Let us compute the kernel of $D_0F(0, \lambda)$. If $\Psi \in X$ satisfies $D_0F(0, \lambda)\Psi = 0$ then according to Lemma 4.3 we have that $\Psi$ is a weak solution of $L_\lambda \Psi = 0$. Then, for $\lambda \neq \lambda_\Phi$ we have $\psi_k = 0$ for all $k \in \mathbb{N}$ and hence $\Psi = 0$. For $\lambda = \lambda_\Phi$ we have $\psi_k = 0$ for all $k \in \mathbb{N}$; $\psi_k \in \text{span}\{\phi^k\}$ such that $\Psi \in \text{span}\{\Phi^k\}$ as claimed. Notice finally that $D_0F(0, \lambda_\Phi) = \text{Id} - \tilde{L}^{-1}_{\lambda_\Phi} P^\Phi = \text{Id} - P^\Phi$ since range $P^\Phi = \text{span}\{\Phi^k\}$ is the eigenspace of $\tilde{L}_{\lambda_\Phi}$ corresponding to the eigenvalue 1. This finishes the proof.

\[\square\]

**Remark 4.5.** Let us briefly describe the difficulty that arises when one considers the bifurcation problem for $V(\lambda, y) = AV(y)$ with $V = V_0 + V_1$, i.e., when multiplication with the bifurcation parameter is extended to the distributional potential $V_1$. In this case one already obtains a problem in verifying the $C^1$-property of the map $F$. Formally one finds

$$D_\lambda F(\Phi, \lambda) = -\tilde{L}^{-1}_\lambda V \tilde{c}_2 \tilde{L}^{-1}_\lambda (\Gamma(\lambda))_{xx} - P^\Phi \Phi.$$

As above, we would expect to have $L^{-1}_\lambda V \tilde{c}_2 \tilde{L}^{-1}_\lambda : Y \to X$ as a bounded linear map. But this is not the case, as a calculation in the case where $V_0 \tilde{c}_2 = 0$ and $V_1(y) = \alpha \delta_0(y)$ shows. Namely, let $A = \tilde{L}^{-1}_\lambda : Y \to X$ and $B = V \tilde{c}_2$. Then $B : X \to H^{-1}(\mathbb{T}; H^{-1}(\mathbb{R}))$ and $C = \tilde{L}^{-1}_\lambda$ is dense in $H^1(\mathbb{T}; L^2(\mathbb{R})) \cap H^{1/2}(\mathbb{T}; H^{1/2}(\mathbb{R})) \subset X$, i.e., we are missing a half-derivative in the regularity gain.

The advantage of formulating the problem (4.11) as $F(\Phi, \lambda) = 0$ relies on the fact that its linearization about $\Phi = 0$ is of the form identity plus compact operator, which provides the Fredholm property for free. Applying the Crandall–Rabinowitz theorem (cf. e.g. [5] or [11, Theorem I.5.1]), we prove that assumption (L0)–(L3) on the family of Schrödinger operators $L^\Phi_\lambda$ sufficient to guarantee the existence of nontrivial small-amplitude solutions of (4.1) provided a certain transversality condition is satisfied, which we can formulate in terms of the potential $V_0$, see (2.2).

**Proof of Theorem 2.3.** Recall from Lemma 4.4 that $D_0F(0, \lambda_\Phi) = \text{Id} - P^\Phi : X \to X$. Moreover, $D_0F(0, \lambda_\Phi)$ is a Fredholm operator of index zero with a one-dimensional kernel spanned by $\Phi^\Phi$. Correspondingly, we can split the underlying space as follows:

$$X = \text{span}\{\Phi^\Phi\} \oplus \text{span}\{\Phi^\Phi\}^{+L^2} = \ker(D_0F(0, \lambda_\Phi)) \oplus \text{range}(D_0F(0, \lambda_\Phi)).$$

Hence, according to the Crandall–Rabinowitz theorem, the existence of a local bifurcation branch of nontrivial solutions (1.4) follows provided that the transversality condition

$$D_0^2F(0, \lambda_\Phi)\Phi^\Phi \notin \text{range}(D_0F(0, \lambda_\Phi)) = \text{span}\{\Phi^\Phi\}^{+L^2}$$
is satisfied. In view of $\bar{L}^{-1}_{\lambda_0}\Phi^* = \Phi^*$ and the symmetry of $\bar{L}^{-1}_{\lambda_0}$ (which follows from the self-adjointness of $L_{\lambda_0}$, $\bar{L}_{\lambda_0}$) the transversality condition holds since

$$\langle D^2_{\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*],L^2(\mathbb{R})\rangle = \langle \bar{L}^{-1}_{\lambda_0}V_0\Phi_{xx},\Phi^* \rangle_{L^2(\mathbb{R})} = \langle V_0\Phi_{xx},\Phi^* \rangle_{L^2(\mathbb{R})} = -\pi k^2 \langle V_0\phi_x^*,\phi_x^* \rangle_{L^2(\mathbb{R})} \neq 0$$

due to assumption (2.2) of the theorem.

Now, we are going to state the bifurcation formulas with the help of the Lyapunov–Schmidt reduction (cf. [11, Theorem 1.2.3]). The Lyapunov–Schmidt reduction theorem in our context reads as follows:

**Theorem 4.6** (Lyapunov–Schmidt reduction, [11], Theorem 1.2.3). Let $F : X \times I \to X$ be a $C^\infty$-map and $X = N \oplus N^\perp_{l^2}$ with $N = \text{span}\{\Phi^*\} = \ker D_{\Phi}F(0,\lambda_0)$ and $\lambda_0 \in I$. There exists a neighborhood $O \times I' \subset \{(\Phi,\lambda) \in X \times \mathbb{R}_+\}$ of the bifurcation point $(0,\lambda_0)$ such that the problem

$$F(\Phi,\lambda) = 0 \quad \text{for} \quad (\Phi,\lambda) \in O \times I'$$

is equivalent to the finite-dimensional problem

$$\eta(\varepsilon\Phi^*,\lambda) := P^*F(\varepsilon\Phi^* + \psi(\varepsilon\Phi^*,\lambda),\lambda) = 0$$

for functions $\eta \in C^\infty(O_N \times I', N)$, $\psi \in C^\infty(O_N \times I', N^\perp_{l^2})$ where $O_N \subset N$ is an open neighborhood of the zero element in $N$. One has that

$$\eta(0,\lambda_0) = \psi(0,\lambda_0) = D_{\Phi}\psi(0,\lambda_0) = 0$$

and solving (4.11) provides a solution

$$\Phi = \varepsilon\Phi^* + \psi(\varepsilon\Phi^*,\lambda)$$

of the infinite-dimensional problem $F(\Phi,\lambda) = 0$.

We have the following Fréchet derivatives:

$$D_{\Phi}F(\Phi,\lambda)[\Phi^*,\Phi^*] = \Phi^* + \bar{L}^{-1}_{\lambda_0}(\Gamma(y)3(\Phi^2\Phi^*)_xx - P^*\Phi^*),$$

$$D^2_{\Phi,\Phi}F(\Phi,\lambda)[\Phi^*,\Phi^*,\Phi^*] = \bar{L}^{-1}_{\lambda_0}(\Gamma(y)6\Phi(\Phi^*)^2)_xx,$$

$$D^3_{\Phi,\Phi,\Phi}F(\Phi,\lambda)[\Phi^*,\Phi^*,\Phi^*,\Phi^*] = \bar{L}^{-1}_{\lambda_0}(\Gamma(y)6(\Phi^3)^2)_xx.$$

According to [11, Section 1.6], we have that

$$\dot{\lambda}(0) = -\frac{1}{2} \frac{\langle D^2_{\Phi,\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle}{\langle D_{\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle}.$$

In view of $F$ being cubic in $\Phi$ it is clear that $\dot{\lambda}(0) = 0$. In this case the second derivative is given by

$$\ddot{\lambda}(0) = -\frac{3}{3} \frac{\langle D^3_{\Phi,\Phi,\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*,\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle}{\langle D^2_{\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle}.$$

**Proposition 4.7.** Let $\{(\Phi(\varepsilon),\lambda(\varepsilon)) \mid |\varepsilon| < \varepsilon_0\} \subset X \times I_{\lambda_0}$ be the local bifurcation curve found in Theorem 2.3 corresponding to the bifurcation point $(0,\lambda_0)$. Then

$$\dot{\lambda}(0) = 0 \quad \text{and} \quad \ddot{\lambda}(0) = -\frac{3\pi}{2} \frac{\int_0^1 \Gamma(y)(\Phi^*)^3(y) dy}{\int_0^1 \Phi(y)(\Phi^*)^2(y) dy}.$$

**Proof.** As already mentioned, the cubic nonlinearity of $F$ implies already that $\dot{\lambda}(0) = 0$. We are left to compute the second derivative of $\lambda$ at the origin. According to the formula in (4.12) we need to compute the third derivative of $\eta$ with respect to $\Phi$ evaluated at $(0,\lambda_0)$. As for instance in [11, Eq. (1.6.5)] we obtain that

$$D^3_{\Phi,\Phi,\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*,\Phi^*,\Phi^*] = P^*D^2_{\Phi,\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*,\Phi^*] + 3P^*D_{\Phi}F(0,\lambda_0)[\Phi^*,D^2_{\Phi,\Phi}\psi(0,\lambda_0)[\Phi^*,\Phi^*]].$$

Again, since $F$ is cubic in $\Phi$, we have that $D^2_{\Phi,\Phi}F(0,\lambda_0) = 0$, whence

$$\dot{\lambda}(0) = -\frac{1}{3} \frac{\langle P^*D^2_{\Phi,\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle}{\langle D^2_{\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle}$$

$$= -\frac{1}{3} \frac{\langle D^2_{\Phi,\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle}{\langle D^2_{\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle}.$$

We have that

$$\langle D^2_{\Phi,\Phi}F(0,\lambda_0)[\Phi^*,\Phi^*,\Phi^*],L^2(\mathbb{R}) \rangle = \langle \bar{L}^{-1}_{\lambda_0}(\Gamma(y)(\Phi^*)^3)_xx,\Phi^* \rangle_{L^2(\mathbb{R})}.$$
Using the symmetry of \( \tilde{L}_{\lambda*} \) together with \( \tilde{L}_{\lambda*}^{-1}\Phi^* = \Phi^* \), we obtain that
\[
\langle D_{\Phi,\Phi} F(0, \lambda) [\Phi^* \Phi^*], \Phi^* \rangle_{L^2(\mathbb{R}^d)} = 0 \quad \text{and} \quad \frac{9}{2} \pi k^2 \int \Gamma(y) (\phi^*)^4(y) \, dy
\]
and we know already that the denominator in \( \tilde{\lambda}(0) \) is given by
\[
\langle D_{\Phi,\Phi} F(0, \lambda) \Phi^*, \Phi^* \rangle_{L^2(\mathbb{R}^d)} = -\pi k^2 \int V_0(y) (\phi^*)^2(y) \, dy.
\]
Summarizing, we conclude that
\[
\tilde{\lambda}(0) = \frac{3 \int \Gamma(y) (\phi^*)^4(y) \, dy}{2 \int V_0(y) (\phi^*)^2(y) \, dy}.
\]

5. Examples for regular \( \Gamma \)

In what follows, we consider specific examples of potentials \( V \) and prove Corollary 2.5 and Corollary 2.6, which state the existence of traveling waves of (1.4) in the specific case when the potentials are given as in (P1), (P2), respectively. Both Corollary 2.5 and Corollary 2.6 are immediate consequences of Theorem 2.3 and Proposition 4.7, provided conditions (L0) - (L3) are satisfied.

Recall that \( V(\lambda, y) = \lambda V_0(y) + V_1(y) \) where in case (P1) we have \( V_0(y) = 1 \) and \( V_1(y) = \alpha_0 \delta_0(y) \); in case (P2) we have \( V_0(y) = 1_{|y| > b} \), \( V_1(y) = \beta 1_{|y| < b} + \alpha_0 \delta_0(y) \). The transversality condition (2.2) is trivially satisfied, since in both cases \( V_0 \) is positive and \( \neq 0 \). It is also clear that (L0) holds true. The beginning of this section will be valid both for (P1) and (P2) since at the general level we may consider (P1) as a special case of (P2) with \( \beta = \lambda \).

