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Parametric resonance of ground states in the nonlinear Schrödinger equation

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Abstract

We study the global existence and long-time behavior of solutions of the initial-value problem for the cubic nonlinear Schrödinger equation with an attractive localized potential and a time-dependent nonlinearity coefficient. For small initial data, we show under some nondegeneracy assumptions that the solution approaches the profile of the ground state and decays in time like $t^{-1/4}$. The decay is due to resonant coupling between the ground state and the radiation field induced by the time-dependent nonlinearity coefficient.

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1. Introduction

We consider the initial-value problem for the nonlinear Schrödinger (NLS) equation in three spatial dimensions:

$$\begin{aligned}i\partial_t u(t, x) &= (-\Delta + V(x))u(t, x) + \gamma(t)|u(t, x)|^2 u(t, x), \\ u(0, x) &= u_0(x),\end{aligned}\tag{1.1}$$

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where $(t, x) \in [0, \infty) \times \mathbb{R}^3$, $u(t, x)$ is a complex-valued function, Δ is the Laplacian in $x \in \mathbb{R}^3$, $V(x)$ is a real-valued potential, and $\gamma(t)$ is the nonlinearity coefficient in the form

$$\gamma(t) = \gamma_0 + \gamma_1 \cos(\omega t), \quad \gamma_0, \gamma_1 \in \mathbb{R}. \quad (1.2)$$

We chose a time harmonic $\gamma(t)$ to simplify the presentation but our results remain valid when $\gamma(t)$ is a more general periodic or even almost periodic function in time, see Section 7.

The NLS equation (1.1) is a mean field model for Bose–Einstein condensates, see [11]. The external potential $V(x)$ models the trapping mechanism of the condensate, while the periodic coefficient $\gamma(t)$ models the dependence of the inter-particle interaction in the vicinity of the Feshbach resonance controlled by the magnetic field [5,7]. The homogenization (averaging) of the NLS equation (1.1) with $\gamma_1 \neq 0$ and $x \in \mathbb{R}^1$ was studied recently in the limit $\omega \gg 1$ [13,14]. When $V(x)$ was taken as a parabolic trapping potential, the solution $u(t, x)$ was shown numerically to approach to a periodically modulated ground state. Parametric resonance between the ground state and the continuous spectrum is removed from the leading order of the averaging method in the limit $\omega \gg 1$ [30]. It is expected however that when $V(x)$ is an attractive localized potential, the radiation field escapes the trap and leads to the radiative decay of the periodically modulated ground state in the long-time behavior of the solution $u(t, x)$ as $t \rightarrow \infty$. We study here this problem in the case of finite ω , $x \in \mathbb{R}^3$ and small norm solutions of the NLS equation (1.1).

In what follows, we use the following notations. Let $L^p(\mathbb{R}^3)$, $p \geq 1$, be the usual Banach spaces of complex-valued measurable functions whose p th power is integrable. Let $H^n(\mathbb{R}^3)$, $n \geq 0$, be the Sobolev spaces of functions which have n generalized derivatives in $L^2(\mathbb{R}^3)$. Let $H^n(\mathbb{R}^3)$, $n < 0$, be the duals of $H^{-n}(\mathbb{R}^3)$ and $L^2_\sigma(\mathbb{R}^3)$ be the weighted L^2 space with the norm:

$$\|f\|_{L^2_\sigma} = \|(1 + |x|^2)^{\sigma/2} f\|_{L^2}. \quad (1.3)$$

Let $\langle \cdot, \cdot \rangle$ denote the scalar product in $L^2(\mathbb{R}^3)$. We assume that the localized potential $V(x)$ satisfies two conditions:

$$|V(x)| \leq \frac{C}{(1 + |x|)^\beta}, \quad C > 0, \quad \beta > 3 \quad \forall x \in \mathbb{R}^3 \quad (1.4)$$

and

$$\nabla V \in L^p(\mathbb{R}^3) \quad \forall p > \frac{3}{2}. \quad (1.5)$$

It follows from the decay condition (1.4) on $V(x)$ that the operator $\mathcal{H} = -\Delta + V(x)$ is self-adjoint on $L^2(\mathbb{R}^3)$ with domain $H^2(\mathbb{R}^3)$, see [12, Theorem 7.5.5]. As a result, the

spectrum of \mathcal{H} consists of finite-dimensional discrete spectrum for negative eigenvalues, absolutely continuous spectrum for nonnegative eigenvalues, and a possible resonance at zero. We assume that the zero-eigenvalue resonance does not occur in the spectrum of \mathcal{H} and denote the projection operator on the absolutely continuous spectrum of \mathcal{H} by \mathcal{P}_c . Adding a technical assumption on the discrete spectrum of \mathcal{H} , we formulate our main result as Theorem 1.

Assumption 1. The self-adjoint operator $\mathcal{H} = -\Delta + V(x)$ in $L^2(\mathbb{R}^3)$ has a unique simple eigenvalue λ in the discrete spectrum, such that

$$\lambda < 0, \quad \lambda + \omega > 0, \tag{1.6}$$

with the corresponding real-valued eigenvector $\psi(x) \in L^2(\mathbb{R}^3)$.

Remark 1.1. Based on the decay of potential (1.4), it follows from [19] that for any $0 \leq \theta < 1$

$$|\psi(x)| \leq C_\theta e^{-\theta\sqrt{-\lambda}|x|} \quad \forall x \in \mathbb{R}^3. \tag{1.7}$$

Consequently,

$$\psi(x), \psi^3(x) \in L^2_\sigma(\mathbb{R}^3) \cap L^p(\mathbb{R}^3) \quad \forall \sigma \geq 0 \quad \forall p \geq 2. \tag{1.8}$$

Theorem 1. *Let Assumption 1 hold and assume that*

$$\Gamma \stackrel{def}{=} \frac{\gamma_1^2}{4} \operatorname{Im} \langle \psi^3, (\mathcal{H} - \lambda - \omega - i0)^{-1} \mathcal{P}_c \psi^3 \rangle \neq 0. \tag{1.9}$$

Then there exists $\varepsilon_0 > 0$ such that for all initial conditions $u_0(x)$ satisfying

$$\varepsilon \stackrel{def}{=} \max\{\|u_0\|_{H^1}, \|u_0\|_{L^2_\sigma}\} < \varepsilon_0 \quad \text{for some } \sigma > \frac{5}{2}, \tag{1.10}$$

the initial-value problem (1.1) is globally well-posed and satisfies the decay estimates for all $t \geq 0$:

$$u(t, x) = e^{-i\lambda t} A(t)\psi(x) + u_d(t, x), \tag{1.11}$$

where

$$|A(t)| \leq \frac{C_0 \varepsilon}{(1 + 4\Gamma \varepsilon^4 t)^{1/4}} \tag{1.12}$$

and

$$\|u_d(t)\|_{L^2_{-\sigma}} \leq \frac{C_1 \varepsilon}{(1+t)^{3/2}} + \frac{C_2 \varepsilon^3}{(1+4\Gamma \varepsilon^4 t)^{3/4}} \tag{1.13}$$

$$\|u_d(t)\|_{L^4} \leq \frac{C_3 \varepsilon}{(1+t)^{3/4}} + \frac{C_4 \varepsilon^2}{(1+4\Gamma \varepsilon^4 t)^{1/2}}, \tag{1.14}$$

with some positive ε -independent constants C_0 – C_4 .

Remark 1.2. Since $\psi^3 \in L^2_{\sigma}(\mathbb{R}^3)$ due to (1.8), the parameter Γ is well-defined. Moreover:

$$\text{Im}\langle \psi^3, (\mathcal{H} - \mu - i0)^{-1} \mathcal{P}_c \psi^3 \rangle = \pi \langle \psi^3, E'(\mu) \psi^3 \rangle \geq 0,$$

where $E'(\mu)$, $\mu \in \mathbb{R}$ is the spectral measure induced by $\mathcal{H} = -\Delta + V(x)$, see [6]. For $\mu = \lambda + \omega > 0$ the above expression is generically positive.

We now explain succinctly the novelty and the difficulties in our paper. If the problem (1.1) were linear, $\gamma(t) \equiv 0$, it would have stable periodic solutions of the form $A_0 e^{-i\lambda t} \psi(x)$, see Section 3.1. The same is true in the case $\gamma(t) \equiv \gamma_0 \neq 0$. Indeed [16], see also [20,21], proves the existence of an asymptotically stable center manifold, formed by periodic in time localized in space solutions (nonlinear ground states), that bifurcates from $\psi(x)$. Any solution of the initial-value problem (1.1) in the case $\gamma(t) \equiv \gamma_0$ with sufficiently small initial data $u_0(x)$ in (1.10) approaches a nonlinear ground state as time goes to infinity. Theorem 1 shows that the central manifold is destroyed by the time periodic perturbation (1.2) with $\gamma_1 \neq 0$. The argument can be easily adapted to handle a general periodic and almost periodic functions $\gamma(t)$. Here is how the argument goes.

We decompose the solution $u(t, x)$ of (1.1) as a sum of projections onto the discrete component, $\psi(x)$, and onto the continuous spectrum of the linear dispersive operator \mathcal{H} , according to representation (1.11), and set up a system of coupled equations for them, (3.2)–(3.3). If there were no discrete component, decay estimates for linear Schrödinger operators, like those in (3.6)–(3.8), would allow us to treat the equation as a small perturbation of a linear equation. In particular small solutions of the nonlinear equation would satisfy estimates analogous to (3.6)–(3.8). Here however, there is also a discrete component. The only way for it to decay is for its energy to leak into the continuous component of \mathcal{H} . At the end of the proof we learn that this passage from the discrete to the continuous component is very slow, almost undetectable for a long time. So the discrete component acts like a long-range forcing term on the system, which makes difficult the proof of decay even for the continuous component. This means that even though we are treating small solutions of a nonlinear problem, we cannot expect to interpret what we have as a small perturbation of a dispersive linear problem and in particular there is no hope of proving decay of type (3.6)–(3.8). In fact we

have two time scales in the system, one from (3.6)–(3.8) and the other from the slow decay of the discrete component, that are nonlinearly coupled. We carefully analyze this coupling via contraction principles in a hierarchy of Banach spaces, a possibly new mathematical tool that we describe in Appendix A. Now the leaking of energy from discrete to continuous is a resonance phenomenon and is due to the oscillations in the nonlinear coupling of the two components. It is mathematically described by a strictly negative term on the right-hand side of (3.2) that eventually dominates the dynamic of the discrete component and lead to its decay (Fermi Golden Rule). We identify such a term via the technique developed in [22], see the next paragraph for more references on Fermi Golden Rule. Condition (1.9) insures that it is strictly negative, but to show that it eventually dominates the dynamics is a different story. In fact on short time scales other terms dominate. To settle the winner on long time scales, we use our sharp analysis of the interaction between the two time scales and comparison principles for ODEs. Because the Fermi Golden Rule term is nonlinear we also need to use exact linearization, see the proof of Lemma 5.1. In this way we prove that the resonance leads to a slow passage of energy from the discrete component to the continuous component where it disperses. This leads to destruction of any small localized initial value $u_0(x)$, according to the decay rates (1.12)–(1.14).

In conclusion, Theorem 1 can be viewed as a nonlinear generalization of the linear quantum resonance results in [3,8–10,22,27]. Nonlinear Fermi Golden rule and nonlinear resonances for wave, Schrödinger and Klein–Gordon-type equations were introduced in [18,23], see also [1]. Relaxation of excited bound states to the ground state due to nonlinear resonances was recently studied in [24,26]. In [18,23] the decay occurs because the nonlinear perturbation breaks a certain symmetry of the linear equation, while in [24,26] the decay is due to the mismatch between the frequency of the ground state and the frequency of the excited state. The generalization to multiple excited states is briefly discussed in [18]. None of these applies to our case. Our result is the first that we know of in which the resonance and decay is induced by time oscillations in the nonlinear perturbation. This case raises two main problems. The first one is lack of conservation of energy because the perturbation is a time-dependent Hamiltonian. Consequently, the energy method cannot be applied to infer the existence of global solutions even for small initial data, see for example [2, Chapter 6.2]. We overcome this difficulty by using a continuation method, see the proof of Theorem 1. The second problem is the appearance of two time scales that are nonlinearly coupled. As described in the previous paragraph, we use methods based on contraction principles, which provide not only a more systematical treatment of the resonant and nonresonant terms but also sharper information on the evolution of solution, when compared to previously employed bootstrapping arguments. Consequently, we can extend our results to the case, when $\lambda + (n - 1)\omega < 0$ but $\lambda + n\omega > 0$ for some integer $n \geq 1$. This case corresponds to a higher-order resonance and it leads to a slower decay rate of the solution $u(t, x)$ like $t^{-1/(4n)}$.

The paper is structured as follows. Section 2 gives local existence results for problem (1.1). The proof of Theorem 1 is given in Section 3, where we decompose problem (1.1) in the form of a coupled system of two differential equations. The proof relies on analysis of each of the two equations which is reported in Sections 4 and 5, respectively.

The H^1 estimates are needed to prevent the finite-time blow up and they are given in Section 6. Section 7 concludes the paper with generalizations and open problems. Appendix A presents applications of the contraction principle in a hierarchy of Banach spaces and it is used in Section 4.

