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A Class of Dirac-Type Operators on the Abstract Boson-Fermion Fock Space and Their Strong Anticommutativity

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1 Introduction

In a previous paper [4], we introduced a family \( \{ Q_S \mid S \in C(\mathcal{H}, \mathcal{K}) \} \) of infinite dimensional Dirac-type operators on the abstract Boson-Fermion Fock space \( \mathcal{F}(\mathcal{H}, \mathcal{K}) \) over the pair \( (\mathcal{H}, \mathcal{K}) \) of two Hilbert spaces \( \mathcal{H} \) and \( \mathcal{K} \), where the index set \( C(\mathcal{H}, \mathcal{K}) \) of the family is the set of all densely defined closed linear operators from \( \mathcal{H} \) to \( \mathcal{K} \), and investigated fundamental properties of them. As is shown in [4], this class of Dirac-type operators has a connection with supersymmetric quantum field theory (SQFT) [19]. Namely \( Q_S \) gives an abstract form of free supercharges in some models of SQFT. Interacting models of SQFT can be constructed from perturbations of \( Q_S \) [4]: For related aspects and further developments, see, e.g., [1], [2], [3], [5], [6], [10], [14], [16], [17], [20], [21].

Generally speaking, Dirac-type operators have something to do with a notion of anticommutativity, because they are related to representations of Clifford algebras, and this aspect may be an essential feature of Dirac-type operators (cf. [7], [8], [9], [11], [12]). A proper notion of anticommutativity, i.e., strong anticommutativity, of (unbounded) self-adjoint operators was given in [27] and developed by some authors (e.g., [25], [22], [7], [9], [11], [12]). In a recent paper [15], a theorem on the strong anticommutativity of two Dirac operators \( Q_S \) and \( Q_T \) was established with application to constructing representations on \( \mathcal{F}(\mathcal{H}, \mathcal{K}) \) of a supersymmetry algebra arising in a two-dimensional relativistic SQFT.

The aim of this note is to review fundamental aspects of the theory of infinite dimensional Dirac-type operators on the abstract Boson-Fermion Fock space and to present a summary of the results on their strong anticommutativity obtained in [15].
2 Dirac-type operators on the abstract Boson-Fermion Fock space—a brief review

Let $\mathcal{H}$ be a Hilbert space and $\otimes^n\mathcal{H}$ be the $n$-fold tensor product Hilbert space of $\mathcal{H}$ $(n = 0, 1, 2, \cdots; \otimes^0(\mathcal{H}) := \mathbb{C})$. We denote by $S_n$ (resp. $A_n$) the symmetrizer (resp. the anti-symmetrizer) on $\otimes^n\mathcal{H}$ and by $S_n(\otimes^n\mathcal{H})$ (resp. $A_n(\otimes^n\mathcal{H})$) its range, which is called the $n$-fold symmetric (resp. anti-symmetric) tensor product of $\mathcal{H}$. The Boson Fock space $\mathcal{F}_b(\mathcal{H})$ and the Fermion Fock space $\mathcal{F}_f(\mathcal{H})$ over $\mathcal{H}$ are respectively defined by

$$\mathcal{F}_b(\mathcal{H}) := \bigoplus_{n=0}^{\infty} S_n(\otimes^n\mathcal{H}), \quad \mathcal{F}_f(\mathcal{H}) := \bigoplus_{n=0}^{\infty} A_n(\otimes^n\mathcal{H}) \tag{2.1}$$

(e.g., [23, §II.4], [18, §5.2]). Let $\mathcal{K}$ be a Hilbert space. Then the Boson-Fermion Fock space $\mathcal{F}(\mathcal{H}, \mathcal{K})$ associated with the pair $\langle \mathcal{H}, \mathcal{K} \rangle$ is defined by

$$\mathcal{F}(\mathcal{H}, \mathcal{K}) := \mathcal{F}_b(\mathcal{H}) \otimes \mathcal{F}_f(\mathcal{K}), \tag{2.2}$$

the tensor product Hilbert space of the Boson Fock space over $\mathcal{H}$ and the Fermion Fock space over $\mathcal{K}$. We denote by $\mathcal{L}(\mathcal{H}, \mathcal{K})$ the set of densely defined closed linear operators from $\mathcal{H}$ to $\mathcal{K}$.