Let us consider the operator
\[
L^k_{\lambda} := -\frac{d^2}{dy^2} + k^2 (1 - \lambda 1_{|y| > b} - \beta 1_{|y| < b} - \alpha_0 \delta_0(y))
\]
with \( \lambda, \beta < 1 \). According to [4] the operator \( L^k_{\lambda} : D(L^k_{\lambda}) \subset L^2(\mathbb{R}) \rightarrow L^2(\mathbb{R}) \) is self-adjoint on the domain
\[
D(L^k_{\lambda}) = \{ \phi \in H^2(\mathbb{R}) \mid \phi \in H^2(-\infty, 0) \cap H^2(0, \infty), \phi'(0+) - \phi'(0-) = -k^2 \lambda \phi(0) \};
\]
thereby (L1) is fulfilled. Moreover, \( \sigma_{\text{ex}}(L_k) = [k^2(1 - \lambda), \infty) \) according to Lemma A.5. Next we consider the point spectrum of \( L_k \), i.e., the eigenvalue problem of finding \( \phi \in D(L^k_{\lambda}) \) with \( L^k_{\lambda} \phi = k^2 \mu \phi \) where \( \mu = k^2 \mu \) is the actual eigenvalue. Setting \( \tilde{\lambda} = \lambda + \mu \) and \( \tilde{\beta} = \mu + \mu \) the eigenvalue problem then reduces to
\[
\begin{cases}
-\phi'' + k^2 (1 - \tilde{\lambda} 1_{|y| > b} - \tilde{\beta} 1_{|y| < b}) \phi = 0, \quad y \in (-\infty, 0) \cup (0, \infty), \\
\phi'(0+) - \phi'(0-) + k^2 \alpha \phi(0) = 0.
\end{cases}
\]
(5.1)

For reasons that will become obvious in the subsequent discussion we suppose \( \mu \) to be so small that \( \tilde{\lambda}, \tilde{\beta} < 1 \).

In Lemma A.6 in the Appendix we show that this problem is solvable (with a one-dimensional eigenspace) if and only if
\[
\frac{\kappa \alpha}{\sqrt[3]{1 - \beta}} = \frac{\sqrt{1 - \beta \sinh(k \sqrt{1 - \beta})} + \sqrt{1 - \lambda \cosh(k \sqrt{1 - \beta})}}{\sqrt{1 - \beta \sinh(k \sqrt{1 - \beta})} + \sqrt{1 - \lambda \cosh(k \sqrt{1 - \beta})}}.
\]
(5.2)

Now we will split the discussion into subsections according to the cases (P1) and (P2), verifying (L2) and (L3) separately.

5.1. (P1) \( \delta \)-potential on a positive background. Here we take \( V_0 = 1 \) and \( V_1 = \alpha_0 \delta_0 \) and \( V(\lambda, y) = \lambda + \alpha_0 \delta_0(y) \) with \( \alpha > 0 \) and \( \lambda < 1 \). In the subsequent results of Lemma 5.1, Lemma 5.2 we verify that the family of linear operators \( L^k_{\lambda} \) satisfies also the assumptions (L2) and (L3) in Theorem 2.3. Since (P1) is a special case of (P2) with \( \lambda = \beta \) we see that the eigenvalue condition (5.2) becomes
\[
\frac{\kappa \alpha}{2 \sqrt{1 - \lambda}} = 1.
\]
(5.3)

This leads to the following lemma.
Lemma 5.1. Let us fix a wavenumber $k_\ast \in \mathbb{N}$ and let $\lambda_\ast < 1$. We determine $\alpha > 0$ such that
\begin{equation}
\alpha = \frac{2\sqrt{1 - \lambda_\ast}}{k_\ast}.
\end{equation}
Then there exists an open interval $I_{\lambda_\ast} \subset \mathbb{R}$ containing $\lambda_\ast$ such that
\[
\dim \ker I_{\lambda_\ast}^k = 1,
\]
and $\ker L_{\lambda_\ast}^k = \{0\}$ for any $(k, \lambda) \in \mathbb{N} \times I_{\lambda_\ast}$ with $(k, \lambda) \neq (k_\ast, \lambda_\ast)$.

Proof. Since we are considering the zero-eigenvalue of $L_{\lambda_\ast}^k$ we have $\mu = 0$ and $\bar{\lambda} = \lambda$. Together with our choice of $\alpha$ the eigenvalue condition (5.3) becomes
\[
k = \frac{\sqrt{1 - \lambda}}{k_\ast}.
\]
Recall that $k \in \mathbb{N}$ is integer valued. Therefore, choosing a sufficiently small interval $I_{\lambda_\ast} \subset (-\infty, 1)$ that contains $\lambda_\ast$ the eigenvalue condition is satisfied for $\lambda \in I_{\lambda_\ast}$ and $k \in \mathbb{N}$ if and only if $\lambda = \lambda_\ast$ and $k = k_\ast$. Moreover, for $k = k_\ast$ and $\lambda = \lambda_\ast$ the eigenspace is one-dimensional. \(\square\)

It is clear that kernel of $L_{\lambda_\ast}^k$ is spanned by the $L^2(\mathbb{R})$-unitary element
\[
\phi^*(y) := \sqrt{k_\ast \sqrt{1 - \lambda_\ast}} e^{-k_\ast \sqrt{1 - \lambda_\ast} \vert y \vert}
\]
since $L_{\lambda_\ast}^k \phi^* = 0$ in $\mathbb{R}\setminus \{0\}$ and it satisfies $\phi''(0+) - \phi''(0-) + \alpha k_\ast^2 \phi(0) = 0$. The above lemma ensures that assumption (L2) is satisfied. The following lemma concerns the spectral properties of $L_{\lambda_\ast}^k$ and shows that assumption (L3) holds true.

Lemma 5.2. There exists an open interval $I_{\lambda_\ast} \subset \mathbb{R}$ containing $\lambda_\ast$ such that the following holds for all $k \geq 3k_\ast$ and all $\lambda \in I_{\lambda_\ast}$: if $L_{\lambda_\ast}^k \phi = f$ for some $f \in L^2(\mathbb{R})$, then
\[
\|\phi\|_{L^2(\mathbb{R})} \leq \frac{1}{k^2} \|f\|_{L^2(\mathbb{R})} \quad \text{and} \quad \|\phi'\|_{L^2(\mathbb{R})} \leq \frac{1}{k} \|f\|_{L^2(\mathbb{R})}.
\]
In particular, there exists a constant $c = c(k_\ast, |I_{\lambda_\ast}|)$, depending on $k_\ast$ and the size of the interval $I_{\lambda_\ast}$, such that
\[
(-ck^2, ck^2) \subset \rho(L_{\lambda_\ast}^k) \quad \text{for every} \quad k \geq 3k_\ast, \lambda \in I_{\lambda_\ast}.
\]

Proof. We show that for any $\lambda < 1$ we have
\[
\|L_{\lambda_\ast}^k \phi\|_{L^2(\mathbb{R})} \geq \frac{1}{2} \left( \|\phi''\|^2_{L^2(-\infty, 0)} + \|\phi''\|^2_{L^2(0, \infty)} \right)
\]
\[
+ 2(1 - \lambda) \left( k^2 - 4k_\ast^2 - \frac{16(\lambda_\ast - \lambda)}{\alpha^2} \right) \|\phi\|^2_{L^2(\mathbb{R})} + \left( \frac{k_\ast^2 \alpha^2}{4} + \lambda_\ast - \lambda \right)^2 k^4 \|\phi\|^2_{L^2(\mathbb{R})},
\]
which proves the assertion. We have that
\[
\|L_{\lambda_\ast}^k \phi\|^2_{L^2(\mathbb{R})} = \int_{-\infty}^{0} (L_{\lambda_\ast}^k \phi)^2 \, dy + \int_{0}^{\infty} (L_{\lambda_\ast}^k \phi)^2 \, dy.
\]
For the first integral on the right hand side, we compute
\[
\int_{-\infty}^{0} (L_{\lambda_\ast}^k \phi)^2 \, dy = \int_{-\infty}^{0} (-\phi'' + k^2(1 - \lambda)\phi)^2 \, dy
\]
\[
= \int_{-\infty}^{0} |\phi''|^2 - 2k^2(1 - \lambda)\phi'' \phi + k^4(1 - \lambda)^2 \phi^2 \, dy
\]
\[
= |\phi''|^2_{L^2(-\infty, 0)} + 2k^2(1 - \lambda)\|\phi''\|^2_{L^2(-\infty, 0)} + k^4(1 - \lambda)^2 \|\phi\|^2_{L^2(-\infty, 0)} - 2k^2(1 - \lambda)\phi(0-)\phi(0),
\]
where we used integration by parts. Similarly, we obtain that
\[
\int_{0}^{\infty} (L_{\lambda_\ast}^k \phi)^2 \, dy = |\phi''|^2_{L^2(0, \infty)} + 2k^2(1 - \lambda)\|\phi''\|^2_{L^2(0, \infty)} + k^4(1 - \lambda)^2 \|\phi\|^2_{L^2(0, \infty)} + 2k^2(1 - \lambda)\phi(0+)\phi(0).
\]
Taking the sum of the two integrals and using for $\phi \in D(L_{\lambda_\ast}^k)$ that
\[
\phi'(0+) - \phi'(0-) = -k^2 \alpha \phi(0)
\]
we find that
\[
\|L_k^2\phi\|_{L^2(\mathbb{R})}^2 = \|\phi''\|_{L^2(-\infty,0)}^2 + \|\phi''\|_{L^2(0,\infty)}^2 + 2\lambda^2(1-\lambda)\|\phi\|_{L^2(\mathbb{R})}^2 + k^4(1-\lambda^2)^2\|\phi\|_{L^2(\mathbb{R})}^2
\]
\[
-\frac{2}{\alpha}(1-\lambda)\left(\phi'(0^+) - \phi'(0^-)\right)^2.
\]
(5.5)

A simple computation together with Young’s inequality implies that
\[
|\phi'(0_+)|^2 \leq 2 \int_0^{\epsilon^2} |\phi'(\eta)|^2 \, d\eta \leq \left(\epsilon \|\phi''\|_{L^2(0,\infty)}^2 + \frac{1}{\epsilon} \|\phi''\|_{L^2(0,\infty)}^2\right)
\]
for any \(\epsilon > 0\). A similar estimate holds for \(|\phi'(0_-)|^2\). Therefore
\[
|\phi'(0_+) - \phi'(0_-)|^2 \leq 2 \left(|\phi'(0_+)|^2 + |\phi'(0_-)|^2\right)
\]
\[
\leq 2 \left(\epsilon \|\phi''\|_{L^2(\mathbb{R})}^2 + \frac{1}{\epsilon} \|\phi''\|_{L^2(0,\infty)}^2\right).
\]
Inserting the latter into (5.5) yields
\[
\|L_k^2\phi\|_{L^2(\mathbb{R})}^2 \geq \left(1 - \frac{4(1-\lambda)}{\alpha} \right) \left(\|\phi''\|_{L^2(-\infty,0)}^2 + \|\phi''\|_{L^2(0,\infty)}^2\right)
\]
\[
+ 2(1-\lambda)(k^2 - \frac{2\lambda}{\alpha})\|\phi\|_{L^2(\mathbb{R})}^2 + k^4(1-\lambda^2)^2\|\phi\|_{L^2(\mathbb{R})}^2.
\]

The choice \(\epsilon = \frac{2}{\alpha}(1-\lambda) = 2ak^2 + \frac{8(\lambda - \lambda^2)}{\alpha}\) implies the claim. \(\square\)

Collecting Lemma 5.1 and Lemma 5.2, we infer that there exists an open interval \(I_{\lambda_0} \subset \mathbb{R}\) containing \(\lambda_0\) such that conditions (L0)–(L3) are satisfied, which concludes the proof of Corollary 2.5. The formulas for \(\bar{\lambda}(0)\) and \(\bar{\lambda}(0)\) follow directly from Proposition 4.7.

