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FORMATION AND DEVELOPMENT
OF COMPETITIVE SKILLS
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CHARACTERISTIC PROPERTY OF THE FADDEEV EQUATION FOR THREE-PARTICLE MODEL OPERATOR ON A ONE-DIMENSIONAL LATTICE

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Abstract: in this paper a model operator (Hamiltonian) $H_{\mu\gamma}$, $\mu, \gamma > 0$ associated to a system of three quantum particles on a one-dimensional lattice that interact via non-local potentials is studied. We construct an analogue of the Faddeev type system of integral equations for the eigenfunctions of $H_{\mu\gamma}$ and give a characteristic property of this system of equations. We describe the essential spectrum of $H_{\mu\gamma}$. It is established that the essential spectrum of $H_{\mu\gamma}$ consists the union of at most three bounded closed intervals.

Keywords: model operator, non-local potentials, system of particles, the Faddeev equation, essential spectrum, Hilbert-Schmidt operator.

ХАРАКТЕРИСТИЧЕСКИЕ СВОЙСТВА УРАВНЕНИЯ ФАДДЕЕВА ДЛЯ ТРЕХЧАСТИЧНОГО МОДЕЛЬНОГО ОПЕРАТОРА НА ОДНОМЕРНОЙ РЕШЕТКЕ

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Аннотация: в этой работе изучен модельный оператор (Гамильтониан) $H_{\mu\gamma}$, $\mu, \gamma > 0$, ассоциированный с системой трех квантовых частиц на одномерной решетке и взаимодействующих с помощью парных нелокальных потенциалов. Построен аналог системы интегральных уравнений типа Фаддеева для собственных функций оператора $H_{\mu\gamma}$ и изучены его характеристические свойства. Описан существенный спектр оператора $H_{\mu\gamma}$. Установлено, что существенный спектр оператора $H_{\mu\gamma}$ состоит из объединения не более чем трех отрезков.

Ключевые слова: модельный оператор, нелокальные потенциалы, система частиц, уравнения Фаддеева, существенный спектр, оператор Гильберта-Шмидта.

It is well-known that in the physical literature, local potentials, i.e., multiplication operators by a function, are typically used. But the potentials constructed, for example, in pseudo-potential theory [1] turn out to be non-local. Such for a periodic operator are given by the sum of local and a finite dimensional potentials. Non-local separable two-particle interactions have been used in nuclear physics and also many-particle problems because of the fact that the two-particle Schrödinger equation is very easily solvable for them, and leads to closed expressions for a large class of such interactions. They have also been used very systematically with Faddeev type equations for the three-particle problem. Their main feature is that the partial-wave t-matrix has a very simple form, and can be continued off the energy-shell in a straightforward manner, a feature which is most important, as is well known, in nuclear physics, and in the Faddeev type equations [2].

In the present paper the model operator (Hamiltonian) $H_{\mu\gamma}$, $\mu, \gamma > 0$ associated to a system of three particles on a one-dimensional lattice and interacting via non-local potentials is considered. One of the important problem in the spectral theory of such operators is to construct an analogue of the Faddeev type system of integral equations for the eigenfunctions of $H_{\mu\gamma}$ and to describe its essential spectrum.

Let us state the problem. We denote by T^1 the one-dimensional torus. The operations addition and multiplication by real numbers elements of $T^1 \subset \mathbb{R}$ should be regarded as operations on \mathbb{R} modulo $2\pi\mathbb{Z}$. For example, if

$$x = \frac{3\pi}{5}, y = \frac{2\pi}{3} \in T^1, \text{ then } x + y = -\frac{11\pi}{15}, 10x = 0 \in T^1.$$

In the Hilbert space $L_2^S(T^2)$ of square-integrable symmetric (complex) functions defined on T^2 , we consider the model operator:

$$H_{\mu,\gamma} := H_0 - \mu V_1 - \mu V_2 - \gamma V_3$$

where H_0 is the multiplication operator by the function $u(\cdot, \cdot)$:

$$(H_0 f)(x, y) = u(x, y) f(x, y)$$

and $V_\alpha, \alpha = 1, 2, 3$ are non-local interaction operators:

$$(V_1 f)(x, y) = v_1(x) \int_{T^1} v_1(t) f(t, y) dt,$$

$$(V_2 f)(x, y) = v_1(y) \int_{T^1} v_1(t) f(x, t) dt,$$

$$(V_3 f)(x, y) = \int_{T^1} v_2(t) f(t, x + y - t) dt.$$

Here $f \in L_2^S(T^2), \mu, \gamma$ are real positive numbers, the functions $v_\alpha(\cdot), \alpha = 1, 2$ are real-valued continuous functions on T^1 and the function $u(\cdot, \cdot)$ is a real-valued symmetric continuous function on T^2 . By the definition, the operators $V_\alpha, \alpha = 1, 2, 3$ are partial integral operators with degenerate kernel of rank 1.

Under these assumptions on the parameters the operator $H_{\mu,\gamma}$ is bounded and self-adjoint.

