Stability of Discrete Ground State

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Abstract

We present new criteria for a self-adjoint operator to have a ground state. As an application, we consider models of “quantum particles” coupled to a massive Bose field and prove the existence of a ground state of them, where the particle Hamiltonian does not necessarily have compact resolvent.

Key words: Ground state; discrete ground state; generalized spin-boson model; Fock space; Dereziński-Gérard model.

1 INTRODUCTION

Let $T$ be a self-adjoint operator on a Hilbert space $\mathcal{H}$, and bounded from below. We say that $T$ has a discrete ground state if the bottom of the spectrum of $T$ is an isolated eigenvalue of $T$. In that case a non-zero vector
in \( \ker(T - E_0(T)) \) is called a ground state of \( T \). Let \( S \) be a symmetric operator on \( \mathcal{H} \). Suppose that \( T \) has a discrete ground state and \( S \) is \( T \)-bounded. By the regular perturbation theory [8, XII] it is already known that \( T + \lambda S \) has a discrete ground state for "sufficiently small" \( \lambda \in \mathbb{R} \). Our aim is to present new criteria for \( T + \lambda S \) to have a ground state.

In Section 2, we prove an existence theorem of a ground state which is useful to show the existence of a ground state of models of quantum particles coupled to a massive Bose field.

In Section 3, we consider the GSB model [2] with a self-interaction term of a Bose field, which we call the GSB + \( \phi^2 \) model. We consider only the case where the Bose field is massive. The GSB model — an abstract system of quantum particles coupled to a Bose field — was proposed in [2]. In [2], A. Arai and M. Hirokawa proved the existence and uniqueness of the GSB model in the case where the particle Hamiltonian \( A \) has compact resolvent. Shortly after that, they proved the existence of a ground state of the GSB model in the case where \( A \) does not have necessarily compact resolvent [4, 3]. In this paper, using a theorem in Section 2, we prove the existence of a ground state of the GSB + \( \phi^2 \) model in the case where \( A \) does not necessarily have compact resolvent.

In Section 4, we consider an extended version of the Nelson type model, which we call the Dereziński-Gérard model [5]. The Dereziński-Gérard model introduced in [5] and J. Dereziński and C. Gérard prove an existence of a ground state for their model under some conditions including that \( A \) has compact resolvent. In Section 4, we prove the existence of a ground state of the Dereziński-Gérard model in the case where \( A \) does not have compact resolvent. Our strategy to establish a ground state is the same as in Section 3.

2 BASIC RESULTS

Let \( \mathcal{H} \) be a separable complex Hilbert space. We denote by \( \langle \cdot, \cdot \rangle_{\mathcal{H}} \) the scalar product on Hilbert space \( \mathcal{H} \) and by \( \| \cdot \|_{\mathcal{H}} \) the associated norm. Scalar product \( \langle f, g \rangle_{\mathcal{H}} \) is linear in \( g \) and antilinear in \( f \). We omit \( \mathcal{H} \) in \( \langle \cdot, \cdot \rangle_{\mathcal{H}} \) and \( \| \cdot \|_{\mathcal{H}} \) respectively if there is no danger of confusion. For a linear operator \( T \) in Hilbert space, we denote by \( D(T) \) and \( \sigma(T) \) the domain and the spectrum of \( T \) respectively. If \( T \) is self-adjoint and bounded from below, then we define

\[
E_0(T) := \inf \sigma(T), \quad \Sigma(T) := \inf \sigma_{\text{ess}}(T),
\]

2
where $\sigma_{\text{ess}}(T)$ is the essential spectrum of $T$. If $T$ has no essential spectrum, then we set $\Sigma(T) = \infty$. For a self-adjoint operator $T$, we denote the form domain of $T$ by $Q(T)$. In this paper, an eigenvector of a self-adjoint operator $T$ with eigenvalue $E_0(T)$ is called a ground state of $T$ (if it exists). We say that $T$ has a ground state if $\dim \ker(T - E_0(T)) > 0$.

The basic results are as follows:

**Theorem 2.1.** Let $H$ be a self-adjoint operator on $\mathcal{H}$, and bounded from below. Suppose that there exists a self-adjoint operator $V$ on $\mathcal{H}$ satisfying the following conditions (i)-(iii):

(i) $D(H) \subset D(V)$.
(ii) $V$ is bounded from below, and $\Sigma(V) > 0$.
(iii) $H - E_0(H) \geq V$ on $D(H)$.

Then $H$ has purely discrete spectrum in the interval $[E_0(H), E_0(H) + \Sigma(V))$. In particular, $H$ has a ground state.

**Proof.** For all $u_1, \ldots, u_{n-1} \in \mathcal{H}$, we have

$$\inf_{\Psi \in \text{L.h.} \left\{ u_1, \ldots, u_{n-1} \right\} \perp \| \Psi \| = 1} \langle \Psi, H \Psi \rangle - E_0(H) \geq \inf_{\Psi \in \text{L.h.} \left\{ u_1, \ldots, u_{n-1} \right\} \perp \| \Psi \| = 1} \langle \Psi, V \Psi \rangle,$$

where L.h. denotes the linear hull of the vectors in $\left\{ \cdots \right\}$. Since $D(H) \subset D(V)$, we have that

$$\inf_{\Psi \in \text{L.h.} \left\{ u_1, \ldots, u_{n-1} \right\} \perp \| \Psi \| = 1} \langle \Psi, V \Psi \rangle \geq \inf_{\Psi \in \text{L.h.} \left\{ u_1, \ldots, u_{n-1} \right\} \perp \| \Psi \| = 1} \langle \Psi, \Psi \rangle.$$

Hence, for all $n \in \mathbb{N}$

$$\mu_n(H) - E_0(H) \geq \mu_n(V).$$

where

$$\mu_n(H) := \sup_{u_1, \ldots, u_{n-1} \in \mathcal{H}} \inf_{\Psi \in \text{L.h.} \left\{ u_1, \ldots, u_{n-1} \right\} \perp \| \Psi \| = 1} \langle \Psi, H \Psi \rangle.$$

By the min-max principle ($\|$ 8, Theorem XIII.1 $\|$), $\lim_{n \to \infty} \mu_n(H) = \Sigma(H)$ and $\lim_{n \to \infty} \mu_n(V) = \Sigma(V)$. Therefore we obtain

$$\Sigma(H) - E_0(H) \geq \Sigma(V) > 0.$$ 

This means that $H$ has purely discrete spectrum in $[E_0(H), E_0(H) + \Sigma(V))$. $\blacksquare$
Theorem 2.2. Let \( H \) be a self-adjoint operator on \( \mathcal{H} \), and bounded from below. Suppose that there exists a self-adjoint operator \( V \) on \( \mathcal{H} \) satisfying the following conditions (i)-(iii):

(i) \( Q(H) \subset Q(V) \).
(ii) \( V \) is bounded from below, and \( \Sigma(V) > 0 \).
(iii) \( H - E_0(H) \geq V \) on \( Q(H) \).

Then \( H \) has purely discrete spectrum in the interval \( [E_0(H), E_0(H) + \Sigma(V)) \).
In particular, \( H \) has a ground state.

Proof. Similar to the proof of Theorem 2.1.

We apply Theorems 2.1 and 2.2 to a perturbation problem of a self-adjoint operator.

Theorem 2.3. Let \( A \) be a self-adjoint operator on \( \mathcal{H} \) with \( E_0(A) = 0 \), and let \( B \) be a symmetric operator on \( D(A) \). Suppose that \( A + B \) is self-adjoint on \( D(A) \) and that there exist constants \( a \in [0, 1) \) and \( b \geq 0 \) such that

\[
|\langle\psi, B\psi\rangle| \leq a\langle\psi, A\psi\rangle + b\|\phi\|^2, \quad \psi \in D(A).
\]

Assume

\[
\frac{b + E_0(A + B)}{1 - a} < \Sigma(A). \tag{1}
\]

Then \( A + B \) has purely discrete spectrum in \( [E_0(A + B), (1 - a)\Sigma(A) - b) \).
In particular, \( A + B \) has a ground state.

Proof. By the assumption we have

\[
A + B - E_0(A + B) \geq (1 - a)A - b - E_0(A + B)
\]
on \( D(A) \), and \( (1 - a)\Sigma(A) - b - E_0(A + B) > 0 \). Hence we can apply Theorem 2.1, to conclude that \( A + B \) has purely discrete spectrum in \( [E_0(A + B), (1 - a)\Sigma(A) - b) \). In particular, \( A + B \) has a ground state.

Remark. It is easily to see that \(-b \leq E_0(A + B) \leq b \). Therefore condition (1) is satisfied if

\[
\frac{2b}{1 - a} < \Sigma(A).
\]
Theorem 2.4. Let $\mathcal{H}, \mathcal{K}$ be complex separable Hilbert spaces. Let $A$ and $B$ be self-adjoint operators on $\mathcal{H}$ and $\mathcal{K}$ respectively. Suppose that $E_0(A) = E_0(B) = 0$. We set

$$T_0 := A \otimes I + I \otimes B.$$ 

Let $Z$ be a symmetric sesquilinear form on $Q(T_0)$, and assume that there exist constants $a_1 \in [0, 1), a_2 \in [0, 1)$ and $b \geq 0$ such that, for all $\Psi \in Q(T_0)$

$$|Z(\Psi, \Psi)| \leq a_1 \langle \Psi, A \otimes I \Psi \rangle_{\text{form}} + a_2 \langle \Psi, I \otimes B \Psi \rangle_{\text{form}} + b \|\Psi\|^2,$$

where $\langle \Psi, A \otimes I \Psi \rangle_{\text{form}} = \|A^{1/2} \otimes I \Psi\|^2$. Therefore, by the KLMN theorem there exists a unique self-adjoint operator $T$ on $\mathcal{H} \otimes \mathcal{K}$ such that $Q(T) = Q(T_0)$ and $T = T_0 + Z$ in the sense of sesquilinear form on $Q(T_0)$. We set

$$s := \min\{(1 - a_1)\Sigma(A), (1 - a_2)\Sigma(B)\}.$$ 

Assume

$$s > b + E_0(T). \tag{2}$$

Then, $T$ has purely discrete spectrum in the interval $[E_0(T), s - b)$. In particular, $T$ has a ground state.

