Complex Classical Fields: A Framework for Reflection Positivity

Arthur Jaffe\textsuperscript{1}, Christian D. Jäkel\textsuperscript{2}, Roberto E. Martinez II\textsuperscript{1}

\textsuperscript{1} Harvard University, Cambridge, MA 02138, USA. E-mail: arthur\_jaffe@harvard.edu; remartin@fas.harvard.edu
\textsuperscript{2} School of Mathematics, Cardiff University, Wales, UK. E-mail: christian.jaekel@mac.com

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Abstract: We explore a framework for complex classical fields, appropriate for describing quantum field theories. Our fields are linear transformations on a Hilbert space, so they are more general than random variables for a probability measure. Our method generalizes Osterwalder and Schrader’s construction of Euclidean fields. We allow complex-valued classical fields in the case of quantum field theories that describe neutral particles.

From an analytic point-of-view, the key to using our method is \textit{reflection positivity}. We investigate conditions on the Fourier representation of the fields to ensure that reflection positivity holds. We also show how reflection positivity is preserved by various spacetime compactifications of $\mathbb{R}^d$ in different coordinate directions.

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1. Classical Fields

1.1. Overview. We study a Fock–Hilbert space $\mathcal{E}$ on which averaged classical fields act as linear transformations. These fields generate an abelian algebra of unbounded operators that are defined on a common, dense, invariant domain. We call a classical field \textit{neutral/charged} if it arises in the description of neutral/charged particles. What is special in our framework is that our neutral fields can be either real or \textit{complex}, so
the usual distinction between real and complex fields does not coincide here with the
distinction between neutral and charged fields. Real neutral fields reduce to the usual
case; complex neutral fields allow for something new.

The two-point function of fields is the integral kernel of an operator $D$, which need
not be hermitian. We require two things: First, the hermitian part of $D$ should have
strictly positive spectrum. Second, the transformation $D$ should be reflection positive.
A precise formulation of reflection positivity is provided in Definition 1 (for the neutral
case) and Definition 2 (for the charged case).

We also deal with charge in a somewhat novel way. In the usual case, a charged field
is represented as a complex-linear combination of two neutral fields. The usual charge
conjugation arises as the complex conjugation of this field; this can be implemented as
a unitary operator. However, in this paper we introduce distinct charged fields $\Phi_{\pm}$—not
related by complex conjugation—whose labels correspond to the fundamental charge
carried by the field. Charge conjugation acts as a unitary transformation $U_c$ on $\mathcal{E}$ such
that $U_c \Phi_{\pm} U_c^{-1} = \Phi_{\mp}$.

1.2. More details. Kurt Symanzik introduced the concept of a Euclidean-invariant
Markoff field associated with an underlying probability distribution of classical fields [18].
Euclidean-covariant classical fields describing neutral scalar particles are typically real,
as are time-zero quantum fields. With the standard distributions that occur for scalar
quantum fields, the zero-particle expectations of products of fields are typically posi-
tive. This is also the case for the vacuum expectation values of time-ordered products
of imaginary-time quantum fields (i.e., the analytic continuation of quantum fields in
Minkowski space). In fact, the analytic continuation of anti-time-ordered vacuum expec-
tation values of quantum fields in Minkowski space should agree with the expectations
of such classical fields.

Edward Nelson formulated a set of mathematical axioms interpreting Euclidean
Markoff fields as random variables. A Markoff field satisfying these axioms yields
a corresponding quantum field [12]. Although these axioms apply beautifully to the
free scalar field [13], and to some other cases, verifying the global Markoff prop-
erty for known examples of interacting scalar fields poses certain difficulties. More-
over, an analogous set of axioms has not been formulated for fermionic or gauge
fields.

Konrad Osterwalder and Robert Schrader discovered an alternative and more-applicable approach based on a property that they called reflection positivity (RP), which
today is often called Osterwalder–Schrader (OS) positivity. Every Euclidean-invariant,
OS-positive and regular set of expectations yields a relativistic, local quantum field
theory [15,16]. Assuming certain growth conditions in both the quantum and classical
framework, the OS axioms for a classical field theory were shown to be equivalent to
the Wightman axioms for a corresponding quantum field. According to Zinoviev, these
growth assumptions can be replaced by a weak spectral condition [20].

RP allows one to give a rigorous meaning to inverse Wick rotation. In addition, RP has
found applications in other areas of mathematical physics, as well as in mathematics.
For example, RP has had an impact on the theory of analytic continuation of group
representations; recent results and extensive references can be found in [10]. Moreover,
RP has had an enormous impact in statistical physics—especially in understanding
properties of the spectrum of the transfer matrix, as well as in the theory of phase
transitions. A contemporary review can be found in [2].
1.3. This work. In this work we demonstrate that by no longer insisting that neutral fields are real, one gains a great deal of added flexibility. A number of relevant problems, which so far were not accessible from Euclidean quantum field theory, can now be formulated in terms of our new framework for complex classical fields. For example, one can study Hamiltonians with complex-valued heat kernels such as, for example, \( H = H_0 + v \cdot P \), with \(|v| < 1\). Up to an overall multiplicative constant, this is the Hamiltonian as seen from a Lorentz frame moving with velocity \( v \). In fact, this was our motivating example, and it arose when we studied the work of Heifets and Osipov [8], which we consider in detail in a separate publication [9].

We also study charged fields. We introduce fields \( \Phi_\pm \) that differ from the usual ones in that charge conjugation \( \Phi_\pm \rightarrow \Phi_\mp \) is given by a unitary transformation different from complex conjugation. We apply this framework to study the thermal equilibrium states of a charged field with a chemical potential at positive temperature in the forthcoming article [9]. Such states and fields occur in the study of the statistical mechanics of Bose–Einstein condensation; see [1].

The expectation values of our classical fields are defined on a “Euclidean Hilbert space.” In this paper we consider Euclidean Fock space, which is the simplest case. The classical fields are represented as unbounded operators and finiteness of their expectation values follows once certain operator domain questions have been resolved. In case the usual description in terms of functional integrals is available, the domain questions in our approach can be resolved, and the two descriptions are equivalent. Our method is similar to the construction of Euclidean fields given by Osterwalder and Schrader [17]. We require RP for the no-particle expectation.

We begin in Sect. 2.1 by studying what transformation properties of the field \( \Phi \) under reflections are equivalent to RP. In Sect. 4 we briefly describe the associated quantization in the Gaussian case. We generalize this for charged fields in Sect. 5. In Sect. 6 we show that RP on \( \mathbb{R}^d \) gives RP on spacetimes \( X \) that are compactified in one or more coordinate directions.

Certain non-Gaussian expectations can then be built as perturbations of the Gaussian case. These examples can be studied using a cut-off and a generalised Feynman–Kac formula [9]. We rely on RP to obtain a robust inner product that one can use to prove useful estimates. This inner product also provides the relation between the Euclidean Fock space \( \mathcal{E} \) and the Hilbert space \( \mathcal{H} \) of quantum theory.

1.4. The problem with measures. One might expect that the complex-valued, symmetric, Schwinger functions are moments of a complex measure. But even for the Gaussian functionals that we consider, a countably-additive, complex measure does not exist. Without measure theory, one loses the possibility to use \( L_p \) estimates to study convergence of integrals. Thus one might lose quantitative control of the theory.

The standard formulation of a real classical field \( \Phi \in S'_\text{real}(\mathbb{R}^d) \), or a complex field \( \Phi \in S'(\mathbb{R}^d) \), is to take it to be a random variable for a probability measure \( d\mu(\Phi) \) on the space of tempered distributions \( S'_\text{real}(\mathbb{R}^d) \) or \( S'(\mathbb{R}^d) \). In the real case the characteristic function of the measure \( d\mu \) is given by

\[
S(f) = \int e^{i\Phi(f)} d\mu(\Phi).
\]

The exact criterion for the existence of a countably-additive probability measure \( d\mu(\Phi) \) on a nuclear space (such as \( S'_\text{real}(\mathbb{R}^d) \) or \( S'(\mathbb{R}^d) \)) is the following:
Proposition 1 (Minlos’ Theorem [11]). A functional $S(f)$ on a nuclear space $S$ is the characteristic functional of a countably-additive, probability measure on the dual space $S'$, if and only if $S(f)$ is continuous, of positive type, and normalized by $S(0) = 1$.

Complex measures are more delicate. Borchers and Yngvason [3] studied possibilities for measures being associated with arbitrary Wightman field theories. In the Gaussian case, there is a clean result for the existence of a complex Gaussian measure. Suppose $d\mu$ is a complex-valued Gaussian with mean zero and covariance $D$, and the resulting characteristic function is given by

$$S_D(f) = e^{-\frac{1}{2} \langle \bar{f}, Df \rangle_{L_2}}.$$  

(2)

Then one has the existence criterion of Proposition 4.4 in [19]:

Proposition 2 (Yngvason’s Criterion). Let $0 < K = K^*$ and $L = L^*$ be bounded transformations on $L_2(\mathbb{R}^d)$ and continuous transformations on $S(\mathbb{R}^d)$. Then there exists a countably-additive, complex-valued, Gaussian measure $d\mu_D(\Phi)$ on $S'_{\text{real}}(\mathbb{R}^d)$ with covariance $D = K + iL$ and with characteristic function $S_D(f)$ if and only if $K^{-1/2}LK^{-1/2}$ is Hilbert–Schmidt on $L_2(\mathbb{R}^d)$.