2. Local existence

We show here that the initial-value problem (1.1) is locally well posed. The local well-posedness in $H^2(\mathbb{R}^3)$ follows from the decay condition (1.4). If the potential $V(x)$ is also sufficiently smooth, such that condition (1.5) is satisfied, the initial-value problem (1.1) is also well posed in $H^1(\mathbb{R}^3)$.

Theorem 2. *Assume that the decay condition (1.4) be satisfied. Then, for every $u_0 \in H^2(\mathbb{R}^3)$ there exists a unique solution $u(t)$ of the initial value problem (1.1) defined on a maximal interval $t \in [0, T_{\max})$ such that*

$$u \in C^1\left([0, T_{\max}), L^2\right) \cap C\left([0, T_{\max}), H^2\right), \tag{2.1}$$

where

$$\text{either } T_{\max} = +\infty \text{ or } \lim_{t \rightarrow T_{\max}} \|u(t)\|_{H^2} = \infty. \tag{2.2}$$

Moreover, $\|u(t)\|_{L^2} \equiv \|u(0)\|_{L^2} \ \forall t \in [0, T_{\max})$, and $u(t)$ depends continuously on the initial data, i.e. if $\lim_{n \rightarrow \infty} u_0^n = u_0$ in $H^2(\mathbb{R}^3)$ then for any closed interval $I \subset [0, T_{\max})$ the solution $u^n(t)$ of problem (1.1) with initial data u_0^n is defined on I for sufficiently large n , and $\lim_{n \rightarrow \infty} u^n(t) = u(t)$ in $C(I, H^2)$.

Proof. Let $\mathcal{T}(t)$, $t \in \mathbb{R}$ be the group of unitary operators on $L^2(\mathbb{R}^3)$ generated by $-i\mathcal{H}$, where $\mathcal{H} = -\Delta + V(x)$, see proof of Theorem 7.5.5 in [12]. In addition, $\mathcal{T}(t)$ is a group of unitary operators on $H^2(\mathbb{R}^3)$ endowed with the graph norm

$$\|f\|_{\mathcal{H}} = \|\mathcal{H}f\|_{L^2} + \|f\|_{L^2}. \tag{2.3}$$

Due to the decay condition (1.4) the above norm is equivalent with the standard one in $H^2(\mathbb{R}^3)$. The initial-value problem (1.1) can be reformulated in the integral form

$$u(t) = \mathcal{T}(t)u_0 - i \int_0^t \mathcal{T}(t-s)\gamma(s)|u(s)|^2u(s) ds. \tag{2.4}$$

Since $\gamma(t)$ is uniformly bounded, the map $F = \gamma(t)|u|^2u : [0, \infty) \times H^2 \rightarrow H^2$ is locally Lipschitz, by the generalization of Lemma 8.1.2 in [12] to $x \in \mathbb{R}^3$. The contraction principle for the integral equation (2.4) finishes the proof, see Theorem 6.1.7 in [12]. \square

Theorem 3. Assume that both conditions (1.4) and (1.5) be satisfied. Then, for every $u_0 \in H^1(\mathbb{R}^3)$ there exists a unique solution $u(t)$ of the initial-value problem (1.1) defined on a maximal interval $t \in [0, T_{\max})$ such that

$$u \in C^1([0, T_{\max}), H^{-1}) \cap C([0, T_{\max}), H^1), \tag{2.5}$$

where

$$\text{either } T_{\max} = +\infty \text{ or } \lim_{t \rightarrow T_{\max}} \|u(t)\|_{H^1} = \infty. \tag{2.6}$$

Moreover, $\|u(t)\|_{L^2} \equiv \|u(0)\|_{L^2}, \forall t \in [0, T_{\max})$, and $u(t)$ depends continuously on the initial data, i.e. if $\lim_{n \rightarrow \infty} u_0^n = u_0$ in $H^1(\mathbb{R}^3)$ then for any closed interval $I \subset [0, T_{\max})$ the solution $u^n(t)$ of problem (1.1) with initial data u_0^n is defined on I for sufficiently large n , and $\lim_{n \rightarrow \infty} u^n(t) = u(t)$ in $C(I, H^1)$.

Proof. Since $\gamma(t)$ is uniformly bounded on $[0, \infty)$, the argument of Theorem 4.4.6 and Remark 4.4.8 in [2] is applied to the proof of theorem. \square

3. Global existence and long-time behavior

We decompose here the solution $u(t)$ into the slow and rapidly varying parts. Using this setting, we prove our main Theorem 1. By Theorems 2 or 3, the solution of the initial-value problem (1.1) satisfies $u(t) \in L^2(\mathbb{R}^3)$ for any $t \in [0, T_{\max})$. By the Spectral Theorem and Assumption 1, any L^2 function can be written as a sum of its projections onto the eigenvector ψ and the continuous spectrum of $\mathcal{H} = -\Delta + V$. Hence we can write

$$u(t) = A(t)e^{-i\lambda t}\psi + u_d(t), \tag{3.1}$$

where $A(t) \in \mathbb{C}$ and $u_d(t) = \mathcal{P}_c u(t)$. Using the orthogonality between ψ and the range of \mathcal{P}_c , the NLS equation (1.1) becomes the coupled system of equations in $A(t)$ and $u_d(t)$:

$$\dot{A} = -i\gamma(t)e^{i\lambda t} \langle \psi, |u|^2 u \rangle, \tag{3.2}$$

$$\dot{u}_d = -i\mathcal{H}u_d - i\gamma(t)\mathcal{P}_c[|u|^2 u], \tag{3.3}$$

where

$$\begin{aligned} |u|^2 u &= |A|^2 A e^{-i\lambda t} \psi^3 + 2|A|^2 \psi^2 u_d + A^2 e^{-2i\lambda t} \psi^2 \bar{u}_d \\ &\quad + 2A e^{-i\lambda t} \psi |u_d|^2 + \bar{A} e^{i\lambda t} \psi u_d^2 + |u_d|^2 u_d. \end{aligned} \tag{3.4}$$

3.1. The case $\gamma(t) \equiv 0$

In the linear case, when $\gamma(t) \equiv 0$, we have

$$A(t) = A_0 = \langle \psi, u_0 \rangle, \quad u_d(t) = \mathcal{T}\mathcal{P}_c u_0, \tag{3.5}$$

where $\mathcal{T}(t) = e^{-i\mathcal{H}t}$ is the group of unitary operators generated by $-i\mathcal{H}$ on $L^2(\mathbb{R}^3)$. Hence, the solution $u(t)$ is a superposition of the bound state $A_0 e^{-i\lambda t} \psi(x)$ and the dispersive part $u_d(t) = e^{-i\mathcal{H}t} \mathcal{P}_c u_0$. Under the decay condition (1.4), the dispersive part satisfies the decay estimates for all $t \geq 0$:

$$\|e^{-i\mathcal{H}t} \mathcal{P}_c f\|_{L^2_\sigma} \leq \frac{D_1}{(1+t)^{3/2}} \|f\|_{L^2_\sigma}, \quad \sigma > \frac{5}{2}, \tag{3.6}$$

$$\|e^{-i\mathcal{H}t} \mathcal{P}_c f\|_{L^4} \leq \frac{D_2}{t^{3/4}} \|f\|_{L^{4/3}}, \tag{3.7}$$

$$\|e^{-i\mathcal{H}t} \mathcal{P}_c f\|_{L^\infty} \leq \frac{D_3}{t^{3/2}} \|f\|_{L^1}, \tag{3.8}$$

where D_1, D_2 , and D_3 are some positive constants. Estimates (3.6) and (3.8) were proved in [6] and [4], respectively. Estimate (3.7) follows from (3.8) by the Riesz–Thorin interpolation argument, since $e^{-i\mathcal{H}t}$ is unitary on $L^2(\mathbb{R}^3)$. Estimates (3.6)–(3.8) imply that $u_d(t)$ decays in the same way as the solution of the free Schrödinger equation in weighted L^2 and L^p norms. We note that slightly stronger assumptions on $V(x)$ would imply that $u_d(t)$ converges as $t \rightarrow \infty$ to the solution of the free Schrödinger equation in the above spaces, see [28].

We consider the resolvent $(\mathcal{H} - \mu - i\delta)^{-1} \mathcal{P}_c$, $\delta > 0$, as a map from $L^2_\sigma(\mathbb{R}^3)$ to $L^2_{-\sigma}(\mathbb{R}^3)$ for some $\sigma > \frac{5}{2}$. By Sections 3 and 8 in [8], the resolvent converges strongly as $\delta \searrow 0$ even when μ is in the spectrum of \mathcal{H} and it satisfies the following decay estimates for all $t \geq 0$:

$$\|e^{-i\mathcal{H}t} (\mathcal{H} - \mu - i0)^{-1} \mathcal{P}_c f\|_{L^2_{-\sigma}} \leq \frac{D_4}{(1+t)^{3/2}} \|f\|_{L^2_\sigma}, \quad \mu \neq 0, \quad \sigma > \frac{5}{2}, \tag{3.9}$$

$$\|e^{-i\mathcal{H}t} (\mathcal{H} - i0)^{-1} \mathcal{P}_c f\|_{L^2_{-\sigma}} \leq \frac{D_5}{(1+t)^{1/2}} \|f\|_{L^2_\sigma}, \quad \sigma > \frac{5}{2}, \tag{3.10}$$

where D_4, D_5 are some positive constants and $(\mathcal{H} - \mu - i0)^{-1}$ denotes the limit as $\delta \searrow 0$.

3.2. The case $\gamma(t) \not\equiv 0$

In the nonlinear case, when $\gamma(t) \not\equiv 0$, the dispersive equation (3.3) can be analyzed with the Duhamel principle in the equivalent integral form:

$$u_d(t) = e^{-i\mathcal{H}t} u_d(0) - i \int_0^t \gamma(s) |A|^2 A(s) e^{-i\lambda s} e^{-i\mathcal{H}(t-s)} \mathcal{P}_c \psi^3 ds + K_A[u_d](t), \tag{3.11}$$

where

$$\begin{aligned}
 K_A[u_d](t) = & -2i \int_0^t \gamma(s)|A|^2(s)e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[\psi^2 u_d(s)] ds \\
 & -i \int_0^t \gamma(s)A^2(s)e^{-2i\lambda s}e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[\psi^2 \bar{u}_d(s)] ds \\
 & -2i \int_0^t \gamma(s)A(s)e^{-i\lambda s}e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[\psi|u_d(s)|^2] ds \\
 & -i \int_0^t \gamma(s)\bar{A}(s)e^{i\lambda t}e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[\psi u_d^2(s)] ds \\
 & -i \int_0^t \gamma(s)e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[|u_d|^2 u_d(s)] ds.
 \end{aligned} \tag{3.12}$$

We show in Section 4 that $K_A[u_d]$ is locally contractive in certain Banach spaces and that the solution $u_d(t)$ can be approximated by

$$u_d(t) \approx e^{-i\mathcal{H}t}u_d(0) - i \int_0^t \gamma(s)e^{-i\lambda s}|A|^2 A(s)e^{-i\mathcal{H}(t-s)}\mathcal{P}_c\psi^3 ds, \tag{3.13}$$

see Lemma 4.2. When representation (3.13) is substituted into the amplitude equation (3.2) via expression (3.4), we obtain a closed, nonlinear, integro-differential equation in $A(t)$. We show in Section 5 that the main contribution in the evolution of $|A(t)|$ comes from the second term on the right-hand side of (3.13). Its leading effect, see (5.13), can be computed with the Fermi Golden rule, introduced in [22].

We underline that the leading order term in the normal form equation (5.13) for the modulus of the amplitude $|A(t)|$ is quintic. This is because of the cubic nonlinearity in (1.1) and the fact that the resonance (Fermi Golden Rule) appears at first order, i.e. (1.6) holds. An $|u|^n u$ nonlinearity in (1.1), with (1.6) valid, gives a $|A|^{2n-1}$ leading order term in (5.13) whereas a cubic nonlinearity with $\lambda + (n-1)\omega < 0$ and $\lambda + n\omega > 0$, $n = 1, 2, \dots$, will give an $|A|^{4n+1}$ leading order term in (5.13). In any case, neglecting $\hat{h}(t)$, (5.13) can be exactly integrated and gives a $t^{-1/m}$ decay of the amplitude, if $|A|^{m+1}$ is the leading order term in (5.13). Under the hypothesis of Theorem 1 we show that, indeed, $\hat{h}(t)$ can be treated perturbatively by using comparison results for ODEs together with linearization and contraction principles. Hence we obtain the decay estimate (1.12), which, in turn, implies the decay estimates (1.13)–(1.14) by using representation (3.13).

We note that the proof of Theorem 1 relies heavily on the tight control of the error in representation (3.13). In this analysis, the smallness of the initial condition, defined by the small parameter ε in (1.10), is crucial. The nonlinearity of operator $K_A[u_d]$ raises two important issues that we need to address before we can treat it perturbatively.