Proof. Similar to the proof of Theorem 2.3. \qed

Remark. It is easy to see that $-b \leq E_0(T) \leq b$. Therefore the condition (2) is satisfied if

$$s > 2b.$$ 

Remark. Theorem 2.4 is essentially same as [4, Theorem B.1]. But our proof is very simple.

3 Ground States of a General Class of Quantum Field Hamiltonians

We consider a model which is an abstract unification of some quantum field models of particles interacting with a Bose field. It is the GSB model [2] with a self-interaction term of the field.

Let $\mathcal{H}$ be a separable complex Hilbert space and $\mathcal{F}_b$ be the Boson Fock space over $L^2(\mathbb{R}^d)$:

$$\mathcal{F}_b := \bigoplus_{n=0}^{\infty} \bigotimes_{s=1}^{n} L^2(\mathbb{R}^d).$$
The Hilbert space of the quantum field model we consider is
\[ \mathcal{F} := \mathcal{H} \otimes \mathcal{F}_b. \]

Let \( \omega : \mathbb{R}^d \to [0, \infty) \) be Borel measurable such that \( 0 < \omega(k) < \infty \) for all most everywhere (a.e.) \( k \in \mathbb{R}^d \). We denote the multiplication operator by the function \( \omega \) acting in \( L^2(\mathbb{R}^d) \) by the same symbol \( \omega \). We set
\[ H_b := d\Gamma_b(\omega) \]
the second quantization of \( \omega \) (e.g. [7, Section X.7]). We denote by \( a(f) \), \( f \in L^2(\mathbb{R}^d) \), the smeared annihilation operators on \( \mathcal{F}_b \). It is a densely defined closed linear operator on \( \mathcal{F}_b \) (e.g. [7, Section X.7]). The adjoint \( a(f)^* \), called the creation operator, and the annihilation operator \( a(g) \), \( g \in L^2(\mathbb{R}^d) \) obey the canonical commutation relations
\[ [a(f), a(g)^*] = \langle f, g \rangle, \quad [a(f), a(g)] = 0, \quad [a(f)^*, a(g)^*] = 0 \]
for all \( f, g \in L^2(\mathbb{R}^d) \) on the dense subspace
\[ \mathcal{F}_0 := \{ \psi = (\psi^{(n)})_{n=0}^{\infty} \in \mathcal{F}_b | \text{there exists a number } n_0 \text{ such that } \psi^{(n)} = 0 \text{ for all } n \geq n_0 \}, \]
where \([X, Y] = XY - YX\). The symmetric operator
\[ \phi(f) := \frac{1}{\sqrt{2}} [a(f)^* + a(f)], \]
called the Segal field operator, is essentially self-adjoint on \( \mathcal{F}_0 \) (e.g. [7, Section X.7]). We denote its closure by the same symbol. Let \( A \) be a positive self-adjoint operator on \( \mathcal{H} \) with \( E_0(A) = 0 \). Then, the unperturbed Hamiltonian of the model is defined by
\[ H_0 := A \otimes I + I \otimes H_b \]
with domain \( D(H_0) = D(A \otimes I) \cap D(I \otimes H_b) \). For \( g_j, f_j \in L^2(\mathbb{R}^d) \), \( j = 1, \ldots, J \), and \( B_j(j = 1, \ldots, J) \) a symmetric operator on \( \mathcal{H} \), we define a symmetric operator
\[ H_1 := \sum_{j=1}^J B_j \otimes \phi(g_j), \]
\[ H_2 := \sum_{j=1}^J I \otimes \phi(f_j)^2. \]
The Hamiltonian of the model we consider is of the form
\[ H(\lambda, \mu) := H_0 + \lambda H_1 + \mu H_2, \]
where \( \lambda \in \mathbb{R} \) and \( \mu \geq 0 \) are coupling parameters.

For \( H(\lambda, \mu) \) to be self-adjoint, we shall need the following conditions [H.1]-[H.3]:

[H.1] \( g_j \in D(\omega^{-1/2}), f_j \in D(\omega^{1/2}) \cap D(\omega^{-1/2}), j = 1, \ldots, J. \)

[H.2] \( D(A^{1/2}) \subset \bigcap_{j=1}^J D(B_j) \) and there exist constants \( a_j \geq 0, b_j \geq 0, j = 1, \ldots, J, \) such that,
\[
\|B_j u\| \leq a_j \|A^{1/2} u\| + b_j \|u\|, \quad u \in D(A^{1/2}).
\]

[H.3] \( |\lambda| \sum_{j=1}^J a_j \|g_j/\sqrt{\omega}\| < 1. \)

Proposition 3.1. Assume [H.1], [H.2] and [H.3]. Then, \( H(\lambda, \mu) \) is self-adjoint with \( D(H(\lambda, \mu)) = D(H_0) \subset D(H_1) \cap D(H_2) \) and bounded from below. Moreover, \( H(\lambda, \mu) \) is essentially self-adjoint on every core of \( H_0. \)

Remark. This proposition has no restriction of the coupling parameter \( \mu \geq 0. \)

To perform a finite volume approximation, we need an additional condition:

[H.4] The function \( \omega(k) \) (\( k \in \mathbb{R}^d \)) is continuous with
\[
\lim_{|k| \to \infty} \omega(k) = \infty,
\]
and there exist constants \( \gamma > 0, C > 0 \) such that
\[
|\omega(k) - \omega(k')| \leq C|k - k'|^{\gamma} [1 + \omega(k) + \omega(k')], \quad k, k' \in \mathbb{R}^d.
\]

Let
\[
m := \inf_{k \in \mathbb{R}^d} \omega(k).
\]

If \( A \) has compact resolvent, we can prove the extension of the previous theorem [2, Theorem 1.2].
Theorem 3.2. Consider the case $m > 0$. Suppose that $A$ has entire purely discrete spectrum. Assume Hypotheses [H.1]-[H.4]. Then, $H(\lambda, \mu)$ has purely discrete spectrum in the interval $[E_0(H(\lambda, \mu)), E_0(H(\lambda, \mu)) + m)$. In particular, $H(\lambda, \mu)$ has a ground state.

Remark. This theorem has no restriction of the coupling parameter $\mu \geq 0$.

Remark. In the case $m > 0$, the condition [H.1] equivalent to the following:

For a vector $v = (v_1, \ldots, v_J) \in \mathbb{R}^J$ and $h = (h_1, \ldots, h_J) \in \bigoplus_{j=1}^J L^2(\mathbb{R}^d)$, we define

$$M_v(h) = \sum_{j=1}^J v_j \|h_j\|.$$  

We set

$$g = (g_1, \ldots, g_J) \in \bigoplus_{j=1}^J L^2(\mathbb{R}^d), \quad f = (f_1, \ldots, f_J) \in \bigoplus_{j=1}^J L^2(\mathbb{R}^d),$$

and

$$a = (a_1, \ldots, a_J), \quad b = (b_1, \ldots, b_J).$$

For $\theta$, $\epsilon$, $\epsilon'$, we introduce the following constants:

$$C_{\theta, \epsilon} := \theta M_a(g/\sqrt{\omega}) + \epsilon M_a(g),$$

$$D_{\theta, \epsilon'} := M_a(g/\sqrt{\omega})/2\theta + \epsilon' M_b(g/\sqrt{\omega}),$$

$$E_{\epsilon, \epsilon'} := M_a(g)/2\epsilon + M_b(g/\sqrt{\omega})/2\epsilon' + M_b(g)/\sqrt{2}.$$  

Let the condition [H.3] be satisfied. Then, we define

$$I_{\lambda, g} := \begin{cases} 
\left( \frac{|\lambda| M_a(g/\sqrt{\omega})}{2}, \frac{1}{|\lambda| M_a(g/\sqrt{\omega})} \right), 
\text{ if } |\lambda| M_a(g/\sqrt{\omega}) \neq 0 \\
[0, \infty], 
\text{ if } |\lambda| M_a(g/\sqrt{\omega}) = 0
\end{cases}$$

It is easy to see that $[1/2, 1] \subset I_{\lambda, g}$. Therefore, for all $\theta \in I_{\lambda, g}$,

$$1 - \theta |\lambda| M_a(g/\sqrt{\omega}) > 0,$$

$$1 - \frac{|\lambda| M_a(g/\sqrt{\omega})}{2\theta} > 0.$$
We define for $\theta \in I_{\lambda,g}$,

$$S_\theta := \{(\epsilon, \epsilon')|\epsilon, \epsilon' > 0, |\lambda|C_{\theta,\epsilon} < 1, |\lambda|D_{\theta,\epsilon'} < 1\}.$$

Next we set

$$\tau_{\theta,\epsilon,\epsilon'} := (1 - |\lambda|C_{\theta,\epsilon})\Sigma(A) - |\lambda|E_{\epsilon,\epsilon'},$$

and

$$T := \{((\theta, \epsilon, \epsilon') \in \mathbb{R}^3|\theta \in I_{\lambda,g}, (\epsilon, \epsilon') \in S_\theta, \tau_{\theta,\epsilon,\epsilon'} > E_0(H(\lambda, \mu))\}.$$ 

**Theorem 3.3.** Consider the case $m > 0$. Suppose that $\sigma_{\text{ess}}(A) \neq \emptyset$. Assume Hypothesis [H.1]-[H.4], and $T \neq \emptyset$. Then, $H(\lambda, \mu)$ has purely discrete spectrum in the interval

$$[E_0(H(\lambda, \mu)), \min\{m + E_0(H(\lambda, \mu)), \sup_{(\theta,\epsilon,\epsilon')\in T} \tau_{\theta,\epsilon,\epsilon'}\}].$$

(4)

In particular, $H(\lambda, \mu)$ has a ground state.