We first present the definitions of basics objects in the Boson Fock space and the Fermion Fock space. More detailed descriptions on Fock space objects can be found, e.g., in [23, §II.4, Example 2], [24, §X.7] and [18, §5.2].

For each vector $\Psi = \{\Psi^{(n)}\}_{n=0}^{\infty} \in \mathcal{F}_b(\mathcal{H})$ ($\Psi^{(n)} \in S_n(\otimes^n\mathcal{H})$), we use the natural identification of $\Psi^{(n)}$ with $\{0, \cdots, 0, \Psi^{(n)}, 0, \cdots\} \in \mathcal{F}_b(\mathcal{H})$. The same applies to vectors in other infinite direct sums of Hilbert spaces.

For a subset $V$ of a Hilbert space, we denote by $\mathcal{L}V$ the subspace algebraically spanned by all the vectors of $V$.

Let $\Omega_b := \{1, 0, 0, \cdots\} \in \mathcal{F}_b(\mathcal{H})$, the boson Fock vacuum in $\mathcal{F}_b(\mathcal{H})$. For a subspace $D$ of $\mathcal{H}$, we define

$$\mathcal{F}_{b, \text{fin}}(D) := \mathcal{L} \{\Omega_b, S_n(f_1 \otimes \cdots \otimes f_n)|n \in \mathbb{N}, f_j \in D, j = 1, \cdots, n\}. \tag{2.3}$$

If $D$ is dense, then $\mathcal{F}_{b, \text{fin}}(D)$ is dense in $\mathcal{F}_b(\mathcal{H})$.

For each $f \in \mathcal{H}$, there exists a unique densely defined closed (unbounded) linear operator $a(f)$ on $\mathcal{F}_b(\mathcal{H})$, called boson annihilation operators (its adjoint $a(f)^*$ is called a boson creation operator), such that (i) for all $f \in \mathcal{H}$, $a(f)\Omega_b = 0$, (ii) for all $n \in \mathbb{N}$, $f_j \in \mathcal{H}$, $j = 1, \cdots, n$,

$$a(f)S_n(f_1 \otimes \cdots \otimes f_n) = \frac{1}{\sqrt{n}} \sum_{j=1}^{n} (f, f_j)_{\mathcal{H}} S_{n-1}(f_1 \otimes \cdots \hat{f}_j \otimes \cdots \otimes f_n),$$

where $\hat{f}_j$ indicates the omission of $f_j$, and (iii) $\mathcal{F}_{b, \text{fin}}(\mathcal{H})$ is a core of $a(f)$. We have

$$S_n(\otimes^n\mathcal{H}) = \overline{\{a(f_1)^* \cdots a(f_n)^* \Omega_b|f_j \in \mathcal{H}, j = 1, \cdots, n\}}, \tag{2.4}$$

where $\overline{\{ \cdot \}}$ denotes the closure of the set $\{ \cdot \}$. The set $\{a(f), a(f)^*|f \in \mathcal{H}\}$ satisfies the canonical commutation relations

$$[a(f), a(g)^*] = (f, g)_{\mathcal{H}}, \quad [a(f), a(g)] = 0, \quad [a(f)^*, a(g)^*] = 0.$$
for all \( f, g \in H \) on \( \mathcal{F}_{b, \text{fin}}(H) \).