The first issue is related to the presence of two time scales in the integral equation (3.11). The first term on the right-hand side is initially $\mathcal{O}(\varepsilon)$ and decays fast, according to the decay estimates (3.6)–(3.8). The second term is initially $\mathcal{O}(\varepsilon^3)$ but decays slowly,

as shown in Section 4. Because $K_A[u_d]$ is a nonlinear operator in $u_d(t)$, it couples the two time scales and leads to a slowly varying error of order $\mathcal{O}(\varepsilon^2)$. We keep the time scales separated and obtain a slowly varying error of order $\mathcal{O}(\varepsilon^4)$ by using the contraction principle in a hierarchy of Banach spaces, described in Appendix A.

The second issue is raised by the dependence of $K_A[u_d]$ on $A(t)$. In order to treat $K_A[u_d]$ perturbatively, we need to obtain some information on the decay rate of $|A(t)|$. However, such information would come from analysis of the amplitude equation (3.2) which can be performed only after we have obtained some estimates on the decay of $u_d(t)$. We show how to get around this vicious circle using the following continuation method:

Proof of Theorem 1. We fix $\sigma > 5/2$ and $\varepsilon > 0$, where ε is defined by the initial condition u_0 in (1.10). By Theorem 3, there exists $T_{\max} > 0$ such that the solution $u(t)$ is continuous and belongs to $H^1(\mathbb{R}^3)$ for all $t \in [0, T_{\max})$. We decompose the solution $u(t)$ according to representation (3.1).

Let the set τ be defined by

$$\tau = \left\{ t \in [0, T_{\max}) : |A(s)| \leq \frac{C\varepsilon}{(1 + 4\Gamma\varepsilon^4s)^{1/4}} \text{ for all } 0 \leq s \leq t \right\}, \tag{3.14}$$

where the constant Γ is defined by (1.9) and the constant C satisfies the inequality:

$$C > C_0 + \mathcal{D}, \tag{3.15}$$

where C_0 is introduced from the condition $|A(0)| \leq C_0\varepsilon$ and the positive constant \mathcal{D} is defined in Lemma 5.1. We will set $C_0 = 1$ without loss of generality.

Note that $T \in \tau$ implies that part of our conclusion, namely (1.12), is valid on $[0, T]$. To get (1.12) for all $t \geq 0$ it is sufficient to show $\tau = [0, T_{\max})$ and $T_{\max} = +\infty$. Here is how:

The interval $[0, T_{\max})$ is a connected topological space with the topology inherited from the standard one on real numbers.

Since $C > C_0$, we have $0 \in \tau$, so the set τ is nonempty.

The set τ is closed in $[0, T_{\max})$ because $A(t)$ is continuous. The continuity of $A(t)$ is a consequence of the continuity of $u(t)$ in $H^1(\mathbb{R}^3)$ and the continuity of the projection operator onto ψ in $L^2(\mathbb{R}^3)$.

In order to show that τ is open in $[0, T_{\max})$ we fix an arbitrary $T \in \tau$. Hence

$$|A(t)| \leq \frac{C\varepsilon}{(1 + 4\Gamma\varepsilon^4t)^{1/4}} \text{ for all } 0 \leq t \leq T. \tag{3.16}$$

Based on (3.16), in Section 4 we analyze (3.11) and basically obtain (3.13) with a tight control of the error on the time interval $t \in [0, T]$, see Lemma 4.2 and Corollary 4.1. We then rely on this information on u_d to analyze the amplitude equation (3.2), see also (3.4) for the explicit dependence on u_d . This is accomplished in Section 5 where

we show that the cubic nonlinear, resonant coupling between the amplitude $A(t)$ and the dispersive part of the system, $u_d(t)$, leads to an improved estimate for $A(t)$ on the time interval $t \in [0, T]$:

$$|A(t)| < \frac{C\varepsilon}{(1 + 4\Gamma\varepsilon^4 t)^{1/4}} \quad \text{for all } 0 \leq t \leq T.$$

This, together with the continuity of $A(t)$, imply that T is in the interior of τ hence the set τ is open in $[0, T_{\max})$, see Lemma 5.3 for details.

In conclusion the set τ is a nonempty, closed and open subset of the connected space $[0, T_{\max})$. Consequently, we have

$$\tau = [0, T_{\max}). \tag{3.17}$$

Finally, based on estimates from Sections 4 and 5 we prove in Section 6 that there exists a positive constant \mathcal{E} , such that

$$\|u(t)\|_{H^1} \leq \mathcal{E} \log(1 + 4\Gamma\varepsilon^4 t) \quad \text{for } t \in \tau, \tag{3.18}$$

see Lemma 6.1. The blow up alternative (2.6) and estimate (3.18) combined with the closure relation (3.17) imply that $T_{\max} = \infty$. Consequently, the solution $u(t)$ is globally defined and the decay estimate (1.12) holds. The decay estimates (1.13)–(1.14) follow from Corollary 4.1 by taking T be any number in $\tau = [0, \infty)$. Hence, the decay estimates (1.13)–(1.14) hold true for any $t \geq 0$. \square

Some remarks follow from the proof of Theorem 1. The parameter ε measures the size of the initial condition. On the time scale $0 < t < (4\Gamma\varepsilon^4)^{-1}$, estimates (1.12)–(1.14) show that the amplitude $|A(t)|$ remains nearly constant, order of $O(\varepsilon)$, while the dispersive part $u_d(t)$ shrinks to the size $u_d(t) \sim \varepsilon^3$. As a result, the initial stage of the dynamics is a fast relaxation of the initial value u_0 to the slowly varying bound state $e^{-i\lambda t} A(t)\psi$. Beyond this time scale, for $t > (4\Gamma\varepsilon^4)^{-1}$, the decay of the bound state occurs, according to decay rate (1.12). As a result, the solution $u(t)$ decays to zero as $t \rightarrow \infty$. Since

$$\Gamma = \frac{\gamma_1^2}{4} \text{Im}\langle \psi^3, (\mathcal{H} - \lambda - \omega - i0)^{-1} \mathcal{P}_c \psi^3 \rangle = \frac{\pi\gamma_1^2}{4} \langle \psi^3, E'(\lambda + \omega)\psi^3 \rangle \searrow 0 \quad \text{as } \omega \rightarrow \infty,$$

the decay time scale diverges in the homogeneous limit $\omega \gg 1$. As a result, the solution $u(t)$ approaches a nondecaying bound state on intermediate time scales in the limit $\omega \gg 1$, when the averaging method is applicable [30].

4. Analysis of the dispersive equation

We fix here an arbitrary time instance $T \in \tau$ and focus on the dispersive equation (3.3) in the integral form (3.11)–(3.12). Main results of this section are given by Lemmas 4.1 and 4.2. In order to define the domain and range of the nonlinear operator K_A , we consider two Banach spaces X and Y , where

$$X = C([0, T], L^2_{-\sigma} \cap L^4 \cap L^2), \tag{4.1}$$

with the norm

$$\|v\|_X = \max \left\{ \sup_{t \in [0, T]} (1+t)^{3/2} \|v(t)\|_{L^2_{-\sigma}}, \sup_{t \in [0, T]} (1+t)^{3/4} \|v(t)\|_{L^4}, \sup_{t \in [0, T]} \|v(t)\|_{L^2} \right\}$$

and

$$Y = C([0, T], L^2_{-\sigma} \cap L^4), \tag{4.2}$$

with the norm

$$\|v\|_Y = \max \left\{ \sup_{t \in [0, T]} (1+4\Gamma\varepsilon^4 t)^{3/4} \|v(t)\|_{L^2_{-\sigma}}, \sup_{t \in [0, T]} (1+4\Gamma\varepsilon^4 t)^{1/2} \|v(t)\|_{L^4} \right\}.$$

As we shall see below, the spaces X , respectively Y , are tailored to the decay estimates satisfied by the first, respectively, second (forcing) term on the right-hand side of (3.11). We use both spaces and an extension of the classical linear superposition principle to locally contractive operators, see Appendix A, to get a very sharp control the $L^2_{-\sigma}$ and L^4 norms of $u_d(t)$ which we then use in analyzing the effect of $u_d(t)$ in the amplitude equation (3.2), see Section 5.

We will be using the convolution estimates:

$$\int_0^t (1+t-s)^{-b} (1+\varepsilon s)^{-a} ds \leq \begin{cases} D(1+\varepsilon t)^{-\min(a,b)} & \text{if } b > 1 \text{ or } a > 1, \\ D\varepsilon^{b-1} (1+\varepsilon t)^{1-a-b} & \text{if } 0 < b < 1 \text{ and } 0 < a < 1 \end{cases} \tag{4.3}$$

and

$$\int_0^t (t-s)^{-b} (1+\varepsilon s)^{-a} ds \leq \begin{cases} D\varepsilon^{b-1} (1+\varepsilon t)^{-\min(a,b)} & \text{if } 0 < b < 1 \text{ and } a > 1, \\ D\varepsilon^{b-1} (1+\varepsilon t)^{1-a-b} & \text{if } 0 < b < 1 \text{ and } 0 < a < 1, \end{cases} \tag{4.4}$$

which are valid for $0 < \varepsilon \leq 1$ and $t > 0$. Using the decay estimates (3.6)–(3.7), the unitarity of $e^{-i\mathcal{H}t}$, $t \in \mathbb{R}$ on $L^2(\mathbb{R}^3)$ and the convolution estimates (4.3)–(4.4), it is

straightforward to show that the forcing terms in the integral equation (3.11) satisfy

$$e^{-i\mathcal{H}t}u_d(0) \in X, \tag{4.5}$$

$$-i \int_0^t \gamma(s)|A|^2A(s)e^{-i\lambda s}e^{-i\mathcal{H}(t-s)}\mathcal{P}_c\psi^3 ds \in Y. \tag{4.6}$$

Moreover X is continuously embedded in Y . We assume without loss of generality that $\varepsilon_0 \leq (4\Gamma)^{-1/4}$. Due to bound (1.10), we have

$$4\Gamma\varepsilon^4 \leq 1 \quad \text{and} \quad \|\cdot\|_X \leq \|\cdot\|_Y.$$

In order to solve the integral equation (3.11) by using a local contraction principle, we first study the Lipschitz properties of the nonlinear operator K_A in the spaces X and Y .

Lemma 4.1. *The operator K_A is a locally Lipschitz operator on both X and Y . More precisely, there exist T -independent positive constants $\mathcal{D}_1, \mathcal{D}_2$, which depend only on Γ , $\sup_{t \in \mathbb{R}} |\gamma(t)|$ and the dispersion constants D_1 – D_3 in (3.6)–(3.8), such that the following estimates are met: $\forall \mathcal{R}_1 > 0 \forall u, v \in X : \|u\|_X, \|v\|_X \leq \mathcal{R}_1\varepsilon$,*

$$\|K_A[u] - K_A[v]\|_X \leq \mathcal{D}_1(C + \mathcal{R}_1)^2\varepsilon^2\|u - v\|_X, \tag{4.7}$$

$$\forall \mathcal{R}_2 > 0 \forall u, v \in Y : \|u\|_Y, \|v\|_Y \leq \mathcal{R}_2\varepsilon,$$

$$\|K_A[u] - K_A[v]\|_Y \leq \mathcal{D}_2(C + \mathcal{R}_2)^2\varepsilon\|u - v\|_Y, \tag{4.8}$$

where C is defined in (3.14).

Proof. Since $K_A[0] = 0$, the invariance of X and Y under K_A will follow from the Lipschitz estimates (4.7)–(4.8). Let $u, v \in X$. For any fixed small $\varepsilon > 0$, there exists large $\mathcal{R}_1 > 0$ such that $\|u\|_X, \|v\|_X \leq \mathcal{R}_1\varepsilon$. Using definition (3.12), we derive the following estimate in $L^2_{-\sigma}(\mathbb{R}^3)$:

$$\begin{aligned} & \|K_A[u](t) - K_A[v](t)\|_{L^2_{-\sigma}} \\ & \leq 3 \sup_{0 \leq s \leq t} |\gamma(s)| \int_0^t |A|^2(s) \|e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[\psi^2|u(s) - v(s)]\|_{L^2_{-\sigma}} ds \\ & \quad + 3 \sup_{0 \leq s \leq t} |\gamma(s)| \int_0^t |A(s)| \|e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[\psi(|u(s)| + |v(s)|)|u(s) - v(s)]\|_{L^2_{-\sigma}} ds \\ & \quad + \sup_{0 \leq s \leq t} |\gamma(s)| \int_0^t \|e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[(|u(s)|^2 + |u(s)v(s)| \\ & \quad + |v(s)|^2)|u(s) - v(s)]\|_{L^2_{-\sigma}} ds. \end{aligned} \tag{4.9}$$