5.2. (P2) A \(\delta\)-potential on a step background. Here we take \(V_0(y) = 1_{|y|\geq b}\), \(V_1(y) = \beta 1_{|y|<b} + \alpha \delta_0(y)\) and \(V(\lambda, y) = \lambda_1 1_{|y|\geq b} + \beta 1_{|y|<b} + \alpha \delta_0(y)\) with \(\beta > 0\), \(\lambda, \beta < 1\). The subsequent two results verify that the family of linear operators \(L_k^2\) satisfies also the assumptions (L2) and (L3) in Theorem 2.3. They are the counterparts to Lemma 5.1 and Lemma 5.2.

Lemma 5.3. Let us fix a wavenumber \(k_0 \in \mathbb{N}\) and let \(\lambda_0 < 1\). We determine \(\alpha > 0\) such that
\[
\frac{k_0 \alpha}{2\sqrt{1-\beta}} = \frac{\sqrt{1 - \beta} \sinh(k_0 \sqrt{1 - \beta})}{\sqrt{1 - \beta} \cosh(k_0 \sqrt{1 - \beta})}.
\]
Then there exists an open interval \(I_{\lambda_0} \subset \mathbb{R}\) containing \(\lambda_0\) such that
\[
\dim \ker L_{\lambda_0}^k = 1,
\]
and \(\ker L_{\lambda_0}^k = \{0\}\) for any \((k, \lambda) \in \mathbb{N} \times I_{\lambda_0}\) with \((k, \lambda) \neq (k_0, \lambda_0)\).

Proof. As before we are considering the zero-eigenvalue of \(L_{\lambda}^2\). Hence we have \(\mu = 0\) and \(\bar{\lambda} = \lambda, \bar{\beta} = \beta\). Then (5.6) amounts to \(L_{\lambda}^k\) having a simple zero eigenvalue, cf. Lemma A.6. It remains to show that for no other value of \(\lambda \in I_{\lambda_0}\) and \(k \in \mathbb{N}\) there is a zero eigenvalue of \(L_{\lambda}^k\). First note that for \(\lambda\) in a bounded interval of \((-\infty, 1)\) there are only finitely many values of \(k \in \{1, \ldots, K\}\) which potentially also fulfill (5.6) since the right-hand side is bounded in \(k\) and the left-hand side tends to infinity as \(k \to \infty\). Now we observe (by a standard calculation) that for fixed \(\lambda = \lambda_0\), the right-hand side of (5.6) divided by \(k\) is monotone decreasing in \(k\). Hence, for given \(\lambda_0\) no other value of \(k \in \{1, \ldots, K\}\) than \(k_0\) fulfills (5.6). Finally, since \(k \in \{1, \ldots, K\}\) needs to be integer valued, we can find a sufficiently small open interval \(I_{\lambda_0} \subset (-\infty, 1)\) containing \(\lambda_0\) such that (5.6) is fulfilled for \((\lambda, k) \in I_{\lambda_0} \times \mathbb{N}\) if and only if \((\lambda, k) = (\lambda_0, k_0)\). \(\square\)

Lemma 5.4. There exists an open interval \(I_{\lambda_0} \subset \mathbb{R}\) containing \(\lambda_0\) such that the following holds for all sufficiently large \(k \in \mathbb{N}\) and all \(\lambda \in I_{\lambda_0}\): if \(L_k^2\phi = f\) for some \(f \in L^2(\mathbb{R})\), then
\[
\|\phi\|_{L^2(\mathbb{R})} \leq \frac{1}{k^2} \|f\|_{L^2(\mathbb{R})} \quad \text{and} \quad \|\phi'\|_{L^2(\mathbb{R})} \leq \frac{1}{k} \|f\|_{L^2(\mathbb{R})}.
\]
(5.7)
In particular, there exists a constant \(c = c(k_0, |I_{\lambda_0}|)\), depending on \(k_0\) and the size of the interval \(I_{\lambda_0}\), such that
\[
(-ck^2, ck^2) \subset \rho(L_k^2) \quad \text{for every} \quad k \quad \text{sufficiently large}, \quad \lambda \in I_{\lambda_0}.
\]
Proof. The proof consists of two parts. First we determine an interval \((-ck^2,cks^2)\) in \(L^k\) for all \(\lambda \in I_{k}\) and all sufficiently large \(k\). This implies the first part of the estimate in (5.7). In the second part of the proof we will show the remaining part of (5.7).

Part 1: Recall that \(\sigma_{ess}(L^k) = [k^2(1 - \lambda), \infty)\), which is consistent with the desired result provided we choose \(I_{k}\) in such a way that it has a positive distance from 1. Subject to this observation we take the bounded interval \(I_{k}\) from Lemma 5.3 and diminish it in the following if necessary. Notice that (5.2) describes all eigenvalues of \(L^k\) of the form \(\tilde{\mu} = k^2\mu\), where \(\mu\) is so small that \(\sup_{x \in I_{k}} \{\lambda = \lambda + \mu\} < 1\) and \(\tilde{\beta} = \beta + \mu < 1\). Now observe that uniformly for \(\lambda \in I_{k}\) and \(\mu \in [-\mu_0, \mu_0]\) for small \(\mu_0 > 0\) the left-hand side of (5.2) tends to \(\infty\) as \(k \to \infty\) whereas the right-hand side stays bounded in \(k\). Therefore the set \([\lambda - \mu_0 k^2, \mu_0 k^2]\) belongs to the resolvent of \(L^k\) for all \(\lambda \in I_{k}\) and all sufficiently large \(k\).

Part 2: We need to distinguish the operator \(L^k_\lambda = -\frac{d^2}{dx^2} + k^2(1 - \lambda - \alpha\delta_0)\) of case (P1) from its counterpart in (P2). Within this part of the proof let us denote it by \(L^k_\lambda,\beta\) and \(L^k_\lambda,\beta\) respectively. The equation for traveling wave solutions (\(6.4\)) is then given by

\[
\Phi_{yy} - (1 - \lambda \Phi_0 - W(y))\Phi_{xx} + \gamma \delta_0 \gamma \Phi(\Phi^{\prime})_{,xx} = 0.
\]

(6.1)

and can be written as a linear differential equation on \(T \times \mathbb{R}\backslash \{0\}\) equipped with a nonlinear boundary condition on \(T\):

\[
\Phi_{yy} - (1 - \lambda \Phi_0 - W(y))\Phi_{xx} = 0, \quad (x, y) \in T \times \mathbb{R}\backslash \{0\},
\]

(6.2)

\[
\Phi_y(x, 0+) - \Phi_y(x, 0-) = c^2 \Phi (\alpha \Phi + \gamma \Phi^{\prime}) (x, 0), \quad x \in T.
\]

(6.3)

In what follows let us assume that \(\Phi\) is even with respect to \(y\). We seek for solutions \(\Phi\) of the form

\[
\Phi(x, y) = \sum_{k \in \mathbb{N}} a_k \phi_k(y; \lambda) \sin(kx),
\]

(6.4)

where \(\phi_k(\cdot; \lambda) \in H^1(\mathbb{R}) \cap H^2(\mathbb{R}\backslash \{0\})\) is an even extension to the linear problem

\[
\mathcal{L}^{\lambda}_{k} \phi_k(y; \lambda) = 0 \quad \text{on } (0, \infty) \quad \text{with} \quad \phi_k(0; \lambda) = 0.
\]

(6.5)

and

\[
\mathcal{L}^{\lambda}_{k} := -\frac{d^2}{dy^2} + k^2(1 - \lambda \Phi_0 - W(y)).
\]

Thus ansatz (6.4) already solves (6.2) and its remains to determine \(a = (a_k)_{k \in \mathbb{N}}\) such that (6.3) is also satisfied. It will be convenient to parameterize the sequence \((a_k)_{k \in \mathbb{N}}\) over \(\mathbb{Z}\) instead of \(\mathbb{N}\) by setting \(a_k = -a_{-k}\). In this way \(\Phi(x, y) = \frac{1}{2} \sum_{k \in \mathbb{Z}} a_k \phi_k(y; \lambda) \sin(kx)\). Here we have defined \(\phi_k(\cdot; \lambda) := \phi_k(\cdot; \lambda)\) for \(k \in \mathbb{N}\). Then, we shall see that for \(s \geq \frac{1}{2}\) the existence of a traveling wave solution \(\Phi\) in the space

\[
X_s = H^s(T; L^2(\mathbb{R})) \cap H^{s-1}(T; H^1(\mathbb{R})) \cap C(\mathbb{R}; H^{s-\frac{1}{2}}(T)) \cap C^1(\mathbb{R}; H^{s-\frac{3}{2}}(T))
\]
follows from the existence of a sequence \( a \in h^s_t(\mathbb{R}) \) satisfying the boundary condition
\[
2a_k\phi_k'(0+;\lambda) = -k^2 \left( a a_k - \frac{\lambda}{4} (a \ast a \ast a)_k \right) \quad \text{for all} \quad k \in \mathbb{N}. \quad (6.6)
\]
Recall that the \( k \)-th Fourier coefficient of \( \Phi^3(x,0) \) is given by \(-\frac{1}{4}(a \ast a \ast a)_k\) (cf. Lemma A.1). Noticing that for \( s \geq \frac{3}{2} \) we have the embedding
\[
X_s \hookrightarrow X = H^2(T; L^2(\mathbb{R})) \cap H^1(T; H^1(\mathbb{R})) \cap C(\mathbb{R}; H^2(\mathbb{T})) \cap C^1(\mathbb{R}; H^1(\mathbb{T})).
\]
As in the previous section we aim to apply bifurcation theory with respect to the parameter \( \lambda \) to obtain the existence of nontrivial solutions \( a \in h^s_t(\mathbb{R}) \) of (6.6) for \( s \geq \frac{5}{2} \) by the Crandall–Rabinowitz theorem. Recall that this time we are working under the the assumptions \((\tilde{L}0)-(\tilde{L}3)\) from Theorem 2.10.

**Remark 6.1.** Existence and properties of the decaying solutions \( \phi_k(\cdot; \lambda) \) of (6.5):

(i) Due to \((\tilde{L}1)\) the problem \( L^k_{0,\lambda} \phi_k = 1_{[-2,-1]} \) on \( \mathbb{R} \) has a unique \( H^2(\mathbb{R}) \) solution. Its restriction to \([0, \infty)\) satisfies (6.5). The fact that \( \phi_k(y;\lambda) \to 0 \) exponentially as \( y \to \infty \) can be seen as follows: Since \( L^\lambda_{0,k} \)

is a self-adjoint operator with \( 0 \in \rho(L^\lambda_{0,k}) \) and the resolvent set is open in \( C \) there exists \( c_{k,\lambda} > 0 \) such that \((-c_{k,\lambda}, c_{k,\lambda}) \subset \rho(L^\lambda_{0,k})\).

Set \( \psi_k(y;\lambda) := e^{\delta_k y} \phi_k(y;\lambda) \). Then
\[
L^\lambda_{0,k} \psi_k(y;\lambda) = B_k \psi_k(y;\lambda) = e^{\delta_k y} 1_{[-2,-1]},
\]
where \( B_k \psi := 2\delta_k \frac{d}{dy} \psi + \delta_k^2 \psi \). One can show that \( B_k \) is \( L^\lambda_{0,k} \)-bounded in the sense that there exist \( a_{k,b} > 0 \) such that
\[
|B_k \psi(1_{2\mathbb{R}})| \leq a_{k,b} |\psi(1_{2\mathbb{R}})| + b_k \|L^\lambda_{0,k} \psi(1_{2\mathbb{R}})\| \quad \text{for all} \quad \psi \in H^2(\mathbb{R}).
\]
In fact, if \( b_k > 0 \) is fixed, then \( a_k := \frac{4\delta_k}{b_k} + 8\delta_k^2 |1 - \lambda V_0 - W|_\infty + 2\delta_k^4 \). For fixed \( b_k \in (0,1) \) let us choose \( \delta_k > 0 \) so small that
\[
a_k^2 + b_k^2 \delta_k^2 < c_{k,\lambda}.
\]

Then \((-\tilde{c}_{k,\lambda}, \tilde{c}_{k,\lambda}) + i \mathbb{R} \subset \rho(L^\lambda_{0,k} + B_k)\), where \( \tilde{c}_{k,\lambda} = c_k - \sqrt{a_k^2 + b_k^2 \delta_k^2}, \) cf. [6, Theorem 2.1 (ii)]. In particular, \( 0 \in \rho(L^\lambda_{0,k} + B) \) so that there exists a unique solution \( \psi_k \in H^2(\mathbb{R}) \) of (6.7).