A similar consideration can be done in the Fermion Fock space \( \mathcal{F}_{f}(K) \). The fermion Fock vacuum \( \Omega_{f} \) in \( \mathcal{F}_{f}(K) \) is defined by \( \Omega_{f} := \{1, 0, 0, \cdots\} \in \mathcal{F}_{b}(K) \). For a subspace \( D \) of \( K \), we define

\[
\mathcal{F}_{f, \text{fin}}(D) := \mathcal{L}\{\Omega_{f}, A_{n}(u_{1} \otimes \cdots \otimes u_{n})|n \geq 1, u_{j} \in D, j = 1, \cdots, n\}. \tag{2.5}
\]

If \( D \) is dense, then \( \mathcal{F}_{f, \text{fin}}(D) \) is dense in \( \mathcal{F}_{f}(K) \).

For each \( u \in K \), there exists a unique bounded linear operator \( b(u) \) on \( \mathcal{F}_{f}(K) \), called fermion annihilation operators on \( \mathcal{F}_{f}(K) \) (b(\( u \))^* is called a fermion creation operator), such that (i) for all \( u \in K \), \( b(u)\Omega_{b} = 0 \), (ii) for all \( n \in \mathbb{N}, u_{j} \in K, j = 1, \cdots, n \),

\[
b(u)A_{n}(u_{1} \otimes \cdots \otimes u_{n}) = \frac{1}{\sqrt{n}} \sum_{j=1}^{n} (-1)^{j-1}(u, u_{j})_{H}S_{n-1}(u_{1} \otimes \cdots \otimes \hat{u}_{j} \otimes \cdots \otimes u_{n})n.
\]

We have

\[
A_{n}(\otimes^{n} K) = \mathcal{L}\{b(u_{1})^{*} \cdots b(u_{n})^{*}\Omega_{f}|u_{j} \in K, j = 1, \cdots, n\}. \tag{2.6}
\]

The set \( \{b(u), b(u)^{*}|u \in K\} \) satisfies the canonical anti-commutation relations

\[
\{(b(u), b(v)^{*}) = (u, v)_{K}, \quad \{b(u), b(v)\} = 0, \quad \{b(u)^{*}, b(v)^{*}\} = 0
\]

for all \( u, v \in K \), where \( \{A, B\} := AB + BA \).

The Fock vacuum in the Boson-Fermion Fock space \( \mathcal{F}(H, K) \) is defined by

\[
\Omega := \Omega_{b} \otimes \Omega_{f}. \tag{2.7}
\]

The annihilation operators \( a(f) \) and \( b(u) \) are extended to operators on \( \mathcal{F}(H, K) \) as

\[
A(f) := a(f) \otimes I, \quad B(u) := I \otimes b(u), \tag{2.8}
\]

where \( I \) denotes identity operator.

For a linear operator \( A \), we denote by \( D(A) \) its domain. Let \( S \in C(H, K) \). Then we define

\[
D_{S} := \mathcal{L}\{A(f_{1})^{*} \cdots A(f_{n})^{*}B(u_{1})^{*} \cdots B(u_{p})^{*}\Omega|n, p \geq 0, f_{j} \in D(S), j = 1, \cdots, n, u_{k} \in D(S^{*}), k = 1, \cdots, p\}, \tag{2.9}
\]

\[
= \mathcal{F}_{b, \text{fin}}(D(S)) \otimes_{\text{alg}} \mathcal{F}_{f, \text{fin}}(D(S^{*})), \tag{2.10}
\]

where \( \otimes_{\text{alg}} \) denotes algebraic tensor product. It follows that \( D_{S} \) is dense in \( \mathcal{F} \). The following proposition is proved in [4].

**Proposition 2.1** There exists a unique densely defined closed linear operator \( d_{S} \) on \( \mathcal{F}(H, K) \) with the following properties: (i) \( D_{S} \) is a core of \( d_{S} \); (ii) for each vector \( \Psi \in D_{S} \) of the form

\[
\Psi = A(f_{1})^{*} \cdots A(f_{n})^{*}B(u_{1})^{*} \cdots B(u_{p})^{*}\Omega, \tag{2.11}
\]
$d_S$ acts as

$$
\begin{align*}
    d_S \Psi &= 0 \quad \text{for } n = 0, \\
    d_S \Psi &= \sum_{j=1}^{n} A(f_1)^* \cdots A(f_j)^* \cdots A(f_n)^* B(Sf_j)^* B(u_1)^* \cdots B(u_p)^* \Omega \quad \text{for } n \geq 1,
\end{align*}
$$

where $A(f_j)^*$ indicates the omission of $A(f_j)^*$. Moreover the following (a)-(d) hold:

(a) $d_S^2 = 0$.