**Remark.** $T \neq \emptyset$ is necessary condition for $A$ to have a discrete ground state. Conversely, if $A$ has a discrete ground state, then $T \neq \emptyset$ holds for sufficiently small $\lambda, \mu$. Therefore the condition $T \neq \emptyset$ is a restriction for the coupling constants $\lambda, \mu$.

* * *

3.1 Proof of Proposition 3.1

In what follows, we write simply

$$H := H(\lambda, \mu).$$

For $D$ a dense subspace of $L^2(\mathbb{R}^d)$, we define

$$F_{\text{fin}}(D) := \text{L.h}[\{\Omega, a(h_1)^* \cdots a(h_n)^* \Omega | n \in \mathbb{N}, h_j \in D, j = 1, \ldots, n\},$$

where $\Omega := (1, 0, 0, \ldots)$ is the Fock vacuum in $F_{\text{fin}}$. We introduce a dense subspace in $F$

$$D_\omega := D(A) \hat{\otimes} F_{\text{fin}}(D(\omega)),$$

where $\hat{\otimes}$ denotes algebraic tensor product. The subspace $D_\omega$ is a core of $H_0$. 

9
Let 
\[ H_{\text{GSB}} := H_0 + \lambda H_1 \]
be a GSB Hamiltonian. The Hamiltonian \( H \) and \( H_{\text{GSB}} \) has the following relation:

**Proposition 3.4.** Let \( D(A) \subset D(B_j) \), \( j = 1, \ldots, J \) and \( f_j \in D(\omega^{1/2}) \). Assume that \( H_{\text{GSB}} \) is bounded from below. Then, for all \( \Psi \in D_\omega \),

\[ \| (H_{\text{GSB}} - E_0)\Psi \|^2 + \| \mu H_2 \Psi \|^2 \leq \| (H - E_0)\Psi \|^2 + D\| \Psi \|^2, \quad (5) \]

where \( D = \mu \sum_{j=1}^J \| \omega^{1/2} f_j \|^2 \) and

\[ E_0 := \inf_{\| \Psi \| = 1} \langle \Psi, H_{\text{GSB}} \Psi \rangle. \]

**Proof.** It is enough to show (5) the case \( \lambda = \mu = 1 \). First we consider the case where \( f_j \in D(\omega) \). Inequality (5) is equivalent to

\[ -2 \text{Re} \langle (H_{\text{GSB}} - E_0)\Psi, H_2\Psi \rangle \leq D\| \Psi \|^2. \quad (6) \]

By \( H_{\text{GSB}} - E_0 \geq 0 \), we have

\[ \langle (H_{\text{GSB}} - E_0)\Psi, I \otimes \phi(f_j)^2\Psi \rangle = \langle [I \otimes \phi(f_j), (H_{\text{GSB}} - E_0)]\Psi, I \otimes \phi(f_j)\Psi \rangle \]
\[ + \langle (H_{\text{GSB}} - E_0)I \otimes \phi(f_j)\Psi, I \otimes \phi(f_j)\Psi \rangle \]
\[ \geq \langle [I \otimes \phi(f_j), H_{\text{GSB}} - E_0]\Psi, I \otimes \phi(f_j)\Psi \rangle. \]

Therefore we have

\[ 2 \text{Re} \langle (H_{\text{GSB}} - E_0)\Psi, \phi(f_j)^2\Psi \rangle \geq -\| \sqrt{\omega} f_j \|^2\| \Psi \|^2. \]

This means inequality (6). Next, we set \( f_j \in D(\sqrt{\omega}) \). Then, there exists a sequence \( \{ f_{jn} \}_{n=0}^\infty \subset D(\omega) \) such that \( f_{jn} \to f_j, \omega^{1/2} f_{jn} \to \omega^{1/2} f_j \) \((n \to \infty)\). By limiting argument, (6) holds with \( f_j \in D(\omega^{1/2}) \).

**Lemma 3.5.** Suppose that \( H_{\text{GSB}} \) is self-adjoint with \( D(H_{\text{GSB}}) = D(H_0) \), essentially self-adjoint on \( D_\omega \), and bounded from below. Let \( f_j \in D(\omega^{1/2}) \cap D(\omega^{-1/2}) \). Then \( H \) is self-adjoint with \( D(H) = D(H_0) \) and essentially self-adjoint on any core of \( H_{\text{GSB}} \) with

\[ \| (H_{\text{GSB}} - E_0)\Psi \|^2 + \| \mu H_2 \Psi \|^2 \leq \| (H - E_0)\Psi \|^2 + D\| \Psi \|^2, \quad \Psi \in D(H_0). \]
Proof. It is well known that \( D(H_b) \subset D(\phi(f_j)^2) \), and \( \phi(f_j)^2 \) is \( H_b \)-bounded (e.g. [1, Lemma 13-16]). Namely, there exist constants \( \eta \geq 0 \) and \( \theta \geq 0 \) such that
\[
\left\| \sum_{j=1}^J \phi(f_j)^2 \psi \right\| \leq \eta \| H_b \psi \| + \theta \| \psi \|, \quad \psi \in D(H_b). \tag{7}
\]
Since \( H_{GSB} \) is self-adjoint on \( D(H_0) \), by the closed graph theorem, we have
\[
\| H_0 \Psi \| \leq \lambda \| H_{GSB} \Psi \| + \nu \| \Psi \|, \quad \Psi \in D(H_0), \tag{8}
\]
where \( \lambda \) and \( \nu \) are non-negative constants independent of \( \Psi \). Hence
\[
\| H_2 \Psi \| \leq \eta \lambda \| H_{GSB} \Psi \| + (\eta \nu + \theta) \| \Psi \|, \quad \Psi \in D(H_0).
\]
We fix a positive number \( \mu_0 \) such that \( \mu_0 < 1/(\mu \lambda) \). Then, by the Kato-Rellich theorem, \( H(\lambda, \mu_0) \) is self-adjoint on \( D(H_{GSB}) \), bounded from below and essentially self-adjoint on any core of \( H_{GSB} \). For a constant \( a \) (\( 0 < a < 1 \)), we set \( \mu_n := (1 + a)^n \mu_0 \). Since \( H_{GSB} \) is self-adjoint on \( D(H_0) \), for each \( j = 1, \ldots, J \) we have \( D(A) \subset D(B) \). Thus by Proposition 3.4, for all \( \Psi \in D_\omega \)
\[
\| (H_{GSB} - E_0) \Psi \|^2 + \| \mu_n H_2 \Psi \|^2 \leq \| (H(\lambda, \mu_n) - E_0) \Psi \|^2 + D \| \Psi \|^2.
\]
If \( H(\lambda, \mu_n) \) is self-adjoint on \( D(H_{GSB}) \), bounded from below and essentially self-adjoint on any core of \( H_{GSB} \), then \( H(\lambda, \mu_{n+1}) \) has the same property. On the other hand, we have \( \mu_n \to \infty \) (\( n \to \infty \)). Hence we conclude that \( H \) is self-adjoint with \( D(H) = D(H_{GSB}) \), bounded from below and essentially self-adjoint on any core of \( H_{GSB} \).

Now, we assume conditions [H.1],[H.2] and [H.3]. Then \( H_{GSB} \) is self-adjoint on \( D(H_0) \), bounded from below and essentially self-adjoint on any core of \( H_0 \)(see [2]). Hence, the assumptions of Lemma 3.5 hold. Thus Proposition 3.1 follows.