This criterion is linked to the desire to write $d\mu_D$ as a phase times a probability measure $d\mu_G$ normalized by the constant $3$, namely

$$d\mu_D(\Phi) = \frac{1}{3} e^{i \frac{1}{2} \langle \Phi, Y\Phi \rangle} d\mu_G(\Phi), \quad \text{so} \ |d\mu_D(\Phi)| \leq \frac{1}{|3|} d\mu_G(\Phi).$$  

(3)

To obtain insight into Yngvason’s Criterion, let us assume for simplicity that $K$ and $L$ commute, and that the spectrum of $K^{-1/2}LK^{-1/2} = LK^{-1}$ is even. Then one finds

$$D^{-1} = |D|^{-2} K - i |D|^{-2} L, \quad G^{-1} = |D|^{-2} K, \quad Y = |D|^{-2} L$$

and

$$3 = \left( \det \left( I - iLK^{-1} \right) \right)^{1/2}.$$ 

Denote the positive eigenvalues of $LK^{-1}$ by $\lambda_j$. Then

$$3 = \left( \prod_j (1 + i\lambda_j)(1 - i\lambda_j) \right)^{1/2} = \left( \prod_j (1 + \lambda_j^2) \right)^{1/2} \geq 1.$$  

(4)

In (4) the product defining $3$ converges if and only if $LK^{-1}$ is Hilbert-Schmidt, which is Yngvason’s Criterion.

In the examples we consider in [9], Yngvason’s Criterion does not apply. In these examples not only is the spectrum of $LK^{-1}$ continuous (and hence not Hilbert-Schmidt), but also an infrared cutoff would yield eigenvalues $\lambda_j$ that would not converge to zero sufficiently rapidly. In this case, as well as in the continuous case without a cutoff, $3$ is infinite.\(^1\)

\(^1\) Related issues arise in Brydges and Imbrie’s study of random walks; see Equation (7.2) of [4]. We thank John Imbrie for bringing this to our attention.
2. Classical Fields as Operators on Hilbert Space

One can define a neutral, random field by introducing the Fock–Hilbert space $\mathcal{E} = \mathcal{E}(\mathcal{K})$ over a one-particle space $\mathcal{K}$. This exponential Hilbert space has the form

$$\mathcal{E} = \bigoplus_{n=0}^{\infty} \mathcal{E}_n, \quad \text{where} \quad \mathcal{E}_0 = \mathbb{C}, \quad \text{and} \quad \mathcal{E}_n = \mathcal{K} \otimes_s \cdots \otimes_s \mathcal{K},$$

and where $\otimes_s$ denotes the symmetric tensor product. Let the distinguished vector $\Omega_0^E = 1 \in \mathcal{E}_0$ denote the zero-particle state.

In the following, we take $\mathcal{K} = L_2(\mathbb{R})$, but one could just as well take $\mathcal{K} = \bigoplus_{j=1}^{N} L_2(\mathbb{R})$ for an $N$-component field. Either $\mathbb{X}$ denotes Euclidean spacetime $\mathbb{R}^d$, a toroidal spacetime $\mathbb{T}^d = \mathbb{S}^1 \times \cdots \times \mathbb{S}^1$, or more generally an intermediate case in which spacetime has the form $\mathbb{X} = X_1 \times \cdots \times X_d$, where each factor $X_j$ either equals $\mathbb{R}$ or a circle $\mathbb{S}^1$ of length $\ell_j$. We let $\mathcal{S}(\mathbb{X})$ denote the $C^\infty$ functions on $\mathbb{X}$ with the topology given by the usual family of seminorms $||f||_{r,s} = \sup_{x \in \mathbb{X}} |x^r D^s f(x)|$. Then $\Phi \in \mathcal{S}(\mathbb{X})$, the dual space of continuous linear functionals on $\mathcal{S}(\mathbb{X})$, and it pairs linearly with test functions $f \in \mathcal{S}(\mathbb{X})$ yielding $\Phi(f) = \int \Phi(x) f(x) dx$.

We assume the neutral random field $\Phi$ is an operator-valued distribution on the Hilbert space $\mathcal{E}$ with each $\Phi(f)$ for $f \in \mathcal{S}(\mathbb{X})$ defined on a common, dense, invariant domain $\mathcal{D} \subset \mathcal{E}$. Note that $\Phi(f)^\ast = \Phi^\ast(f)$ on the domain $\mathcal{D}$. This domain includes $\Omega_0^E$ and is invariant under the action of the field, namely $\Phi(f)\mathcal{D} \subset \mathcal{D}$. The characteristic functional of a neutral field is defined as the exponential

$$S(f) = \langle \Omega_0^E, e^{i \Phi(f)} \Omega_0^E \rangle_{\mathcal{E}} = \sum_{n=0}^{\infty} \frac{i^n}{n!} \langle \Omega_0^E, \Phi(f)^n \Omega_0^E \rangle_{\mathcal{E}},$$

and we assume this series converges for all $f \in \mathcal{S}(\mathbb{X})$. In the Gaussian case with mean zero, $\langle \Omega_0^E, \Phi(f)^{2n} \Omega_0^E \rangle_{\mathcal{E}} = (2n-1)!! \langle \Omega_0^E, \Phi(f)^{2} \Omega_0^E \rangle_{\mathcal{E}}^{n}$ demonstrating convergence explicitly. We reinterpret this for charged fields in Sect. 5.

For Gaussian fields with a bounded two point function $D$, the exponential series for the vector $e^{i \Phi(f)} \Omega_0^E$ converges strongly, and the characteristic function (1) is well-defined by its exponential series. In the case of real, neutral fields, non-Gaussian expectations, associated with an action $\mathfrak{A}$, approximated by cut-off actions $\mathfrak{A}_n$, have been constructed. One replaces the expectation $\langle \Omega_0^E, \cdot \Omega_0^E \rangle_{\mathcal{E}}$ with a sequence of normalized expectations of the form

$$\omega_n(\cdot) = \frac{\langle \Omega_0^E, e^{-\mathfrak{A}_n} \cdot \Omega_0^E \rangle_{\mathcal{E}}}{\langle \Omega_0^E, e^{-\mathfrak{A}_n} \Omega_0^E \rangle_{\mathcal{E}}},$$

yielding another translation invariant expectation in the limit $n \to \infty$. Some corresponding Euclidean Hilbert spaces have been given by constructive quantum field theory; see [6].

2.1. Neutral, classical fields: the case $\mathbb{X} = \mathbb{R}^d$. In this section, we consider fields on Euclidean spacetime, $\mathbb{X} = \mathbb{R}^d$, with the one-particle space $\mathcal{K} = L_2(\mathbb{R}^d)$. The annihilation operator (which is actually a densely-defined bilinear form on $\mathcal{E} \times \mathcal{E}$) has non-vanishing matrix elements from $\mathcal{E}_n$ to $\mathcal{E}_{n-1}$. In the Fourier representation it acts as

$$(A(k)f)_{n-1}(k_1, \ldots, k_{n-1}) = \sqrt{n} f_n(k, k_1, \ldots, k_{n-1}).$$
Then \([A(k), A(k')] = 0\). The adjoint creation form \(A(k)^*\) satisfies the usual canonical relations, \([A(k), A(k')^*] = \delta(k - k')\). Define the complex coordinates

\[ \tilde{Q}(k) = A(k)^* + A(-k). \]

These coordinates mutually commute, \([\tilde{Q}(k), \tilde{Q}(k')] = 0\), and also

\[ \tilde{Q}^*(k) = \tilde{Q}(-k), \quad \text{and} \quad \{\Omega_0^E, \tilde{Q}(k) \tilde{Q}(k') \Omega_0^E\} = \delta(k + k'). \]

The Gaussian coordinate field \(Q(x)\) is the Fourier transform of \(\tilde{Q}(k)\), namely

\[ Q(x) = (2\pi)^{-d/2} \int \tilde{Q}(k) e^{ik \cdot x} dk. \]

Take the general Gaussian, neutral, scalar, classical field \(\Phi(x)\) to be a linear function of \(Q(x)\). Assume that for some given function \(\tilde{\sigma}(k)\),

\[ \Phi(x) = (2\pi)^{-d/2} \int \tilde{Q}(k) \tilde{\sigma}(k) e^{ik \cdot x} dk. \]

Whatever the choice of \(\tilde{\sigma}(k)\), the fields \(\Phi(x)\) and their adjoints mutually commute,

\[ [\Phi(x), \Phi(x')] = [\Phi(x), \Phi^*(x')] = 0. \]

The field \(\Phi(x) = \Phi^*(x)\) is hermitian in case that \(\tilde{\sigma}(k) = \overline{\sigma(-k)}\), or, equivalently, when \(\sigma = \overline{\sigma}\) is real.\(^2\) In the standard free, Euclidean-field example, one takes \(\tilde{\sigma}(k) = (k^2 + m^2)^{-1/2}\).