By the dispersive estimate (3.6) and Hölder inequalities we have for any $0 \leq s \leq t \leq T$:

$$\begin{aligned} \|e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[\psi^2|u(s) - v(s)]\|_{L^2_{-\sigma}} &\leq \frac{D_1}{(1+t-s)^{3/2}} \|(1+|x|^2)^{\sigma/2}\psi^2|u(s) - v(s)\|_{L^2} \\ &\leq \frac{D_1\|(1+|x|^2)^\sigma\psi^2\|_{L^\infty}}{(1+t-s)^{3/2}} \|u(s) - v(s)\|_{L^2_{-\sigma}} \\ &\leq \frac{D_1\|(1+|x|^2)^\sigma\psi^2\|_{L^\infty}}{(1+t-s)^{3/2}(1+s)^{3/2}} \|u - v\|_X, \end{aligned}$$

and, similarly

$$\begin{aligned} &\|e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[|\psi(|u(s)| + |v(s)|)|u(s) - v(s)]\|_{L^2_{-\sigma}} \\ &\leq \frac{D_1}{(1+t-s)^{3/2}} \|(1+|x|^2)^{\sigma/2}\psi(|u(s)| + |v(s)|)|u(s) - v(s)\|_{L^2} \\ &\leq \frac{D_1\|(1+|x|^2)^{\sigma/2}\psi\|_{L^\infty}}{(1+t-s)^{3/2}} \|u + v\|_{L^4} \|u - v\|_{L^4} \\ &\leq \frac{2D_1\mathcal{R}_1\varepsilon\|(1+|x|^2)^{\sigma/2}\psi\|_{L^\infty}}{(1+t-s)^{3/2}(1+s)^{3/2}} \|u - v\|_X. \end{aligned}$$

For the third term in estimate (4.9), we avoid putting a weight like $(1+|x|^2)^{\sigma/2}$, $\sigma > 0$, on u or v and switch to L^p -type estimates. This important modification is needed due to the fact that if $u(t) \in H^1(\mathbb{R}^3)$ is the solution of the NLS equation (1.1), then $\|u(t)\|_{L^2_\sigma}$ grows in time, according to Theorem 1. Using the dispersive estimate (3.8), we have for any $0 \leq s \leq t \leq T$:

$$\begin{aligned} &\|e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[(|u(s)|^2 + |u(s)v(s)| + |v(s)|^2)|u(s) - v(s)]\|_{L^2_{-\sigma}} \\ &\leq \|(1+|x|^2)^{-\sigma}\|_{L^2} \|e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[(|u(s)|^2 + |u(s)v(s)| + |v(s)|^2)|u(s) - v(s)]\|_{L^\infty} \\ &\leq \frac{3D_3}{2(t-s)^{3/2}} \| |u|^2 + |v|^2 \|_{L^2} \|u - v\|_{L^2} \leq \frac{3D_3\mathcal{R}_1^2\varepsilon^2}{(t-s)^{3/2}(1+s)^{3/2}} \|u - v\|_X. \end{aligned}$$

It follows from (3.14) that $|A(s)| \leq C\varepsilon$ for $0 \leq s \leq T$. As a result, the above estimates can be combined as follows:

$$\begin{aligned} &\|K_A[u](t) - K_A[v](t)\|_{L^2_{-\sigma}} \\ &\leq 3 \sup_{0 \leq s \leq t} |\gamma(s)| D_1 C^2 \varepsilon^2 \int_0^t (1+t-s)^{-3/2} (1+s)^{-3/2} ds \|u - v\|_X \\ &\quad + 6 \sup_{0 \leq s \leq t} |\gamma(s)| D_1 C \mathcal{R}_1 \varepsilon^2 \int_0^t (1+t-s)^{-3/2} (1+s)^{-3/2} ds \|u - v\|_X \end{aligned}$$

$$\begin{aligned}
 &+ 3 \sup_{0 \leq s \leq t} |\gamma(s)| D_3 \mathcal{R}_1^2 \varepsilon^2 \int_0^{t_1} (t-s)^{-3/2} (1+s)^{-3/2} ds \|u-v\|_X \\
 &+ \sup_{0 \leq s \leq t} |\gamma(s)| \int_{t_1}^t \|e^{-i\mathcal{H}(t-s)} \mathcal{P}_c[(|u(s)|^2 + |u(s)v(s)| + |v(s)|^2) \\
 &\times |u(s) - v(s)|]\|_{L^2_{-\sigma}} ds, \tag{4.10}
 \end{aligned}$$

where $t_1 = \max(0, t - 1)$. We split the last integral term in order to avoid the non-integrable singularity of $(t - s)^{-3/2}$ at $s = t$. The first three terms on the right-hand side of (4.10) are estimated with the convolution inequality (4.3). The fourth term is estimated with the dispersive estimate (3.7) as follows:

$$\begin{aligned}
 &\int_{t_1}^t \|e^{-i\mathcal{H}(t-s)} \mathcal{P}_c[(|u(s)|^2 + |u(s)v(s)| + |v(s)|^2) |u(s) - v(s)|]\|_{L^2_{-\sigma}} ds \\
 &\leq \| (1 + |x|^2)^{-\sigma/2} \|_{L^4} \int_{t_1}^t \|e^{-i\mathcal{H}(t-s)} \mathcal{P}_c[(|u(s)|^2 + |u(s)v(s)| + |v(s)|^2) \\
 &\quad \times |u(s) - v(s)|]\|_{L^4} ds \\
 &\leq \frac{3D_2}{2} \int_{t_1}^t (t-s)^{-3/4} \| (|u(s)|^2 + |v(s)|^2) |u(s) - v(s)| \|_{L^{4/3}} ds \\
 &\leq 3D_2 \mathcal{R}_1^2 \varepsilon^2 \int_{t_1}^t (t-s)^{-3/4} (1+s)^{-9/4} ds \|u-v\|_X \\
 &\leq 3D_2 \mathcal{R}_1^2 \varepsilon^2 (1+t)^{-9/4} \|u-v\|_X. \tag{4.11}
 \end{aligned}$$

Combining all the estimates, we have

$$\|K_A[u](t) - K_A[v](t)\|_{L^2_{-\sigma}} \leq (1+t)^{-3/2} \tilde{D}_1 (C + \mathcal{R}_1)^2 \varepsilon^2 \|u-v\|_X, \tag{4.12}$$

where the positive constant \tilde{D}_1 depends only on $\sup_{t \in \mathbb{R}} |\gamma(t)|$ and the dispersion constant D_1 – D_3 in the decay estimates (3.6)–(3.8). For the L^4 estimates in space X , we proceed similarly to the previous computations:

$$\begin{aligned}
 &\|K_A[u](t) - K_A[v](t)\|_{L^4} \\
 &\leq 3 \sup_{0 \leq s \leq t} |\gamma(s)| D_2 \int_0^t |A|^2(s) (t-s)^{-3/4} \|\psi^2 |u(s) - v(s)|\|_{L^{4/3}} ds \\
 &+ 3 \sup_{0 \leq s \leq t} |\gamma(s)| D_2 \int_0^t |A(s)| (t-s)^{-3/4} \|\psi (|u(s)| + |v(s)|) |u(s) - v(s)|\|_{L^{4/3}} ds \\
 &+ \sup_{0 \leq s \leq t} |\gamma(s)| D_2 \int_0^t (t-s)^{-3/4} \| (|u(s)|^2 + |u(s)v(s)| \\
 &\quad + |v(s)|^2) |u(s) - v(s)| \|_{L^{4/3}} ds. \tag{4.13}
 \end{aligned}$$

By Hölder inequalities:

$$\begin{aligned} \|\psi^2|u(s) - v(s)|\|_{L^{4/3}} &= \|(1 + |x|^2)^{\sigma/2}\psi^2(1 + |x|^2)^{-\sigma/2}|u(s) - v(s)|\|_{L^{4/3}} \\ &\leq \|(1 + |x|^2)^{\sigma/2}\psi^2\|_{L^4} \|u(s) - v(s)\|_{L^2_{-\sigma}} \\ &\leq \frac{\|(1 + |x|^2)^{\sigma/2}\psi^2\|_{L^4}}{(1 + s)^{3/2}} \|u - v\|_X, \end{aligned}$$

$$\begin{aligned} &\|\psi(|u(s)| + |v(s)|)|u(s) - v(s)|\|_{L^{4/3}} \\ &\leq \|(1 + |x|^2)^{\sigma/2}\psi\|_{L^\infty} \| |u(s)| + |v(s)| \|_{L^4} \|u(s) - v(s)\|_{L^2_{-\sigma}} \\ &\leq \frac{2\mathcal{R}_1\varepsilon}{(1 + s)^{9/4}} \|(1 + |x|^2)^{\sigma/2}\psi\|_{L^\infty} \|u - v\|_X \end{aligned}$$

and

$$\begin{aligned} &\|(|u(s)|^2 + |u(s)v(s)| + |v(s)|^2)|u(s) - v(s)|\|_{L^{4/3}} \\ &\leq \frac{3}{2} \| |u(s)|^2 + |v(s)|^2 \|_{L^2} \|u(s) - v(s)\|_{L^4} \\ &\leq \frac{3 \max(\|u(s)\|_{L^4}^2, \|v(s)\|_{L^4}^2)}{(1 + s)^{3/4}} \|u - v\|_X \\ &\leq \frac{3\mathcal{R}_1^2\varepsilon^2}{(1 + s)^{9/4}} \|u - v\|_X. \end{aligned}$$

By plugging the above estimates in (4.13) and using the convolution inequality (4.4) together with $|A(s)| \leq C\varepsilon$ for $0 \leq s \leq T$, we obtain

$$\|K_A[u](t) - K_A[v](t)\|_{L^4} \leq (1 + t)^{-3/4} \tilde{D}_2(C + \mathcal{R}_1)^2\varepsilon^2 \|u - v\|_X, \tag{4.14}$$

where the positive constant \tilde{D}_2 depends only on $\sup_{t \in \mathbb{R}} |\gamma(t)|$ and the dispersion constants D_1 – D_3 in the decay estimates (3.6)–(3.8). For the L^2 estimate we proceed as in (4.9) and (4.13) but, for the first two terms, we use the unitarity of $e^{-i\mathcal{H}t}$, $t \in \mathbb{R}$ on $L^2(\mathbb{R}^3)$:

$$\begin{aligned} &\|K_A[u](t) - K_A[v](t)\|_{L^2} \\ &\leq 3 \sup_{0 \leq s \leq t} |\gamma(s)| \int_0^t |A|^2(s) \|\psi^2|u(s) - v(s)|\|_{L^2} ds \\ &\quad + 3 \sup_{0 \leq s \leq t} |\gamma(s)| \int_0^t |A(s)| \|\psi(|u(s)| + |v(s)|)|u(s) - v(s)|\|_{L^2} ds \\ &\quad + \left\| \int_0^t \gamma(s) e^{-i\mathcal{H}(t-s)} \mathcal{P}_c[|u(s)|^2 u(s) - |v(s)|^2 v(s)] ds \right\|_{L^2}. \end{aligned}$$

By the Hölder inequalities:

$$\begin{aligned} \|\psi^2|u(s) - v(s)|\|_{L^2} &\leq \| (1 + |x|^2)^{\sigma/2} \psi^2 \|_{L^\infty} \|u(s) - v(s)\|_{L^2_{-\sigma}} \\ &\leq \frac{\| (1 + |x|^2)^{\sigma/2} \psi^2 \|_{L^\infty}}{(1 + s)^{3/2}} \|u - v\|_X \end{aligned}$$

and

$$\begin{aligned} \|\psi(|u(s)| + |v(s)|)|u(s) - v(s)|\|_{L^2} &\leq \|\psi\|_{L^\infty} \| |u(s)| + |v(s)| \|_{L^4} \|u(s) - v(s)\|_{L^4} \\ &\leq \frac{2\mathcal{R}_1 \varepsilon \|\psi\|_{L^\infty}}{(1 + s)^{3/2}} \|u - v\|_X, \end{aligned}$$

so the first two terms in (4.15) are bounded. For the last term, we denote

$$w(s) = |u(s)|^2 u(s) - |v(s)|^2 v(s)$$

and use the Strichartz estimates, see formula (2.3.5) in [2],

$$\left\| \int_0^t \gamma(s) e^{-i\mathcal{H}(t-s)} \mathcal{P}_c w(s) ds \right\|_{L^2} \leq C \|w(s, x)\|_{L^{8/5}([0,t], L^{4/3})},$$

where C is a constant. Now

$$\begin{aligned} \|w(s)\|_{L^{4/3}} &\leq \frac{3}{2} \| (|u(s)|^2 + |v(s)|^2) (|u(s) - |v(s)||) \|_{L^{4/3}} \\ &\leq \frac{3}{2} \| |u(s)|^2 + |v(s)|^2 \|_{L^2} \|u(s) - v(s)\|_{L^4} \\ &\leq \frac{3\mathcal{R}_1^2 \varepsilon^2}{(1 + s)^{9/4}} \|u - v\|_X. \end{aligned}$$

Hence

$$\left\| \int_0^t \gamma(s) e^{-i\mathcal{H}(t-s)} \mathcal{P}_c w(s) ds \right\|_{L^2} \leq 3D_1 \mathcal{R}_1^2 \varepsilon^2 \sup_{0 \leq s \leq t} |\gamma(s)| \|u - v\|_X (1 + s)^{-9/4} \| \cdot \|_{L^{8/5}([0,t])}.$$

In conclusion

$$\left\| \int_0^t \gamma(s) e^{-i\mathcal{H}(t-s)} \mathcal{P}_c w(s) ds \right\|_{L^2} \leq 3D_1 \sup_{0 \leq s \leq t} |\gamma(s)| \mathcal{R}_1^2 \varepsilon^2 \|u - v\|_X.$$

Using the above estimates in bound (4.15) and taking into account that $|A(s)| \leq \mathcal{C}\varepsilon$ for $0 \leq s \leq T$, we obtain

$$\|K_A[u](t) - K_A[v](t)\|_{L^2} \leq \tilde{D}_3(\mathcal{C} + \mathcal{R}_1)^2 \varepsilon^2 \|u - v\|_X, \tag{4.15}$$

where the positive constant \tilde{D}_3 depends only on $\sup_{t \in \mathbb{R}} |\gamma(t)|$ and the dispersion constants $D_1 - D_3$ in the decay estimates (3.6)–(3.8). Combining estimates (4.12), (4.14), and (4.15), we obtain estimate (4.7), where $\mathcal{D}_1 \geq \max\{\tilde{D}_1, \tilde{D}_2, \tilde{D}_3\}$.