3.2 Proofs of Theorems 3.2 and 3.3

Throughout this subsection, we assume Hypotheses [H.1]-[H.4] and \( m > 0 \).
For a parameter $V > 0$, we define the set of lattice points by

$$\Gamma_V := \frac{2\pi \mathbb{Z}^d}{V} := \left\{ k = (k_1, \ldots, k_d) \mid k_j = \frac{2\pi n_j}{V}, n_j \in \mathbb{Z}, j = 1, \ldots, d \right\}$$

and we denote by $l^2(\Gamma_V)$ the set of $l^2$ sequences over $\Gamma_V$. For each $k \in \Gamma_V$ we introduce

$$C(k, V) := \left[ k_1 - \frac{\pi}{V}, k_1 + \frac{\pi}{V} \right] \times \cdots \times \left[ k_d - \frac{\pi}{V}, k_d + \frac{\pi}{V} \right] \subset \mathbb{R}^d,$$

the cube centered about $k$. By the map

$$U : l^2(\Gamma_V) \ni \{h_l\}_{l \in \Gamma_V} \mapsto (V/2\pi)^{d/2} \sum_{l \in \Gamma_V} h_l \chi_{l,V}(\cdot) \in L^2(\mathbb{R}^d),$$

we identify $l^2(\Gamma_V)$ with a subspace in $L^2(\mathbb{R}^d)$, where $\chi_{l,V}(\cdot)$ is the characteristic function of the cube $C(l, V) \subset \mathbb{R}^d$. It is easy to see that $l^2(\Gamma_V)$ is a closed subspace of $L^2(\mathbb{R}^d)$. Let

$$\mathcal{F}_{b,V} := \mathcal{F}_b(l^2(\Gamma_V)) = \bigoplus_{n=0}^{\infty} \bigotimes_{s} l^2(\Gamma_V),$$

the boson Fock space over $l^2(\Gamma_V)$. We can identify $\mathcal{F}_{b,V}$ the closed subspace of $\mathcal{F}_b$ by the operator $\Gamma(U) := \bigoplus_{n=0}^{\infty} \bigotimes^n U$, where we define $\bigotimes^0 U = 0$. For each $k \in \mathbb{R}^d$, there exists a unique point $k_V \in \Gamma_V$ such that $k \in C(k_V, V)$. Let

$$\omega_V(k) := \omega(k_V), \quad k \in \mathbb{R}^d$$

be a lattice approximate function of $\omega(k)$ and let

$$H_{b,V} := d\Gamma(\omega_V)$$

be the second quantization of $\omega_V$. We define a constant

$$C_V := C d^\gamma \left( \frac{\pi}{V} \right) \left( \frac{1}{2m} + 1 \right),$$

where $C$ and $\gamma$ were defined in [H.4]. In what follows we assume that

$$C_V < 1.$$ 

This is satisfied for all sufficiently large $V$. 12
Lemma 3.6. [2, Lemma 3.1]. We have

\[ D(H_{b,V}) = D(H_b), \]

and

\[ \| (H_b - H_{b,V}) \Psi \| = \frac{2C_V}{1 - C_V} \| H_b \Psi \|, \quad \Psi \in D(H_b). \]

First we consider the case where \( g_j \)'s and \( f_j \)'s are continuous, and finally, by limiting argument, we treat a general case. For a constant \( K > 0 \), we define \( g_{j,K}, f_{j,K}, \) and \( g_{j,K,V}, f_{j,K,V} \) as follows:

\[
\begin{align*}
g_{j,K}(k) &:= \chi_K(k_1) \cdots \chi_K(k_d)g_j(k), \\
g_{j,K,V}(k) &:= \sum_{\ell \in \Gamma_{V,J} \mid |\ell_i| < K} g_j(\ell) \chi_{\ell,V}(k),
\end{align*}
\]

\[
\begin{align*}
f_{j,K}(k) &:= \chi_K(k_1) \cdots \chi_K(k_d)f_j(k), \\
f_{j,K,V}(k) &:= \sum_{\ell \in \Gamma_{V,J} \mid |\ell_i| < K} f_j(\ell) \chi_{\ell,V}(k),
\end{align*}
\]

where \( \chi_K \) denotes the characteristic function of \([-K, K]\).

Lemma 3.7. For all \( j = 1, \ldots, J \),

\[
\begin{align*}
\lim_{V \to \infty} \| g_{j,K,V} - g_{j,K} \| &= 0, & \lim_{V \to \infty} \| g_{j,K,V} / \sqrt{\omega V} - g_{j,K} / \sqrt{\omega} \| &= 0, \\
\lim_{K \to \infty} \| g_{j,K} - g_j \| &= 0, & \lim_{K \to \infty} \| g_{j,K} / \sqrt{\omega} - g_j / \sqrt{\omega} \| &= 0, \\
\lim_{V \to \infty} \| f_{j,K,V} - f_{j,K} \| &= 0, & \lim_{V \to \infty} \| f_{j,K,V} / \sqrt{\omega V} - f_{j,K} / \sqrt{\omega} \| &= 0, \\
\lim_{K \to \infty} \| f_{j,K} - f_j \| &= 0, & \lim_{K \to \infty} \| f_{j,K} / \sqrt{\omega} - f_j / \sqrt{\omega} \| &= 0, \\
\lim_{K \to \infty} \| \sqrt{\omega} f_{j,K} - \sqrt{\omega} f_j \| &= 0, & \lim_{V \to \infty} \| \sqrt{\omega V} f_{j,K,V} - \sqrt{\omega} f_{j,K} \| &= 0.
\end{align*}
\]

Proof. Similar to the proof of [2, Lemma 3.10].

We introduce a new operator:

\[ H_{0,V} := A \otimes I + I \otimes H_{b,V}, \]

\[ H_{1,K} := \sum_{j=1}^J B_j \otimes \phi(g_{j,K}), \]

\[ H_{1,K,V} := \sum_{j=1}^J B_j \otimes \phi(g_{j,K,V}), \]

13
\[
H_{2,K} := \sum_{j=1}^{J} I \otimes \phi(f_{j,K})^2,
\]
\[
H_{2,K,V} := \sum_{j=1}^{J} I \otimes \phi(f_{j,K,V})^2,
\]

and define
\[
H_K := H_0 + \lambda H_{1,K} + \mu H_{2,K},
\]
\[
H_{K,V} := H_{0,V} + \lambda H_{1,K,V} + \mu H_{2,K,V}.
\]

**Lemma 3.8.** (i) \(H_K\) is self-adjoint with \(D(H_K) = D(H_0) \subset D(H_{1,K}) \cap D(H_{2,K})\), bounded from below, and essentially self-adjoint on any core of \(H_0\).

(ii) For all large \(V\), \(H_{K,V}\) is self-adjoint with \(D(H_{K,V}) = D(H_0) \subset D(H_{1,K,V}) \cap D(H_{2,K,V})\), bounded from below, and essentially self-adjoint on any core of \(H_{0,V}\).

**Proof.** Similar to the proof of Proposition 3.1.

**Lemma 3.9.** For all \(z \in \mathbb{C} \setminus \mathbb{R}\), and \(K > 0\),
\[
\lim_{K \to \infty} \| (H_K - z)^{-1} - (H - z)^{-1} \| = 0,
\]
\[
\lim_{V \to \infty} \| (H_{K,V} - z)^{-1} - (H_K - z)^{-1} \| = 0.
\]

**Proof.** Similar to the proof of Lemma 3.5.

The following fact is well known:

**Lemma 3.10.** The operator \(H_{b,V}\) is reduced by \(\mathcal{F}_{b,V}\) and \(H_{b,V}[\mathcal{F}_{b,V}]\) equal to the second quantization of \(\omega_V|\Gamma_V|^2\) on \(\mathcal{F}_{b,V}\).

**Lemma 3.11.** \(H_{K,V}\) is reduced by \(\mathcal{F}_{V}\).

**Proof.** Similar to the proof of Lemma 3.7.

**Lemma 3.12.** We have
\[
H_{K,V}[\mathcal{F}_V] \geq E_0(H_{K,V}) + m.
\]
Lemma 3.13. Let $T_n$ and $T$ be a self-adjoint operators on a separable Hilbert space and bounded from below. Suppose that $T_n \to T$ in norm resolvent sense as $n \to \infty$ and $T_n$ has purely discrete spectrum in the interval $[E_0(T_n), E_0(T_n) + c_n]$ with some constant $c_n$. If $c := \limsup_{n \to \infty} c_n > 0$, then $T$ has purely discrete spectrum in $[E_0(T), E_0(T) + c]$.

Proof. There exists a sequence $\{c_{n_j}\}_{j=1}^{\infty} \subset \{c_n\}_{n=1}^{\infty}$ so that $c_{n_j} \to c(j \to \infty)$. So, for all $\epsilon > 0$ and for sufficiently large $j$, the spectrum of $T_{n_j}$ in $[E_0(T_{n_j}), E_0(T_{n_j}) + c - \epsilon)$ is discrete. Therefore, applying Lemma 3.12 we find that the spectrum of $T$ in $[E_0(T), E_0(T) + c - \epsilon)$ is discrete. Since $\epsilon > 0$ is arbitrary, we get the conclusion.

Now, if $A$ has compact resolvent, by a method similar to the proof of Theorem 1.2 we can prove Theorem 3.2. Therefore, we only prove Theorem 3.3.