In configuration space, the definition (9) amounts to the relation

\[ \Phi(x) = (2\pi)^{-d/2} (\sigma Q) (x). \]

Here, one defines the convolution operator \(\sigma\) by

\[ (\sigma f)(x) = (2\pi)^{-d/2} \int \sigma(x - x') f(x') dx' \]

where

\[ \sigma(x) = (2\pi)^{-d/2} \int \tilde{\sigma}(k) e^{ik \cdot x} dk. \]

The expectation of two fields defines an operator \(D: \mathcal{K} \mapsto \mathcal{K}\) with integral kernel

\[ D(x, x') = \{\Omega_0^E, \Phi(x) \Phi(x') \Omega_0^E\}. \]

One can introduce commuting, canonically-conjugate coordinates (which generally do not enter the functional integrals), namely

\[ \tilde{P}(k) = \frac{i}{2} \left( A(k)^* - A(-k) \right) = \tilde{P}(-k)^*. \]

\(^2\) For a transformation \(S\) on \(L_2\) with integral kernel \(S(x'; x)\), the integral kernel of the transpose \(S^T\) is \(S(x; x')\), the kernel of the complex-conjugate \(\overline{S}\) is \(\overline{S(x'; x)}\), and the kernel of the hermitian-adjoint \(S^*\) is \(\overline{S(x'; x)}\). The operator \(S\) is defined to be symmetric if \(S = S^T\), is defined to be real if \(S = \overline{S}\), and is defined to be hermitian if \(S = S^*\). The kernel of a translation-invariant operator has the form \(S(x; x') = S(x - x')\). In Fourier space:

\[ \overline{S^T}(k) = S(-k), \quad \overline{S}(k) = \overline{S(-k)}, \quad \text{and} \quad \overline{S^*}(k) = \overline{S(k)}. \]
so

\[ [\tilde{P}(k), \tilde{Q}(k')] = -i\delta(k + k'). \]

In case that \(\sigma^T\) is invertible, the conjugate field is

\[ \Pi(x) = (2\pi)^{d/2}(\sigma^T)^{-1} P(x) = (2\pi)^{-d/2} \int \tilde{\sigma}(-k)^{-1} \tilde{P}(k)e^{ik\cdot x} \, dk. \]

With these conventions, \([\Pi(x), \Phi(x')] = -i\delta(x - x').\]

2.2. Schwinger functions. The zero-particle expectations

\[ S_n(x_1, \ldots, x_n) = \{\Omega_0^E, \Phi(x_1) \cdots \Phi(x_n) \Omega_0^E\}_\mathcal{E} \]

satisfy a Gaussian recursion relation,

\[ S_n(x_1, \ldots, x_n) = \sum_{j=2}^n S_2(x_1, x_j) S_{n-2}(x_2, \ldots, x_j, \ldots, x_n), \quad (12) \]

where \(x_j\) denotes the omission of \(x_j\) and

\[ S_2(x, x') = D(x - x') = (2\pi)^{-d} \int \tilde{\sigma}(k) \tilde{\sigma}(-k) e^{ik\cdot(x - x')} \, dk. \quad (13) \]

Commutativity of the fields assures that \(D(x)\) is an even function, \(D(x - x') = D(x' - x)\).

So

\[ D = \sigma \sigma^T = \sigma^T \sigma = D^T, \quad \text{and} \quad (2\pi)^{d/2} \tilde{D}(k) = \tilde{\sigma}(k) \tilde{\sigma}(-k). \quad (14) \]

Given \(\tilde{D}(k)\), the general solution for \(\tilde{\sigma}(k)\) is

\[ \tilde{\sigma}(k) = (2\pi)^{d/4} \tilde{D}(k)^{1/2} e^{h(k)}, \]

with \(h(k)\) an odd function \(h(k) = -h(-k)\). Here, we take the straightforward choice \(h(k) = 0\), so

\[ \tilde{\sigma}(k) = (2\pi)^{d/4} \tilde{D}(k)^{1/2} = \tilde{\sigma}(-k), \]

and thus \((8)\) equals

\[ \Phi(x) = (2\pi)^{-d/4} \int \tilde{Q}(k) \tilde{D}(k)^{1/2} e^{ik\cdot x} \, dk. \quad (15) \]

Note that the recursion relation \((12)\) ensures that

\[ \langle \Omega_0^E, \Phi(f)^{2n} \Omega_0^E \rangle_{\mathcal{E}} = (2n - 1)!! \langle \tilde{f}, Df \rangle^n_{L_2}. \]

We want to ensure that multiplication by \(\tilde{D}(k)^{1/2}\) defines a continuous transformation of Schwartz space \(S(X)\) into itself. This requires choosing an appropriate square root. Consider the case \(\tilde{D}(k) = \tilde{K}(k) + i\tilde{L}(k)\), with \(0 < \tilde{K}\), and \(\tilde{L}\) real. One can use the positive square root of \(\tilde{K}(k)\) to write

\[ (2\pi)^{-d/4} \tilde{\sigma}(k) = \tilde{D}(k)^{1/2} = \tilde{K}(k)^{1/2} \left(1 + i \tilde{L}(k) \tilde{K}(k)^{-1}\right)^{1/2}. \]
Here, one chooses the square root $\bar{D}(k)^{1/2}$ so that $K(k)^{1/2}$ is positive, and the real part of the term $(1 + i \tilde{L}(k)K(k)^{-1})$ lies in the complex half-plane with real part greater than 1. Since we assume that multiplication by $D$ is self-adjoint on $\mathcal{D}$, we have

$$\|D\| = \|D^* D\|^{1/2} = \|\sigma\|^2 < \infty.$$  

In fact, it is convenient to assume a stronger bound to ensure good properties for the time-zero fields. Let us decompose $D = K + iL$ into its real and imaginary parts

$$K = \frac{1}{2} (D + D^*), \quad \text{and} \quad L = \frac{i}{2} (-D + D^*).$$

We assume that there are strictly positive constants $M_1, M_2, M_3$ such that for $C = (-\Delta + m^2)^{-1}$,

$$M_1 C \leq K \leq M_2 C, \quad \text{and} \quad \pm K^{-1/2} L K^{-1/2} \leq M_3. \tag{16}$$

Now decompose the field into its real and imaginary parts,

$$\Phi(f) = c(f) + i d(f),$$

where $c(f) = \frac{1}{2} (\Phi(f) + \Phi^*(f))$ and $d(f) = -\frac{i}{2} (\Phi(f) - \Phi^*(f))$. Let $\mathcal{F}_{\frac{1}{2}}$ denote the Hilbert space of functions on $\mathbb{R}^{d-1}$ with inner product

$$\langle f, g \rangle_{\mathcal{F}_{\frac{1}{2}}} = \langle f, (2\mu)^{-1} g \rangle_{L_2(\mathbb{R}^{d-1})}, \tag{17}$$

where $\mu = (-\nabla^2 + m^2)^{1/2}$.

**Proposition 3.** Assume the bounds (16). Then for $f, g \in L_2$ the closure of $\Phi(f)$ is normal and commutes with the closure of $\Phi(g)$. The fields $c(f)$ and $d(f)$ are essentially self-adjoint on $\mathcal{D}$, and their closures commute. These results extend to $f = \delta \otimes h$ for $h \in \mathcal{F}_{\frac{1}{2}}(\mathbb{R}^{d-1})$.

**Proof.** The operator $\sigma = (K + iL)^{1/2}$ acting on $L_2(\mathbb{R}^d)$ is invertible as long as $K$ is invertible. The latter follows from the first bound in the assumption (16). As a consequence, each vector $\Psi$ in the dense subset $\mathcal{D} \subset \mathcal{E}$ can be represented as $\Psi = \mathcal{F}_\Psi \Omega_{\mathcal{D}}^2$, 

"
where $F_\psi$ is a polynomial in fields. The degree of this polynomial equals the maximum number of particles in the vector. Thus, for $f \in C_0^\infty$,

$$
\| \Phi(f)^n \Psi \|_E = \| \Phi(f)^n \Phi(f)^n \Omega_0^E, F_\psi F_\psi \Omega_0^E \|^{1/2}
\leq \| \Phi(f)^n \Phi(f)^n \Omega_0^E \|^{1/2} \| F_\psi F_\psi \Omega_0^E \|^{1/2}
\leq (4n - 1)!^{1/4} \| D \|^{1/2} \| f \|_n \| \Phi f \Omega_0^E \|^{1/2}
\leq M2^n n!^{1/2} \| D \|_2^{n/2} \| f \|_2 \| \Phi f \Omega_0^E \|^{1/2}.
$$

(18)

Here, $M$ is a constant. The same bound holds for $\| \Phi(f)^n \Psi \|_E$, and as $\Phi(f)$ commutes with $F_\psi(f)$ it shows that $\Psi$ is an analytic vector for $c(f)$ and for $d(f)$. One can extend this bound to all $f \in L_2(\mathbb{R}^d)$ by limits, so $\Phi(f)$ is also defined in this case. The essential self-adjointness follows from Nelson’s Lemma 5.1 of [14]. The commutativity of the closures of $c(f)$ and $d(g)$ follows from a similar estimate for $c(f)^n d(g)^n \Psi$, showing that the sums

$$
\sum_{n,n'=1}^N \frac{i^{n+n'}}{n!n'} c(f)^n d(g)^{n'} \Psi = \sum_{n,n'=1}^N \frac{i^{n+n'}}{n!n'} d(g)^{n'} c(f)^n \Psi
$$

converge to $e^{ic(f)} e^{id(g)} \Psi = e^{id(g)} e^{ic(f)} \Psi$ as $N \to \infty$. The vectors $\Psi \in \mathcal{D}$ are dense, so the exponentials commute as unitaries. The same is true with $f$ and $g$ interchanged.

