bu yerda bloklar Ω_n statsionar yechimi orqali quyidagicha ifodalanadi va $T_{\pm}$, D_n (shu jumladan, D_0 uch bloki) (3) hamda (4)-tenglamalarda berilgan.

Birlashish nuqtasi ustuvorlik masalasini faqat L_0 tarkibidagi D_0 bloki orqali o'zgartiradi; G_0 bloki esa diagonalligicha qoladi, chunki nochiziqlik har bir tugunning o'zida ta'sir ko'rsatadi. Agar D_0 dan $\kappa_0\sigma_1$ bog'lanishi olib tashlansa, (30) sistema zanjir masalasining ikkita mustaqil nusxasiga ajraladi, bu esa mantiqiy to'g'rilikni tekshirish bo'lib xizmat qiladi.

Xulosa. Ushbu ishda to'rt qirrali yulduzsimon PT-simmetrik diskret panjaradagi soliton yechimlari o'rganildi. Markaziy kvadrimer va to'rtta yarim cheksiz tarmoqdan tashkil topgan tuzilma uchun nochiziqli Shredinger tenglamasi asosida matematik model qurildi. Chiziqli xos qiymat masalasi blok-uchdiagonalli operator ko'rinishida ifodalanib, PT-simmetriyaning buzilish chegarasi aniqlandi. Solitonlarning chiziqli barqarorligi g'alayonlanish nazariyasi yordamida tekshirildi va barqarorlik spektrlari parametrlarga bog'liq holda tahlil qilindi. Natijalar shuni ko'rsatdiki, lokalizatsiya kengligi hamda kuchayish-susayish profilining o'zgarishi PT-simmetriya buzilish chegarasiga va solitonlarning barqarorligiga sezilarli ta'sir ko'rsatadi.

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THRESHOLD ASYMPTOTICS FOR EIGENVALUES OF A TWO-PARTICLE DISCRETE SCHRÖDINGER OPERATOR ON A THREE-DIMENSIONAL LATTICE

Annotation. *We study threshold asymptotics for eigenvalues of the zero-quasimomentum fiber operator $H_{\mu_1\mu_2}(0)$ for a two-particle discrete Schrödinger operator on the three-dimensional lattice $\mathbb{Z}^3$. The operator is restricted to the coordinate-antisymmetric invariant subspace. In this subspace the on-site interaction and the symmetric nearest-neighbor components vanish; hence the reduced problem is governed by a rank-one perturbation depending only on μ_2. The Lippmann–Schwinger reduction gives a scalar Fredholm determinant. We obtain necessary and sufficient conditions for isolated eigenvalues below and above the essential spectrum, identify the critical coupling constants, and prove linear threshold asymptotics of the corresponding eigenvalue branches.*

Keywords: *Two-particle discrete Schrödinger operator, zero quasimomentum, coordinate-antisymmetric subspace, essential spectrum, Fredholm determinant, threshold asymptotics.*

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UCH O'LCHAMLI PANJARADA IKKI ZARRACHALI DISKRET SHRYODINGER OPERATORI XOS QIYMATLARINING BO'SAG'A ASIMPTOTIKALARI

Annotatsiya. *Maqolada uch o'lchamli $\mathbb{Z}^3$ panjaradagi ikki zarrachali diskret Shryodinger operatorining nol kvazimomentga mos $H_{\mu_1\mu_2}(0)$ fiber operatori koordinata bo'yicha antisimmetrik invariant qism fazoda o'rganiladi. Ushbu qism fazoda tugundagi o'zaro ta'sir va eng yaqin qo'shni tugunlar o'zaro ta'sirining simmetrik komponentlari yo'qolib, masala faqat μ_2 ga bog'liq rangi birga teng qo'zg'alishga keltiriladi. Lippmann–Schwinger tenglamasi orqali xos qiymat masalasi skalyar Fredholm determinantiga reduksiya qilinadi. Muhim spektr* $[0,24]$ *dan pastda va yuqorida xos qiymatlarning mavjudligi hamda yago-*

naligi uchun zarur va yetarli shartlar, kritik bog'lanish konstantalari va xos qiymatlar uchun chiziqli bo'sag'a asimptotikalari aniqlanadi.