The following inequality is known
\[
|\langle \Psi, H_1 \Psi \rangle| \leq C_{\theta,\epsilon}(\Psi, A \otimes I \Psi) + D_{\theta,\epsilon}(\Psi, I \otimes H_b(\Psi)) + E_{\epsilon,\epsilon'}||\Psi||^2,
\]
where $\Psi \in D(H_0)$ is arbitrary. Thus we have,
\[
H \geq (1 - |\lambda|C_{\theta,\epsilon})A \otimes I + (1 - |\lambda|D_{\theta,\epsilon})I \otimes H_b + \mu H_2 - |\lambda|E_{\epsilon,\epsilon'}.
\]
Let $I_{\lambda,g}(K), C_{\theta,\epsilon}(K), D_{\theta,\epsilon}(K)$ and $E_{\epsilon,\epsilon'}(K)$ are $I_{\lambda,g}, C_{\theta,\epsilon}, D_{\theta,\epsilon}, E_{\epsilon,\epsilon'}$ with $g_j, f_j$ replaced by $g_{j,K}, f_{j,K}$ respectively, and let $I_{\lambda,g}(K, V), C_{\theta,\epsilon}(K, V), D_{\theta,\epsilon}(K, V)$ and $E_{\epsilon,\epsilon'}(K, V)$ are $I_{\lambda,g}, C_{\theta,\epsilon}, D_{\theta,\epsilon}, E_{\epsilon,\epsilon'}$ with $g_j, f_j$ and $\omega$ replaced by $g_{j,K,V}, f_{j,K,V}$ and $\omega_V$ respectively. Then we have

Lemma 3.14. The following operator inequalities hold:
\[
H_K \geq (1 - |\lambda|C_{\theta,\epsilon}(K))A \otimes I + (1 - |\lambda|D_{\theta,\epsilon}(K))I \otimes H_b + \mu H_{2,K} - |\lambda|E_{\epsilon,\epsilon'}(K) \quad \text{on} \quad D(H_0),
\]
\[
H_{K,V} \geq (1 - |\lambda|C_{\theta,\epsilon}(K, V))A \otimes I + (1 - |\lambda|D_{\theta,\epsilon}(K, K))I \otimes H_{b,V} + \mu H_{2,K,V} - |\lambda|E_{\epsilon,\epsilon'}(K, V) \quad \text{on} \quad D(H_0).
\]

Proof. Similar to the calculation of [2, (2.12)]
By Lemma 3.7, we have
\[
\lim_{V \to \infty} C_{\theta, \epsilon}(K, V) = C_{\theta, \epsilon}(K), \quad \lim_{K \to \infty} C_{\theta, \epsilon}(K) = C_{\theta, \epsilon},
\]
(9)
\[
\lim_{V \to \infty} D_{\theta, \epsilon'}(K, V) = D_{\theta, \epsilon'}(K), \quad \lim_{K \to \infty} D_{\theta, \epsilon'}(K) = D_{\theta, \epsilon'},
\]
(10)
\[
\lim_{V \to \infty} E_{\epsilon, \epsilon'}(K, V) = E_{\epsilon, \epsilon'}(K), \quad \lim_{K \to \infty} E_{\epsilon, \epsilon'}(K) = E_{\epsilon, \epsilon'}.
\]
(11)
Let \((\theta, \epsilon, \epsilon') \in T\), namely
\[
\tau_{\theta, \epsilon, \epsilon'} = (1 - |\lambda|C_{\theta, \epsilon}(K, V))\Sigma(A) - |\lambda|E_{\epsilon, \epsilon'} > E_0(H).
\]
Formulas (9)-(11) and Lemma 3.9 imply that for all large \(V\) there exists a constant \(K_0 > 0\) such that for all \(K > K_0\),
\[
(1 - |\lambda|C_{\theta, \epsilon}(K, V))\Sigma(A) - |\lambda|E_{\epsilon, \epsilon'}(K, V) > E_0(H_{K,V}),
\]
(12)
\[
|\lambda|C_{\theta, \epsilon}(K, V) < 1, \quad |\lambda|D_{\theta, \epsilon'}(K, V) < 1.
\]
(13)
By Lemma 3.11, \(H_{K,V}\) is reduced by \(\mathcal{F}_V\). Therefore, \(H_{K,V}\) satisfies the following inequality:
\[
H_{K,V}[\mathcal{F}_V \geq (1 - |\lambda|C_{\theta, \epsilon}(K, V))A \otimes I[\mathcal{F}_V] + (1 - |\lambda|D_{\theta, \epsilon'}(K, V))I \otimes H_{b,V}[\mathcal{F}_V] - |\lambda|E_{\epsilon, \epsilon'}(K, V).
\]
(14)
Since \(H_{b,V}[\mathcal{F}_V\) has compact resolvent, the bottom of essential spectrum of the right hand side of (14) is equal to
\[
(1 - |\lambda|C_{\theta, \epsilon}(K, V))\Sigma(A) - |\lambda|E_{\epsilon, \epsilon'}(K, V).
\]
By Lemma 3.12, we have \(E_0(\mathcal{F}_V) = E_0(H_{K,V})\). Thus, applying Theorem 2.1 with \(H_{K,V}[\mathcal{F}_V\), we have that \(H_{K,V}[\mathcal{F}_V\) has purely discrete spectrum in \([E_0(H_{K,V}), \min\{E_0(H_{K,V}) + m, (1 - |\lambda|C_{\theta, \epsilon}(K, V))\Sigma(A) - |\lambda|E_{\epsilon, \epsilon'}(K, V)\})\). Since this fact and Lemma 3.12, \(H_{K,V}\) has purely discrete spectrum in
\[
[E_0(H_{K,V}),\min\{E_0(H_{K,V}) + m, (1 - |\lambda|C_{\theta, \epsilon}(K, V))\Sigma(A) - |\lambda|E_{\epsilon, \epsilon'}(K, V)\}].
\]
By Lemma 3.9 and Lemma 3.13, we have that for all sufficiently large \(K > 0\), \(H_K\) has purely discrete spectrum in \([E_0(H_K),\min\{E_0(H_K) + m, (1 - |\lambda|C_{\theta, \epsilon}(K, V))\Sigma(A) - |\lambda|E_{\epsilon, \epsilon'}(K)\}]). Similarly, \(H\) has purely discrete spectrum in \([E_0(H(\lambda, \mu)),\min\{m + E_0(H(\lambda, \mu)), \tau_{\theta, \epsilon, \epsilon'}\}]). Since \((\theta, \epsilon, \epsilon') \in T\) is arbitrary, \(H\) has purely discrete spectrum in (4). Finally, we have to consider the case where \(g_j\)’s and \(f_j\)’s are not necessarily continuous. But, that argument were already discussed in [4]. So we skip that argument.
4 Ground State of the Dereziński-Gérard Model

We consider a model discussed by J. Dereziński and C. Gérard [5]. We take the Hilbert space of the particle system is taken to be

\[ \mathcal{H} = L^2(\mathbb{R}^N). \]

The Hilbert space for the Dereziński-Gérard (DG) model is given by

\[ \mathcal{F} := \mathcal{H} \otimes \mathcal{F}_b(L^2(\mathbb{R}^d)). \]

We identify \( \mathcal{F} \) as

\[ \bigoplus_{n=0}^{\infty} \left[ \mathcal{H} \otimes \bigotimes_{s} L^2(\mathbb{R}^d) \right]. \]

Hence, if we denote that \( \Psi \in (\Psi^{(n)})_{n=0}^{\infty} \in \mathcal{F} \), each \( \Psi^{(n)} \) belongs to \( \mathcal{H} \otimes [\bigotimes_{s} L^2(\mathbb{R}^d)] \). We denote by \( \mathcal{B}(\mathcal{K}, \mathcal{J}) \) the set of bounded linear operators from \( \mathcal{K} \) to \( \mathcal{J} \). For \( v \in \mathcal{B}(\mathcal{H}, \mathcal{H} \otimes L^2(\mathbb{R}^d)) \), we define an operator \( \tilde{a}^*(v) \) by

\[
(\tilde{a}^*(v)\Psi)^{(n)} := \sqrt{n}(I_\mathcal{H} \otimes S_n)(v \otimes I_{\otimes_{s} L^2(\mathbb{R}^d)})\Psi^{(n-1)}, \quad (n \geq 1),
\]

\[ \Psi \in D(\tilde{a}^*(v)) := \left\{ \Psi = (\Psi^{(n)})_{n=0}^{\infty} \in \mathcal{F} \left| \sum_{n=0}^{\infty} \| (\tilde{a}^*(v)\Psi)^{(n)} \|^2 \right| < \infty \right\}. \]

We set

\[ D_0 := \{ \Psi = (\Psi^{(n)})_{n=0}^{\infty} \in \mathcal{F} | \text{there exists a constant } n_0 \in \mathbb{N}, \]

\[ \text{such that, for all } n \geq n_0, \Psi^{(n)} = 0 \}. \]

Throughout this section, we write simply \( I_n := I_{\otimes_{s} L^2(\mathbb{R}^d)} \). It is easy to see that:

**Proposition 4.1.** \( \tilde{a}^*(v) \) is a closed linear operator and \( D_0 \) is a core of \( \tilde{a}^*(v) \).

So we set

\[ \tilde{a}(v) := (\tilde{a}^*(v))^* \]

the adjoint operator of \( \tilde{a}^*(v) \).
Proposition 4.2. The operator $\tilde{a}(v)$ has the following properties:

\[
D(\tilde{a}(v)) = \left\{ \Psi = (\Psi^{(n)})_{n=0}^{\infty} \mid \sum_{n=0}^{\infty} (n+1) \| (I_{\mathcal{H}} \otimes S_n)(v^* \otimes I_n)\Psi^{(n+1)} \|_2^2 < \infty \right\}
\]

(15)

\[
(\tilde{a}(v)\Psi)^{(n)} = \sqrt{n+1} I_{\mathcal{H}} \otimes S_n (v^* \otimes I_n)\Psi^{(n+1)}, \quad \Psi \in D(\tilde{a}(v)),
\]

(16)

and $D_0$ is a core of $\tilde{a}(v)$.

Proof. For $\Phi \in \mathcal{F}$, $\Psi \in D(\tilde{a}^*(v))$,

\[
\langle \Phi, \tilde{a}^*(v)\Psi \rangle = \sum_{n=1}^{\infty} \langle \Phi^{(n)}, (I_{\mathcal{H}} \otimes S_n)(v \otimes I_{n-1})\Psi^{(n-1)} \rangle
\]

\[
= \sum_{n=0}^{\infty} \sqrt{n+1} \langle v^* \otimes I_n \Phi^{(n+1)}, \Psi^{(n)} \rangle
\]

\[
= \sum_{n=0}^{\infty} \langle \sqrt{n+1} (I_{\mathcal{H}} \otimes S_n)(v^* \otimes I_n)\Phi^{(n+1)}, \Psi^{(n)} \rangle.
\]

This implies (15) and (16). It is easy to prove that $D_0$ is a core of $\tilde{a}(v)$.  