In general, use (16) to show that

$$
| D | = (K^2 + L^2)^{1/2} = K^{1/2} \left( I + K^{-1} L^2 K^{-1} \right)^{1/2} K^{1/2}
\leq \left( 1 + M_3^2 \right)^{1/2} K \leq \left( 1 + M_3^2 \right)^{1/2} M_2 C.
$$

This ensures

$$
\| \Phi(f) \Omega_0^E \|_E^2 = \langle f, | D | f \rangle_{L^2} \leq \left( 1 + M_3^2 \right)^{1/2} M_2 \langle f, C f \rangle_{L^2}.
$$

We use this to restrict to time zero. If $f = \delta \otimes h$, then

$$
\langle f, | D | f \rangle_{L^2} \leq \left( 1 + M_3^2 \right)^{1/2} M_2 \langle f, C f \rangle_{L^2}
= \left( 1 + M_3^2 \right)^{1/2} M_2 \langle h, h \rangle_{H^{-1/2}}.
$$

The argument then proceeds for the time-zero fields in the same manner as for the spacetime averaged field. 

\[\square\]

3. Time Reflection

Let $\tilde{\vartheta}$ denote time reflection on $\mathbb{R}^d$, namely $\tilde{\vartheta} : (t, x) \mapsto (-t, x)$, and also let $\vartheta$ denote the implementation of time reflection as a real, self-adjoint, unitary transformation on $L_2(\mathbb{R}^d)$. Let $\Theta = \vartheta^* = \vartheta^{-1}$ denote the push-forward of $\tilde{\vartheta}$ to a corresponding time-reflection unitary on $\mathcal{E}$. The operator $\Theta$ acts on each tensor product $\mathcal{E}_n$ as the $n$-fold tensor product of $\tilde{\vartheta}$, and $\Theta \Omega_0^E = \Omega_0^E$. 

Proposition 4. Time-reflection transforms the neutral field $\Phi(x)$ defined by (15) according to
\begin{equation}
\Theta \Phi(x) \Theta = \Phi^*(\vartheta x) \quad \text{if and only if} \quad \vartheta \sigma^T \vartheta = \sigma^*.
\end{equation}

In case that (19) holds, both $\vartheta D$ and $D \vartheta$ are self-adjoint operators on $L_2(\mathbb{R}^d)$. In fact,
\begin{equation}
\vartheta D = \sigma^* \vartheta \sigma \quad \text{and} \quad D \vartheta = \sigma \vartheta \sigma^*.
\end{equation}

Proof. Since $\vartheta(E, k) = (-E, k)$, the unitary $\vartheta$ acts as $(\vartheta f)(k) = f(\vartheta k)$ on $\mathcal{E}_1$. Thus, $\Theta$ has the property $\Theta A(k) \Theta = A(\vartheta k)$, and as a consequence $\Theta Q(k) \Theta = Q(\vartheta k)$. Using (9), one has
\begin{align*}
\Theta \Phi(x) \Theta &= (2\pi)^{-d/2} \int \Theta \bar{Q}(k) \Theta \bar{\sigma}(k) e^{ik \cdot x} \, dk \\
&= (2\pi)^{-d/2} \int \bar{Q}(\vartheta k) \bar{\sigma}(k) e^{ik \cdot x} \, dk \\
&= (2\pi)^{-d/2} \int \bar{Q}(k) \bar{\sigma}(\vartheta k) e^{i(k \cdot \vartheta x)} \, dk \\
&= \left( (2\pi)^{-d/2} \int \bar{Q}(-k) \bar{\sigma}(\vartheta k) e^{-i(k \cdot \vartheta x)} \, dk \right)^* \\
&= \left( (2\pi)^{-d/2} \int \bar{Q}(k) \bar{\sigma}(-\vartheta k) e^{i(k \cdot \vartheta x)} \, dk \right)^*.
\end{align*}

This equals $\Phi^*(\vartheta x)$ if and only if $\bar{\sigma}(-\vartheta k) = \bar{\sigma}(k)$. The equivalent condition on $\sigma$ in configuration space is $\vartheta \sigma \vartheta = \sigma$. Since $\vartheta^2 = I$ this is also equivalent to $\vartheta \sigma^T \vartheta = \sigma^*$. As $D$ is given by (14),
\begin{equation}
\vartheta D = (\vartheta \sigma^T \vartheta) \vartheta \sigma = \sigma^* \vartheta \sigma,
\end{equation}
as claimed, and this is clearly self-adjoint. Moreover, $D \vartheta = \sigma \vartheta \sigma^*$ is also self-adjoint. \hfill \Box

3.1. Time-reflection positivity. Consider the positive-time half-space
\begin{equation}
\mathbb{R}^+_d = [0, \infty) \times \mathbb{R}^{d-1};
\end{equation}
the negative-time half-space $\mathbb{R}^d_-$ is defined similarly. Let $L_2(\mathbb{R}^d_\pm)$ denote the subspace of $L_2(\mathbb{R}^d)$ consisting of functions supported in $\mathbb{R}^d_\pm$. Let $\mathcal{E}_{\pm, 0} \subset \mathcal{E}$ denote the subspace of finite linear combinations $A = \sum_{j=1}^N c_j e^{i \Phi(f_j)} \Omega_0^\pm$, for $f_j \in S(\mathbb{R}^d_\pm)$, and let $\mathcal{E}_\pm$ denote its closure in $\mathcal{E}$. The Osterwalder–Schrader reflection form on $\mathcal{E}_{+, 0} \times \mathcal{E}_{+, 0}$ (or, alternatively, on $\mathcal{E}_{-, 0} \times \mathcal{E}_{-, 0}$) is
\begin{equation}
(A, B)_\mathcal{H} = \langle A, \Theta B \rangle_\mathcal{E}.
\end{equation}
This extends by continuity to $\mathcal{E}_{\pm} \times \mathcal{E}_{\pm}$. Thus, the left hand side extends to a pre-inner product on equivalence classes $[A] = A + n \in \mathcal{E}_\pm$. Here, $n \in \mathcal{E}_\pm$ is an element of the null space of the form $\langle \cdot, \cdot \rangle_{\mathcal{H}}$. For simplicity denote the equivalence class $[A]$ by $A$. The space $\mathcal{H}$ is the completion of the equivalence classes in this inner product. Let $M$ denote the $N \times N$ matrix with entries
\begin{equation}
M_{jj'} = S(f_j - \vartheta f_j), \quad \text{where} \quad f_j \in \mathcal{E} \quad \text{for} \quad j = 1, \ldots, N.
\end{equation}
**Definition 1** (RP). Various possible formulations of RP (Osterwalder–Schrader Positivity) with respect to time reflection are:

(i) One has $0 \leq \Theta$ on either $\mathcal{E}_+$ or $\mathcal{E}_-$. If both hold, then $\Theta$ is doubly RP.

(ii) The functional $S(f)$ is RP with respect to $\vartheta$, if for every choice of $N \in \mathbb{N}$ and for all functions $f_j \in S(\mathbb{R}^d)$ the matrix $M$ in (21) is positive definite. The functional $S(f)$ is also RP, if $M$ is positive for $f_j \in S(\mathbb{R}^d_-)$. If both conditions hold, then $S(f)$ is doubly-reflection positive.

(iii) A symmetric operator $D = D^T$ on $L_2(\mathbb{R}^d)$ is RP with respect to $\vartheta$, if $0 \leq \vartheta D$ on $L_2(\mathbb{R}^d_+)$. It is also RP if $0 \leq \vartheta D$ on $L_2(\mathbb{R}^d_-)$. The latter is equivalent to $0 \leq D \vartheta$ on $L_2(\mathbb{R}^d_+)$. The operator $D$ is doubly RP if both conditions hold.

**Proposition 5.** Let $\Phi$ be a field on $\mathcal{E}$ defined by (15), and assume (19). Then

(i) The characteristic functional $S(f)$ defined in (6) satisfies $S(f) = S(-\vartheta \overline{f})$.

(ii) The matrix $M = M^*$ defined in (21) is hermitian.

(iii) Statements (i) and (ii) of Definition 1 are equivalent.

(iv) All three Statements (i), (ii), and (iii) of Definition 1 are equivalent in case that

$$S(f) = e^{-\frac{1}{2} \langle \overline{f}, Df \rangle_{L^2}}, \quad \text{with } D = \sigma \sigma^T = D^T. \quad (22)$$

**Proof.** The equivalence of Statements (i) and (ii) of Definition 1 follows from the identity

$$\langle A, A \rangle_{OS} = \sum_{j,j'=1}^N \overline{c_j} c_{j'} S(f_{j'} - \vartheta \overline{f_j}) = \sum_{j,j'=1}^N \overline{c_j} c_{j'} M_{jj'}, \quad (23)$$

which is a consequence of

$$\langle A, A \rangle_{OS} = \sum_{j,j'=1}^N \overline{c_j} c_{j'} \left( e^{i\Phi(f_j)} \Omega^E_0, e^{i\Phi(f_{j'})} \Omega^E_0 \right)_{\mathcal{E}}$$

$$= \sum_{j,j'=1}^N \overline{c_j} c_{j'} \left( \Omega^E_0, e^{-i\Phi^*(\vartheta f_j)} \Theta e^{i\Phi(f_{j'})} \Omega^E_0 \right)_{\mathcal{E}}.$$

As $\Theta \Omega^E_0 = \Omega^E_0$, one can substitute $\Theta e^{-i\Phi^*(\vartheta f_j)} \Theta = e^{-i\Phi(\vartheta f_j)}$ to give (23).