The boundedness of \( \psi_k \) then implies that \( |\phi_k(y;\lambda)| \leq e^{-\delta_k y} \) decays exponentially on the half-line \([0, \infty)\). This result is also known as “exponential dichotomy”. Assumption \((\tilde{L}3)\) may be interpreted as some kind of generalized uniform exponential dichotomy with respect to \( k \in \mathbb{N} \) and \( \lambda \in I_{\lambda_0} \).

(ii) In the specific examples \((P1)\) and \((P2)\) which we consider at the end of this section, the family of ansatz-functions \((\phi_k(\cdot;\lambda))_{k \in \mathbb{N}}\) satisfies a true uniform exponential dichotomy with respect to \( k \in \mathbb{N} \) and \( \lambda \in I_{\lambda_0} \) that is, there exists \( C, \delta > 0 \) independent of \( k \in \mathbb{N} \) and \( \lambda \in I_{\lambda_0} \) such that \( |\phi_k(y;\lambda)| \leq Ce^{-\delta y} \) for all \( y \geq 0 \). This leads to an exponential decay in \( y \)-direction of the traveling solution \( \Phi \) of (1.4) and in particular it implies \((\tilde{L}3)\).

(iii) Notice also that \( \phi_k(0;\lambda) \neq 0 \), since otherwise (by an odd reflection around zero) we would obtain an eigenfunction of \( L^\lambda_{0,k} \) for the eigenvalue 0. This is excluded by assumption \((\tilde{L}1)\). Likewise we see that \( \phi_k'(0;\lambda) \neq 0 \) (using an even reflection around zero).

**Remark 6.2.** If \( V_0, W \) are bounded, even functions and there exists \( \tilde{v} > 0 \) such that
\[
1 - \lambda V_0(y) - W(y) \geq \tilde{v} \quad \text{for all} \quad \lambda \in I_{\lambda_0}, \ y \in \mathbb{R},
\]
then assumption \((\tilde{L}0), (\tilde{L}1), \) and \((\tilde{L}3)\) are satisfied. Clearly, if \( 1 - \lambda V_0 - W \geq \tilde{v} \), then \( L^\lambda_{0,k} \) is a self-adjoint operator with \( \sigma(L^\lambda_{0,k}) \subset [k^2\tilde{v}, \infty); \) thus \( 0 \in \rho(L^\lambda_{0,k}) \) and \((\tilde{L}1)\) is satisfied. As explained in Remark 6.1 (i), condition \((\tilde{L}1)\) implies the existence of a solution \( \phi_k(\cdot, \lambda) \in H^2(0, \infty) \) with
\[
-\phi_k'' + k^2 (1 - \lambda V_0(y) - W(y)) \phi_k = 0 \quad \text{on} \quad (0, \infty)
\]
and \( \phi_k(0;\lambda) = 1 \). Multiplying (6.8) with \( \phi_k \) and integrating over the half line \((0, \infty)\), we obtain that
\[
-\phi_k'(0+;\lambda) = \int_0^\infty |\phi_k'|^2 dy + k^2 \int_0^\infty (1 - \lambda V_0 - W) \phi_k^2 dy.
\]
On the other hand, multiplying (6.8) with \( \phi'_k \) and integrating over \((0, \infty)\) yields

\[
(\phi'_k)^2(0_+; \lambda) = -k^2 \int_0^\infty (1 - \lambda V_0 - W)(\phi'_k)^2 \, dy \\
= -2k \int_0^\infty k \sqrt{1 - \lambda V_0 - W} \phi_k \phi'_k \sqrt{1 - \lambda V_0 - W} \, dy \\
\leq k \| \sqrt{1 - \lambda V_0 - W} \|_x \left( \int_0^\infty |\phi'_k|^2 \, dy + k^2 \int_0^\infty (1 - \lambda V_0 - W) \phi_k^2 \, dy \right) \\
= -k \| \sqrt{1 - \lambda V_0 - W} \|_x \phi'_k(0_+; \lambda),
\]

where we used relation (6.9) in the last equality. We deduce that \( \phi'(0_+; \lambda) < 0 \) and

\[
|\phi'_k(0_+; \lambda)| \leq k \| \sqrt{1 - \lambda V_0 - W} \|_x. \tag{6.10}
\]

Estimating the \( L^2 \)-norm of \( \phi_k(\cdot; \lambda) \), we obtain that

\[
\| \phi_k(\cdot; \lambda) \|_2^2 = \frac{1}{\nu} \| \sqrt{\nu} \phi_k(\cdot; \lambda) \|_2^2 \leq \frac{1}{\nu} \int_0^\infty (1 - \lambda V_0 - W) \phi_k^2 \, dy \leq \frac{1}{\nu k^2} |\phi'_k(0_+; \lambda)| \leq \frac{1}{\nu k^2} \sqrt{1 - \lambda V_0 - W} \|_x,
\]

where we used (6.9) and (6.10). In particular, we find that \( \| \phi_k(\cdot; \lambda) \|_2 \leq 1 \) as claimed in (\( \tilde{L}.3 \)).

For \( s \geq 0 \) denote the linearization of (6.6) around \( a = 0 \) by

\[
A_\lambda : h^s_2(\mathbb{R}) \subset h^{s - 2}_2(\mathbb{R}) \to h^{s - 2}_2(\mathbb{R}), \quad (A_\lambda a)_k := A_k^a a_k \quad \text{for} \quad k \in \mathbb{Z},
\]

where

\[
A_k^a := 2 \phi'_k(0_+; \lambda) + k^2 \alpha \quad \text{for} \quad k \in \mathbb{Z}.
\]

Then (6.6) can be written as

\[
A_\lambda a - n(a) = 0, \quad \text{where} \quad n(a)_k = \frac{\gamma}{4} (a \ast a \ast a)_k.
\tag{6.11}
\]

For \( m \in \mathbb{Z} \) let us denote by \( e_m \in l^2_2(\mathbb{R}) \) the sequence, which satisfies \( e_k^m = 0 \) for \( k \neq \pm m \) and \( e_m^m = -e_{-m}^m = \frac{1}{\nu} \).

**Lemma 6.3.** Assume (\( L.0 \))-\( (\tilde{L}.3 \)). Then

\[
\| \phi_k(\cdot; \lambda) \|_{L^\infty(\mathbb{R})} \leq k^{\frac{1}{2}}, \quad \| \phi'_k(\cdot; \lambda) \|_{L^2(\mathbb{R})} \leq k, \quad \| \phi'^2_k(\cdot; \lambda) \|_{L^\infty(\mathbb{R})} \leq k^{\frac{1}{2}} \tag{6.12}
\]

uniformly for \( \lambda \in I_\lambda \). In particular, \( |\phi'_k(0; \lambda)| \leq |k|^{\frac{1}{2}} \) and consequently \( A_k^a = \alpha k^2 + O(k^{\frac{1}{2}}) \) as \( k \to \pm \infty \).

**Proof.** By a result of Komornik, cf. [13], the estimate

\[
|u|_{\mathcal{C}} \leq C \| u \|_{L^2}
\]

holds true for every solution \( u \) of \(-u'' + q(y)u = 0 \) on \((a, b)\) with the constant \( C = \max \{ 6 \sqrt{|q|_{L^1(a, b)}}, \frac{12}{\sqrt{\nu b - a}} \} \).

We apply this result to the solutions \( \phi_k(\cdot; \lambda) \) of (6.5) with \( q = k^2(1 - \lambda V_0 - W), a \geq 0 \) and \( b = a + c \) with \( c := 2(\sqrt{1 - \lambda V_0 - W} \|_x k)^{-1} \). Then

\[
6 \sqrt{|q|_{L^1(a, b)}} \leq 6k \sqrt{1 - \lambda V_0 - W} \|_x \sqrt{c} = 6 \sqrt{2} \sqrt{k} \sqrt{1 - \lambda V_0 - W} \|_x = \frac{12}{\sqrt{b - a}}
\]

and thus for a constant \( \tilde{C} \) only depending on \( 1 - \lambda V_0 - W \|_x \) we have \( \| \phi_k(\cdot; \lambda) \|_{L^\infty(a, b)} \leq k^{\frac{1}{2}} \tilde{C} |\phi_k(\cdot; \lambda)|_{L^2(a, b)} \leq k^{\frac{1}{2}} \) by (\( \tilde{L}.3 \)). Since \( a \geq 0 \) was arbitrary we obtain the first part of (6.12).

Multiplying (6.5) with \( u, u' \) and integrating from \( a \geq 0 \) to \( \infty \) we get

\[
\int_a^\infty k^2(1 - \lambda V_0(y) - W(y))\phi_k(y; \lambda)^2 + \phi'_k(y; \lambda)^2 \, dy = -\phi_k(a; \lambda)\phi'_k(a; \lambda), \tag{6.13}
\]

\[
\int_a^\infty 2k^2(1 - \lambda V_0(y) - W(y))\phi_k(y; \lambda)\phi'_k(y; \lambda) \, dy = -\phi'_k(a; \lambda)^2, \tag{6.14}
\]

respectively. Using (\( \tilde{L}.3 \)) and applying the Cauchy-Schwarz inequality to (6.14) we find

\[
\| \phi'_k(\cdot; \lambda) \|_{L^2} \leq k^2 \| \phi'_k(\cdot; \lambda) \|_{L^2(0, \infty)} \tag{6.15}
\]
and from (6.13), (6.15) we get
\[
\|\phi_k^\prime(\cdot; \lambda)\|_{L^2(0, \infty)} \leq k^2 + \|\phi_k(\cdot; \lambda)\|_{L^\infty(0, \infty)} \|\phi_k^\prime(\cdot; \lambda)\|_{L^\infty(0, \infty)} \\
\leq k^2 + \|\phi_k(\cdot; \lambda)\|_{L^\infty(0, \infty)} k\|\phi_k^\prime(\cdot; \lambda)\|_{L^2(0, \infty)}.
\]
The $L^\infty$--estimate from the first part of the lemma leads to
\[
\|\phi_k^\prime(\cdot; \lambda)\|_{L^2(0, \infty)} \leq k^2 + k^2 \|\phi_k(\cdot; \lambda)\|_{L^2(0, \infty)}^2 \leq k^2 + C k^2 + \epsilon\|\phi_k^\prime(\cdot; \lambda)\|_{L^2(0, \infty)},
\]
where we have used Young’s inequality with exponents $4/3$ and $4$. This implies the second inequality in (6.12). Inserting this into (6.15) we obtain the third inequality in (6.12). \hfill \Box

**Lemma 6.4.** Assume $(\bar{L}0)$--$(\bar{L}3)$ and let $s \geq 0$. Then the operator $A_{\lambda} : h^{s}_{\Phi}(\mathbb{R}) \subset h^{s-2}_{\Phi}(\mathbb{R}) \to h^{s-2}_{\Phi}(\mathbb{R})$ is self-adjoint. Its spectrum is discrete and consist of the values $(A_{\lambda}^k)_{k \in \mathbb{N}}$. Moreover $\ker A_{\lambda a} = \text{span}\{\varepsilon_k^a\}$ and $\ker A_{\lambda} = \{0\}$ for $\lambda \in I_{\lambda a} \setminus \{\lambda_a\}$.