An analogue of the Segal field operator is defined by

\[
\tilde{\phi}(v) := \frac{1}{\sqrt{2}} (\tilde{a}(v) + \tilde{a}^*(v)).
\]

Let $A$ be a non-negative self-adjoint operator on $\mathcal{H}$ with $E_0(A) = 0$. Then the Hamiltonian of the DG model is defined by

\[
H_{DG} := A \otimes I + I \otimes H_b + \tilde{\phi}(v).
\]

We call it the Dereziński-Gérard Hamiltonian. Here $H_b$ is the second quantization of $\omega$ introduce in Section 3. Let

\[
H_0 := A \otimes I + I \otimes H_b.
\]

Throughout this section we assume the following conditions:

[DG.1] There is a Borel measurable function $v(x,k) \in \mathbb{C}$, $(x \in \mathbb{R}^N, k \in \mathbb{R}^d)$, such that

\[
(vf)(x,k) = v(x,k)f(x), \quad f \in L^2(\mathbb{R}^d).
\]

18
We need also the following assumption:

\[ \text{DG.2} \]

\[
\text{ess} \sup_{x \in \mathbb{R}^N} \int_{\mathbb{R}^d} \left| \frac{v(x,k)}{\sqrt{\omega(k)}} \right|^2 \, dk < \infty.
\]

**Proposition 4.3.** Assume [DG.1] and [DG.2]. Then \( H_{DG} \) is self-adjoint with \( D(H_{DG}) = D(H_0) \), and essentially self-adjoint on any core of \( H_0 \).

For a finite volume approximation, we introduce the following hypotheses:

\[ \text{DG.3} \]

There exists a nonnegative function \( \tilde{v} \in L^2(\mathbb{R}^d) \) and function \( \tilde{o} : \mathbb{R} \to \mathbb{R} \), such that

\[
\text{ess} \sup_{x \in \mathbb{R}^n} \left| v(x,k) - v(x,\ell) \right| \leq \tilde{v}(k)\tilde{o}(|k - \ell|), \quad \text{a.e. } k, \ell \in \mathbb{R}^d
\]

\[
\lim_{t \downarrow 0} \tilde{o}(t) = 0.
\]

\[ \text{DG.4} \]

\[
\text{ess} \sup_{x \in \mathbb{R}^n} \int_{([-K,K]^d)^c} |v(x,k)|^2 \, dk = o(K^0),
\]

where

\([[-K,K]^d]^c := \mathbb{R}^d \setminus (I \times \cdots \times I), \quad I := [-K,K]\]

and, \( o(t^0) \) satisfies \( \lim_{t \to 0} o(t^0) = 0 \).

Let \( m \) be defined by (3). Let

\[
D := \frac{1}{2} \inf_{0 < \epsilon' < \frac{\|v\|_{L^2(\mathbb{R}^N)}}{\|v/\sqrt{\omega}\|_{L^2}}} \left( \epsilon' + \frac{1}{\epsilon'} \right). \tag{17}
\]

Here, \( v/\sqrt{\omega} \) is a multiplication operator by the function \( v(x,k)/\sqrt{\omega(k)} \) from \( L^2(\mathbb{R}^N) \) to \( L^2(\mathbb{R}^N) \otimes L^2(\mathbb{R}^d) \). In the case \( m > 0 \), we can establish the existence of a ground state of \( H_{DG} \):  

**Theorem 4.4.** Let \( m > 0 \). Suppose that [DG.1]-[DG.4] and [H.4] hold, and suppose

\[
\Sigma(A) - \|v\| D - E_0(H_{DG}) > 0.
\]
Then, $H_{DG}$ has purely discrete spectrum in

$$[E_0(H_{DG}), \min\{E_0(H_{DG}) + m, \Sigma(A) - \|v\|D\}).$$

In particular $H_{DG}$ has a ground state.

Remark. In the case where $A$ has compact resolvent, this theorem has been proved in [5]. A new aspect here is in that $A$ does not necessarily have compact resolvent. Also our method is different from that in [5].

4.1 Proof of Proposition 4.3

Lemma 4.5. Let $M(x) = (\int_{\mathbb{R}^d} |v(x, k)|^2 dk)^{1/2}$, $x \in \mathbb{R}^N$ and $M : L^2(\mathbb{R}^N) \rightarrow L^2(\mathbb{R}^N)$ be a multiplication operator by the function $M(x)$. Then

$$\|vf\|^2 = \|Mf\|^2, \quad f \in L^2(\mathbb{R}^N).$$

In particular, $\|v\| = \|M\| = (\text{ess.sup}_{x \in \mathbb{R}^N} \int_{\mathbb{R}^d} |v(x, k)|^2 dk)^{1/2}$ hold.

Proof. By the Fubini’s theorem, we have

$$\|vf\|^2 = \int_{\mathbb{R}^d} dk \int_{\mathbb{R}^N} dx |v(x, k)|^2 |f(x)|^2 = \int_{\mathbb{R}^N} \left( |f(x)|^2 \int_{\mathbb{R}^d} |v(x, k)|^2 dk \right) dx.$$

This means the result.

The adjoint $v^*$ has the following form:

Lemma 4.6. For all $g \in \mathcal{H} \otimes L^2(\mathbb{R}^d)$,

$$(v^*g)(x) = \int_{\mathbb{R}^d} v(x, k)^* g(x, k) dk, \quad \text{a.e. } x \in \mathbb{R}^d. \quad (18)$$

Proof. For all $f \in \mathcal{H}$, we have

$$\langle g, vf \rangle = \int dx \int dk g(x, k)^* v(x, k) f(x)$$

$$= \int dx \left( \int g(x, k)^* v(x, k) dk \right) f(x).$$

Since $f$ is arbitrary, this proves (18).
Lemma 4.7. $\tilde{a}(v)$ is
\[
D(\tilde{a}(v)) = \left\{ \Psi \in F \left| \sum_{n=0}^{\infty} (n+1) \int_{\mathbb{R}^{d+n}} dx dk_1 \cdots dk_n \left| \int_{\mathbb{R}^d} dk v(k,x)^* \Psi^{(n+1)}(x,k,k_1,\ldots,k_n) \right|^2 < \infty \right. \right\}
\]
\[
(\tilde{a}(v)\Psi)^{(n)}(x,k_1,\ldots,k_n) = \sqrt{n+1} \int_{\mathbb{R}^d} v(x,k)^* \Psi^{(n+1)}(x,k,k_1,\ldots,k_n), \ \text{a.e.} \ (\Psi \in D(\tilde{a}(v)))
\]

Proof. Using Lemma 4.6, we have
\[
(v^* \otimes I_n)\Psi^{(n+1)}(x,k_1,\ldots,k_n) = \int_{\mathbb{R}^d} v^*(x,k)\Psi^{(n+1)}(x,k,k_1,\ldots,k_n) dk.
\]
This is invariant for all permutations of $k_1,\ldots,k_n$. Therefore, using Proposition 4.2, we get
\[
(\tilde{a}(v)\Psi)^{(n)}(x,k_1,\ldots,k_n) = \sqrt{n+1} \int_{\mathbb{R}^d} v(x,k)^* \Psi^{(n+1)}(x,k,k_1,\ldots,k_n) dk.
\]

Lemma 4.8. Suppose that [DG.1] and [DG.2] hold. Then, $D(\tilde{a}(v)) \subseteq D(I \otimes H_{b}^{1/2})$ and
\[
\|\tilde{a}(v)\Phi\| \leq \|v/\sqrt{\omega}\| \|I \otimes H_{b}^{1/2}\|, \ \Phi \in D(I \otimes H_{b}^{1/2}).
\]
Proof. By (19), we have for all $\Phi \in D(\tilde{a}(v))$
\[
\|(\tilde{a}(v)\Phi)^{(n)}\|^2 = (n+1) \int_{\mathbb{R}^{d+n}} dx dk_1 \cdots dk_n \left| \int_{\mathbb{R}^d} \sqrt{\omega(k)} \frac{1}{\sqrt{\omega(k)}} v(x,k)^* \Phi^{(n+1)}(x,k,k_1,\ldots,k_n) dk \right|^2.
\]
Using the Schwarz inequality, one has
\[
\left| \int_{\mathbb{R}^d} \sqrt{\omega(k)} \frac{1}{\sqrt{\omega(k)}} v(x,k)^* \Phi^{(n+1)}(x,k,k_1,\ldots,k_n) dk \right|^2 \leq \int_{\mathbb{R}^d} |v(x,k)|^2 \sqrt{\omega(k)} dk \cdot \int_{\mathbb{R}^d} \omega(k) |\Phi^{(n+1)}(x,k,k_1,\ldots,k_n)|^2 dk.
\]
Hence, for every $\Phi \in \mathcal{D}_0 \cap D(I \otimes H^{1/2}_b)$, we have

$$\| (\tilde{a}(v) \Phi)^{(n)} \|^2 \leq \left( \mathop{\text{ess}} \sup \int_{\mathbb{R}^d} \left| \frac{v(x, k)}{\sqrt{\omega(k)}} \right|^2 \, dk \right)(n + 1) \times \int_{\mathbb{R}^{dn+1}} \prod_{k \neq k_j} \omega(k) \| \Phi^{(n+1)}(x, k, k_1, \ldots, k_n) \|^2 \right) \times \int_{\mathbb{R}^{dn+1}} \prod_{k \neq k_j} \omega(k) \| \Phi^{(n+1)}(x, k, k_1, \ldots, k_n) \|^2 \right)$$

$$= \left( \mathop{\text{ess}} \sup \int_{\mathbb{R}^d} \left| \frac{v(x, k)}{\sqrt{\omega(k)}} \right|^2 \, dk \right) \times \int_{\mathbb{R}^{dn+1}} \prod_{k \neq k_j} \omega(k) \| \Phi^{(n+1)}(x, k, k_1, \ldots, k_n) \|^2 \right)$$

$$= \left\| \frac{v}{\sqrt{\omega}} \right\| \| (I \otimes H^{1/2}_b \Phi)^{(n+1)} \|^2.$$

Therefore

$$\| \tilde{a}(v) \Phi \| \leq \left\| \frac{v}{\sqrt{\omega}} \right\| \| (I \otimes H^{1/2}_b \Phi)^{(n+1)} \|^2.$$

Since, $\mathcal{D}_0 \cap D(I \otimes H^{1/2}_b)$ is a core of $I \otimes H^{1/2}_b$, one can extend this inequality to all $\Phi \in D(I \otimes H^{1/2}_b)$, and $D(I \otimes H^{1/2}_b) \subset D(\tilde{a}(v))$ holds.