To verify that $S(f) = S(-\vartheta \overline{f})$ is valid, compute

$$S(-\vartheta \overline{f}) = \left( \Omega^E_0, e^{-i\Phi(\vartheta f)} \Omega^E_0 \right)_{\mathcal{E}} = \left( \Omega^E_0, e^{i\Phi(\vartheta f)} \Theta \Omega^E_0 \right)_{\mathcal{E}} = \left( \Omega^E_0, e^{-i\Phi^*(\vartheta f)} \Theta e^{i\Phi(f)} \Omega^E_0 \right)_{\mathcal{E}}$$

$$= \left( \Omega^E_0, e^{i\Phi(f)} \Omega^E_0 \right)_{\mathcal{E}} = S(f).$$

Using this relationship one also sees that the matrix $M$ is hermitian, for

$$M_{jj'} = S(f_{j'} - \vartheta \overline{f_j}) = S(-\vartheta \overline{f_{j'}} + f_j) = M_{j'j}.$$
Finally consider the Gaussian characteristic function (22). Now we show the equivalence of Statements (ii) and (iii) of Definition 1. Take \( A \in \mathcal{E}_{+,0} \) and choose \( N = 2 \), \( f_1 = -i\lambda f \), and \( f_2 = 0 \). Then for
\[
c_1 = \lambda^{-1} = -c_2,
\]
one can take the limit \( \lambda \to 0 \) of \( 0 \leq \langle A, A \rangle_{\mathcal{H}} \). This is just
\[
0 \leq \langle \Phi(f)\Omega_0^E, \Theta \Phi(f)\Omega_0^E \rangle_{\mathcal{E}} = \langle \Omega_0^E, \Phi^*(\overline{f}) \Theta \Phi(f)\Omega_0^E \rangle_{\mathcal{E}}
= \langle \Omega_0^E, \Phi(\vartheta \overline{f}) \Phi(f)\Omega_0^E \rangle_{\mathcal{E}} = \langle f, \vartheta Df \rangle_{L_2}.
\]
Hence, Statement (ii) ensures \( 0 \leq \vartheta D \) on \( L_2(\mathbb{R}_+^d) \).

The converse is also true. To see this, use
\[
\sum_{j,j'=1}^N \overline{c}_j c_{j'} M_{jj'} = \sum_{j,j'=1}^N \overline{c}_j c_{j'} S(f_{jj'} - \overline{\vartheta f_{jj'}}) = \sum_{j,j'=1}^N \overline{d}_j d_{j'} e^{\langle f_{jj'}, \vartheta Df_{jj'} \rangle_{L_2}},
\]
where
\[
d_j = c_j e^{-\frac{1}{2}\langle f_{jj'}, Df_{jj'} \rangle_{L_2}}.
\]
In fact,
\[
\sum_{j,j'=1}^N \overline{c}_j c_{j'} S(f_{jj'} - \overline{\vartheta f_{jj'}}) = \sum_{j,j'=1}^N \overline{c}_j c_{j'} e^{-\frac{1}{2}\langle f_{jj'}, \vartheta f_{jj'} \rangle_{L_2}} \left( c_{j'} e^{-\frac{1}{2}\langle f_{jj'}, Df_{jj'} \rangle_{L_2}} \right)
\times e^{\frac{1}{2}\langle f_{jj'}, \vartheta Df_{jj'} \rangle_{L_2}}
= \sum_{j,j'=1}^N \overline{d}_j d_{j'} e^{\frac{1}{2}\langle f_{jj'}, \vartheta (D+D^T) f_{jj'} \rangle_{L_2}}
= \sum_{j,j'=1}^N \overline{d}_j d_{j'} e^{\langle f_{jj'}, \vartheta Df_{jj'} \rangle_{L_2}}. \tag{24}
\]
The second to last equality follows from using \( \vartheta D^*\vartheta = D \) in
\[
\langle \vartheta f_{jj'}, D\vartheta f_{jj'} \rangle_{L_2} = \langle D\vartheta f_{jj'}, \vartheta f_{jj'} \rangle_{L_2} = \langle \overline{\vartheta f_{jj'}}, D^*\vartheta f_{jj'} \rangle_{L_2} = \langle \overline{\vartheta f_{jj'}}, D\vartheta f_{jj'} \rangle_{L_2},
\]
and from
\[
\langle f_{jj'}, D\vartheta f_{jj'} \rangle_{L_2} = \langle D\vartheta f_{jj'}, f_{jj'} \rangle_{L_2} = \langle \vartheta f_{jj'}, D^*f_{jj'} \rangle_{L_2}
= \langle \vartheta f_{jj'}, D^T f_{jj'} \rangle_{L_2} = \langle f_{jj'}, \vartheta D^T f_{jj'} \rangle_{L_2}.
\]
The last inequality in (24) then is a consequence of the symmetry of \( D \).
Thus, Statement (ii) of Definition 1 on $\mathcal{E}_+$ follows from the positivity of the matrix $K$ with entries

$$K_{jj'} = \langle f_j, \partial D f_j' \rangle_{L^2} \quad \text{for } f_j \in L_2(\mathbb{R}^d_+) .$$

In fact, we now see that $I \leq K$. The assumption $0 \leq \partial D$ on $L_2(\mathbb{R}^d_+)$ means that the matrix $k$ with entries $k_{jj'} = \langle f_j, \partial D f_j' \rangle_{L^2}$ has non-negative eigenvalues for $f_j \in L_2(\mathbb{R}^d_+)$. The same is true for the matrix $k^\circ_n$ with entries $k^\circ_n_{jj'} = (k_{jj'})^n$. In fact, the matrix $k^\circ_n$ equals $k^{\otimes n}$ on the diagonal, and the eigenvalues $\lambda_j(K)$ of the matrix $K = \sum_{n=0}^{\infty} n!^{-1} k^\circ_n$ with entries $K_{jj'} = e^{k_{jj'}}$ equal 1 plus an eigenvalue of a positive matrix. Consequently, $1 \leq \lambda_j(K)$, as claimed.

A function $f \in L_2(\mathbb{R}^d_+)$, if and only if $\partial f \in L_2(\mathbb{R}^d_+)$. Thus, Statement 1 on $\mathcal{E}_-$ is equivalent to $0 \leq \partial^2 D \partial = D \partial$ on $L_2(\mathbb{R}^d_+)$. □

4. Quantization

If the time reflection $\Theta$ is reflection positive (or doubly reflection positive), then the form (20) defines a pre-Hilbert space (or two pre-Hilbert spaces) $\mathcal{H}_{\pm,0}$ whose elements are equivalence classes

$$\hat{A} = \{ A + n \} ,$$

where $A, n \in \mathcal{E}_+$ or $A, n \in \mathcal{E}_-$ and where $n$ is an element of the null space of the form (20). In either case, the inner product on $\mathcal{H}_{\pm,0}$ is given by the form (20). Let $\mathcal{H}_{\pm}$ denote the completions of the pre-Hilbert spaces $\mathcal{H}_{\pm,0}$.

In case the characteristic functional $S(f)$ is both time-translation invariant and reflection positive, one obtains a positive Hamiltonian operator from the RP inner product. This follows from the standard construction provided in [15], so we refer to this operator as the $OS$-$Hamiltonian$. Let the time translation group $T(t)$ act on functions as

$$(T(s)f)(t, x) = f(t - s, x).$$

If $S(T(s)f) = S(f)$ for all $s$, then $S(f)$ is time-translation invariant. In this case, $T(t)$ acts as a unitary transformation on $\mathcal{E}$, and

$$T(t) : \mathcal{E}_+ \to \mathcal{E}_+ \quad \text{for } 0 \leq t .$$

**Proposition 6** (OS-Hamiltonian). Let $\wedge$ denote the canonical projection from $\mathcal{E}_\pm$ to $\mathcal{H}_\pm$ resulting from the reflection-positive OS form. Then the maps

$$R(t)_{\pm} = \hat{T}(t)$$

are contraction semigroups with infinitesimal generators $H_{\pm}$, namely $R_{\pm}(t) = e^{-t H_{\pm}}$ with $0 \leq H_{\pm}$.

The proof of this proposition follows from the arguments given in [15]. In the Gaussian case, let $h_{\pm}$ denote the restriction of $H_{\pm}$ to the one-particle subspace $\mathcal{H}_{1,\pm} \subset \mathcal{H}_\pm$. If the functional $S(f)$ has covariance $D$, the reflection positivity condition on the one-particle space requires $0 \leq \partial D$ on $L_2(\mathbb{R}^d_+)$. For example, if $f \in L_2(\mathbb{R}^d_+)$, then

$$\langle f, \partial D f \rangle_{L^2} = \langle F, F \rangle_{\mathcal{H}_{1,\pm}} .$$
where \( F = \int_0^\infty e^{-it^*} f_i \, dt \) and \( f_i(x) = f(t, x) \). Likewise, if \( f \in L_2(\mathbb{R}^d) \), then one has
\[
\langle f, \vartheta \, Df \rangle_{L_2} = \langle F, F \rangle_{\mathcal{H}_{1,-}} \quad \text{for} \quad F = \int_{-\infty}^0 e^{it^*} f_i \, dt.
\]

### 4.1. Spatial reflection-positivity for the neutral field

In a fashion similar to time-reflection, one considers spatial reflections. The spatial reflection through a plane orthogonal to a given spatial vector \( \mathbf{n} \in \mathbb{R}^{d-1} \) is \( \pi_n: (t, \mathbf{x}) \mapsto (t, \mathbf{x} - 2(\mathbf{n} \cdot \mathbf{x}) \mathbf{n}) \). Let \( \pi_n \) denote the action that this reflection induces as a real, self-adjoint, unitary on \( L_2(\mathbb{R}^d) \).