(b) For each complete orthonormal system (CONS) $\{e_n\}_{n=1}^{\infty}$ of $\mathcal{K}$ with $e_n \in D(S^*)$,

$$
d_S \Psi = \sum_{n=1}^{\infty} A(S^* e_n) B(e_n)^* \Psi, \quad \Psi \in D_S,
$$

where the convergence is taken in the strong topology of $\mathcal{F}(\mathcal{H}, \mathcal{K})$.

(c) For each CONS $\{\phi_n\}_{n=1}^{\infty}$ of $\mathcal{H}$ with $\phi_n \in D(S)$, we have

$$
(\Phi, d_S \Psi)_{\mathcal{F}(\mathcal{H}, \mathcal{K})} = \lim_{N \to \infty} \left( \Phi, \sum_{n=1}^{N} A(\phi_n) B(\phi_n)^* \Psi \right)_{\mathcal{F}(\mathcal{H}, \mathcal{K})}, \quad \Phi, \Psi \in D_S.
$$

(d) $D_S \subset D(d_S^*)$ and

$$
d_S^* \Psi = \sum_{k=1}^{p} (-1)^{k-1} A(S^* u_k)^* A(f_1)^* \cdots A(f_n)^* B(u_1)^* \cdots B(u_k)^* \cdots B(u_p)^* \Omega
$$

for vectors $\Psi$ of the form (2.11) with $p \geq 1$. In the case $p = 0$, we have $d_S^* \Psi = 0$.

A Dirac-type operator on $\mathcal{F}(\mathcal{H}, \mathcal{K})$ is defined by

$$
Q_S = d_S + d_S^* \tag{2.12}
$$

with $D(Q_S) = D(d_S) \cap D(d_S^*)$.

Let $A$ be a self-adjoint operator on a Hilbert space $\mathcal{X}$. Then there is a unique self-adjoint operator $A_n$ on $\otimes^n \mathcal{X}$ such that $\otimes_n^{\text{alg}} D(A)$ is a core of $D(A_n)$ and, for all $f_j \in D(A)$, $j = 1, \ldots, n$, $A_n(f_1 \otimes \cdots \otimes f_n) = \sum_{j=1}^{n} f_1 \otimes \cdots \otimes f_{j-1} \otimes A f_j \otimes f_{j+1} \otimes \cdots \otimes f_n$ ([23, §VIII.10, Corollary]). Putting $A_0 = 0$, one can define a self-adjoint operator

$$
d\Gamma(A) := \bigoplus_{n=0}^{\infty} A_n \tag{2.13}
$$

on $\otimes_{n=0}^{\infty} \otimes^n \mathcal{X}$, called the second quantization of $A$ ([23, §VIII. 10, Example 2], [18, §5.2]). It is easy to show that $d\Gamma(A)$ is reduced by $\mathcal{F}_{\#}(\mathcal{X})$ ($\# = b, f$). We denote the reduced part of $d\Gamma(A)$ to $\mathcal{F}_{\#}(\mathcal{X})$ by $d\Gamma_{\#}(A)$. We put

$$
N_{\#} := d\Gamma_{\#}(I) \tag{2.14}
$$
called the number operator on $\mathcal{F}_{\#}(\mathcal{X})$.