Kalit so'zlar: *Ikki zarrachali diskret Shryodinger operatori, nol kvazimoment, koordinata-antisimmetrik qism fazo, muhim spektr, Fredholm determinanti, bo'sag'a asimptotikasi.*

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ПОРОГОВЫЕ АСИМПТОТИКИ СОБСТВЕННЫХ ЗНАЧЕНИЙ ДВУХЧАСТИЧНОГО ДИСКРЕТНОГО ОПЕРАТОРА ШРЁДИНГЕРА НА ТРЁХМЕРНОЙ РЕШЁТКЕ

Аннотация. *В статье рассматривается фибер-оператор $H_{\mu_1\mu_2}(0)$ двухчастичного дискретного оператора Шрёдингера на решётке $\mathbb{Z}^3$ в координатно-антисимметричном инвариантном подпространстве. В этом подпространстве одноузельное взаимодействие и симметрические компоненты взаимодействия ближайших соседей не дают вклада, поэтому редуцированный оператор является возмущением ранга один, зависящим только от μ_2. С помощью уравнения Липпмана–Швингера задача о собственных значениях вне существенного спектра $[0,24]$ сводится к скалярному определителю Фредгольма. Получены необходимые и достаточные условия существования изолированных собственных значений, критические константы связи и линейные пороговые асимптотики.*

Ключевые слова: *двухчастичный дискретный оператор Шрёдингера, нулевой квазиимпульс, координатно-антисимметричное подпространство, существенный спектр, определитель Фредгольма, пороговая асимптотика.*

1. Introduction. Two-particle discrete Schrödinger operators on lattices are a basic class of models in the spectral theory of finite-particle quantum systems. In lattice models the compactness of the Brillouin zone and the band structure of the free dispersion allow one to analyze threshold effects, bound states and parameter-dependent changes in the discrete spectrum with high precision; see, for example, [1–10].

We consider the zero-quasimomentum fiber of a two-particle lattice Hamiltonian on $\mathbb{Z}^3$ with on-site and nearest-neighbor interactions. The essential spectrum of this fiber is the interval $[0,24]$. The zero-quasimomentum operator admits invariant subspaces generated by permutation symmetries of the relative momentum variables. The present paper focuses on the coordinate-antisymmetric subspace

$$L^{2,e,a_{12}}(\mathbb{T}^3) = \{f \in L^{2,e}(\mathbb{T}^3): f(p_1,p_2,p_3) = -f(p_2,p_1,p_3)\}.$$

The main reason for studying this subspace is that the generator $\varphi(p) = \cos p_1 - \cos p_2$ vanishes at both threshold points $(0,0,0)$ and (π,π,π). This cancellation removes the leading square-root singularity which appears in the fully symmetric subspace. As a result, the eigenvalue branches have a linear leading term with respect to the deviation of the coupling constant from its critical value. The aim of the paper is to isolate this mechanism and give a complete one-parameter description of the isolated eigenvalues near both edges of the essential spectrum.

The structure of the paper is as follows. Section 2 introduces the zero-quasimomentum fiber and its reduction in the coordinate-antisymmetric subspace. Section 3 derives the Lippmann–Schwinger determinant and gives the eigenvalue count. Section 4 proves the criticality and threshold asymptotic formulas. Section 5 contains the conclusion.

2. Model and reduction to the coordinate-antisymmetric subspace. Let $\mathbb{T}^3$ be the three-dimensional torus (Brillouin zone) and let $L^{2,e}(\mathbb{T}^3)$ denote the Hilbert space of even square-integrable functions. After the Fourier transform and the Floquet–Bloch decomposition, the two-particle Hamiltonian is represented as the direct integral of fiber operators

$$\mathbb{H}_{\mu_1\mu_2} \simeq \int_{\mathbb{T}^3}^{\oplus} H_{\mu_1\mu_2}(K)\,dK,$$

where

$$H_{\mu_1\mu_2}(K) = H_0(K) + V_{\mu_1\mu_2}.$$

Here $H_0(K)$ is the multiplication operator by

$$\mathcal{E}_K(p) = 4\sum_{j=1}^{3}\left(1 - \cos\frac{K_j}{2}\cos p_j\right), \qquad p \in \mathbb{T}^3,$$

and the finite-rank perturbation is

$$(V_{\mu_1\mu_2}f)(p) = \frac{\mu_1}{8\pi^3}\int_{\mathbb{T}^3} f(q)\,dq + \frac{\mu_2}{4\pi^3}\sum_{j=1}^{3}\cos p_j \int_{\mathbb{T}^3}\cos q_j f(q)\,dq.$$