Let \( \pi_n \) denote the push-forward of \( \pi_n \) to a real, self-adjoint unitary on \( \mathcal{E} \). Instead of the positive-time subspace \( L_2(\mathbb{R}^d^+ \mathbb{R}^d^+) \) that arose in the study of time reflection in Sect. 3, use the subspace of functions \( L_2(\mathbb{R}^d_{n^+} \mathbb{R}^d_{n^-}) \) supported on one side of the reflection hyperplane. Let \( \mathcal{E}_{n^\pm} \subset \mathcal{E} \) denote the closure of the subspace spanned by the vectors \( \left\{ e^{i\Phi(f)} \Omega_0^E \right\} \) with \( f \in S(\mathbb{R}^d_{n^\pm}) \).

Spatial reflection \( \Pi_n \) leaves \( \Omega_0^E \) invariant and maps \( f(E, k) \in \mathcal{E}_1 \) to \( f(\pi_n k) \). In Fourier space
\[
\pi_n(E, k) = (E, k - 2(k \cdot \mathbf{n}) \mathbf{n})
\]
and \( \pi_n^2 k = k \). Spatial-reflection transforms the \( \tilde{Q}(k) \)'s according to \( \Pi_n \tilde{Q}(k) \Pi_n = \tilde{Q}(\pi_n k) \). Following the proof of Proposition 4, we obtain:

**Proposition 7** (Spatial Reflection of the Field). Let the neutral field \( \Phi(x) \) be defined by (15) on \( \mathcal{E} \). Then the spatial-reflection \( \Pi_n \) transforms \( \Phi \) according to
\[
\Pi_n \Phi(x) \Pi_n = \Phi^*(\pi_n x),
\]
if and only if
\[
\pi_n \sigma^T \pi_n = \sigma^*.
\]
If (26) holds, then \( \pi_n D = \sigma^* \pi_n \sigma = D^* \pi_n \). Thus
\[
\pi_n D = (\pi_n D)^* \quad \text{and} \quad D \pi_n = (D \pi_n)^*
\]
are self-adjoint operators on \( L_2(\mathbb{R}^d) \).

One can formulate spatial reflection positivity by substituting \( \pi_n \) for \( \vartheta \) and \( \Pi_n \) for \( \Theta \), and \( \mathcal{E}_{n^\pm} \) for \( \mathcal{E}_\pm \) in Definition 1. Spatial reflection positivity gives a pre-inner product
\[
\langle A, B \rangle_{\mathcal{H}(n)} = \langle A, \Pi_n B \rangle_{\mathcal{E}}
\]
on \( \mathcal{E}_{n^+} \), as well as new requirements on the transformation of the field or on \( D \). The proof of the following result is identical to the proof of Proposition 5.

**Proposition 8** (Spatial-Reflection Positivity). If one replaces \( \vartheta, \Theta, \mathbb{R}^d_{n^\pm}, \mathcal{E}_\pm \) in the statement of Proposition 5 by \( \pi_n, \Pi_n, \mathbb{R}^d_{n^\pm}, \mathcal{E}_{n^\pm} \), respectively, then the proposition remains valid.
5. Charged Fields

One defines charged fields $\Phi_\pm(x)$ to replace the usual hermitian-conjugate fields $\Phi(x)$ and $\Phi^*(x)$. These fields are linear in the complex coordinates $\tilde{Q}_\pm(k)$ and the kernels $\sigma_\pm$, whose properties we elaborate on below. Similar to (15), take the charged fields to be

$$\Phi_\pm(x) = (2\pi)^{-d/2} \int \tilde{Q}_\pm(k) \tilde{\sigma}_\pm(k) e^{ik \cdot x} dk.$$  

(28)

While one might regard the charged coordinates $\tilde{Q}_\pm$, or their Fourier transforms $Q_\pm$, as linear combinations of two independent sets of neutral coordinates $Q_\pm = \frac{1}{\sqrt{2}} (Q_1 \pm i Q_2)$, here we do not require this. We take independent creation and annihilation operator-valued distributions $A^*_\pm(k)$ and $A_\pm(k)$, which act on a Fock–Hilbert space $\mathcal{E}$ and satisfy the relations

$$[A_\pm(k), A^*_\pm'(k')] = \delta_{\pm \pm'} \delta(k - k'), \quad \text{and} \quad [A_\pm(k), A_\pm'(k')] = 0.$$  

One can decompose the one-particle space into a direct sum

$$\mathcal{E}_1 = \mathcal{E}_1^+ \oplus \mathcal{E}_1^-.$$  

Correspondingly, the Fock space $\mathcal{E}$ decomposes into the tensor product $\mathcal{E} = \mathcal{E}^+ \otimes \mathcal{E}^-$. One defines the complex coordinates as

$$\tilde{Q}_+(k) = A^*_+(k) + A_-(k),$$

and

$$\tilde{Q}_-(k) = A^*_-(k) + A_+(k), \quad \text{so} \quad \tilde{Q}_+(k) = \tilde{Q}^*_-(k).$$  

(29)

These coordinates all mutually commute,

$$[\tilde{Q}_\pm(k), \tilde{Q}_{\pm'}(k')] = 0 = [\tilde{Q}_\pm(k), \tilde{Q}^*_{\pm'}(k')]$$  

As a consequence, the fields and their adjoints commute

$$[\Phi_\pm(x), \Phi_{\pm'}(x')] = [\Phi_\pm(x), \Phi^*_{\pm'}(x')] = 0.$$  

The characteristic function of the charged field depends on two variables

$$S(f_+, f_-) = \left| \Omega^\mathcal{E}_0, e^{i\Phi_+(f_+) + i\Phi_-(f_-)} \Omega^\mathcal{E}_0 \right|_\mathcal{E}.$$  

---

3 Note that we use “±” here to label charges, while in earlier sections we use this notation to label positive and negative time subspaces, etc. We hope that this causes no confusion.

4 The spaces $\mathcal{E}^\pm$ labelled with a superscript denote spaces where each particle has positive or negative charge. The spaces $\mathcal{E}_\pm$ are subspaces of vectors at positive or negative times. However, for the fields themselves, and some other associated operators, we retain the notation used elsewhere in this section to label charges by subscripts.
5.1. Twist symmetry of the charged field. Define two number operators

\[ N_\pm = \int A_\pm^*(k)A_\pm(k)\,dk. \]

In terms of these, the total number operator is \( N = N_+ + N_- \). The charge (or vortex number) is \( F = N_+ - N_- \). The vortex number \( F \) implements the twist transformation on the field:

\[ e^{i\alpha F} \tilde{Q}_\pm(k)e^{-i\alpha F} = e^{\pm i\alpha} \tilde{Q}_\pm(k), \quad \alpha \in \mathbb{C}. \]

As a consequence,

\[ e^{i\alpha F} \Phi_\pm(x)e^{-i\alpha F} = e^{\pm i\alpha} \Phi_\pm(x). \]

Moreover, the zero-particle vector is twist invariant, \( e^{i\alpha F} \Omega_0^E = \Omega_0^E \). Unitarity of \( e^{i\alpha F} \) then ensures the vanishing of the diagonal expectations

\[ \langle \Omega_0^E, \Phi_+(x') \Omega_0^E \rangle_E = \langle \Omega_0^E, \Phi_-(x') \Omega_0^E \rangle_E = 0. \]

The remaining two-point functions do not vanish. Let

\[ D(x - x') = (2\pi)^{-d} \int \tilde{\sigma}_+(k)\tilde{\sigma}_-(-k) e^{ik \cdot (x - x')}\,dk \]

be the kernel of the operator

\[ D = \sigma_+\sigma_-^T = \sigma_-^T\sigma_+ \quad \text{with transpose} \quad D^T = \sigma_-\sigma_+^T = \sigma_+^T\sigma_- . \]  

Then

\[ \langle \Omega_0^E, \Phi_+(x') \Omega_0^E \rangle_E = D(x - x'), \]

and

\[ \langle \Omega_0^E, \Phi_-(x') \Omega_0^E \rangle_E = D^T(x - x'). \]

As \( \sigma_+, \sigma_- \) are both translation invariant, they commute. Using these relations, the characteristic function of the charged field is

\[ S(f_+, f_-) = \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} \langle \Omega_0^E, \Phi_+(f_+)^n\Phi_-(f_-)^n \Omega_0^E \rangle_E \]

\[ = e^{-\langle T_+Df_- \rangle_{L^2}}. \]

Finally, note that

\[ D = D^*, \quad \text{either if} \quad \sigma_\pm = (\sigma_\pm)^* \quad \text{or if} \quad \sigma_\pm = \overline{\sigma_\pm}. \]

Also

\[ D = D^T, \quad \text{either if} \quad \sigma_+ = \sigma_- \quad \text{or if} \quad \sigma_\pm = \sigma_\mp^T. \]