Let $u, v \in Y$. For any fixed small $\varepsilon > 0$, there exists large $\mathcal{R}_2 > 0$, such that $\|u\|_Y, \|v\|_Y \leq \mathcal{R}_2 \varepsilon$. The proof of estimate (4.8) follows closely that of estimate (4.7) with the simplification that the space Y requires smaller decay in time. On the other hand, it also requires that $|A(t)|$ decays on $[0, T]$, which is not necessary in the proof of bound (4.7). Similarly to estimate (4.9), we use the dispersive estimate (3.6), definition (3.12), and the decay estimate (3.14) and obtain the following estimate in $L^2_{-\sigma}(\mathbb{R}^3)$:

$$\begin{aligned} & \|K_A[u](t) - K_A[v](t)\|_{L^2_{-\sigma}} \\ & \leq 3 \sup_{0 \leq s \leq t} |\gamma(s)| \int_0^t \frac{\mathcal{C}^2 \varepsilon^2}{(1 + 4\Gamma \varepsilon^4 s)^{1/2}} \frac{D_1}{(1 + t - s)^{3/2}} \|\psi^2(u(s) - v(s))\|_{L^2_{\sigma}} ds \\ & \quad + 3 \sup_{0 \leq s \leq t} |\gamma(s)| \int_0^t \frac{\mathcal{C} \varepsilon}{(1 + 4\Gamma \varepsilon^4 s)^{1/4}} \frac{D_1}{(1 + t - s)^{3/2}} \|\psi(u^2(s) - v^2(s))\|_{L^2_{\sigma}} ds \\ & \quad + \sup_{0 \leq s \leq t} |\gamma(s)| \int_0^t \|e^{-i\mathcal{H}(t-s)} \mathcal{P}_c[|u(s)|^2 + |u(s)v(s)| + |v(s)|^2] |u(s) - v(s)|\|_{L^2_{-\sigma}} ds. \end{aligned} \tag{4.16}$$

The first two integrals are bounded by the Hölder inequalities and the properties of functions in Y :

$$\begin{aligned} \|\psi^2(u(s) - v(s))\|_{L^2_{\sigma}} & \leq \|(1 + |x|^2)^{\sigma} \psi^2\|_{L^{\infty}} \|u(s) - v(s)\|_{L^2_{-\sigma}} \\ & \leq \frac{\|(1 + |x|^2)^{\sigma} \psi^2\|_{L^{\infty}}}{(1 + 4\Gamma \varepsilon^4 s)^{3/4}} \|u - v\|_Y \end{aligned}$$

and

$$\begin{aligned} \|\psi(u^2(s) - v^2(s))\|_{L^2_{\sigma}} & \leq \|(1 + |x|^2)^{\sigma/2} \psi\|_{L^{\infty}} (\|u(s)\| + \|v(s)\|)_{L^4} \|u(s) - v(s)\|_{L^4} \\ & \leq \frac{2\mathcal{R}_2 \varepsilon \|(1 + |x|^2)^{\sigma/2} \psi\|_{L^{\infty}}}{1 + 4\Gamma \varepsilon^4 s} \|u - v\|_Y. \end{aligned}$$

The last integral term is bounded with the estimates in $L^4(\mathbb{R}^3)$:

$$\begin{aligned} & \|e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[|u(s)|^2 + |u(s)v(s)| + |v(s)|^2]|u(s) - v(s)|\|_{L^2_{-\sigma}} \\ & \leq \| (1 + |x|^2)^{-\sigma} \|_{L^4} \left\| e^{-i\mathcal{H}(t-s)}\mathcal{P}_c[|u(s)|^2 + |u(s)v(s)| + |v(s)|^2]|u(s) - v(s)| \right\|_{L^4} \\ & \leq \frac{3D_2}{2(t-s)^{3/4}} \| |u|^2 + |v|^2 \|_{L^2} \|u - v\|_{L^4} \\ & \leq \frac{3D_2\mathcal{R}_2^2\varepsilon^2}{(t-s)^{3/4}(1 + 4\Gamma\varepsilon^4s)^{3/2}} \|u - v\|_Y. \end{aligned}$$

Plugging the above estimates into (4.16) and using the convolution inequalities (4.3)–(4.4) we obtain

$$\|K_A[u](t) - K_A[v](t)\|_{L^2_{-\sigma}} \leq \tilde{D}_4(\mathcal{C} + \mathcal{R}_2)^2\varepsilon(1 + 4\Gamma\varepsilon^4t)^{-3/4} \|u - v\|_Y, \tag{4.17}$$

where the positive constant \tilde{D}_4 depends only on Γ , $\sup_{t \in \mathbb{R}} |\gamma(t)|$ and the dispersion constants D_1 – D_3 in the decay estimates (3.6)–(3.8).

The estimates in X , given in (4.13)–(4.14), extend to similar estimates in Y . Although the functions u, v decay slowly in time but the slow decay is compensated by the decay in $|A(s)|$, given by (3.14). As a result, we have

$$\|K_A[u](t) - K_A[v](t)\|_{L^4} \leq \tilde{D}_5(\mathcal{C} + \mathcal{R}_2)^2\varepsilon(1 + 4\Gamma\varepsilon^4t)^{-1/2} \|u - v\|_Y, \tag{4.18}$$

where the positive constant \tilde{D}_5 depends on Γ , $\sup_{t \in \mathbb{R}} |\gamma(t)|$, and the dispersion constant D_1 – D_3 in the decay estimates (3.6)–(3.8). Combining (4.17) and (4.18), we find estimate (4.8), where $\mathcal{D}_2 \geq \max\{\tilde{D}_4, \tilde{D}_5\}$. \square

In Appendix A we extend the classical principle of superposition from forced linear equations to the fixed points of nonlinear, locally contractive operators in a hierarchy of Banach spaces. In the particular case of the integral equation (3.11), this principle implies that the solution $u_d(t)$ can be written as a sum of a function in X and a function in Y . The former is the response to the first forcing term and, although it is relatively large at the beginning as $O(\varepsilon)$, it decays fast in time. The latter can be interpreted as the response to the second forcing term and, although it is relatively small at the beginning as $O(\varepsilon^3)$, it decays very slowly in time and eventually dominates. Because the two forcing terms have different initial sizes and evolve on different time scales, separation of each term is essential in the proof of our main result. We note that modulation equations were used in [23,24,26] to separate the time scales between similar terms. We completely avoid using the modulation equations and obtain sharper results by relying on the contraction principle of Appendix A.

Lemma 4.2. *There exists a T -independent positive constant \mathcal{D} , which depends only on Γ , $\sup_{t \in \mathbb{R}} |\gamma(t)|$, and the dispersion constants D_1 – D_3 in the decay estimates (3.6)–(3.8), such that the solution $u_d(t)$ of the integral equation (3.11) belongs to Y for*

$$\varepsilon < \varepsilon_0 \leq \frac{1}{2} \mathcal{D}^{-1} \mathcal{C}^{-3}. \tag{4.19}$$

Moreover, the solution $u_d(t)$ can be written as

$$u_d(t) = f(t) + v_d(t) + E_d(t) = e^{-i\mathcal{H}t} u_d(0) + f(t) + K_A[f + v_d](t) + F_d(t), \tag{4.20}$$

where

$$f(t) = -i \int_0^t \gamma(s) |A|^2 A(s) e^{-i\lambda s} e^{-i\mathcal{H}(t-s)} \mathcal{P}_c \psi^3 ds \tag{4.21}$$

and

$$\|v_d\|_X \leq \mathcal{D}\varepsilon, \quad \|E_d\|_Y \leq \mathcal{D}\mathcal{C}^5 \varepsilon^3, \quad \|F_d\|_Y \leq \mathcal{D}\mathcal{C}^7 \varepsilon^4. \tag{4.22}$$

Proof. We apply Proposition A.2 from Appendix A to the integral equations (3.11) and

$$v_d(t) = e^{-i\mathcal{H}t} u_d(0) + K_A[v_d](t). \tag{4.23}$$

Hypothesis (A.1), (A.2) and (A.11) hold because of Lemma 4.1. To verify (A.12)–(A.16), we fix $L_1 = L_2 = 1/2$. Due to inclusions (4.5)–(4.6), there exist constants \mathcal{D}_3 and \mathcal{D}_4 , such that

$$\begin{aligned} \|e^{-i\mathcal{H}t} u_d(0)\|_X &\leq \mathcal{D}_3 \varepsilon \\ \|e^{-i\mathcal{H}t} u_d(0) + f(t)\|_Y &\leq \|e^{-i\mathcal{H}t} u_d(0)\|_Y + \|f(t)\|_Y \leq \mathcal{D}_4 \varepsilon (1 + \mathcal{C}^3 \max\{\varepsilon \Gamma^{-1/4}, \varepsilon^2\}). \end{aligned}$$

Let $R_1 = 2\mathcal{D}_3 \varepsilon$ and $R_2 = 3\mathcal{D}_4 \varepsilon$. Then, Eqs. (A.13), (A.15) and (A.16) hold with the above choices of $L_{1,2}$ and $R_{1,2}$, provided that $\mathcal{D} \geq \max\{\Gamma^{-1/4}, 2^{-1/2}\}$. To simplify the expression of the Lipschitz constants in bounds (4.7)–(4.8) we assume that $\mathcal{D} \geq \max\{2\mathcal{D}_3, 3\mathcal{D}_4\}$ and $\mathcal{C} > \mathcal{D}$, according to inequality (3.15). The Lipschitz constants for $K_A[u]$ in the balls of radius R_1 for X and R_2 for Y are dominated by

$$L_X(R_1) \leq 4\mathcal{D}_3 \mathcal{C}^2 \varepsilon^2, \quad L_Y(R_2) \leq 4\mathcal{D}_4 \mathcal{C}^2 \varepsilon. \tag{4.24}$$

Conditions (A.12) and (A.14) with $L_1 = L_2 = 1/2$ hold provided that bound (4.19) holds. With the above constraints, Proposition A.2 is now applied to our case, when

$$\|v_d\|_X \leq 2\mathcal{D}_3 \varepsilon, \quad \|f(t)\|_Y \leq \mathcal{D}_4 \Gamma^{-1/4} \mathcal{C}^3 \varepsilon^2. \tag{4.25}$$

For the Lipschitz constants, we can use (4.24) which are both less than 1/2. As a result, estimates (4.22) follow directly from (A.19) and (A.21) provided that

$$\mathcal{D} \geq \max\{2\mathcal{D}_3, 8\mathcal{D}_1\mathcal{D}_4\Gamma^{-1/4}, 32\mathcal{D}_2^2\mathcal{D}_4\Gamma^{-1/4}\}, \tag{4.26}$$

where the constants $\mathcal{D}_{1,2}$ are defined in bounds (4.7)–(4.8). \square

Corollary 4.1. *The solution $u_d(t)$ of the integral equation (3.11) satisfies the decay estimates for $0 \leq t \leq T$, $T \in \tau$:*

$$\|u_d(t) - f(t)\|_{L^2_{-\sigma}} \leq \frac{\mathcal{D}\varepsilon}{(1+t)^{3/2}} + \frac{\mathcal{D}\mathcal{C}^7\varepsilon^4}{(1+4\Gamma\varepsilon^4t)^{3/4}}, \tag{4.27}$$

$$\|u_d(t)\|_{L^2_{-\sigma}} \leq \frac{\mathcal{D}\varepsilon}{(1+t)^{3/2}} + \frac{\mathcal{D}\mathcal{C}^5\varepsilon^3}{(1+4\Gamma\varepsilon^4t)^{3/4}}, \tag{4.28}$$

$$\|u_d(t)\|_{L^4} \leq \frac{\mathcal{D}\varepsilon}{(1+t)^{3/4}} + \frac{\mathcal{D}\mathcal{C}^3\varepsilon^2}{(1+4\Gamma\varepsilon^4t)^{1/2}}. \tag{4.29}$$

Proof. Bounds (4.28) and (4.29) follow from (4.20), (4.22), and (4.25). Bound (4.27) is obtained from (4.20) and (4.23) by direct calculation of $\|K_A[v_d + f]\|_{L^2_{-\sigma}}$ that uses estimates (4.25) and the argument for the $L^2_{-\sigma}$ norms in Lemma 4.1. \square

5. Normal form reduction of the amplitude equation

We analyze here the amplitude equation (3.2) on the time interval $[0, T]$, $T \in \tau$. It shows explicitly the decay of $A(t)$ due to the coupling with the dispersive part $u_d(t)$. In what follows \mathcal{D} , \mathcal{D}_1 , \mathcal{D}_2 , etc., denote T -independent positive constants that depend only on Γ , $\sup_{t \in \mathbb{R}} |\gamma(t)|$, and the dispersion constants D_1 – D_4 in the decay estimates (3.6)–(3.9). In general, these constants are slightly bigger than the constant \mathcal{D} , defined in Lemma 4.2. Main results of this section are given by Lemmas 5.1, 5.2, and 5.3.