Let

$$
\Gamma_\# = (-1)^{I \otimes N_\#}. 
$$

(2.15)

We introduce an operator

$$
\Delta_S := d\Gamma_b(S^*S) \otimes I + I \otimes d\Gamma_f(SS^*)
$$

(2.16)

acting in $\mathcal{F(H,K)}$, which is nonegative and self-adjoint (cf. [23, §VIII.10, Corollary]). For a linear operator $A$ on a Hilbert space, we set

$$
C^\infty(A) := \cap_{n=1}^\infty D(A^n).
$$

Let

$$
\mathcal{D}_S^\infty = \mathcal{L}\left\{ A(f_1)^* \cdots A(f_n)^* B(u_1)^* \cdots B(u_p)^* \Omega \mid n, p \geq 0, f_j \in C^\infty(S^*S), \right.
$$

$$
\left. j = 1, \cdots, n, u_k \in C^\infty(SS^*), k = 1, \cdots, p \right\}.
$$

(2.17)

**Theorem 2.2** [4]

(i) The operator $Q_S$ is self-adjoint, and essentially self-adjoint on every core of $\Delta_S$. In particular, $Q_S$ is essentially self-adjoint on $\mathcal{D}_S^\infty$.

(ii) The operator $\Gamma_\#$ leaves $D(Q_S)$ invariant and

$$
\Gamma_\# Q_S + Q_S \Gamma_\# = 0
$$

on $D(Q_S)$.

(iii) The following operator equations hold:

$$
\Delta_S = Q_S^2 = d_S^* d_S + d_S d_S^*.
$$

**Remark 2.1** The operators $d_S$ and $d_S^*$ leave $\mathcal{D}_S^\infty$ invariant and so does $Q_S$.

Because of part (iii) of Theorem 2.2, we call the operator $\Delta_S$ the Laplacian associated with the Dirac-type operator $Q_S$. 

3 Strong anticommutativity of the Dirac-type operators

Let $A$ and $B$ be self-adjoint operators on a Hilbert space. We say that $A$ and $B$ strongly commute if their spectral measures commute. On the other hand, $A$ and $B$ are said to strongly anticommute if $e^{itB}A \subset Ae^{-itB}$ for all $t \in \mathbb{R}$ ([27], [22]). It turns out that this definition is symmetric in $A$ and $B$ [22].

For various Dirac-type operators, the notion of strong anticommutativity plays an important role ([7], [8], [10], [11]).

For each $S \in C(\mathcal{H}, \mathcal{K})$, the operator

$$L_S := \begin{pmatrix} 0 & S^* \\ S & 0 \end{pmatrix}$$

acting in $\mathcal{H} \oplus \mathcal{K}$ is self-adjoint. This operator is an abstract Dirac operator on the Hilbert space $\mathcal{H} \oplus \mathcal{K}$[26, Chapter 5].

The strong anticommutativity of $Q_S$ and $Q_T$ ($S, T \in C(\mathcal{H}, \mathcal{K})$) is characterized as follows.

**Theorem 3.1** Let $S, T \in C(\mathcal{H}, \mathcal{K})$. Then $Q_S$ and $Q_T$ strongly anticommute if and only if $L_S$ and $L_T$ strongly anticommute. In that case, $S \pm T \in C(\mathcal{H}, \mathcal{K})$ and $Q_{S \pm T} = Q_S \pm Q_T$.

This theorem is one of the main results of the paper [15], which establishes a beautiful correspondence between the strong anticommutativity of $L_S$ and $L_T$ and that of $Q_S$ and $Q_T$.

To prove Theorem 3.1, we need some fundamental facts in the theory of strongly anticommuting self-adjoint operators [27, 22] as well as its applications, together with the following lemma. For the details, see [15].

**Lemma 3.2** Let $S, T \in C(\mathcal{H}, \mathcal{K})$. Suppose that $L_S$ and $L_T$ strongly anticommute. Then the following (i)-(v) hold:

(i) $S \pm T \in C(\mathcal{H}, \mathcal{K})$ and $(S \pm T)^* = S^* \pm T^*$.

(ii) $|S|$ and $|T|$ strongly commute.

(iii) $|S^*|$ and $|T^*|$ strongly commute.