Since $V_{\mu_1\mu_2}$ is finite-rank, Weyl's theorem implies

$$\sigma_{\text{ess}}\left(H_{\mu_1\mu_2}(K)\right) = \sigma\left(H_0(K)\right) = [\mathcal{E}_{\min}(K), \mathcal{E}_{\max}(K)].$$

In particular, for $K = 0$,

$$\mathcal{E}_0(p) = 4(3 - \cos p_1 - \cos p_2 - \cos p_3), \qquad \sigma_{\text{ess}}\left(H_{\mu_1\mu_2}(0)\right) = [0,24].$$

Let S_3 be the group of permutations of (p_1, p_2, p_3). Since both $\mathcal{E}_0$ and $V_{\mu_1\mu_2}$ are invariant under these permutations, the corresponding orthogonal symmetry subspaces reduce $H_{\mu_1\mu_2}(0)$. In particular,

$$L^{2,e}(\mathbb{T}^3) = L^{2,e,s}(\mathbb{T}^3) \oplus L^{2,e,a_{12}}(\mathbb{T}^3) \oplus L^{2,e,mix}(\mathbb{T}^3),$$

and

$$H_{\mu_1\mu_2}(0) = H^{s}_{\mu_1\mu_2}(0) \oplus H^{a_{12}}_{\mu_2}(0) \oplus H^{mix}_{\mu_2}(0).$$

Define

$$\alpha_3^{a_{12}}(p) = \frac{\cos p_1 - \cos p_2}{\sqrt{8\pi^3}}.$$

This function belongs to $L^{2,e,a_{12}}(\mathbb{T}^3)$ and $\| \alpha_3^{a_{12}} \| = 1$. For every $f \in L^{2,e,a_{12}}(\mathbb{T}^3)$, one has

$$V_{\mu_1\mu_2}f = V^{a_{12}}_{\mu_2}f = \mu_2\left(f, \alpha_3^{a_{12}}\right)\alpha_3^{a_{12}}.$$

Indeed, the integral of f is zero by antisymmetry, and the cosine moments satisfy

$$\int_{\mathbb{T}^3}\cos q_1 f(q)\,dq = -\int_{\mathbb{T}^3}\cos q_2 f(q)\,dq, \qquad \int_{\mathbb{T}^3}\cos q_3 f(q)\,dq = 0.$$

Consequently, in this coordinate-antisymmetric subspace, only the component generated by $\alpha_3^{a_{12}}$ contributes to the perturbation.

Thus the reduced Hamiltonian is

$$H^{a_{12}}_{\mu_2}(0) = H_0(0) + \mu_2\left(\cdot, \alpha_3^{a_{12}}\right)\alpha_3^{a_{12}}.$$

This operator is independent of the on-site coupling μ_1. Moreover,

$$\sigma_{\text{ess}}\left(H^{a_{12}}_{\mu_2}(0)\right) = [0,24].$$

3. Lippmann–schwinger determinant and eigenvalue count. For a complex number z outside the interval $[0,24]$ define

$$a(z) = \int_{\mathbb{T}^3} \frac{\left(\alpha_3^{a_{12}}(p)\right)^2}{\mathcal{E}_0(p) - z}\,dp = \frac{1}{8\pi^3}\int_{\mathbb{T}^3} \frac{(\cos p_1 - \cos p_2)^2}{\mathcal{E}_0(p) - z}\,dp.$$

The Lippmann–Schwinger equation reduces the eigenvalue problem for $H^{a_{12}}_{\mu_2}(0)$ outside $[0,24]$ to the scalar equation

$$\Delta^{a_{12}}_{\mu_2}(z) = 1 + \mu_2 a(z) = 0.$$

Therefore zeros of $\Delta^{a_{12}}_{\mu_2}$ in $(-\infty, 0) \cup (24, \infty)$ are exactly isolated eigenvalues of $H^{a_{12}}_{\mu_2}(0)$, counted with multiplicity.