We eliminate the fast oscillations in the phase of $A(t)$ in the amplitude equation (3.2) with the cubic term (3.4):

$$\begin{aligned} \frac{d|A|^2}{dt} &= 2\gamma(t)|A|^2(t) \operatorname{Im} \left[\overline{A}(t)e^{i\lambda t} \langle \psi^3, u_d(t) \rangle \right] \\ &\quad + 2\gamma(t) \operatorname{Im} \left[\overline{A}^2(t)e^{2i\lambda t} \langle \psi^2, u_d^2(t) \rangle \right] \\ &\quad + 2\gamma(t) \operatorname{Im} \left[\overline{A}(t)e^{i\lambda t} \langle \psi, |u_d|^2 u_d(t) \rangle \right]. \end{aligned} \tag{5.1}$$

The leading-order contribution of $u_d(t)$ appears in the first term on the right-hand side of (5.1). Let

$$g(t) = \frac{\gamma(t)}{|A(t)|} \operatorname{Im} \left[\bar{A}^2(t) e^{2i\lambda t} \langle \psi^2, u_d^2(t) \rangle \right] + \frac{\gamma(t)}{|A(t)|} \operatorname{Im} \left[\bar{A}(t) e^{i\lambda t} \langle \psi, |u_d|^2 u_d(t) \rangle \right] \quad (5.2)$$

and rewrite the amplitude equation (5.1) in the form:

$$\frac{d|A|}{dt} = \gamma(t)|A|(t) \operatorname{Im} \left[\bar{A}(t) e^{i\lambda t} \langle \psi^3, u_d(t) \rangle \right] + g(t). \quad (5.3)$$

By the Hölder inequalities, we have for $t \in [0, T]$:

$$\begin{aligned} |\langle \psi^2, u_d^2(t) \rangle| &= |\langle (1 + |x|)^{2\sigma} \psi^2, (1 + |x|)^{-2\sigma} u_d^2(t) \rangle| \\ &\leq \| (1 + |x|)^\sigma \psi \|_{L^\infty}^2 \| u_d(t) \|_{L^2_{-\sigma}}^2 \\ &\leq \frac{\mathcal{D}_1 \varepsilon^2}{(1 + t)^3} + \frac{\mathcal{D}_1 \mathcal{C}^{10} \varepsilon^6}{(1 + 4\Gamma \varepsilon^4 t)^{3/2}}, \end{aligned}$$

where, for the last inequality, we have used estimate (4.28), as well as the inequality:

$$\forall a, b > 0 : \quad (a + b)^2 \leq 2(a^2 + b^2). \quad (5.4)$$

Similarly,

$$\begin{aligned} |\langle \psi, |u_d|^2 u_d(t) \rangle| &= |\langle (1 + |x|)^\sigma \psi, (1 + |x|)^{-\sigma} u_d(t) |u_d|^2(t) \rangle| \\ &\leq \| (1 + |x|)^\sigma \psi \|_{L^\infty} \| u_d(t) \|_{L^2_{-\sigma}} \| u_d(t) \|_{L^4}^2 \\ &\leq \frac{\mathcal{D}_2 \varepsilon^2}{(1 + t)^{12/5}} + \frac{\mathcal{D}_2 \mathcal{C}^{12} \varepsilon^7}{(1 + 4\Gamma \varepsilon^4 t)^{7/4}}, \end{aligned}$$

where, for the last inequality, we have used estimates (4.28)–(4.29), as well as

$$\forall a, b, c, d > 0 : \quad (a + b)(c + d)^2 \leq 2^{4/3} \frac{a^{7/3} + b^{7/3}}{7/3} + 2^{5/2} \frac{c^{7/2} + d^{7/2}}{7/2}. \quad (5.5)$$

Inequality (5.5) can be obtained from Young and Hölder inequalities. Taking into account that $|A(t)|$ decays on $[0, T]$, $T \in \tau$, we obtain the estimate for $t \in [0, T]$:

$$|g(t)| \leq \frac{\mathcal{D}_3 \varepsilon^2}{(1 + t)^{12/5}} + \frac{\mathcal{D}_3 \mathcal{C}^{12} \varepsilon^7}{(1 + 4\Gamma \varepsilon^4 t)^{7/4}}. \quad (5.6)$$

Let $u_d(t) = f(t) + (u_d(t) - f(t))$, where $f(t)$ is the forcing term from the bound state, given in (4.21). We rewrite the amplitude equation (5.3) in the form:

$$\frac{d|A|}{dt} = \gamma(t)|A|(t) \operatorname{Im} \left[\overline{A}(t)e^{i\lambda t} \langle \psi^3, f(t) \rangle \right] + h(t), \tag{5.7}$$

where, due to estimates (4.27) and (5.6), the correction term $h(t)$ satisfies the estimate for $t \in [0, T]$:

$$|h(t)| \leq \frac{D_4 C^2 \varepsilon^3}{(1+t)^{3/2} (1+4\Gamma \varepsilon^4 t)^{1/2}} + \frac{D_4 C^9 \varepsilon^6}{(1+4\Gamma \varepsilon^4 t)^{5/4}} + \frac{D_4 \varepsilon^2}{(1+t)^{12/5}} + \frac{D_4 C^{12} \varepsilon^7}{(1+4\Gamma \varepsilon^4 t)^{7/4}}. \tag{5.8}$$

The effect of $f(t)$ in the amplitude equation (5.7) becomes evident if we integrate by parts once. For rigorous computations, we use weighted L^2 spaces with weights $w_{\pm} = (1 + |x|)^{\pm\sigma}$. Using notations:

$$\gamma(t) = \gamma_0 + \gamma_1 \cos(\omega t) = \sum_{j=-1}^1 \gamma^j e^{-i\omega_j t},$$

where $\gamma^0 = \gamma_0$, $\gamma^{\pm 1} = \gamma_1/2$, $\omega_0 = 0$, and $\omega_{\pm 1} = \pm|\omega|$, we compute the inner product in (5.7) as follows:

$$\begin{aligned} & \langle \psi^3, f(t) \rangle \\ &= -i \left\langle \psi^3, \int_0^t \gamma(s) |A|^2 A(s) e^{-i\lambda s} e^{-i\mathcal{H}(t-s)} \mathcal{P}_c \psi^3 ds \right\rangle \\ &= -i \sum_{j=-1}^1 \gamma^j \left\langle w_+ \psi^3, \int_0^t |A|^2 A(s) w_- e^{-i(\lambda + \omega_j)s} e^{-i\mathcal{H}(t-s)} \mathcal{P}_c \psi^3 ds \right\rangle \\ &= -|A|^2 A(t) \sum_{j=-1}^1 \gamma^j \langle w_+ \psi^3, w_- e^{-i\mathcal{H}t} e^{i(\mathcal{H} - \lambda - \omega_j)s} (\mathcal{H} - \lambda - \omega_j - i0)^{-1} \mathcal{P}_c \psi^3 \rangle \Big|_{s=0}^{s=t} \\ &\quad + \sum_{j=-1}^1 \gamma^j \int_0^t \partial_s (|A|^2 A(s)) e^{-i(\lambda + \omega_j)s} \langle w_+ \psi^3, w_- e^{-i\mathcal{H}(t-s)} \\ &\quad \times (\mathcal{H} - \lambda - \omega_j - i0)^{-1} \mathcal{P}_c \psi^3 \rangle ds \\ &= -|A|^2 A(t) \sum_{j=-1}^1 \gamma^j e^{-i(\lambda + \omega_j)t} \langle w_+ \psi^3, w_- (\mathcal{H} - \lambda - \omega_j - i0)^{-1} \mathcal{P}_c \psi^3 \rangle + \tilde{h}(t), \tag{5.9} \end{aligned}$$

where

$$\begin{aligned} \tilde{h}(t) &= |A|^2 A(0) \sum_{j=-1}^1 \gamma^j \langle w_+ \psi^3, w_- e^{-i\mathcal{H}t} (\mathcal{H} - \lambda - \omega_j - i0)^{-1} \mathcal{P}_c \psi^3 \rangle \\ &+ \sum_{j=-1}^1 \gamma^j \int_0^t \partial_s (|A|^2 A(s)) e^{-i(\lambda + \omega_j)s} \langle w_+ \psi^3, w_- e^{-i\mathcal{H}(t-s)} \\ &\times (\mathcal{H} - \lambda - \omega_j - i0)^{-1} \mathcal{P}_c \psi^3 \rangle ds. \end{aligned}$$

In order to estimate $\tilde{h}(t)$, we note that

$$|\partial_s (|A|^2 A(s))| \leq 3|A|^2(s) |\partial_s A(s)|$$

and, by virtue of the amplitude equation (3.2),

$$|\partial_s A(s)| = |\gamma(s) \langle \psi, \mathcal{P}_c |u|^2 u(s) \rangle| \leq \sup \gamma \|w_+ \psi\|_{L^\infty} \|u\|_{L^2_{-\sigma}} \|u\|_{L^4}^2 \tag{5.10}$$

Using decomposition (3.1) and estimates (3.14) and (4.28)–(4.29) for $A(s)$ and $u_d(s)$ on $s \in [0, T]$, we obtain

$$|\partial_s (|A|^2 A(s))| \leq \frac{\mathcal{D}_5 \mathcal{C}^5 \varepsilon^5}{(1 + 4\Gamma \varepsilon^4 t)^{5/4}}. \tag{5.11}$$

Using estimates (3.9) and (5.11), we obtain for $t \in [0, T]$:

$$|\tilde{h}(t)| \leq \frac{\mathcal{D}_6 \varepsilon^3}{(1+t)^{3/2}} + \frac{\mathcal{D}_6 \mathcal{C}^5 \varepsilon^5}{(1 + 4\Gamma \varepsilon^4 t)^{5/4}}. \tag{5.12}$$

After straightforward calculations, the amplitude equation (5.7) simplifies to the form:

$$\frac{d|A|}{dt} = (-\Gamma + \rho(t)) |A(t)|^5 + \hat{h}(t), \tag{5.13}$$

where the positive parameter Γ is given by (1.9), the function $\rho(t)$ is periodic with mean zero:

$$\begin{aligned} \rho(t) &= -\cos(2\omega t) \frac{\gamma_1^2}{4} \langle \psi^3, \text{Im}(\mathcal{H} - \lambda - \omega - i0)^{-1} \mathcal{P}_c \psi^3 \rangle \\ &+ \sin(2\omega t) \frac{\gamma_1^2}{4} \left[\langle \psi^3, \text{Re}(\mathcal{H} - \lambda - \omega - i0)^{-1} \mathcal{P}_c \psi^3 \rangle - \langle \psi^3, (\mathcal{H} - \lambda + \omega)^{-1} \mathcal{P}_c \psi^3 \rangle \right] \end{aligned}$$

$$\begin{aligned}
 & -\cos(\omega t) \frac{\gamma_0 \gamma_1}{2} \langle \psi^3, \text{Im}(\mathcal{H} - \lambda - \omega - i0)^{-1} \mathcal{P}_c \psi^3 \rangle \\
 & + \sin(\omega t) \frac{\gamma_0 \gamma_1}{2} \left[\langle \psi^3, \text{Re}(\mathcal{H} - \lambda - \omega - i0)^{-1} \mathcal{P}_c \psi^3 \rangle \right. \\
 & \left. - \langle \psi^3, (\mathcal{H} - \lambda + \omega)^{-1} \mathcal{P}_c \psi^3 \rangle \right]
 \end{aligned} \tag{5.14}$$

and the function $\hat{h}(t)$ is given by

$$\hat{h}(t) = h(t) + \gamma(t) |A|(t) \text{Im} \left[\bar{A}(t) e^{i\lambda t} \tilde{h}(t) \right]. \tag{5.15}$$

Due to estimates (5.8) and (5.12), the function $\hat{h}(t)$ is bounded for $t \in [0, T]$ by:

$$\begin{aligned}
 |\hat{h}(t)| \leq R(t) &= \frac{\mathcal{D}_7 \mathcal{C}^2 \varepsilon^3}{(1+t)^{3/2} (1+4\Gamma \varepsilon^4 t)^{1/2}} + \frac{\mathcal{D}_7 \mathcal{C}^9 \varepsilon^6}{(1+4\Gamma \varepsilon^4 t)^{5/4}} \\
 &+ \frac{\mathcal{D}_7 \varepsilon^2}{(1+t)^{12/5}} + \frac{\mathcal{D}_7 \mathcal{C}^{12} \varepsilon^7}{(1+4\Gamma \varepsilon^4 t)^{7/4}}.
 \end{aligned} \tag{5.16}$$

We note that an equivalent way of writing $\Gamma - \rho(t)$ is

$$\Gamma - \rho(t) = \sum_{j=-1}^1 |\gamma_j|^2 \langle w_+ \psi^3, w_- (\mathcal{H} - \lambda - \omega_j - i0)^{-1} \mathcal{P}_c \psi^3 \rangle,$$

such that

$$|\Gamma - \rho(t)| \leq D_4 \sup_{t \in \mathbb{R}} |\gamma(t)|^2 \|\psi^3\|_{L^2_\sigma}, \tag{5.17}$$

where D_4 is the constant in estimate (3.9). In the rest of this section, we analyze the decay estimate on the amplitude $|A(t)|$ from the amplitude equation (5.13). By taking the upper bound in (5.13), we consider the following comparison equation:

$$\frac{dB}{dt} = (-\Gamma + \rho(t)) B^5 + R(t), \quad B(0) = \varepsilon, \tag{5.18}$$

where $B(t)$ is a real-valued function, while parameters $\Gamma > 0$, ε , $\rho(t)$, and $R(t)$ are given by (1.9), (1.10), (5.14), and (5.16), respectively.