(iv) $\mathcal{D}(S^*S) \cap \mathcal{D}(T^*T) \subset \mathcal{D}(T^*S) \cap \mathcal{D}(S^*T)$ and, for all $f \in \mathcal{D}(S^*S) \cap \mathcal{D}(T^*T)$,

$$T^*S + S^*T)f = 0.$$

(v) $\mathcal{D}(SS^*) \cap \mathcal{D}(TT^*) \subset \mathcal{D}(TS^*) \cap \mathcal{D}(ST^*)$ and, for all $u \in \mathcal{D}(SS^*) \cap \mathcal{D}(TT^*)$,

$$(TS^* + ST^*)u = 0.$$

The authors of [27] and [22] call this notion simply anticommutativity, but, to be definite, we call it strong anticommutativity.
In terms of $S$ and $T$, a necessary and sufficient condition for $L_S$ and $L_T$ to strongly anticommute is given as follows.

**Proposition 3.3** Let $S, T \in C(H,K)$. Then $L_S$ and $L_T$ strongly anticommute if and only if the following (i) and (ii) hold:

(i) $S \pm T \in C(H,K)$ and $(S \pm T)^* = S^* \pm T^*$.

(ii) For all $f, g \in D(S) \cap D(T)$ and $u, v \in D(S^*) \cap D(T^*)$,

$$(Sf,Tg) + (Tf,Sg) = 0, \quad (S^*u,T^*v) + (T^*u,S^*v) = 0.$$  

4 Application to constructing representations of a supersymmetry algebra

We consider Fock space representations of the algebra $A_{\text{SUSY}}$ generated by four elements $Q_1, Q_2, H, P$ with defining relations

$$Q_1^2 = H + P, \quad Q_2^2 = H - P, \quad Q_1Q_2 + Q_2Q_1 = 0.$$  

(4.1)

This algebra is called a *supersymmetry algebra*, which arises in a relativistic SQFT in the two-dimensional space-time ([19], [13]). The elements $H, P$ and $Q_j$ ($j = 1, 2$) are called the *Hamiltonian*, the momentum operator and the *supercharge*, respectively.

We recall a definition from [13]. Let $F$ be a Hilbert space, $D$ a dense subspace of $F$, and $H, P, Q_1, Q_2$ be linear operators on $F$. We say that $\{F, D, H, P, Q_1, Q_2\}$ is a symmetric representation of $A_{\text{SUSY}}$ if $H, P, Q_1$ and $Q_2$ are symmetric and leave $D$ invariant satisfying (4.1) on $D$. A symmetric representation $\{F, D, H, P, Q_1, Q_2\}$ of $A_{\text{SUSY}}$ is said to be integrable if (i) $H, P, Q_1$ and $Q_2$ are essentially self-adjoint (denote their closures by $\tilde{H}, \tilde{P}, \tilde{Q}_1$ and $\tilde{Q}_2$, respectively); (ii) $\{\tilde{H}, \tilde{P}, \tilde{Q}_1\}$ and $\{\tilde{H}, \tilde{P}, \tilde{Q}_2\}$ are families of strongly commuting self-adjoint operators, respectively (iii) $\tilde{H}$ and $\tilde{P}$ satisfy the relativistic spectral condition

$$\pm \tilde{P} \leq \tilde{H}.$$  

(4.2)

Suppose that $L_S$ and $L_T$ strongly anticommute. Then, by Lemma 3.3(ii) and (iii), $S^*S$ and $T^*T$ strongly commute, and $SS^*$ and $TT^*$ strongly commute. Hence $S^*S + T^*T$ and $SS^* + TT^*$ are nonnegative, self-adjoint, and $S^*S - T^*T$ and $SS^* - TT^*$ are essentially self-adjoint. Therefore we can define self-adjoint operators

$$H_{S,T} := \frac{1}{2} \{d\Gamma_b(S^*S + T^*T) \otimes I + I \otimes d\Gamma_f(SS^* + TT^*)\},$$  

(4.3)

$$P_{S,T} := \frac{1}{2} \{d\Gamma_b(S^*S - T^*T) \otimes I + I \otimes d\Gamma_f(SS^* - TT^*)\}^{-}$$  

(4.4)

where for a closable linear operator $A$, $\tilde{A}$ (or $A^-$) denotes its closure. Note that $H_{S,T}$ is nonnegative, but, $P_{S,T}$ may be neither bounded below nor bounded above.