Thus there are in principle four ways that \( D = D^* = D^T = \overline{D} \). They are: (i) \( \sigma_+ = \sigma_- = \sigma_+^* = \sigma_-^* \), or (ii) \( \sigma_+ = \sigma_+^T = \overline{\sigma_+} \) along with \( \sigma_- = \sigma_-^T = \overline{\sigma_-} \), or (iii) \( \sigma_+ = \sigma_- = \overline{\sigma_+} \), or (iv) \( \sigma_+ = \sigma_- = \sigma_+^T \).
5.2. Matrix notation for the charged field. We combine the two components $\Phi_{\pm}$ of the charged field into a vector

$$\Phi = \begin{pmatrix} \Phi_+ \\ \Phi_- \end{pmatrix}$$

that pairs with test functions $f = \begin{pmatrix} f_+ \\ f_- \end{pmatrix}$, to yield a field acting on $\mathcal{E}$,

$$\Phi(f) = \sum_{\alpha = \pm} \Phi_{\alpha}(f_{\alpha}).$$

Likewise, combine the various two-point functions of the charged field into a $2 \times 2$ matrix of operators $D$ with entries indexed by $\alpha = \pm$, each acting on $L_2(\mathbb{R}^d)$. Let $L_2 = L_2(\mathbb{R}^d) \oplus L_2(\mathbb{R}^d)$, and let $\bar{f}$ denote complex conjugation of $f$. Then, with $D$ defined by (30), let

$$D = \begin{pmatrix} 0 & D \\ D^T & 0 \end{pmatrix}.$$ 

One observes that $D$ is symmetric, $D = D^T$. The two-point function for the field $\Phi$ is

$$\langle \Omega_0^F, \Phi(f)\Phi(g)\Omega_0^F \rangle_{\mathcal{E}} = \left\langle \bar{f}, D g \right\rangle_{L_2} = \langle \Omega_0^F, \Phi(g)\Phi(f)\Omega_0^F \rangle_{\mathcal{E}}.$$

The second identity arises from the commutativity of the field. Equivalent to commutativity is the relation

$$\langle g, D f \rangle_{L_2} = \langle D^* \bar{g}, f \rangle_{L_2} = \langle \bar{Dg}, f \rangle_{L_2} = \langle \bar{f}, D g \rangle_{L_2}.$$ 

Note also that

$$\left\langle \bar{f}, D g \right\rangle_{L_2} = \left\langle \bar{f}_+, D g_+ \right\rangle_{L_2} + \left\langle \bar{g}_+, D f_- \right\rangle_{L_2},$$

so

$$\left\langle \bar{f}, D f \right\rangle_{L_2} = 2 \left\langle \bar{f}_+, D f_- \right\rangle_{L_2}. \quad (33)$$

In fact,

$$\left\langle \bar{f}_-, D^T g_+ \right\rangle_{L_2} = \langle D^T g_+, \bar{f}_- \rangle_{L_2} = \left\langle D^* \bar{g}_+, f_- \right\rangle_{L_2} = \langle \bar{g}_+, D f_- \rangle_{L_2}.$$ 

Proposition 9. The characteristic function $S(f_+, f_-)$ of (31) has the standard form of a Gaussian,

$$S(f) = \left\langle \Omega_0^F, e^{i\Phi(f)}\Omega_0^F \right\rangle_{\mathcal{E}} = e^{-\frac{1}{2} \left\langle \bar{f}, D f \right\rangle_{L_2}} = S(f_+, f_-) = e^{-\left\langle \bar{f}_+, D f_- \right\rangle_{L_2}}.$$ 

(34)
Proof. The product of \( n \in \mathbb{N} \) fields with test functions \( f^{(j)} \) with components \( f^{(j)}_{\alpha} \), \( j = 1, \ldots, n \), is

\[
\Phi(f^{(1)}) \cdots \Phi(f^{(n)}) = \sum_{\alpha_1, \ldots, \alpha_n = \pm} \Phi_{\alpha_1}(f^{(1)}_{\alpha_1}) \cdots \Phi_{\alpha_n}(f^{(n)}_{\alpha_n}). \tag{35}
\]

As the fields are linear in creation and annihilation operators, the zero-particle expectation of such a product satisfies the Gaussian recursion relation

\[
\left\langle \Omega^E_0, \Phi(f^{(1)}) \cdots \Phi(f^{(n)}) \Omega^E_0 \right\rangle_E = \sum_{j=2}^{n} \left\langle \Omega^E_0, f^{(1)}, Df^{(j)} \right\rangle_{L_2} \times \left\langle \Omega^E_0, \Phi(f^{(2)}) \cdots \Phi(f^{(j)}) \cdots \Phi(f^{(n)}) \Omega^E_0 \right\rangle_E.
\]

Here \( \Phi(f^{(j)}) \) indicates that one omits the term with index \( j \) from the product. Moreover, the expression (35) is a multi-linear, symmetric function of the \( f^{(j)} \)'s, so it is determined uniquely—using a polarization identity—as a linear combination of powers \( \Phi(g)^n \), where \( g \) is one of the \( 2^n \) functions \( \pm f^{(1)} \pm \cdots \pm f^{(n)} \).

Hence, the expectations

\[
\left\langle \Omega^E_0, \Phi(f^{(1)}) \cdots \Phi(f^{(n)}) \Omega^E_0 \right\rangle_E
\]

are determined uniquely by the characteristic function \( S(f) \). From the recursion relation, we infer that

\[
\left\langle \Omega^E_0, \Phi(f)^n \Omega^E_0 \right\rangle_E = \begin{cases} 0, & \text{if } n \text{ is odd} \\ (2k - 1)!! \left\langle \overline{f}, Df \right\rangle_{L_2}^k, & \text{if } n = 2k \end{cases},
\]

so \( S(f) = e^{-\frac{1}{2} \left\langle \overline{f}, Df \right\rangle_{L_2}} \). Also \( S(f) = S(f_+, f_-) \) as a consequence of the second identity in (33).

5.3. Charge conjugation. We define charge conjugation as a unitary transformation \( U_c \) on \( \mathcal{E} \). We substitute \( \Phi_+ \) for the ordinary charged field \( \varphi = \frac{1}{\sqrt{2}} (\varphi_1 + i \varphi_2) \) representing positive charge and \( \Phi_- \) for the hermitian conjugate field \( \varphi^* = \frac{1}{\sqrt{2}} (\varphi_1 - i \varphi_2) \) representing negative charge. Thus, hermitian conjugation reverses the charge for the ordinary field, while charge conjugation of our classical field is determined by the action of the charge-conjugation matrix

\[
\mathcal{C} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \mathcal{C}^* = \mathcal{C}^T = \overline{\mathcal{C}} = \mathcal{C}^{-1}. \tag{36}
\]

Note that \( \mathcal{C} \) is a \( 2 \times 2 \) matrix that acts on the components of the field, i.e.,

\[
(\mathcal{C} \Phi)(x) = \begin{pmatrix} \Phi_-(x) \\ \Phi_+(x) \end{pmatrix}.
\]

The unitary charge-conjugation operator \( U_c \) on \( \mathcal{E} \) is defined by setting

\[
U_c \Phi(f^{(1)}) \cdots \Phi(f^{(n)}) \Omega^E_0 = (\mathcal{C} \Phi)(f^{(1)}) \cdots (\mathcal{C} \Phi)(f^{(n)}) \Omega^E_0,
\]

and \( U_c \Omega^E_0 = \Omega^E_0 \).
5.4. Complex conjugation. Next we consider complex conjugation of the classical field, defined by

\[ \overline{\Phi}(x) = \begin{pmatrix} \Phi_1^+(x) \\ \Phi_2^-(x) \end{pmatrix} = (\Phi^*)^T(x). \]

As the charge conjugation is connected with hermitian conjugation, it is natural that the existence of a positive measure on the fields entails that the expectation

\[ \langle \Omega_0 \mid C\Phi(x)\Phi(x')\Omega_0 \rangle_{\mathcal{E}} = (\mathcal{C}D)(x, x') \]

is the kernel of a positive transformation

\[ \mathcal{C}D = \begin{pmatrix} D^T & 0 \\ 0 & D \end{pmatrix} \text{ on } L_2. \]

This will be the case, if and only if \( D \) itself is positive on \( L_2 \). Thus, a positive measure is associated with the condition

\[ 0 \leq \sum_{j, j'=1}^N c_j \overline{c}_{j'} S(f_j - \overline{c} f_{j'}), \]

for any choice of \( f_j \in L_2 \) and \( c_j \in \mathbb{C} \).

5.5. Time reflection. Let \( \Theta \) denote the unitary time reflection on \( \mathcal{E} \), namely

\[ \Theta = \begin{pmatrix} \bar{\Theta} & 0 \\ 0 & \bar{\Theta} \end{pmatrix}. \]

In order to recover the usual properties of the charged fields, we expect that they should transform under time inversion as

\[ \Theta \Phi(x) \Theta = \mathcal{C} \overline{\Phi}(\vartheta x), \]

or in components

\[ \Theta \Phi_\pm(x) \Theta = \Phi_\mp^\pm(\vartheta x). \quad (37) \]

In fact, we have the following criterion.