**Proof.** Due to Lemma 6.3 and since $\phi_{-k} = \phi_k$ for all $k \in \mathbb{Z}$ one can verify that $A_{\lambda} : h^{s}_{\Phi}(\mathbb{R}) \subset h^{s-2}_{\Phi}(\mathbb{R}) \to h^{s-2}_{\Phi}(\mathbb{R})$ acting like an infinite dimensional diagonal matrix is self-adjoint. Using the characterizing of the spectrum via Weyl-sequences one sees that $A_{\lambda}$ has the spectrum $\sigma(A_{\lambda}) = \text{clos}(A_{\lambda}^k : k \in \mathbb{N})$. Due to Lemma 6.3 the set $\{A_{\lambda}^k : k \in \mathbb{N}\}$ is discrete and hence $\sigma(A_{\lambda}^k)$ consists of the set of eigenvalues $\{A_{\lambda}^k : k \in \mathbb{N}\}$. Finally, let us determine the kernel of $A_{\lambda}$. On the one hand, $a \in \ker A_{\lambda}$ if and only if there exists $k \in \mathbb{N}$ such that $A_{\lambda}^k a = 0$, and in this case $a = e^k$ (here we use that $A_{\lambda}^k = A_{\lambda}^{-k}$). On the other hand, using the characterization of the domain of $L_{\lambda}^k$ from Section 5.1 we know that $L_{\lambda}^k \phi = 0$ if and only if $\tilde{\phi}(x) = \phi_k(\cdot; \lambda)$ and $A_{\lambda}^k a = 0$. Thus, bringing both facts together and using assumption $(\bar{L}2)$ we obtain the final claim of the lemma. \hfill \Box

Similarly as in (4.3) we define the operator
\[
\bar{A}_{\lambda} := A_{\lambda} + P^* a,
\]
where $P^* a = a_{k^*} e^{k^*}$. 

**Lemma 6.5.** Assume $(\bar{L}0)$--$(\bar{L}3)$ and $s \geq 0$. Then we have that $0 \in \rho(\bar{A}_{\lambda})$ for all $\lambda \in I_{\lambda a}$ and hence $\bar{A}_{\lambda}^{-1} : h^{s-2}_{\Phi}(\mathbb{R}) \to h^{s}_{\Phi}(\mathbb{R})$ is a bounded linear operator. Moreover, if $f \in h^{s}_{\Phi}(\mathbb{R})$, $s \geq \frac{5}{2}$ is given and $a \in h^{s}_{\Phi}(\mathbb{R})$ solves
\[
a = \bar{A}_{\lambda}^{-1}(-\gamma M(f) + P^* a) \quad \text{where} \quad M(f) := k^2 f_k
\]
then $\Phi(x, y) := \sum_{k \in \mathbb{N}} a_k \phi_k(x; \lambda) \sin(k x)$ satisfies $\Phi \in X_{\lambda}$ and solves
\[
L_{\lambda} \Phi + \gamma \delta_0(y) F_{xx} = 0
\]
for $F(x, y) := \sum_{k \in \mathbb{N}} f_k \phi_k(y; \lambda) \sin(k x)$ in the weak sense, i.e.,
\[
\int_{\mathbb{R}} \int_{\mathbb{R}} \Phi_y \Psi_y - (1 - \lambda V_0(y) - W(y)) \Phi_x \Psi \, dy \, dx + \int_{\mathbb{R}} \left( \alpha \Phi_{xx}(x, 0) + \gamma F_{xx}(x, 0) \right) \Psi(x, 0) \, dx = 0
\]
for any $\Psi \in H^1(T; H^1(\mathbb{R}))$.

**Proof.** Lemma 6.4 says that $\ker A_{\lambda a} = \text{span}\{\varepsilon_k^a\}$ and $\ker A_{\lambda} = \{0\}$ for any $\lambda \in I_{\lambda a} \setminus \{\lambda_a\}$. We need to show that $0 \in \rho(\bar{A}_{\lambda})$ for any $\lambda \in I_{\lambda a}$. Let $b \in h^{s-2}_{\Phi}(\mathbb{R})$ be arbitrary, then $\bar{A}_{\lambda} a = b$ if and only if
\[
\begin{cases}
A_{\lambda}^k a_k = b_k, & \text{if } k \neq k^*, \\
A_{\lambda}^k a_k + a_k = b_k, & \text{if } k = k^*,
\end{cases}
\]
which is equivalent to
\[
a_k = \frac{1}{A_{\lambda}^k} b_k \quad \text{if } k \neq k^* \quad \text{and} \quad a_{k^*} = \frac{1}{A_{\lambda}^{k^*} + 1} b_{k^*}.
\]
Due to Lemma 6.3 we obtain that for any $b \in h^{s-2}_{\Phi}(\mathbb{R})$ the sequence $a$ defined by (6.17) belongs to $h^{s}_{\Phi}(\mathbb{R})$ and solve $\bar{A}_{\lambda} a = b$; whence $0 \in \rho(\bar{A}_{\lambda})$.

Now suppose that $f \in h^{s}_{\Phi}(\mathbb{R})$ with $s \geq \frac{5}{2}$ and that $a \in h^{s}_{\Phi}(\mathbb{R})$ solves (6.16). The regularity of $\Phi$ follows from Lemma A.3. Moreover, $(\bar{A}_{\lambda} a)_k = -\gamma k^2 f_k$ and hence
\[
2\phi_k^\prime(0; \lambda) a_k + \alpha k^2 a_k = -\gamma k^2 f_k.
\]
Using that
\[
L_{0, \lambda} \phi_k = 0 \text{ on } \mathbb{R}\setminus\{0\} \text{ for all } k \in \mathbb{N},
\]
we deduce by testing with $a_k \psi_k \in H^1(\mathbb{R})$ and summing for $1 \leq k \leq K_0$ that
\[
0 = \sum_{k=1}^{K_0} \int_\mathbb{R} a_k \phi_k'(\psi_k + k^2(1 - \lambda V_0(y) - W(y)) \phi_k \psi_k dy + a_k(\phi_k'(0_+; \lambda) - \phi_k'(0_-; \lambda)) \psi_k(0).
\]
Since $\phi_k(\cdot; \lambda)$ is even with respect to $y$ we obtain by (6.18)
\[
0 = \sum_{k=1}^{K_0} \int_\mathbb{R} a_k \phi_k'(\psi_k + k^2(1 - \lambda V_0(y) - W(y)) \phi_k \psi_k dy - \alpha k^2 a_k \phi_k(0; \lambda) \psi_k(0) - \gamma k^2 f_k \psi_k(0).
\]
Taking the limit $K_0 \to \infty$ in the previous equation will lead to
\[
0 = \int_\mathbb{T} \Phi_z \psi_y - (1 - \lambda V_0(y) - W(y)) \Phi_{zx} \psi + \int_\mathbb{T} (\alpha \Phi_{xx}(x, 0) + \gamma F_{xx}(x, 0)) \psi(x, 0) dx
\]
for any $\Psi \in H^1(\mathbb{T}; H^1(\mathbb{R}))$ due to the following estimates:
\[
\int_\mathbb{T} \int_\mathbb{R} |\Phi_z \psi_y| dy dx \leq \sum_{k \in \mathbb{N}} \|a_k \phi_k'\|_{L^2(\mathbb{R})} \|\psi_k\|_{L^2(\mathbb{R})} \leq \|\Phi\|_{L^2(\mathbb{T}; H^1(\mathbb{R}))} \|\Psi\|_{L^2(\mathbb{T}; H^1(\mathbb{R}))}
\]
\[
\leq C\|a\|_{H^1(\mathbb{R})} \|\Psi\|_{L^2(\mathbb{T}; H^1(\mathbb{R}))},
\]
\[
\int_\mathbb{T} \int_\mathbb{R} \left| (1 - \lambda V_0(y) - W(y)) \Phi_{zx} \psi \right| dy dx \leq \sum_{k \in \mathbb{N}} \left| 1 - \lambda V_0 - W \right|_{L^\infty(\mathbb{R})} k^2 \|\phi_k\|_{L^2(\mathbb{R})} \|\psi_k\|_{L^2(\mathbb{R})}
\]
\[
\leq \left| 1 - \lambda V_0 - W \right|_{L^\infty(\mathbb{R})} \|\Phi\|_{H^2(\mathbb{T}; L^2(\mathbb{R}))} \|\Psi\|_{L^2(\mathbb{T}; L^2(\mathbb{R}))}
\]
\[
\leq C\|a\|_{H^2(\mathbb{R})} \|\Psi\|_{L^2(\mathbb{T}; L^2(\mathbb{R}))},
\]
\[
\int_\mathbb{T} \left| \Phi_{xx}(x, 0) \Psi(x, 0) \right| dx \leq \sup_y \left| \Phi_{xx}(\cdot, y) \right|_{L^2(\mathbb{T})} \left| \Psi(\cdot, y) \right|_{L^2(\mathbb{T})}
\]
\[
\leq \left| \Phi \right|_{C(\mathbb{R}; L^2(\mathbb{T}))} \|\Psi\|_{C(\mathbb{R}; L^2(\mathbb{T}))}
\]
\[
\leq C\|a\|_{H^2(\mathbb{R})} \|\Psi\|_{C(\mathbb{R}; L^2(\mathbb{T}))},
\]
\[
\int_\mathbb{T} \left| F_{xx}(x, 0) \Psi(x, 0) \right| dx \leq \|f\|_{L^2(\mathbb{T})} \|\Psi\|_{C(\mathbb{R}; L^2(\mathbb{T}))}
\]
\[
\leq C\|a\|_{H^2(\mathbb{R})} \|\Psi\|_{C(\mathbb{R}; L^2(\mathbb{T}))}
\]
\]

Together with the continuous embeddings $H^1(\mathbb{T}; H^1(\mathbb{R})) \subset L^2(\mathbb{T}; H^1(\mathbb{R})) \cap C(\mathbb{R}; L^2(\mathbb{T}))$ and $h^s(\mathbb{R}) \subset h^{s/2}(\mathbb{R}) \subset h^s(\mathbb{R})$ (cf. Lemma 6.7(ii) below) but is no longer a Fredholm operator from $h^s(\mathbb{R}) \to h^s(\mathbb{R})$ since the co-dimension of its image is infinite. The Fredholm property at $\lambda = \lambda_*$, however, is important for applying the Crandall–Rabinowitz theorem for bifurcation.

The following lemma provides the necessary preparations to apply bifurcation theory to $G(a, \lambda) = 0$.

**Lemma 6.7.** Let $s \geq \frac{1}{2}$. The map $G : h^s(\mathbb{R}) \times I_{\lambda_*} \to h^s(\mathbb{R})$ is a $C^\infty$-map. Moreover the following holds:

(i) The function $\phi_k$ is continuously differentiable with respect to $\lambda$ and $\psi_k(y; \lambda) := \partial_\lambda \phi_k(y; \lambda)$ satisfies
\[
L_{\lambda,k} \phi_k = k^2 V_0(y) \phi_k \text{ on } (0, \infty), \quad \psi_k(0; \lambda) = 0
\]
\[
\text{and } \psi_k'(0; \lambda) = k^2 \int_0^\infty V_0 \phi_k^2 dy = O(k^2).
\]
(ii) The linearization of $G$ about $a = 0$, given by
\[ D_a G(0, \lambda) = \mathrm{Id} - \tilde{A}_\lambda^{-1} P^* : h^s_\lambda(\mathbb{R}) \to h^s_\lambda(\mathbb{R}) \]
is a Fredholm operator of index zero. Its kernel is trivial for $\lambda \in I_{\lambda_*}$, $\lambda \neq \lambda_*$ and it is given by $\text{span}\{e^{k\pi}\}$ if $\lambda = \lambda_*$. 

(iii) The mixed second derivative of $G$ about $a = 0$ is given by
\[ D^2_{Aa}(0, \lambda) = \tilde{A}_\lambda^{-1} B \tilde{A}_\lambda^{-1} P^* : h^s_\lambda(\mathbb{R}) \to h^{s+2}_\lambda(\mathbb{R}) \subset h^s_\lambda(\mathbb{R}), \]
where $B : h^{s+2}_\lambda(\mathbb{R}) \to h^s_\lambda(\mathbb{R})$ is the pointwise multiplication with $2\psi_k(0; \lambda)$. 