For a self-adjoint operator $A$, we denote by $E_A$ its spectral measure. Let

$$D_{S,T} := \mathcal{L}(E_{[\alpha, \beta]}(a,b)]E_{[\epsilon, \delta]}([c,d])\Psi|\Psi \in \mathcal{F}(H,K), 0 \leq a < b < \infty, 0 \leq c < d < \infty.$$  

(4.5)

We can prove the following theorem (for the proof, see [15]).
Theorem 4.1 Let $S, T \in C(H, K)$ and suppose that $L_S$ and $L_T$ strongly anticommute. Then $\{\mathcal{F}(H, K), D_{S,T}, H_{S,T}, P_{S,T}, Q_S, Q_T \}$ is an integrable representation of $A_{SUSY}$.

We give only one basic example from SQFT (for other examples, see [19], [4]).

**Example** Let $\mathcal{H} = \mathcal{K} = L^2(\mathbb{R})$ and $\mathbb{R} \ni p \mapsto \omega(p)$ be a nonnegative function on $\mathbb{R}$ which is Borel measurable, almost everywhere (a.e.) finite with respect to the Lebesgue measure on $\mathbb{R}$, and satisfies $|p| \leq \omega(p), \ a.e. \ p \in \mathbb{R}$.

Let 
$$
\nu(p) = \sqrt{\lambda p + \omega(p)}
$$

with $\lambda \in [0, 1]$ (a constant parameter) and $\theta(p)$ be an a.e. finite real-valued Borel measurable function on $\mathbb{R}$. Define the operators $S$ and $T$ on $L^2(\mathbb{R})$ to be the multiplication operators by the functions

$$
S(p) := i\nu(p)e^{i\theta(p)}, \ T(p) := \nu(-p)e^{i\theta(p)},
$$

respectively. Then it is easy to see that $S$ and $T$ satisfy the conditions (i) and (ii) in Proposition 3.3 with $D(T) = D(S) = D(S^*) = D(T^*)$ and

$$
S^*S = SS^* = \lambda p + \omega, \quad T^*T = TT^* = -\lambda p + \omega,
$$

$$
S^*T = TS^* = -i\sqrt{\omega^2 - \lambda^2 p^2}, \quad T^*S = ST^* = i\sqrt{\omega^2 - \lambda^2 p^2}.
$$

Hence, by Proposition 3.3, $L_S$ and $L_T$ strongly anticommute. Therefore, by Theorem 4.1, $\{\mathcal{F}(L^2(\mathbb{R}), L^2(\mathbb{R})), D_{S,T}, H_{S,T}, P_{S,T}, Q_S, Q_T \}$ with these $S$ and $T$ is an integrable representation of $A_{SUSY}$. We have

$$
H_{S,T} = d\Gamma_b(\omega) \otimes I + I \otimes d\Gamma_f(\omega),
$$

$$
P_{S,T} = \lambda(d\Gamma_b(p) \otimes I + I \otimes d\Gamma_f(p)).
$$

Note that $H_{S,T}$ and $P_{S,T}$ are independent of $\theta$.

If $\omega(p) = \sqrt{p^2 + m^2}$ with a constant $m \geq 0, \lambda = 1$ and $\theta = 0$, then $H_{S,T}$ and $P_{S,T}$ are respectively the Hamiltonian and the momentum operator of a free relativistic SQFT in the two-dimensional space-time, called the $N = 1$ Wess-Zumino model (cf. [19]).

**References**