**Lemma 4.9.** On $\mathcal{D}_0$, $\tilde{a}(v)$ and $\tilde{a}^*(v)$ satisfy the following commutation relation:

$$[\tilde{a}(v), \tilde{a}^*(v)] = \int_{\mathbb{R}^d} |v(\cdot, k)|^2 \, dk.$$

where the right hand side is a multiplication operator by the function : $x \mapsto \int_{\mathbb{R}^d} |v(x, k)|^2 \, dk$.

**Proof.** Let $\Phi \in \mathcal{D}_0$. By the definition of $\tilde{a}^*(v)$, and using Proposition 4.2, we get

$$([\tilde{a}^*(v), \tilde{a}(v)] \Phi)^{(n)} = (\tilde{a}(v)\tilde{a}^*(v) \Phi)^{(n)} - (\tilde{a}(v)^*\tilde{a}(v) \Phi)^{(n)}$$

$$= \sqrt{n + 1} I_\mathcal{H} \otimes S_n (\Phi) - \sqrt{n} (I \otimes I_n) (\tilde{a}(v)^* \Phi)^{(n+1)}$$

$$- \sqrt{n} (I \otimes S_n) (\Phi) (v \otimes I_{n-1}) (\tilde{a}(v) \Phi)^{(n-1)}.$$
Hence, we have

\[
([\tilde{a}^*(v), \tilde{a}(v)] \Phi)^{(n)}(x, k_1, \ldots, k_n) = \left( n + 1 \right) \int_{\mathbb{R}^d} v(x, k)^* (I \otimes S_{n+1}(v \otimes I_{n-1}) \Phi^{(n)})(x, k, k_1, \ldots, k_n) \, dk
- n \frac{1}{n} \sum_{j=1}^{n} v(x, k_j) (v^* \otimes I_{n-1} \Phi^{(n)})(x, k_1, \ldots, \hat{k}_j, \ldots, k_n)
\]

\[
= \int_{\mathbb{R}^d} dk \, v(x, k)^* \left( v(x, k) \Phi^{(n)}(x, k_1, \ldots, k_n) + \sum_{j=1}^{n} v(x, k_j) \Phi^{(n)}(x, k, k_1, \ldots, \hat{k}_j, \ldots, k_n) \right)
- \sum_{j=1}^{n} v(x, k_j) \int_{\mathbb{R}^d} dk v(x, k)^* \Phi^{(n)}(x, k, k_1, \ldots, \hat{k}_j, \ldots, k_n)
\]

\[
= \left( \int_{\mathbb{R}^d} |v(x, k)|^2 \right) \Phi(x, k_1, \ldots, k_n).
\]

Here \(^\sim\) indicates the omission of the object wearing the hat.

**Lemma 4.10.** Assume, \([DG.1]\) and \([DG.2]\). Then \(D(I \otimes H_1^{1/2}) \subset D(\tilde{a}^*(v))\) and for all \(\Phi \in D(I \otimes H_1^{1/2})\),

\[
\|\tilde{a}^*(v) \Phi\|^2 \leq \|v/\sqrt{\omega}\|^2 \|I \otimes H_1^{1/2} \Phi\|^2 + \|v\|^2 \|\Phi\|^2. \quad (20)
\]

**Proof.** For all \(\Phi \in \mathcal{D}_0 \cap D(I \otimes H_1^{1/2})\), we have

\[
\|\tilde{a}^*(v) \Phi\|^2 = \langle \Phi, \tilde{a}(v) \tilde{a}^*(v) \Phi \rangle = \langle \Phi, \tilde{a}^*(v) \tilde{a}(v) \Phi \rangle + \left( \int_{\mathbb{R}^d} |v(\cdot, k)|^2 \right) \Phi, \Phi \rangle
\]

\[
\leq \|\tilde{a}(v) \Phi\|^2 + \|v\|^2 \|\Phi\|^2.
\]

Thus we can apply Lemma 4.8 to obtain the result.

**Proof of Proposition 4.3.** By Lemma 4.8 and 4.10, the operator \(\tilde{\phi}(v)\) is \(I \otimes H_1^{1/2}\)-bounded. Hence \(\tilde{\phi}(v)\) is infinitesimally small with respect to \(I \otimes H_b\). Namely, for all \(\epsilon > 0\), there exists a constant \(c_\epsilon > 0\), such that,

\[
\|\tilde{\phi}(v) \Phi\| \leq \epsilon \|I \otimes H_b \Phi\| + c_\epsilon \|\Phi\|, \quad \Phi \in D(I \otimes H_b).
\]

23
Since $A \geq 0$, we have
\[ \| \tilde{v}(v) \Phi \| \leq \epsilon \| H_0 \Phi \| + c \| \Phi \|, \quad \Phi \in D(H_0). \]
Thus we can apply the Kato-Rellich theorem to obtain the conclusion of Proposition 4.3.

4.2 Proof of Theorem 4.4

In this subsection we suppose that the assumption of Theorem 4.4 holds. Let $F_{b,V}$, $\omega_V$, $H_{b,V}$, $H_{0,V}$, $F_V$, $\Gamma_V$, $\chi_{\ell,V}(k)$ be an object already defined in Section 3, respectively. Suppose that $\chi_K$ is a characteristic function of \([-K,K]\).

For a parameter $K > 0$, we define $v_K \in B(H, H \otimes L^2(\mathbb{R}^d))$ by
\[
(v_K f)(x, k) := \chi_{[−K,K]}(k)v(x,k)f(x).
\]
and $v_K, V \in B(H, H \otimes L^2(\mathbb{R}^d))$ by
\[
(v_{K,V} f)(x, k) := \sum_{\ell \in \Gamma_V, |\ell| \leq K} \chi_{\ell,V}(k)v(x, \ell)f(x).
\]

Lemma 4.11. The following hold:
\[ \| v_K - v_K, V \| \to 0 \ (V \to \infty), \quad \| v_K - v \| \to 0 \ (K \to \infty). \]  \hfill (21)
\[ \left\| \frac{v_K}{\sqrt{\omega}} - \frac{v_{k,V}}{\sqrt{\omega}} \right\| \to 0 \ (V \to \infty), \quad \left\| \frac{v}{\sqrt{\omega}} - \frac{v_K}{\sqrt{\omega}} \right\| \to 0 \ (K \to \infty). \]  \hfill (22)

Proof. By [DG.3] and [DG.4], we have
\[
\| v_K - v_K, V \|^2 = \text{ess.sup}_{x \in \mathbb{R}^N} \int_{\mathbb{R}^d} \left| \chi_K(k)v(x, k) - \sum_{\ell \in \Gamma_V, |\ell| \leq K} v(x, \ell)\chi_{\ell,V}(k) \right|^2 dk
\]
\[
= \text{ess.sup}_{x \in \mathbb{R}^N} \int_{\mathbb{R}^d} \sum_{\ell \in \Gamma_V, |\ell| \leq K} \chi_{\ell,V}(k)|v(x, k) - v(x, \ell)|^2 dk
\]
\[
\leq \text{ess.sup}_{x \in \mathbb{R}^N} \int_{\mathbb{R}^d} \sum_{\ell \in \Gamma_V, |\ell| \leq K} \chi_{\ell,V}(k)|\tilde{v}(k)|^2 |k - \ell|^2 dk
\]
\[
\leq \int_{\mathbb{R}^d} \sum_{\ell \in \Gamma_V, |\ell| \leq K} \chi_{\ell,V}(k)|\tilde{v}(k)|^2 |k - \ell|^2 dk.
\]
It follows from the property of $\tilde{o}$ that for every $\epsilon > 0$, there exists a constant $V_0 > 0$ such that, for all $V > V_0$,

$$\chi_{\ell,V}(k)\tilde{o}(|k - \ell|)^2 \leq \epsilon \chi_{\ell,V}(k).$$

Therefore,

$$\|v_K - v_{K,V}\|^2 \leq \epsilon \int_{\mathbb{R}^d} \sum_{|\ell| < K} \chi_{\ell,V}(k) |\tilde{o}(k)|^2 dk = \epsilon \|\tilde{v}\|_{L^2(\mathbb{R}^d)}. $$

Hence the first one of (21) holds. The second one is a direct result of condition [DG.4]:

$$\|v_K - v\|^2 = \text{ess. sup} \int_{\mathbb{R}^d} |\chi_K(k) - 1|^2 |v(x,k)|^2 dk$$

$$= \text{ess. sup} \int_{[-K,K]^d} |v(x,k)|^2 dk = o(K^0) \to 0 \ (K \to \infty).$$

Using [H.4], one can easily check (22).