Proof. (i) We are only interested in $\psi_k(\cdot, \lambda) = \tilde{\phi}_\lambda(\cdot, \lambda)$ on $[0, \infty)$. To find $\psi_k(\cdot, \lambda)$ we differentiate $L^\lambda_{0, \lambda} \phi_k = 0$ on $(0, \infty)$, $\phi_k(0; \lambda) = 1$ with respect to $\lambda \in I_{\lambda_*}$ and obtain (6.20). If we define $Q \phi_k(\cdot, \lambda) : \mathbb{R} \to \mathbb{R}$ as the odd extension around $y = 0$ of $\phi_k(\cdot, \lambda) : (0, \infty) \to \mathbb{R}$ then we see that $\psi_k(\cdot, \lambda)$ is given by $\psi_k(\cdot, \lambda) = (L^\lambda_{0, \lambda})^{-1}(k^2V_0Q \phi_k(\cdot, \lambda))[0, \infty)$. Testing the differential equation in (6.20) with $\phi_k$ and noting that $L^\lambda_{0, \lambda} \phi_k = 0$ on $(0, \infty)$ we find
\[ \langle L^\lambda_{0, \lambda} \phi_k, \phi_k \rangle_{L^2(0, \infty)} = \langle \psi_k, \phi_k \rangle_{L^2(0, \infty)} = \psi_k(0, \lambda) = O(k^2), \]
as claimed, in view of $\langle L^\lambda_{0, \lambda} \psi_k, \phi_k \rangle_{L^2(0, \infty)} = \frac{c^0}{\lambda^k} \int_0^\infty \phi_k(\xi) \lambda^k \phi_k(\xi) dy = O(k^2)$ because $V_0 \in L^\infty(\mathbb{R})$ and $(L3)$. 

(ii) The mapping properties of $G$ follow from Remark 6.6. The differentiability of the cubic nonlinearity $a \ast a \ast a$ with respect to $a$ is also a straightforward property of the Banach algebra property of $h^s(\mathbb{R})$. The differentiability property of $G$ with respect to $\lambda$ follows from differentiability of $\lambda \mapsto \phi_k(0; \lambda)$ as given in (i). As in Lemma 4.4 the Fredholm property of $D_a G(0, \lambda)$ is satisfied since it is a compact perturbation of the identity and the characterization of the kernel of can be seen in a similar way using Lemma 6.4. 

(iii) Note that $\frac{\partial^2}{\partial \lambda^2} A^1 = \frac{\partial^2}{\partial \lambda^2} A^2 = 2\psi_k(0; \lambda)$. Since $\psi_k(0; \lambda) = O(k^2)$ by (i) we have the mapping property $B : h^{s+2}_\lambda(\mathbb{R}) \to h^s_\lambda(\mathbb{R})$. \hfill $\Box$

We are now in a position to apply the Crandall–Rabinowitz theorem for $G(a, \lambda) : h^s_\lambda(\mathbb{R}) \times I_{\lambda_*} \to X_s$ for $s \geq \frac{5}{2}$ in order to prove Theorem 2.10 provided that the transversality condition in (2.6) is satisfied.

**Proof of Theorem 2.10.** The existence result follows from the Crandall–Rabinowitz theorem applied to $G(a, \lambda) = 0$. Successfully applied, it provides an interval $I_{\lambda_*} \subset \mathbb{R}$ containing $\lambda_*$, and a smooth curve through $(0, \lambda_*)$ of the form
\[ \{(a(\varepsilon), \lambda(\varepsilon)) \mid |\varepsilon| < \varepsilon_0\} \subset h^s(\mathbb{R}) \times I_{\lambda_*} \]
of nontrivial solutions of (6.11) with $\lambda(0) = \lambda_*$ and $D_a a(0) = e^{k\pi}$. The curve $(a(\varepsilon), \lambda(\varepsilon)) \subset h^s(\mathbb{R}) \times I_{\lambda_*}$ then translates via $\Phi(\varepsilon)(x, y) = \sum_{n \in \mathbb{Z}} a(\varepsilon) \phi_n(y, \lambda(\varepsilon)) \sin(k(x-r))$ and by Lemma 6.5 into the curve $\{(\Phi(\varepsilon)(\lambda(\varepsilon)) \mid |\varepsilon| < \varepsilon_0\}$ for all of nontrivial solutions of (6.1) with the stated property. The Crandall–Rabinowitz theorem requires that the linearization
\[ D_a G(0, \lambda_*) = 1 - \tilde{A}_\lambda^{-1} P^* : h^s_\lambda(\mathbb{R}) \to h^s_\lambda(\mathbb{R}) \]
is a Fredholm operator of index zero with $\text{dim ker } D_a G(0, \lambda_*) = 1$ and the transversality condition
\[ D^2_{Aa}(0, \lambda_*) e^{k\pi} \neq \text{range } D_a G(0, \lambda_*) \]
is satisfied. The Fredholm property is already shown in Lemma 6.7 (ii) and the kernel of $D_a G(0, \lambda_*)$ is one dimensional and spanned by $e^{k\pi}$, that is
\[ \ker D_a G(0, \omega_*) = \text{span}\{e^{k\pi}\}. \]

Concerning the transversality condition (6.21), assume on the contrary that there exists $b \in h^s(\mathbb{R})$ such that
\[ D^2_{Aa}(0, \lambda_*) e^{k\pi} = D_a G(0, \lambda_*) b. \]

Then,
\[ \langle D^2_{Aa} G(0, \lambda_*) e^{k\pi}, e^{k\pi} \rangle_{L^2(\mathbb{R})} = \langle D_a G(0, \lambda_*) b, e^{k\pi} \rangle_{L^2(\mathbb{R})}. \]

Using the formulas from Lemma 6.7 (ii) and (iii) and the fact that $\tilde{A}_\lambda^{-1} P^* = P^*$ together with the symmetry of $\tilde{A}_\lambda^{-1}$ we obtain that
\[ 2\psi_k'(0; \lambda_*) = \langle B e^{k\pi}, e^{k\pi} \rangle_{L^2(\mathbb{R})} = \langle D^2_{Aa} G(0, \lambda_*) e^{k\pi}, e^{k\pi} \rangle_{L^2(\mathbb{R})} = \langle D_a G(0, \lambda_*) b, e^{k\pi} \rangle_{L^2(\mathbb{R})} = \langle b - P^* b, e^{k\pi} \rangle_{L^2(\mathbb{R})} = 0. \]
But due to Lemma 6.7 (i) this is a contradiction to (2.6).

Similarly as in the previous section, we determine the bifurcation formulas. The Fréchet derivatives of $G$ with respect to $a$ are given by

$$D_a G(a, \lambda)e^{k_a} = e^{k_a} - \bar{A}^{-1}_\lambda \left( \frac{3}{4} \gamma M(a \ast a \ast e^{k_a}) + e^{k_a} \right)$$

$$D_{aa}^2 G(a, \lambda)[e^{k_a}, e^{k_a}] = -\frac{3}{2} \gamma \bar{A}^{-1} (M(a \ast e^{k_a} \ast e^{k_a}))$$

$$D_{aaa}^3 G(a, \lambda)[e^{k_a}, e^{k_a}, e^{k_a}] = -\frac{3}{2} \gamma \bar{A}^{-1} (M(e^{k_a} \ast e^{k_a} \ast e^{k_a}))$$

where $M$ is defined as in (6.19).

**Proposition 6.8.** Let $\{(a, \omega) \mid |\omega| < \varepsilon_0 \} \subset \mathfrak{h}^4(\mathbb{R}) \times I_{\lambda_*}$ be the local bifurcation curve found in Theorem 2.10 corresponding to the bifurcation point $(0, \lambda_*)$. Then

$$\hat{\lambda}(0) = 0 \quad \text{and} \quad \tilde{\lambda}(0) = -\frac{3\gamma}{4 \int_0^\infty V_0(y) \phi_{k_a}^2 dy}.$$

**Proof.** The proof follows essentially the lines of the proof of Proposition 4.7. We obtain that $\hat{\lambda}(0) = 0$, which is due to the cubic character of the nonlinearity and

$$\hat{\lambda}(0) = -\frac{1}{3} \frac{\langle D_{aaa}^3 G(0, \lambda_*)[e^{k_a}, e^{k_a}, e^{k_a}], e^{k_a} \rangle}{\langle D_{aa}^2 G(0, \lambda_*)e^{k_a}, e^{k_a} \rangle},$$

Due to Lemma 6.7 (i) and (6.22) the denominator is given by

$$\langle D_{aa}^2 G(0, \lambda_*)e^{k_a}, e^{k_a} \rangle = 2 \int_0^\infty k^2 V_0(y) \phi_{k_a}^2 dy,$$

and the numerator reads

$$\langle D_{aaa}^3 G(0, \lambda_*)[e^{k_a}, e^{k_a}, e^{k_a}], e^{k_a} \rangle = -\frac{3}{2} \gamma k^2 (e^{k_a} \ast e^{k_a} \ast e^{k_a})_{k_a}.$$

Since $(e^{k_a} \ast e^{k_a} \ast e^{k_a})_{k_a} = -3$, as shown in Lemma A.2, the statement follows.

## 7. Examples for distributional $\Gamma$

In what follows we prove Corollary 2.13 and Corollary 2.14, which state the existence of traveling waves for (1.4) in the specific cases, when the potentials are given as in (P1) and (P2), respectively.

### 7.1. (P1) $V$ a $\delta$-potential on a positive background

We consider the particular case when $V_0 = 1, W = 0$ so that we have a positive constant background potential with a multiple of a delta potential on top, i.e.,

$$V(\lambda, y) = \lambda + \alpha \delta_0(y).$$

We verify the conditions $(\tilde{L}_0) - (\tilde{L}_3)$ of Theorem 2.10; thereby proving part one of Corollary 2.13. Let us fix a wavenumber $k_a \in \mathbb{N}$ and a value $\lambda_* < 1$. We determine $\alpha > 0$ from

$$\alpha = \frac{2 \sqrt{1 - \lambda_*}}{k_a}.$$

Notice that the transversality condition and $(\tilde{L}_0)$ are trivially satisfied. Moreover, the validity of $(\tilde{L}_1)$ and $(\tilde{L}_3)$ follow immediately from Remark 6.2, since $1 - \lambda V_0 - W = 1 - \lambda > 0$. Condition $(\tilde{L}_2)$ is exactly the same as $(L2)$ since our operator $L^\lambda_\chi$ is the same as the one considered in Case 2.5 of (P1). Since the choice of $\alpha, k_a, \lambda_{*}$ is the same as in Corollary 2.5 condition $(\tilde{L}_1)$ holds and we are finished with treating this example. Now, Corollary 2.13 follows from Theorem 2.10 and the bifurcation formulas are an immediate consequence of Proposition 6.8.
7.2. (P2) \textbf{A \(\delta\)-potential on a step background.} Now, we consider the case when \(V_0 = 1_{|y|\geq b}, W = \beta 1_{|y| < b}\) for some \(b > 0\) so that the potential \(V\) is given by

\[ V(\lambda, y) = \lambda 1_{|y|\geq b} + \beta 1_{|y| < b} + \alpha \delta_0(y). \]

Again we verify the conditions \((\tilde{L}0) - (\tilde{L}3)\) of Theorem 2.10; thereby proving Corollary 2.14. First we fix a wavenumber \(k_0 \in \mathbb{N}\) and a value \(\lambda_* < 1\). According to Corollary 2.14 we have to distinguish between the case \(\beta < 1\), \(\beta > 1\), and \(\beta = 1\). Notice that the transversality condition and \((\tilde{L}0)\) are trivially satisfied for all \(\beta \in \mathbb{R}\).

Let us begin with the case \(\beta < 1\). The validity of \((\tilde{L}1)\) and \((\tilde{L}3)\) follow immediately from Remark 6.2, since \(1 - \lambda V_0 - W = (1 - \lambda)1_{|y|\geq b} + (1 - \beta 1_{|y| < b}) > 0\). It remains to consider \((\tilde{L}2)\). But again the operator \(L^k_\lambda\) is the same as the one considered in Corollary 2.5 of Case (P1) and the choice of \(\alpha\) in Corollary 2.14 is exactly the same as in Corollary 2.6 of Case (P1). Hence \((\tilde{L}1)\) holds and this example is complete.