Note that Schrödinger operators of the form (1) associated with a system of three particles on a lattice were studied in many works, see e.g., [3-17]. In [3,4] the sufficient conditions for the finiteness and infiniteness of the discrete spectrum are found. In [5] it was proved that the essential spectrum of a three-particle Schrödinger operator on a lattice is the union of at most finitely many closed intervals even in the case where the corresponding two-particle Schrödinger operator on a lattice has an infinite number of eigenvalues. In [6] the Efimov effect for (1) was demonstrated when the parameter function $u(\cdot, \cdot)$ has a special form. Spectral properties of operator matrices, whose one of the diagonal elements have a form (1) were studied in [18-28].

The spectrum, the essential spectrum and the discrete spectrum of a bounded self-adjoint operator will be denoted by $\sigma(\cdot), \sigma_{ess}(\cdot)$ and $\sigma_{disc}(\cdot)$, respectively.

For any $x \in T^1$ and μ, γ we define an analytic functions $\Delta_\mu^{(1)}(x; \cdot)$ and $\Delta_\gamma^{(2)}(x; \cdot)$ in $\mathbb{C} \setminus [m(x); M(x)]$ by

$$\Delta_\mu^{(1)}(x; z) := 1 - \mu \int_{T^1} \frac{v_1^2(t) dt}{u(x, t) - z}, \quad \Delta_\gamma^{(2)}(x; z) := 1 - \gamma \int_{T^1} \frac{v_2(t) dt}{u(t, x - t) - z},$$

where the numbers $m(x)$ and $M(x)$ are defined by

$$m(x) := \min_{y \in T^1} u(x, y) \text{ and } M(x) := \max_{y \in T^1} u(x, y)$$

Let σ_1 resp. σ_2 be the set of all complex numbers $z \in \mathbb{C} \setminus [m(x); M(x)]$ such that the equality $\Delta_\mu^{(1)}(x; z) = 0$ resp. $\Delta_\gamma^{(2)}(x; z) = 0$ holds for some $x \in T^1$ and

$$m := \min_{x, y \in T^1} u(x, y), \quad M := \max_{x, y \in T^1} u(x, y), \quad \sigma = \sigma_1 \cup \sigma_2 \cup [m; M].$$

We introduce the following vector space

$$L_2^{(2)}(T^1) := \{(f_1, f_2): f_\alpha \in L_2(T^1), \alpha = 1, 2\}.$$

In our analysis of the essential and discrete spectrum of $H_{\mu,\gamma}$ the crucial role is played by the Faddeev-Newton-type operator matrix $T(z), z \in \mathbb{C} \setminus \sigma$ acting on $L_2^{(2)}(T^1)$ as

$$T(z) := \begin{pmatrix} T_{11}(z) & T_{12}(z) \\ T_{21}(z) & 0 \end{pmatrix}$$

with the entries $T_{ij}(z): L_2(T^1) \rightarrow L_2(T^1), i, j = 1, 2$:

$$(T_{11}(z)g_1)(x) = \frac{\mu v_1(x)}{\Delta_\mu^{(1)}(x; z)} \int_{T^1} \frac{v_1(t) g_1(t) dt}{u(x, t) - z};$$

$$(T_{12}(z)g_2)(x) = \frac{\gamma}{\Delta_\mu^{(1)}(x; z)} \int_{T^1} \frac{v_1(t - x) g_2(t) dt}{u(t, t - x) - z};$$

$$(T_{21}(z)g_1)(x) = \frac{\mu}{\Delta_\gamma^{(2)}(x; z)} \int_{T^1} \frac{v_1(x - t)(v_2(t) + v_2(x - t)) g_1(t) dt}{u(t, t - x) - z}.$$

We note that for each $z \in C \setminus \Sigma$ the entries $T_{ij}(z)$ belong to the Hilbert-Schmidt class and therefore, $T(z)$ is a compact operator.

The following theorem is an analog of the well-known Faddeev's result for the operator $H_{\mu\gamma}$ and establishes a connection between eigenvalues of $H_{\mu\gamma}$ and $T(z)$.

Theorem 1. *The number $z \in C \setminus \Sigma$ is an eigenvalue of the operator $H_{\mu\gamma}$ if and only if the number $\lambda = 1$ is an eigenvalue of the operator $T(z)$. Moreover, the eigenvalues z and 1 have the same multiplicities.*

We point out that the matrix equation $T(z)g = g$ is an analogue of the Faddeev type system of integral equations for eigenfunctions of $H_{\mu\gamma}$.

The following theorem describes the location of the essential spectrum of $H_{\mu\gamma}$.

Theorem 2. *The essential spectrum of $H_{\mu\gamma}$ is coincide with the Σ , that is, $\sigma_{ess}(H_{\mu\gamma}) = \Sigma$. Moreover, the set Σ consists no more than three bounded closed intervals.*

In the following we introduce the new subsets of the essential spectrum of $H_{\mu\gamma}$: the sets $\sigma_1 \cup \sigma_2$ and $[m: M]$ are called two- and three-particle branches of the essential spectrum of $H_{\mu\gamma}$, respectively.

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