Lemma 5.1. *There exists a T -independent constant \mathcal{D} such that if ε satisfies the bound:*

$$\varepsilon < \varepsilon_0 \leq \frac{1}{2} \mathcal{D}^{-1} \mathcal{C}^{-9}, \tag{5.19}$$

then the initial-value problem (5.18) is well posed on $t \in [0, T]$. Moreover, the solution $B(t)$ satisfies the bounds for $t \in [0, T]$:

$$0 \leq B(t) \leq \frac{D\varepsilon}{(1 + 4\Gamma\varepsilon^4 t)^{1/4}} + \frac{D\mathcal{C}^9 \varepsilon^2}{(1 + 4\Gamma\varepsilon^4 t)^{1/4}}. \tag{5.20}$$

Proof. We will treat the correction term $R(t)$ perturbatively and linearize around the solution of the dominant equation:

$$\frac{dB_0}{dt} = (-\Gamma + \rho(t))B_0^5, \quad B_0(0) = \varepsilon. \tag{5.21}$$

Using separation of variables, we have the solution:

$$B_0(t) = \frac{\varepsilon}{(1 + 4\varepsilon^4 \Omega(t))^{1/4}}, \quad t \geq 0, \tag{5.22}$$

where

$$\Omega(t) = \int_0^t (\Gamma - \rho(s)) ds. \tag{5.23}$$

Even though $\Omega(t)$ may take negative values, $B_0(t)$ is defined for all $t \geq 0$, if ε is sufficiently small. Indeed, since $\rho(t)$ is continuous and periodic on \mathbb{R} with mean zero we have that $\Omega(t)$ is continuous on \mathbb{R} and:

$$\lim_{t \rightarrow \infty} \frac{\Omega(t)}{t} = \Gamma > 0. \tag{5.24}$$

Therefore, there exists $N > 0$ such that $\Omega(t) \geq 0$ for $t > N$. But $\Omega(t)$ is continuous on $[0, N]$, hence bounded. Let us denote

$$\Omega_{\max} = \sup_{0 \leq t \leq N} \Omega(t), \quad \Omega_{\min} = \inf_{0 \leq t \leq N} \Omega(t), \tag{5.25}$$

where the minimum of $\Omega(t)$ and the maximum of $\Omega(t) - \Gamma t$ are in fact attained on $t \in [0, 2\pi/\omega]$ because of the periodicity of $\rho(t)$. In the case $\Omega_{\min} < 0$ we choose

$$\varepsilon < \varepsilon_0 \leq (-1/\Omega_{\min})^{1/4},$$

and $B_0(t)$ is well defined for all $t \geq 0$. We note that $\Omega(t)$ can be estimated on $t \in [0, N]$ by using (5.17) and (5.23) in terms of $\sup_{t \in \mathbb{R}} |\gamma(t)|$ and the dispersive constant D_4 in

the decay estimate (3.9). Hence the above restriction on ε_0 can be accommodated in bound (5.19). Proceeding in a similar manner, we show that

$$B_0(t) \leq \frac{\mathcal{D}_1 \varepsilon}{(1 + 4\Gamma \varepsilon^4 t)^{1/4}}, \tag{5.26}$$

where \mathcal{D}_1 satisfies the bounds:

$$\sup_{0 \leq t < \infty} \left(\frac{1 + 4\Gamma \varepsilon^4 t}{1 + 4\varepsilon^4 \Omega(t)} \right)^{1/4} \leq \mathcal{D}_1 < \infty. \tag{5.27}$$

More precisely, we introduce the auxiliary function

$$M(t) = \frac{1 + 4\Gamma \varepsilon^4 t}{1 + 4\varepsilon^4 \Omega(t)} : [0, \infty) \rightarrow \mathbb{R}, \tag{5.28}$$

such that $M(0) = 1$ and

$$\lim_{t \rightarrow \infty} M(t) = \lim_{t \rightarrow \infty} \frac{\frac{1}{t} + 4\Gamma \varepsilon^4}{\frac{1}{t} + 4\varepsilon^4 \frac{\Omega(t)}{t}} = \frac{4\Gamma \varepsilon^4}{4\Gamma \varepsilon^4} = 1. \tag{5.29}$$

Hence there exist $N > 0$ such that $M(t) \leq 3/2$, for $t > N$. But $M(t)$ is continuous, hence bounded on the compact interval $[0, N]$. If we choose

$$\mathcal{D}_1 \geq \left(\max \left(\frac{3}{2}, \sup_{t \in [0, N]} M(t) \right) \right)^{1/4},$$

then bound (5.27) holds. The latter implies (5.26) due to the exact solution (5.22). We represent solution of the comparison equation (5.18) as $B(t) = B_0(t) + B_1(t)$, where $B_1(t)$ satisfies

$$\frac{dB_1}{dt} = 5B_0^4(t)(-\Gamma + \rho(t))B_1(t) + (-\Gamma + \rho(t)) \sum_{k=2}^5 \binom{5}{k} B_0^{5-k}(t) B_1^k(t) + R(t), \tag{5.30}$$

such that $B_1(0) = 0$. Since the right-hand side of (5.30) is continuous in t and locally Lipschitz in the dependent variable B_1 , the initial-value problem (5.30) is locally well posed. In order to show that it is also well posed on $t \in [0, T]$, we use the propagator of the linear part to write the solution of Eq. (5.30) in the integral form:

$$\begin{aligned} B_1(t) = K[B_1](t) &= \sum_{k=2}^5 \binom{5}{k} \int_0^t U(t, s)(-\Gamma + \rho(s)) B_0^{5-k}(s) B_1^k(s) ds \\ &+ \int_0^t U(t, s) R(s) ds, \end{aligned} \tag{5.31}$$

where

$$U(t, s) = \left(\frac{1 + 4\varepsilon^4 \Omega(s)}{1 + 4\varepsilon^4 \Omega(t)} \right)^{5/4}. \tag{5.32}$$

Under condition (5.19), we prove that the operator $K[B_1]$ is a contraction on the ball of radius $\mathcal{R}\varepsilon^2$, where $0 < \mathcal{R} \leq \mathcal{DC}^9$, in the Banach space $Z = C([0, T], \mathbb{R})$ equipped with the norm:

$$\|f\|_Z = \sup_{t \in [0, T]} (1 + 4\Gamma\varepsilon^4 t)^{1/4} |f(t)|. \tag{5.33}$$

It is clear from bound (5.27) and similar computations that there exists the constant \mathcal{D}_2 , such that

$$\sup_{t \in [0, \infty)} \left(\frac{1 + 4\Gamma\varepsilon^4 t}{1 + 4\varepsilon^4 \Omega(t)} \right)^{5/4} \sup_{s \in [0, \infty)} \left(\frac{1 + 4\varepsilon^4 \Omega(s)}{1 + 4\Gamma\varepsilon^4 s} \right)^{5/4} \leq \mathcal{D}_2 < \infty \tag{5.34}$$

and

$$|U(t, s)| \leq \mathcal{D}_2 \left(\frac{1 + 4\Gamma\varepsilon^4 s}{1 + 4\Gamma\varepsilon^4 t} \right)^{5/4} \quad \text{for all } s, t \in [0, \infty). \tag{5.35}$$

Consider two arbitrary functions $B_2(t), B_3(t)$ in $C([0, T], \mathbb{R})$ such that $\|B_j\|_Z \leq \mathcal{R}\varepsilon^2$ where the constant $\mathcal{R} > 0$ will be determined later. Then

$$\begin{aligned} \|K[B_2] - K[B_3]\|_Z &\leq \|B_2 - B_3\|_Z \sup_{t \in [0, T]} |-\Gamma + \rho(t)| \\ &\times \sum_{k=2}^5 \binom{5}{k} \sup_{t \in [0, T]} (1 + 4\Gamma\varepsilon^4 t)^{1/4} \\ &\times \int_0^t |U(t, s)| \|B_0^{5-k}(s)\| k (\mathcal{R}\varepsilon^2)^{k-1} (1 + 4\Gamma\varepsilon^4 s)^{-k/4} ds \\ &\leq \mathcal{D}_3 \|B_2 - B_3\|_Z \left(\sum_{k=2}^5 k \binom{5}{k} (\mathcal{R}\varepsilon)^{k-1} \right) \varepsilon^4 (1 + 4\Gamma\varepsilon^4 t)^{1/4} \\ &\times \int_0^t \left(\frac{1 + 4\Gamma\varepsilon^4 s}{1 + 4\Gamma\varepsilon^4 t} \right)^{5/4} (1 + 4\Gamma\varepsilon^4 s)^{-5/4} ds, \end{aligned}$$

where we used estimates (5.35) for $U(t, s)$, (5.26) for $B_0(t)$ and (5.17) for $(-\Gamma + \rho(t))$. The integral can be computed explicitly, such that

$$\|K[B_2] - K[B_3]\|_Z \leq \Gamma^{-1} \mathcal{D}_4 \mathcal{R} \varepsilon (1 + \mathcal{R} \varepsilon + (\mathcal{R} \varepsilon)^2 + (\mathcal{R} \varepsilon)^3) \|B_2 - B_3\|_Z. \tag{5.36}$$

Let $L \leq 1/2$ be the Lipschitz constant and assume that

$$\varepsilon \leq \mathcal{R}^{-1} \min\left(\frac{1}{2}, \frac{1}{4} \Gamma \mathcal{D}_4^{-1}\right). \tag{5.37}$$

The ball of radius $\mathcal{R} \varepsilon^2$ is invariant under $K[B_1]$, if the inhomogeneous term in K satisfies:

$$\left\| \int_0^t U(t, s) R(s) ds \right\|_Z \leq (1 - L) \mathcal{R} \varepsilon^2 \leq \frac{1}{2} \mathcal{R} \varepsilon^2, \tag{5.38}$$

which is proved from estimates (5.16) and (5.35). As a result, we obtain

$$\left\| \int_0^t U(t, s) R(s) ds \right\|_Z \leq \mathcal{D}_5 \mathcal{C}^9 \varepsilon^2. \tag{5.39}$$

If we choose $\mathcal{R} = 2\mathcal{D}_5 \mathcal{C}^9$ and $\mathcal{D} \geq \max\{2\mathcal{D}_5, 4\Gamma^{-1} \mathcal{D}_4 \mathcal{D}_5\}$, bounds (5.37) and (5.38) are satisfied provided that bound (5.19) holds. By the contraction principle applied to the amplitude equation (5.31), the solution $B_1(t)$ exists and is unique in the ball of radius $\mathcal{R} \varepsilon^2 \leq \mathcal{D} \mathcal{C}^9 \varepsilon^2$. As a result, the initial-value problem (5.30) is well posed on $t \in [0, T]$ and the solution $B_1(t)$ belongs to the ball of radius smaller than $\mathcal{D} \mathcal{C}^9 \varepsilon^2$ in the Banach space $Z = C([0, T], \mathbb{R})$ with norm (5.33), such that

$$|B_1(t)| \leq \frac{\mathcal{D} \mathcal{C}^9 \varepsilon^2}{(1 + 4\Gamma \varepsilon^4 t)^{1/4}} \quad \text{for all } t \in [0, T]. \tag{5.40}$$

Combining the bounds (5.26) and (5.40), we derive estimate (5.20). \square

Lemma 5.2. *Assume $T \in \tau$ and that the bound (5.19) is satisfied. Then, the amplitude $|A(t)|$ is bounded by the solution $B(t)$ as follows:*

$$|A(t)| \leq B(t) \quad \text{for all } t \in [0, T].$$

Proof. By Lemma 5.1, there exists a unique solution $B(t)$ of the comparison equation (5.18) on $t \in [0, T]$. By relations (5.13) and (5.16), we have

$$\frac{d|A|}{dt} \leq \frac{dB}{dt} \quad \text{for all } t \in [0, T], \tag{5.41}$$

and

$$|A(0)| \leq \varepsilon = B(0). \tag{5.42}$$

Then, the lemma follows from the comparison principle for ODEs, see [15, p. 168]. \square

Lemma 5.3. *The set τ is open in $[0, T_{\max})$.*

Proof. Combining Lemmas 5.1 and 5.2, we have

$$|A(t)| \leq \frac{\mathcal{D}\varepsilon(1 + \mathcal{C}^9\varepsilon)}{(1 + 4\Gamma\varepsilon^4t)^{1/4}} \quad \forall t \in [0, T], \tag{5.43}$$

provided that $T \in \tau$ and bound (5.19) holds. Due to inequalities (5.19) and (3.15), we have: $\mathcal{D}(1 + \mathcal{C}^9\varepsilon) < \mathcal{C}$. Hence

$$|A(t)| < \frac{\mathcal{C}\varepsilon}{(1 + 4\Gamma\varepsilon^4t)^{1/4}} \quad \forall t \in [0, T]. \tag{5.44}$$

Since $A(t)$ is continuous, there exists $\delta > 0$ such that the above inequality holds for all $t \in [0, T + \delta)$. Consequently, $(T - \delta, T + \delta) \subset \tau$, where the set τ is defined in (3.14). Since $T \in \tau$ is arbitrary, we infer that τ is open in $[0, T_{\max})$. \square

6. H^1 estimates

We prove here the upper bound (3.18), which excludes the finite time blow-up at $T < \infty$.