Next we consider the case \(\beta > 1\). Here we have made the choices

\[ \sqrt{\beta - 1}b = \pi \]

and

\[ \alpha = 2\sqrt{1 - \lambda_*}. \]

We are left to verify \((\tilde{L}1) - (\tilde{L}3)\) of Theorem 2.10. For \((\tilde{L}1)\) we need to consider the operator \(L^k_{0, \lambda} = -\frac{d^2}{dy^2} + k^2 (1 - \lambda 1_{|y|\geq b} - \beta 1_{|y| < b}) : H^2(\mathbb{R}) \to L^2(\mathbb{R})\) which is self-adjoint with \(\sigma_{ess}(L^k_{0, \lambda}) \subset [k^2 (1 - \lambda), \infty)\). Thus \(0 \in \rho(L^k_{0, \lambda})\) if and only if \(L^k_{0, \lambda} \phi = 0\) for some \(\phi \in H^2(\mathbb{R})\) implies that \(\phi = 0\). In other words: we need to rule out that \(L^k_{0, \lambda}\) has a zero eigenvalue. This can be seen from Lemma A.6 in the Appendix if we set \(\alpha = 0\) (no delta potential in the equation) and \(\mu = 0\), i.e., \(\lambda = \lambda_*\) and \(\beta = \beta\). Moreover, we need to make the obvious changes \(\sqrt{1 - \beta} = i \sqrt{\beta - 1}\) and \(\sinh(ix) = \frac{1}{2} \sin(x), \cosh(ix) = \cos(x)\). Following the ansatz \((A.1)\) for the eigenfunction we obtain \(c_0 = d_0\) and \(c_1 = d_1\) due to the \(C^1\)-matching at \(x = 0\). Moreover, the choice of \(\sqrt{\beta - 1}b = \pi\) results in the invertible matrices

\[ M_\pm = \left( \begin{array}{cc} 0 & -e^{-k \sqrt{1 - \lambda b}} \\ \pm \sqrt{1 - \lambda} e^{-k \sqrt{1 - \lambda b}} \end{array} \right). \]

Hence the conclusion \(c_1 = -d_1\) from Lemma A.6 holds and leads to \(c_1 = d_1 = 0\). An inspection of the \(C^1\)-compatibility at \(y = \pm b\) then yields \(c_2 = d_2 = c_0 = d_0 = 0\). Therefore, there is no zero-eigenvalue of \(L^k_{0, \lambda}\) for any \(k \in \mathbb{N}\) and any \(\lambda \in (-\infty, 1)\) and \((\tilde{L}1)\) holds.

Concerning \((\tilde{L}2)\) we need to study a zero-eigenvalue of \(L^k_\lambda\). The answer is again given by Lemma A.6 in the Appendix since we already know the invertibility of the matrices \(M_\pm\). Hence the eigenvalue condition is given by \((5.2)\) with the obvious changes from the hyperbolic functions to the trigonometric function and reads

\[ \frac{k \alpha}{\sqrt{\beta - 1}} = -\sqrt{\beta - 1} \sin(k \sqrt{\beta - 1}y) + \sqrt{1 - \lambda} \cos(k \sqrt{\beta - 1}y). \]

In view of \(\sqrt{\beta - 1}b = \pi\) this reduces to

\[ \alpha = \frac{2 \sqrt{1 - \lambda}}{k}, \]

and hence \(L^k_\lambda\) has a zero-eigenvalue if and only if \(k = k_0\) and \(\lambda = \lambda_*\). Thus \((\tilde{L}2)\) holds. Finally, in order to verify \((\tilde{L}3)\), we compute the function \(\phi_k\) which solve \(L^k_\lambda \phi_k = 0\) on \((0, \infty)\) with \(\phi_k(0) = 1\). From Lemma A.6 we obtain

\[ \phi_k(y, \lambda) = \cos(k \sqrt{\beta - 1}y) + ie_c \sin(k \sqrt{\beta - 1}y), \quad \phi_k(y, \lambda) = e^{c e^{-k \sqrt{1 - \lambda y}}, \quad y \in [0, b], \]

with \(c_1 = \frac{1}{\sqrt{1 - \lambda}}\) and \(c_2 = e^{k \lambda \sqrt{1 - \lambda}} (-1)^k\). Computing the \(L^2\)-norm of \(\phi_k\) we find that

\[ \frac{1}{2} |\phi_k(\cdot, \lambda)|^2_{L^2(\mathbb{R})} = \int_0^b \left( \cos(k \sqrt{\beta - 1}y) - \frac{1 - \lambda}{\sqrt{\beta - 1}} \sin(k \sqrt{\beta - 1}y) \right)^2 dy + \int_b^\infty e^{2 k \sqrt{1 - \lambda} (b - y)} dy \]

\[ = \frac{1}{2 k \sqrt{1 - \lambda}} + \frac{1}{2} \frac{1 - \lambda}{\beta - 1} \leq C \left( 1 + \frac{1}{\sqrt{k}} \right), \]

where the constant \(C > 0\) is independent of \(k\) and can be chosen uniformly for \(\lambda\) sufficiently close to \(\lambda_*\). This shows the validity of \((\tilde{L}3)\).
The last case to be considered is $\beta = 1$. Also here, we are left to verify conditions ($\tilde{L}1$), ($\tilde{L}2$), and ($\tilde{L}3$). First we find that in this case with $\tilde{\lambda} = \lambda$ and $\tilde{\beta} = \beta = 1$ condition (5.2) is replaced by
\[
\frac{k\alpha}{2} = \frac{\sqrt{1-\lambda}}{1 + \sqrt{1-\lambda} k \beta},
\] which follows from a suitable adaptation of Lemma A.6. A zero eigenvalue of $L^k_{\alpha,\lambda}$ correspond to values $k, \lambda$ satisfying (7.1) with $\alpha = 0$ which is impossible. Since $\sigma_{ess}(L^k_{0,\lambda}) = [k^2(1-\lambda), \infty)$ this shows that ($\tilde{L}1$) holds. If we recall the definition of $\alpha$, i.e.,
\[
\alpha = \frac{2\sqrt{1-\lambda}}{k_\alpha (1 + \sqrt{1-\lambda} k_\beta)}
\] and compare with the 0-eigenvalue condition (7.1) we see that this ensures that 0 is a (simple) eigenvalue of $L^k_{\lambda}$ if and only if $\lambda = \lambda_\alpha$ and $k = k_\alpha$. Hence, ($\tilde{L}2$) holds. To see ($\tilde{L}3$) we compute (also with the help of an adaptation of Lemma A.6) that the functions $\phi_k$ solving $L^k_\lambda \phi_k = 0$ on $(0, \infty)$ with $\phi_k(0) = 1$ are given by
\[
\begin{align*}
\phi_k(y, \lambda) &= 1 + c_1 y, & y \in [0, b], \\
\phi_k(y, \lambda) &= c_2 e^{-k\sqrt{1-\lambda} y}, & y \geq b
\end{align*}
\] with $c_1 = \frac{\sqrt{1-\lambda}}{k\sqrt{1-\lambda} + 1}$ and $c_2 = \frac{e^{k\sqrt{1-\lambda} - 1}}{k\sqrt{1-\lambda} + 1}$. From this we directly calculate that $\|\phi_k(\cdot, \lambda)\|_{L^2(\mathbb{R})}^2 = O(1)$ as $k \to \infty$ uniformly for $\lambda$ sufficiently close to $\lambda_\alpha$. Hence, ($\tilde{L}3$) holds.

Now, Corollary 2.14 follows from Theorem 2.10.

**Appendix A. Auxiliary results**

**Lemma A.1.** Let $A(x) = \sum_{k \in \mathbb{N}} a_k \sin(kx)$, then
\[
A^3(x) = -\frac{1}{4} \sum_{k \in \mathbb{N}} (a * a * a)_k \sin(kx),
\] where $a = (a_k)_{k \in \mathbb{Z}}$ is an infinite sequence with $a_k = -a_{-k}$ for all $k \in \mathbb{Z}$. The notation $(a * a * a)_k$ is used to denote the $k$-th entry in the sequence obtained by convolution $a * a * a$.

**Proof.** If $a$ is a sequence as above then using $a_k = -a_{-k}$ for all $k$ we find that
\[
\sum_{k \in \mathbb{Z}} \left(-\frac{1}{2}a_k\right) e^{ikx} = \sum_{k \in \mathbb{Z}} \frac{1}{2} a_k \sin(kx) = \sum_{k \in \mathbb{N}} a_k \sin(kx) = A(x),
\] and
\[
A^3(x) = \sum_{k \in \mathbb{Z}} \frac{1}{8} i (a * a * a)_k e^{ikx}.
\] We are going to show that the Fourier coefficients $(a * a * a)_k$ are odd with respect to $k$. Notice first that
\[
(a * a * a)_k = \sum_{j \in \mathbb{Z}} \left(a_{k-j} a_j\right) a_j.
\] We also have that
\[
(a * a * a)_{-k} = \sum_{j \in \mathbb{Z}} \left(\sum_{l \in \mathbb{Z}} a_{k-j-l} a_l\right) a_j = -\sum_{j \in \mathbb{Z}} \left(\sum_{l \in \mathbb{Z}} a_{k+j+l} a_l\right) a_j
\]
\[
= -\sum_{j \in \mathbb{Z}} \left(\sum_{l \in \mathbb{Z}} a_{k-j-l} a_{j-l}\right) a_{-j} = -\sum_{j \in \mathbb{Z}} \left(\sum_{l \in \mathbb{Z}} a_{k-j-1} a_{j-l}\right) a_j = -(a * a * a)_k.
\] From this we deduce that
\[
A^3(x) = \sum_{k \in \mathbb{Z}} \frac{1}{8} i (a * a * a)_k e^{ikx} = -\frac{1}{8} \sum_{k \in \mathbb{Z}} (a * a * a)_k \sin(kx) = -\frac{1}{4} \sum_{k \in \mathbb{N}} (a * a * a)_k \sin(kx).
\] \[\square\]
Lemma A.2. Let \( k \in \mathbb{N} \) and \( \varepsilon^k \) be a sequence such that \( \varepsilon^k = 0 \) if \( k \neq \pm k^* \), \( \varepsilon^k = -\varepsilon^{-k} = 1 \). Then,

\[
(e^k * \varepsilon^k * e^k)_k = \begin{cases} 
1, & \text{if } k = 3k^*, \\
-1, & \text{if } k = -3k^*, \\
3, & \text{if } k = k^*, 
\end{cases}
\]

Proof. The convolution \( e^k * \varepsilon^k * e^k \) is given by

\[
(e^k * \varepsilon^k * e^k)_k = \sum_{j \in \mathbb{Z}} \left( \sum_{l \in \mathbb{Z}} \varepsilon^k_{k-j} e^k_l \right) e^k_j = \sum_{l \in \mathbb{Z}} \varepsilon^k_{k-l} - e^k_l = \sum_{l \in \mathbb{Z}} \varepsilon^k_{k+2k-l} e^k_l
\]

and the claim follows.

Lemma A.3. Let \( a \in h^s(\mathbb{R}) \) for some \( s \geq 0 \) and define \( \Phi(x, y) = \sum_{k \in \mathbb{Z}} a_k \phi_k(y; \lambda) \sin(kx) \) for \( x \in T, y \in \mathbb{R} \). Then

- (i) \( \Phi \in H^s(T, L^2(\mathbb{R})) \)
- (ii) \( \Phi \in H^{s-1}(T, H^1(\mathbb{R})) \)
- (iii) \( \Phi \in H^{s-2}(T, H^2(0, \infty)) \)
- (iv) \( \Phi \in C(\mathbb{R}, H^{s-\frac{1}{2}}(T)) \)
- (v) \( \Phi \in C^1(\mathbb{R}, H^{s-\frac{3}{2}}(T)) \)

Proof. We verify that

\[
\| \Phi \|^2_{H^s(T, L^2(\mathbb{R}))} \leq C \sum_{k \in \mathbb{Z}} a_k^2 \| \phi_k \|^2_{L^2(\mathbb{R})} \leq C \| a \|^2_{H^s(\mathbb{R})},
\]

\[
\| \Phi \|^2_{H^{s-1}(T, H^1(\mathbb{R}))} \leq C \sum_{k \in \mathbb{Z}} a_k^2 \| \phi'_k \|^2_{L^2(\mathbb{R})} \leq C \| a \|^2_{H^s(\mathbb{R})},
\]

\[
\| \Phi \|^2_{H^{s-2}(T, H^2(0, \infty))} \leq C \sum_{k \in \mathbb{Z}} a_k^2 \| \phi''_k \|^2_{L^2(0, \infty)} \leq C(1 + \| 1 - \lambda V_0 - W \|_{L^\infty(\mathbb{R})} \sum_{k \in \mathbb{Z}} a_k^2 \| \phi_k \|^2_{L^2(0, \infty)} \leq C \| a \|^2_{H^s(\mathbb{R})},
\]

\[
\| \Phi \|^2_{C(\mathbb{R}, H^{s-\frac{1}{2}}(T))} \leq C \sum_{k \in \mathbb{Z}} a_k^2 \| \phi_k \|^2_{H^{s-\frac{1}{2}}(T)} \leq C \| a \|^2_{H^s(\mathbb{R})},
\]

\[
\| \Phi \|^2_{C^1(\mathbb{R}, H^{s-\frac{3}{2}}(T))} \leq C \sum_{k \in \mathbb{Z}} a_k^2 \| \phi_k \|^2_{H^{s-\frac{3}{2}}(T)} \leq C \| a \|^2_{H^s(\mathbb{R})}.
\]

Lemma A.4. For \( s \geq 1 \) the space \( h^s(\mathbb{R}) \) is a Banach algebra with respect to convolution.