We introduce two operators:

$$H_{DG}(K) := A \otimes I + I \otimes H_b + \tilde{\phi}(v_K),$$

$$H_{DG}(K,V) := A \otimes I + I \otimes H_{b,V} + \tilde{\phi}(v_{K,V}).$$

**Lemma 4.12.**

(i) $H_{DG}(K)$ is self-adjoint with $D(H_{DG}(K)) = D(H_0)$, bounded from below, and essentially self-adjoint on any core of $H_0$.

(ii) For sufficiently large $V > 0$, $H_{DG}(K,V)$ is self-adjoint with domain $D(H_{DG}(K,V)) = D(H_0)$, bounded from below, and essentially self-adjoint on any core of $H_0$.

**Proof.** Similar to the proof of Proposition 4.3.

**Lemma 4.13.** For all $z \in \mathbb{C} \setminus \mathbb{R}$,

$$\lim_{V \to \infty} \|(H_{DG}(K,V) - z)^{-1} - (H_{DG}(K) - z)^{-1}\| = 0,$$

$$\lim_{K \to \infty} \|(H_{DG}(K) - z)^{-1} - (H_{DG} - z)^{-1}\| = 0.$$

**Proof.** Similar to the proof of [2, Lemma 3.5].
Lemma 4.14. The operator $H_{DG}(K, V)$ is reduced by $F_V$.

Proof. We identify $v(x, \ell)$ with multiplication operator by $v(\cdot, \ell)$. By abuse of symbols, we denote $\chi_{\ell,V}(\cdot)$ by $\chi_{\ell,V}(k)$. Then

$$(\tilde{a}^*(v(x, \ell)\chi_{\ell,V}(k))\Phi)^{(n)} = \sqrt{n}(I \otimes S_n)(v(x, \ell)\chi_{\ell,V}(k) \otimes I)\Phi^{(n-1)} = \sqrt{n}v(x, \ell)S_n(\chi_{\ell,V} \otimes \Phi^{(n-1)}) = \chi(x, \ell)\sqrt{n}S_n(\chi_{\ell,V} \otimes \Phi^{(n-1)}).$$

Hence, we have

$$\tilde{a}^*(v(x, \ell)\chi_{\ell,V}(k))\Phi = v(x, \ell) \otimes a^*(\chi_{\ell,V})\Phi.$$ 

Therefore, we get

$$\tilde{a}^*(v_K, V) = \sum_{\ell \in \Gamma_V \mid |\ell| < K} v(\cdot, \ell) \otimes a^*(\chi_{\ell,V}). \tag{23}$$

Hence, its adjoint is

$$\tilde{a}(v_K, V) = \sum_{\ell \in \Gamma_V \mid |\ell| < K} v(\cdot, \ell) \otimes a(\chi_{\ell,V}). \tag{24}$$

This means that the operator $H_{DG}(K, V)$ is a special case of the GSB Hamiltonian (see [2]). Hence, by [2, Lemma 3.7] $H_{DG}(K, V)$ is reduced by $F_V$. \hfill \qed

Lemma 4.15. $H_{DG}(K, V)[F_{\perp}^V \geq E_0(H_{DG}(K, V)) + m$

Proof. Similar to the proof of [2, Lemma 3.10]. \hfill \qed

Lemma 4.16. For all $\Phi \in D(I \otimes H_1^{1/2})$, and for all $\ell' > 0$,

$$|\langle \Phi, \tilde{a}^*(v)\Phi \rangle| \leq \frac{\ell'}{\|v\\|} \frac{\|v\\|^2}{\sqrt{\omega}} \|I \otimes H_1^{1/2}\|^2 + \frac{\|v\\|}{2} \left( \ell' + \frac{1}{\ell'} \right) \|\Phi\|^2.$$
Proof. For all \( \Phi \in D(I \otimes H^{1/2}_b) \), \( \epsilon' > 0 \),

\[
|\langle \Phi, \tilde{\phi}(v)\Phi \rangle| \leq \frac{1}{\sqrt{2}} \left( \epsilon \| \tilde{a}(v)\Phi \|^2 + \frac{1}{4\epsilon} \| \Phi \|^2 + \epsilon \| \tilde{a}^*(v)\Phi \|^2 + \frac{1}{4\epsilon} \| \Phi \|^2 \right)
\leq \frac{1}{\sqrt{2}} \left( 2\epsilon \left\| \frac{v}{\sqrt{\omega}} \right\|^2 \| I \otimes H^{1/2}_b\Phi \|^2 + \epsilon \| v \|^2 \| \Phi \|^2 + \frac{1}{2\epsilon} \| \Phi \|^2 \right)
= \sqrt{2}\epsilon \left\| \frac{v}{\sqrt{\omega}} \right\|^2 \| I \otimes H^{1/2}_b\Phi \|^2 + \frac{1}{2} \left( \sqrt{2}\epsilon \| v \| + \frac{1}{\sqrt{2\epsilon}} \| v \| \right) \| \Phi \|^2,
\]

where we have used Lemma 4.8 and 4.10. Let \( \sqrt{2\epsilon} \| v \| =: \epsilon' \). Then, for all \( \epsilon' > 0 \), we have

\[
|\langle \Phi, \tilde{\phi}(v)\Phi \rangle| \leq \frac{\epsilon'}{\| v \|} \left\| \frac{v}{\sqrt{\omega}} \right\|^2 \| I \otimes H^{1/2}_b\Phi \|^2 + \frac{1}{2} \left( \epsilon' + \frac{1}{\epsilon'} \right) \| \Phi \|^2.
\]

Proof of Theorem 4.4. From (23) and (24), \( H_{DG}(K, V) \) is equal to the special case of the GSB model. Therefore, \( H_{DG}(K, V)[F_V \] has the same form with \( H_{DG}(K, V) \). Using Lemma 4.16 we have on \( D(H_0) \cap F_V \)

\[
H_{DG}(K, V) = A \otimes I + I \otimes H_{b,V} + \tilde{\phi}(v_{K,V})
\geq A \otimes I + I \otimes H_{b,V} - \frac{\epsilon'}{\| v_{K,V} \|} \| \frac{v_{K,V}}{\sqrt{\omega_V}} \| \| I \otimes H_{b,V} - \| v_{K,V} \| \left( \epsilon' + \frac{1}{\epsilon'} \right)
= A \otimes I + \left( 1 - \frac{\epsilon'}{\| v_{K,V} \|} \| \frac{v_{K,V}}{\sqrt{\omega_V}} \| \right) I \otimes H_{b,V} - \| v_{K,V} \| \left( \epsilon' + \frac{1}{\epsilon'} \right), \tag{25}
\]

where \( \epsilon' > 0 \) is an arbitrary constant. By Lemma 3.10, \( H_{b,V}[F_{b,V} \) has compact resolvent. Thus, for \( \epsilon' > 0 \) satisfying

\[
1 - \frac{\epsilon'}{\| v_{K,V} \|} \| \frac{v_{K,V}}{\sqrt{\omega_V}} \|^2 > 0, \tag{26}
\]

the bottom of the essential spectrum of (25) is equal to

\[
\Sigma(A) - \frac{\| v_{K,V} \|}{2} \left( \epsilon' + \frac{1}{\epsilon'} \right).
\]
Let, \( D_K \) and \( D_{K,V} \) be \( D \) with \( v \) replaced by \( v_K, v_{K,V} \), respectively. It is easy to see that
\[
\lim_{K \to \infty} D_K = D, \quad \lim_{V \to \infty} D_{K,V} = D_K.
\]

By Lemma 4.13, one has
\[
\lim_{K \to \infty} E_0(H_{DG}(K)) = E_0(H_{DG}), \quad \lim_{V \to \infty} E_0(H_{DG}(K,V)) = E_0(DG(K)).
\]

From the assumption of Theorem 4.4, for all \( K > 0 \), there exists a constant \( V_0 \) such that for \( V > V_0 \),
\[
\Sigma(A) - \frac{\|v_{K,V}\|}{2} D_{K,V} - E_0(H_{DG}(K,V)) > 0.
\]

By the definition of \( D_{K,V} \), for all \( K > 0 \) and \( V > V_0 \), and for all \( \epsilon' \) which satisfies (26), we have
\[
\Sigma(A) - \frac{\|v_{K,V}\|}{2} \left( \epsilon' + \frac{1}{\epsilon'} \right) > E_0(H_{DG}(K,V)).
\]

Therefore, by Theorem 2.1, we have that \( H_{DG}(K,V) \) has purely discrete spectrum in
\[
[E_0(H_{DG}(K,V)), \Sigma(A) - \|v_{K,V}\| D_{K,V}].
\]

This fact and Lemma 4.15 mean that \( H_{DG}(K,V) \) has purely discrete spectrum in
\[
[E_0(H_{DG}(K,V)), \min \{ E_0(H_{DG}(K,V)) + m, \Sigma(A) - \|v_{K,V}\| D_{K,V} \}].
\]

Finally, we use Lemma 3.13 and Lemma 4.13, to conclude that \( H_{DG} \) has purely discrete spectrum in the interval
\[
[E_0(H_{DG}), \min \{ E_0(H_{DG}) + m, \Sigma(A) - \|v\| D \}]
\]

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References