Lemma 6.1. *There exists a constant $\mathcal{E} > 0$ such that*

$$\|u(t)\|_{H^1} \leq \mathcal{E} \log(1 + 4\Gamma\varepsilon^4t) \quad \text{for } t \in \tau. \tag{6.1}$$

Proof. Assume that $u_0 \in H^2(\mathbb{R}^3)$. By Theorem 2, the inner product of u_t with the NLS equation (1.1) is defined, and

$$\operatorname{Re} \left[\langle u_t, (-\Delta + V)u + \gamma(t)|u|^2u \rangle \right] = 0. \tag{6.2}$$

Since $u(t) \in H^2(\mathbb{R}^3)$, $u_t(t) \in L^2(\mathbb{R}^3)$, and $|u|^2u(t) \in H^2(\mathbb{R}^3)$ by Theorem 2, an elementary computation transforms (6.2) to the form of the energy conservation equation

$$\frac{d}{dt} \left[\langle u, (-\Delta + V)u + \frac{1}{2}\gamma(t)\|u\|_{L^4}^4 \rangle \right] = -\|u\|_{L^4}^4 \dot{\gamma}(t). \tag{6.3}$$

Using decomposition (3.1), we obtain

$$\frac{d}{dt} \left[\lambda |A(t)|^2 + \langle u_d, (-\Delta + V)u_d \rangle + \gamma(t) \frac{1}{2} \|u\|_{L^4}^4 \right] = \dot{\gamma}(t) \frac{1}{2} \|u\|_{L^4}^4. \tag{6.4}$$

As a result,

$$\begin{aligned} \|\nabla u_d(t)\|_{L^2}^2 &\leq \|V\|_\infty (\|u(t)\|_{L^2}^2 + |A(t)|^2) + \|u(0)\|_{H^1}^2 + \|V\|_\infty \|u(0)\|_{L^2}^2 \\ &\quad - \lambda (|A(t)|^2 + |A(0)|^2) + \frac{1}{2} (|\gamma_0| + |\gamma_1|) (\|u(t)\|_{L^4}^4 + \|u(0)\|_{L^4}^4) \\ &\quad + 4\omega |\gamma_1| \int_0^t (|A(s)|^4 \|\psi\|_{L^4}^4 + \|u_d(s)\|_{L^4}^4) ds. \end{aligned} \tag{6.5}$$

Since $\|u(t)\|_2 = \|u(0)\|_2$ by Theorem 2, and $t \in \tau$ by Lemma 5.3, we use estimates (3.14) and (4.29) and derive the H^1 bound (6.1) in the case $u_0 \in H^2(\mathbb{R}^3)$. By the standard density argument for $H^2 \leftrightarrow H^1$ and the continuous dependence of u_0 in Theorem 3, the bound (6.1) still holds for $u_0 \in H^1(\mathbb{R}^3)$. \square

7. Generalizations and open problems

The main Theorem 1 can be extended with obvious modifications to the case of almost periodic time-dependent nonlinearity coefficient:

$$\gamma(t) = \sum_{n=1}^{\infty} \gamma_n \cos(\omega_n t + \theta_n), \quad \sum_{n=1}^{\infty} |\gamma_n| < \infty,$$

where $\gamma_n \in \mathbb{C}$, $\omega_n, \theta_n \in \mathbb{R} \forall n \in \mathbb{N}$ and there exists $\delta > 0$ such that $|\lambda + \omega_n| \geq \delta$ whenever $\gamma_n \neq 0$. In particular, the main theorem extends to the case of general periodic perturbations, when $\omega_n = n\omega$, $n \in \mathbb{N}$, provided that the resonance between the bound state and the lowest radiation mode is excluded, i.e. $\lambda + n\omega \neq 0$ whenever $\gamma_n \neq 0$. We need to exclude such resonances because estimate (3.10), as opposed to estimate (3.9), is not sufficient for our argument to work. Our preliminary calculations show that, for $\lambda + (n - 1)\omega < 0$ and $\lambda + n\omega > 0$, $n = 1, 2, \dots$, the decay of the bound state occurs with the rate:

$$\|u(t)\|_{L^2_{-\sigma}} \sim t^{-1/(4n)}.$$

There are three open problems beyond the scope of the current manuscript. The first one is to extend the main theorem to the case of resonance with the lowest radiation mode, as we have mentioned above. The second open problem is to consider the NLS equation (1.1) in the space of lower dimensions. Since bound (3.7) on the dispersive

part in L^p depends on the space dimension, there are obstacles in finding invariant subspaces for the integral operator $K_A[u_d]$ in the space of one and two dimensions. The obstacles could be removed by increasing the power of the nonlinearity term in the NLS equation (1.1) to make it supercritical [25]. This, of course, will result in a different power for the dominant term in (5.13) and, consequently, a different decay rate of the amplitude. However, problems of dispersion and nonlinearity management [30] are formulated for the NLS equation in one dimension with cubic nonlinearity.

The third open problem is to investigate the nonlinear Fermi Golden Rule in the case of large-norm initial data. Persistence of stable large-norm bound states for $\gamma(t) \equiv \gamma_0$ is an open question but it is believed that they are present below a threshold which is not necessarily small, see [17]. The threshold is related with blow-up in the attractive case $\gamma_0 < 0$ or with disappearance of the trapping effect in the repelling case $\gamma_0 > 0$. For such stable large-norm bound states, the amount of radiation generated through resonance will be small for small γ_1 and our proofs could be generalized to show the eventual destruction of the bound states. An interesting but very difficult question for the attractive case $\gamma_0 < 0$ is: what is the effect of the resonance on initial data that would otherwise blow up in finite time? Does it slow down or even arrest the blow up?

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Appendix A. Contraction principles and fixed points estimates in a hierarchy of Banach spaces

Let $(Y, \|\cdot\|_Y)$ be a Banach space and $K : Y \rightarrow Y$ a locally Lipschitz operator, i.e. for any $u, v \in Y$ such that $\|u\|_Y, \|v\|_Y \leq R$ there exist $L_Y(R) > 0$ with the property

$$\|K[u] - K[v]\|_Y \leq L_Y(R)\|u - v\|_Y. \quad (\text{A.1})$$

Assume that

$$K[0] = 0 \quad (\text{A.2})$$

and consider an abstract equation:

$$u = f + K[u] = K_1[u], \quad f \in Y. \quad (\text{A.3})$$

The classical contraction principle for a locally Lipschitz operator is

Proposition A.1. Assume that there exist the constants $L < 1$ and $R > 0$ such that:

$$L_Y(R) \leq L, \tag{A.4}$$

$$\|f\|_Y \leq (1 - L)R. \tag{A.5}$$

Then Eq. (A.3) has an unique solution u in the ball of radius R of the Banach space Y . Moreover, for any $v \in Y$, $\|v\|_Y \leq R$ and $n = 0, 1, \dots$ we have:

$$\|u - K_1^n[v]\|_Y \leq \frac{\|K_1^{n+1}[v] - K_1^n[v]\|_Y}{1 - L} \leq \frac{L^n}{1 - L} \|K_1[v] - v\|_Y. \tag{A.6}$$

In particular, for $v = f$ we get

$$\|u - K_1^n[f]\|_Y \leq \frac{L^n}{1 - L} \|K[f]\|_Y \leq \frac{L^{n+1}}{1 - L} \|f\|_Y. \tag{A.7}$$

Proof. Apply the contraction principle to K_1 in the ball of radius R of the Banach space Y , see for example [29]. \square

Consider another abstract equation

$$u = g + f + K[u] = K_2[u], \quad g \in X, \quad f \in Y, \tag{A.8}$$

where $(X, \|\cdot\|_X)$ is a Banach space continuously embedded in Y , $X \hookrightarrow Y$. The embedding implies that both g and $g + f$ are in Y . Assuming that (A.5) holds with f replaced by $f + g$, the previous proposition applies and the solution u of (A.8) satisfies:

$$\|u - K_2^n[f + g]\|_Y \leq \frac{L^{n+1}}{1 - L} \|f + g\|_Y$$

for $n = 0, 1, \dots$. However, the above estimate does not use information that the forcing term g belongs to a “better” space. Nevertheless, assume that we can find a solution $v \in X \subset Y$, $\|v\|_Y \leq R$ of

$$v = g + K[v]. \tag{A.9}$$

Then

$$\|f + v\|_Y = \|f + g + K[v]\|_Y = \|K_2[v]\|_Y \leq R$$

since v is in the ball of radius R in Y which is left invariant by K_2 . Hence we can use $f + v$ in (A.6) and get:

$$\begin{aligned} \|u - K_2^n[f + v]\|_Y &\leq \frac{L^n}{1 - L} \|K_2[f + v] - f - v\|_Y \\ &= \frac{L^n}{1 - L} \|K[f + v] + g - v\|_Y \\ &= \frac{L^n}{1 - L} \|K[f + v] - K[v]\|_Y \\ &\leq \frac{L^{n+1}}{1 - L} \|f\|_Y \end{aligned} \tag{A.10}$$

for $n = 0, 1, \dots$

Now the existence of v with the above properties could be inferred from assuming that the fixed point problem (A.9) satisfies the hypotheses of Proposition A.1 but in the Banach space X . We have thus proved the following result:

Proposition A.2. *In addition to (A.1) and (A.2), assume that K is locally Lipschitz in X , i.e. for any $u, v \in X$ such that $\|u\|_X, \|v\|_X \leq Q$ there exist $L_X(Q) > 0$ with the property*

$$\|K[u] - K[v]\|_X \leq L_X(Q)\|u - v\|_Y. \tag{A.11}$$

Furthermore, assume that there exist constants $L_i < 1, i = 1, 2$ and $R_i > 0, i = 1, 2$ such that:

$$L_X(R_1) \leq L_1, \tag{A.12}$$

$$\|g\|_X \leq (1 - L_1)R_1 \tag{A.13}$$

and

$$L_Y(R_2) \leq L_2, \tag{A.14}$$

$$\|g + f\|_Y \leq (1 - L_2)R_2 \tag{A.15}$$

and also assume that

$$B_1 = \{v \in X : \|v\|_X \leq R_1\} \subset B_2 = \{u \in Y : \|u\|_Y \leq R_2\}. \tag{A.16}$$

Then there exist a unique solution $u \in B_2$ of (A.8) and a unique solution $v \in B_1$ of (A.9) with the following properties:

$$\|v - g\|_X \leq \frac{\|K[g]\|_X}{1 - L_1} \leq \frac{L_1}{1 - L_1} \|g\|_X, \quad (\text{A.17})$$

$$\|u - K_2^n[f + v]\|_Y \leq \frac{L_2^{n+1}}{1 - L_2} \|f\|_Y \quad (\text{A.18})$$

for $n = 0, 1, 2, \dots$. In particular, for $n = 0, 1$ we have

$$\|u - v - f\|_Y \leq \frac{L_2}{1 - L_2} \|f\|_Y, \quad (\text{A.19})$$

$$\|u - g - f\|_Y \leq \frac{L_1}{1 - L_1} \|g\|_X + \frac{L_2}{1 - L_2} \|f\|_Y, \quad (\text{A.20})$$

$$\|u - g - f - K[v + f]\|_Y \leq \frac{L_2^2}{1 - L_2} \|f\|_Y. \quad (\text{A.21})$$

Lemma 4.2 is a specific application of Proposition A.2. Moreover, an inductive procedure can generalize bound (A.20) as follows:

$$\|u - f_1 - f_2 - \dots - f_m\|_m \leq \frac{L_1^2}{1 - L_1} \|f_1\|_1 + \frac{L_2^2}{1 - L_2} \|f_2\|_2 + \dots + \frac{L_m^2}{1 - L_m} \|f_m\|_m,$$

where u is the solution of

$$u = f_1 + f_2 + \dots + f_m + K[u], \quad f_i \in X_i, \quad i = 1, 2, \dots, m$$

with $(X_i, \|\cdot\|_i)$, $i = 1, 2, \dots, m$ Banach spaces that satisfy $X_1 \hookrightarrow X_2 \hookrightarrow \dots \hookrightarrow X_m$ and on which K is contractive with corresponding Lipschitz constants L_i , $i = 1, 2, \dots, m$.

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