Proof. In this proof we use the \( l^1 \)-norm \( \| a \|_{l^1(\mathbb{R})} = \sum_{k \in \mathbb{Z}} |a_k| \) for a sequence \( a = (a_k)_{k \in \mathbb{Z}} \in l^1(\mathbb{R}) \), i.e., the Banach space of all real sequences with finite \( l^1 \)-norm. Due to convexity we have the inequality

\[
|k|^s \leq 2^{s-1}(|k| + |l|)^s.
\]

Therefore, if \( a, b \in h^s(\mathbb{R}) \) then

\[
|k|^s(a * b)_k = |k|^s \sum_{l \in \mathbb{Z}} |a_{k-l}b_l| \leq 2^{s-1} \sum_{l \in \mathbb{Z}} |k-l|^s |a_{k-l}| |b_l| + |a_{k-l}| |l|^s |b_l|.
\]

Using the convolution inequality \( \| \tilde{a} \tilde{b} \|_{l^2(\mathbb{R})} \leq \| \tilde{a} \|_{l^2(\mathbb{R})} \| \tilde{b} \|_{l^2(\mathbb{R})} \) once for \( (\tilde{a})_k = |k|^s |a_k| \), \( (\tilde{b})_k = |b_k| \) and once for \( (\tilde{a})_k = |a_k| \), \( (\tilde{b})_k = |b_k| \) we get

\[
\| a * b \|_{h^s(\mathbb{R})} \leq 2^{s-1}(\| a \|_{H^s(\mathbb{R})} \| b \|_{H^s(\mathbb{R})} + \| a \|_{H^s(\mathbb{R})} \| b \|_{H^s(\mathbb{R})}).
\]

Finally, \( a \in h^s(\mathbb{R}) \) implies \( a \in l^1(\mathbb{R}) \) due to

\[
\sum_{k \in \mathbb{Z}} |a_k| = \sum_{k \in \mathbb{Z}} |a_k||k| + 1 \frac{1}{|k| + 1} \leq C \| a \|_{H^s(\mathbb{R})} \leq C \| a \|_{H^s(\mathbb{R})}.
\]
Lemma A.5. Let \( L = -\frac{d^2}{dy^2} + q(y) \) with \( q \in L^\infty(\mathbb{R}) \) be a self-adjoint operator on \( L^2(\mathbb{R}) \) with domain \( D(L) = H^2(\mathbb{R}) \). Then, for any \( \alpha \in \mathbb{R} \), we have that \( L_\alpha := L + \alpha \delta_0 \) is self-adjoint with domain \( D(L_\alpha) = \{ u \in H^1(\mathbb{R}) \cap (H^2(0, \infty) \cup H^2(-\infty, 0)) \mid u'(0^+) - u'(0^-) = -\alpha u(0) \} \). Moreover for any \( \alpha \in \mathbb{R} \) the following holds:

(i) For sufficiently large \( \mu > 0 \) we have that \( (L_\alpha + \mu)^{-1} : H^{-1}(\mathbb{R}) \to H^1(\mathbb{R}) \) is bounded.

(ii) \( \sigma_{ess}(L_\alpha) = \sigma_{ess}(L) \).

Proof. A proof for the self-adjointness of \( L_\alpha \) for any \( \alpha \in \mathbb{R} \) is given in [4]. For (i) we first note that \( L_\alpha \) is a semi-bounded self-adjoint operator so that \( L_\alpha + \mu \) is a positive operator for \( \mu > 0 \) sufficiently large. Its bilinear form \( b_{L_\alpha + \mu} : H^1(\mathbb{R}) \times H^1(\mathbb{R}) \to \mathbb{R} \) is coercive and equivalent to the standard \( H^1(\mathbb{R}) \)-inner product. Therefore, any \( f \in H^{-1}(\mathbb{R}) \) can be represented by a unique \( u \in H^1(\mathbb{R}) \) such that \( b_{L_\alpha + \mu}(u, \phi) = f(\phi) \) for any \( \phi \in H^1(\mathbb{R}) \) and \( b_{L_\alpha + \mu}(u, u) = \| \phi \|_{H^{-1}(\mathbb{R})}^2 \). This proves (i).

For (ii) we may take \( \lambda < 0 \) sufficiently negative such that \( \lambda \in \rho(L) \cap \rho(L_\alpha) \cap \mathbb{R} \) since both \( L, L_\alpha \) are semi-bounded from below. Using (i) we may also assume \( \lambda \) sufficiently negative that \( (\lambda - L_\alpha)^{-1} : H^{-1}(\mathbb{R}) \to H^1(\mathbb{R}) \) is bounded. By Weyl’s criterion it is sufficient to show that the operator \( W_\lambda := (\lambda - L)^{-1} - (\lambda - L_\alpha)^{-1} : L^2(\mathbb{R}) \to L^2(\mathbb{R}) \) is compact in order to prove the statement. Since

\[
W_\lambda = (\lambda - L_\alpha)^{-1} - ((\lambda - L_\alpha)(\lambda - L) - 1) = (\lambda - L_\alpha)^{-1} \circ (\lambda - L_\alpha)(\lambda - L) - 1 \circ H^{-1}(\mathbb{R}) \to H^1(\mathbb{R}) \quad H^1(\mathbb{R}) \to H^{-1}(\mathbb{R}) \quad L^2(\mathbb{R}) \to L^2(\mathbb{R})
\]

and since \( L - L_\alpha = -\alpha \delta_0 : H^1(\mathbb{R}) \to H^{-1}(\mathbb{R}) \) is a bounded operator with 1-dimensional range spanned by \( \delta_0 \) we see that \( W_\lambda \) is indeed compact. This finishes the proof. \( \square \)

Lemma A.6. Let \( \tilde{\lambda}, \tilde{\beta} < 1 \). Then the eigenvalue problem (5.1) is solvable for \( \phi \in D(L_\lambda^1) \) if and only if (5.2) holds. In this case the eigenspace is one-dimensional.

Proof. Solutions of the differential equation in (5.1) have to be of the form

\[
\phi(y, \lambda) = \begin{cases} c_2 e^{-k \sqrt{1 - \tilde{\beta} y}} + c_1 \sinh(k \sqrt{1 - \tilde{\beta} y}), & y \geq b, \\
\begin{align*}
c_0 \cosh(k \sqrt{1 - \tilde{\beta} y}) + c_1 \sinh(k \sqrt{1 - \tilde{\beta} y}), & \quad y \in [0, b], \\
d_0 \cosh(k \sqrt{1 - \tilde{\beta} y}) + d_1 \sinh(k \sqrt{1 - \tilde{\beta} y}), & \quad y \in [-b, 0], \\
d_2 e^{k \sqrt{1 - \lambda y}}, & \quad y \leq -b,
\end{align*}
\end{cases}
\]  

(A.1)

with \( C^1 \)-compatibility conditions at \( x = \pm b \) and continuity at \( x = 0 \). The latter implies \( c_0 = d_0 \) and the condition \( \phi'(0^+) - \phi'(0^-) + k^2 \alpha \phi(0) = 0 \) at \( x = 0 \) translates into

\[
k\sqrt{1 - \tilde{\beta}}(c_1 - d_1) + k^2 \alpha c_0 = 0. 
\]  

(A.2)

The \( C^1 \)-compatibility leads to the following set of four equations

\[
\begin{cases}
c_0 \cosh(k \sqrt{1 - \tilde{\beta} b}) + c_1 \sinh(k \sqrt{1 - \tilde{\beta} b}) = c_2 e^{-k \sqrt{1 - \lambda b}}, \\
\sqrt{1 - \tilde{\beta}}(c_0 \sinh(k \sqrt{1 - \tilde{\beta} b}) + c_1 \cosh(k \sqrt{1 - \tilde{\beta} b})) = -k \sqrt{1 - \tilde{\lambda}} c_2 e^{-k \sqrt{1 - \lambda b}}, \\
d_0 \cosh(k \sqrt{1 - \tilde{\beta} b}) - d_1 \sinh(k \sqrt{1 - \tilde{\beta} b}) = d_2 e^{-k \sqrt{1 - \lambda b}}, \\
\sqrt{1 - \tilde{\beta}}(-d_0 \sinh(k \sqrt{1 - \tilde{\beta} b}) + d_1 \cosh(k \sqrt{1 - \tilde{\beta} b})) = \sqrt{1 - \tilde{\lambda}} d_2 e^{-k \sqrt{1 - \lambda b}}.
\end{cases}
\]

These four equations can be written as

\[
\begin{pmatrix} M_+ & 0 \\ 0 & M_- \end{pmatrix} \begin{pmatrix} c_2 \\ d_2 \end{pmatrix} = \begin{pmatrix} -c_0 \cosh(k \sqrt{1 - \tilde{\beta} b}) \\ -k \sqrt{1 - \tilde{\beta}} c_0 \sinh(k \sqrt{1 - \tilde{\beta} b}) \\ -c_0 \cosh(k \sqrt{1 - \tilde{\beta} b}) \\ -k \sqrt{1 - \tilde{\beta}} c_0 \sinh(k \sqrt{1 - \tilde{\beta} b}) \end{pmatrix} = \begin{pmatrix} e^{-k \sqrt{1 - \lambda b}} \\ e^{-k \sqrt{1 - \lambda b}} \end{pmatrix}
\]

with

\[
M_\pm = \begin{pmatrix} \pm \sinh(k \sqrt{1 - \tilde{\beta} b}) & e^{-k \sqrt{1 - \lambda b}} \\ \sqrt{1 - \tilde{\beta}} \cosh(k \sqrt{1 - \tilde{\beta} b}) & \pm \sqrt{1 - \tilde{\lambda}} e^{-k \sqrt{1 - \lambda b}} \end{pmatrix}.
\]
Since both $M_+$ and $M_-$ are invertible we see that w.l.o.g. we can choose $c_0 = 1$. Moreover, the structure of the linear systems yields that $c_1 = -d_1$ and $c_2 = d_2$. Finally, solving for $c_1, c_2$ we get
\[
c_1 = \frac{\sqrt{1 - \beta \sinh(k \sqrt{1 - \beta b})} + \sqrt{1 - \lambda \cosh(k \sqrt{1 - \beta b})}}{\sqrt{1 - \lambda \cosh(k \sqrt{1 - \beta b})} + \sqrt{1 - \beta \sinh(k \sqrt{1 - \beta b})}},
\]
\[
c_2 = e^{k \sqrt{1 - \lambda b}}(c_1 \sinh(k \sqrt{1 - \beta b}) + \cosh(k \sqrt{1 - \beta b})).
\]
Inserting $c_1, d_1 = -c_1$ and $c_0 = 1$ into (A.2) yields the condition (5.2) as claimed. It also shows that the eigenspace is one-dimensional (the only degree of freedom is the choice of $c_0$ which we took to be 1 w.l.o.g.). \qed

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