The following properties of $a(z)$ are used below. The function a is analytic outside the interval $[0,24]$, real-valued on the real gaps, and strictly increasing on both $(-\infty, 0)$ and $(24, \infty)$. Moreover,

$$\lim_{z\to-\infty} a(z) = 0, \qquad \lim_{z<0,\, z\to 0} a(z) = a(0) > 0,$$

and

$$\lim_{z>24,\, z\to 24} a(z) = -a(0), \qquad \lim_{z\to+\infty} a(z) = 0.$$

The first-order threshold expansions are

$$a(z) = a(0) - a'(0)(-z) + O((-z)^2), \qquad z < 0,\ z \to 0,$$

and

$$a(z) = -a(0) + a'(0)(z - 24) + O((z - 24)^2), \qquad z > 24,\ z \to 24,$$

where

$$a'(0) = \frac{1}{8\pi^3}\int_{\mathbb{T}^3} \frac{(\cos p_1 - \cos p_2)^2}{\left(\mathcal{E}_0(p)\right)^2}\,dp > 0.$$

These expansions follow from the local relations

$$\mathcal{E}_0(p) = 2|p|^2 + O(|p|^4), \qquad \cos p_1 - \cos p_2 = -\frac{1}{2}(p_1^2 - p_2^2) + O(|p|^4)$$

near $p = 0$, and from the substitution $p = (\pi, \pi, \pi) + q$ near the upper threshold. Hence the quotient

$$\frac{(\cos p_1 - \cos p_2)^2}{\big(\mathcal{E}_0(p)\big)^2}$$

is locally bounded at the threshold point, so the derivative $a'(0)$ is finite.

Put

$$\mu_{\text{low}} = -\frac{1}{a(0)}, \qquad \mu_{\text{up}} = \frac{1}{a(0)}.$$

Theorem 3.1. The following assertions hold.

(i) If $\mu_2 \geq \mu_{\text{low}}$, then $H_{\mu_2}^{a_{12}}(0)$ has no eigenvalues in $(-\infty, 0)$. If $\mu_2 < \mu_{\text{low}}$, then it has a unique eigenvalue $E_{\text{low}}(\mu_2) \in (-\infty, 0)$.

(ii)If $\mu_2 \leq \mu_{\text{up}}$, then $H_{\mu_2}^{a_{12}}(0)$ has no eigenvalues in $(24, \infty)$. If $\mu_2 > \mu_{\text{up}}$, then it has a unique eigenvalue $E_{\text{up}}(\mu_2) \in (24, \infty)$.

Proof. Since a is strictly increasing, it maps $(-\infty, 0)$ onto $\big(0, a(0)\big)$ and $(24, \infty)$ onto $(-a(0), 0)$. The equation $1 + \mu_2 a(z) = 0$ therefore has exactly one solution in $(-\infty, 0)$ iff $\mu_2 < -1/a(0)$, and exactly one solution in $(24, \infty)$ iff $\mu_2 > 1/a(0)$. This proves the theorem. □

4. Threshold eigenvalues and asymptotics. At the critical coupling constants, the threshold points are genuine L^2-eigenvalues. For $\mu_2 = \mu_{\text{low}}$, an eigenfunction corresponding to the lower threshold 0 is

$$\psi_0(p) = \frac{\alpha_3^{a_{12}}(p)}{\mathcal{E}_0(p)}.$$

For $\mu_2 = \mu_{\text{up}}$, an eigenfunction corresponding to the upper threshold 24 is

$$\psi_{24}(p) = \frac{\alpha_3^{a_{12}}(p)}{\mathcal{E}_0(p) - 24}.$$

Indeed, near $p = 0$ one has $\alpha_3^{a_{12}}(p) = O(|p|^2)$ and $\mathcal{E}_0(p) = O(|p|^2)$; hence ψ_0 is locally bounded. The same argument at (π, π, π) gives $\psi_{24} \in L^2(\mathbb{T}^3)$. Moreover,

$$\big(H_0(0) + \mu_{\text{low}}(\cdot, \alpha_3^{a_{12}})\alpha_3^{a_{12}}\big)\psi_0 = 0,$$

and

$$\big(H_0(0) + \mu_{\text{up}}(\cdot, \alpha_3^{a_{12}})\alpha_3^{a_{12}}\big)\psi_{24} = 24\psi_{24}.$$

Thus μ_{low} and μ_{up} are respectively the unique lower- and upper-critical coupling constants.

The main asymptotic result is as follows.

Theorem 4.1. Let $E_{\text{low}}(\mu_2)$ and $E_{\text{up}}(\mu_2)$ be the eigenvalues described in Theorem 3.1. Then

$$E_{\text{low}}(\mu_2) = c_1(\mu_2 - \mu_{\text{low}}) + o(\mu_2 - \mu_{\text{low}}), \qquad \mu_2 < \mu_{\text{low}}, \quad \mu_2 \to \mu_{\text{low}},$$

and

$$E_{\text{up}}(\mu_2) = 24 + c_1\big(\mu_2 - \mu_{\text{up}}\big) + o\big(\mu_2 - \mu_{\text{up}}\big), \qquad \mu_2 > \mu_{\text{up}}, \quad \mu_2 \to \mu_{\text{up}},$$

where

$$c_1 = \frac{a^2(0)}{a'(0)} > 0.$$

Proof. We prove the lower-edge case. Let $\mu_2 < \mu_{\text{low}}$ be close to μ_{low} and put

$$\beta = -E_{\text{low}}(\mu_2) > 0.$$

The determinant equation becomes

$$F^-(\mu_2, \beta) := \Delta_{\mu_2}^{a_{12}}(-\beta) = 0.$$

Using the expansion of $a(z)$ at 0,

$$F^-(\mu_2, \beta) = 1 + \mu_2 a(0) - \mu_2 a'(0)\beta + O(\beta^2).$$

Since $\mu_{\text{low}} = -1/a(0)$,

$$F^-(\mu_{\text{low}}, 0) = 0, \qquad \frac{\partial F^-}{\partial \beta}(\mu_{\text{low}}, 0) = -\mu_{\text{low}} a'(0) = \frac{a'(0)}{a(0)} > 0.$$

The implicit function theorem gives

$$\beta(\mu_2) = -\frac{a^2(0)}{a'(0)}(\mu_2 - \mu_{\text{low}}) + o(\mu_2 - \mu_{\text{low}}).$$

Since $E_{\text{low}}(\mu_2) = -\beta(\mu_2)$, the first formula follows.

The proof at the upper edge is identical, using the expansion of $a(z)$ as $z > 24,\ z \to 24$. □

Remark 4.2. The leading terms are linear in the coupling deviation. This is different from the quadratic threshold law in the fully symmetric subspace. The distinction is caused by the vanishing of $\varphi(p) = \cos p_1 - \cos p_2$ at both band edges, which makes the threshold integral regular to first order.

5. Conclusion, The zero-quasimomentum two-particle discrete Schrödinger operator on $\mathbb{Z}^3$ has been analyzed in the invariant subspace $L^{2,e,a_{12}}(\mathbb{T}^3)$. In this invariant subspace, the on-site interaction does not contribute and the reduced perturbation has rank one. Using the Lippmann–Schwinger equation, the eigenvalue problem is converted into the scalar equation $\Delta_{\mu_2}^{a_{12}}(z) = 1 + \mu_2 a(z) = 0$, which yields a complete eigenvalue count below and above the essential spectrum $[0,24]$.

The critical values are $\mu_{\text{low}} = -1/a(0)$ and $\mu_{\text{up}} = 1/a(0)$. At these values, the corresponding thresholds 0 and 24 are L^2-eigenvalues. The isolated eigenvalue branches approaching these thresholds have linear asymptotics with coefficient $c_1 = a^2(0)/a'(0) > 0$.

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EGRI CHIZIQLI QUVUR O'TKAZGICHLARNING DINAMIK HARAKATINI QOVUSHQOQ-IRSIY QOBIQ NAZARIYASI ASOSIDA MATEMATIK MODELLASHTIRISH

Annotatsiya. *Maqolada suyuqlik oqib o'tuvchi egri chiziqli (torusial) qobiq-quvur segmentining erkin va so'nuvchi tebranishlari qobiq nazariyasi asosida o'rganiladi. Ilgari faqat mukammal elastik material uchun qurilgan model Boltsman–Volterra irsiy-qovushqoq nazariyasi va Rjanitsin–Koltunov yadrosi asosida umumlashtiriladi; natijada tebranish chastotasi kompleks miqdor sifatida aniqlanadi, uning haqiqiy qismi tebranish chastotasini, mavhum qismi esa tizimning so'nish xususiyatini tavsiflaydi. Bubnov–Galerkin usuli yordamida masala kompleks koeffitsiyentli transsendent chastota tenglamasiga keltiriladi va bu tenglama Myuller usuli bilan sonli yechiladi. Egrilik radiusi, quvur nisbiy uzunligi L/d, oqim tezligi,*