**Proposition 10** (Time Reflection). The field transforms according to (37) if and only if

\[ \vartheta \sigma_\pm^T \vartheta = \sigma_\mp^*. \quad (38) \]

In this case,

\[ (\vartheta \mathcal{C}) \mathcal{D} (\vartheta \mathcal{C}) = \mathcal{D}^* = \overline{\mathcal{D}}. \quad (39) \]

and the operator \( \vartheta \mathcal{C}D \) equals

\[ \vartheta \mathcal{C}D = \begin{pmatrix} \vartheta D^T & 0 \\ 0 & \vartheta D \end{pmatrix} = \begin{pmatrix} \sigma_\mp^* \vartheta \sigma_\mp & 0 \\ 0 & \sigma_\mp^* \vartheta \sigma_\mp \end{pmatrix}, \quad (40) \]

which is self-adjoint on \( L_2 \).
Proof. In terms of components,
\[ \Theta \Phi_\pm(x) \Theta = (2\pi)^{-d/2} \int \Theta \bar{\Phi}_\pm(k) \Theta \bar{\sigma}_\pm(k) e^{ik \cdot x} \, dk \]
\[ = (2\pi)^{-d/2} \int \bar{Q}_\mp(\theta k) \bar{\sigma}_\mp(k) e^{ik \cdot x} \, dk \]
\[ = (2\pi)^{-d/2} \int \bar{Q}_\mp^*(-\theta k) \bar{\sigma}_\mp(k) e^{ik \cdot x} \, dk \]
\[ = (2\pi)^{-d/2} \int \bar{Q}_\mp^*(k) \bar{\sigma}_\mp(-\theta k) e^{-i k \cdot (\theta x)} \, dk \]
\[ = (2\pi)^{-d/2} \left( \int \bar{Q}_\mp^*(k) \bar{\sigma}_\mp(-\theta k) e^{i k \cdot (\theta x)} \, dk \right)^*. \]

Thus, the desired equivalence (37) is equivalent to \( \bar{\sigma}_\pm \) satisfying the relation \( \bar{\sigma}_\pm(-\theta k) = \bar{\sigma}_\mp(k) \). In configuration space this is equivalent to the operator relation (38).

Note that the self-adjoint, unitary operator on \( L_2 \), given by
\[ \vartheta C = \begin{pmatrix} 0 & \vartheta \\ \vartheta & 0 \end{pmatrix}, \]
yields
\[ (\vartheta C) D (\vartheta C) = \begin{pmatrix} 0 & \vartheta D^T \vartheta \\ \vartheta D \vartheta & 0 \end{pmatrix}. \]
Hence, relation (39) is equivalent to \( \vartheta D \vartheta = D^* \) and \( \vartheta D^T \vartheta = D^{T*} \), namely to the self-adjointness of \( \vartheta D \) and of \( \vartheta D^T \) on \( L_2 \). In the case that (38) holds, one can use (30) to infer \( \vartheta D = \vartheta \sigma^+ \vartheta_+ = \sigma^*_+ \vartheta \vartheta_+ \). Thus, \( \vartheta D \) is self-adjoint on \( L_2 \). Likewise, \( \vartheta D^T = \vartheta \sigma^+_+ \sigma_- = \sigma^*_+ \vartheta \sigma_- \) is self-adjoint on \( L_2 \). As a consequence, one infers that
\[ \vartheta C D = \begin{pmatrix} \vartheta D^T & 0 \\ 0 & \vartheta D \end{pmatrix} = \begin{pmatrix} \sigma^*_+ \vartheta \sigma_- & 0 \\ 0 & \sigma^*_+ \vartheta \sigma_+ \end{pmatrix}, \]
which has the desired form (40) and is self-adjoint on \( L_2 \). □

5.6. Time-reflection positivity for the charged field. To study time-reflection positivity of \( \Theta \) on \( E_+ \), take the Osterwalder–Schrader form for the charged field to be
\[ \langle \cdot, \cdot \rangle_{H} = \langle \cdot, \Theta \cdot \rangle_{E}. \]
(41)

Let \( L_{2+} = L_2(\mathbb{R}^d_+) \oplus L_2(\mathbb{R}^d_+) \).

Definition 2. The functional \( S(f) \) is time-reflection positive if
\[ 0 \leq \sum_{j,j'=1}^N c_j \bar{c}_{j'} S(f_j - \vartheta C \bar{f}_{j'}), \]
for any choices of \( f_j \in L_{2+} \) and \( c_j \in \mathbb{C}, j = 1, \ldots, N \). It is also time-reflection positive if (42) holds for any choices of \( f_j \in L_{2-} \) and \( c_j \in \mathbb{C}, j = 1, \ldots, N \). In case both conditions hold, then \( S(f) \) is doubly time-reflection positive.
Proposition 11. Time-reflection positivity on $E_+$ is equivalent to the statement that
\[ 0 \leq \vartheta \mathcal{C} D = \left( \begin{array}{cc} \vartheta \hat{D}^T & 0 \\ 0 & \vartheta \hat{D} \end{array} \right) = \left( \begin{array}{cc} \sigma^+ \vartheta \sigma_- & 0 \\ 0 & \sigma^+ \vartheta \sigma_+ \end{array} \right) \] on $L_{2,+}$.  
(43)

Proof. As the characteristic function for the charged field is Gaussian, we infer from the proof of Proposition 5 that positivity of the OS form (41) on $E$ is equivalent to positivity of the two point function
\[ \langle \Phi(f) \Omega_{0}^{E}, \Phi(g) \Omega_{0}^{E} \rangle_{\mathcal{H}} = \langle f, \vartheta \mathcal{C} D g \rangle_{L_2}, \]
for $f \in L_{2,+} = L_{2}(\mathbb{R}^{d}_{+}) \oplus L_{2}(\mathbb{R}^{d}_{+})$. For $f, g \in L_{2,+}$ we claim that the putative inner product of two such vectors in $\mathcal{H}$ is
\[ \langle \Phi(f) \Omega_{0}^{E}, \Phi(g) \Omega_{0}^{E} \rangle_{\mathcal{H}} = \langle f, \vartheta \mathcal{C} D g \rangle_{L_2}, \]
where
\[ \vartheta \mathcal{C} D = \left( \begin{array}{cc} \vartheta \hat{D}^T & 0 \\ 0 & \vartheta \hat{D} \end{array} \right) = \left( \begin{array}{cc} \sigma^+ \vartheta \sigma_- & 0 \\ 0 & \sigma^+ \vartheta \sigma_+ \end{array} \right). \]
From (44) we infer that positivity of the OS form on $E$ is equivalent to (43), as claimed.

In fact,
\[ \langle \Phi(f) \Omega_{0}^{E}, \Phi(g) \Omega_{0}^{E} \rangle_{\mathcal{H}} = \langle \Phi(f) \Omega_{0}^{E}, \Phi(g) \Omega_{0}^{E} \rangle_{\mathcal{E}} = \langle f, \vartheta \mathcal{C} D g \rangle_{L_2}. \]
\(\square\)

5.7. Spatial-reflection positivity for the charged field. One can formulate spatial reflection positivity by substituting $L_{2}(\mathbb{R}^{d}_{n/+})$ for $L_{2}(\mathbb{R}^{d})$, substituting $\pi_n$ for $\vartheta$, substituting $\Pi_n$ for $\Theta$, and substituting $E_{n/+}$ for $E_+$ in (41). Spatial reflection positivity gives a pre-inner product
\[ \langle A, B \rangle_{\mathcal{H}(n)} = \langle A, \Pi_n B \rangle_{E} , \]
on $E_{n,+0}$, as well as new requirements on the transformation of the field and of $D$.

Proposition 12 (Spatial-Reflection). If one replaces $\vartheta, \Theta, \Pi_n, \mathbb{R}_{n/+}, E_+$ in the statement of Proposition 10 by $\pi_n, \Pi_n, \mathbb{R}_{n/+}, E_{n/+}$, respectively, then the proposition remains valid.

Proposition 13 (Spatial-Reflection Positivity). If one replaces $\vartheta, \Theta, \Pi_n, \mathbb{R}_{n/+}$ and $E_+$ in the statement of Proposition 11 by $\pi_n, \Pi_n, \mathbb{R}_{n/+}$ and $E_{n/+}$, respectively, then the proposition remains valid.
6. Compactification

In this section we show that reflection positivity carries over when we compactify one coordinate \( x_j \in \mathbb{R} \) on the line to a corresponding coordinate on a circle \( x_j \in S^1 \).

We consider spacetimes of the general form \( \mathbf{X} = X_1 \times \cdots \times X_d \), where each factor \( X_i \) either equals \( \mathbb{R} \) (the real line) or \( S^1 \) (a circle of length \( \ell_j \)). Denote the first coordinate by \( t = x_0 \) and let \( x = (t, x) \). Compactification of a coordinate \( x_j \in X_j \) means replacing the coordinate \( x_j \in \mathbb{R} \) by a corresponding coordinate \( x_j \in S^1 \). One denotes this compactification as

\[
\mathbf{X} = X_1 \times \cdots \times X_{j-1} \times \mathbb{R} \times X_{j+1} \times \cdots \times X_d \\
\longrightarrow \mathbf{X}^{cj} = X_1 \times \cdots \times X_{j-1} \times S^1 \times X_{j+1} \times \cdots \times X_d.
\]

Of course one can take \( \mathbf{X}^{cj} \) as a new \( \mathbf{X} \), and continue to compactify. The minimally compactified space is \( \mathbb{R}^d \); the maximally compactified space is the torus \( T^d \), with periods \( \beta = \ell_0, \ell_1, \ldots, \ell_{d-1} \).

Parameterize the compactified coordinate \( x_j \) as

\[
x_j \in S^1 = [-\frac{1}{2} \ell_j, \frac{1}{2} \ell_j],
\]

and the positive-subspace of \( X_j \) by

\[
X_{j+} = (S^1_+)_j = [0, \frac{1}{2} \ell_j], \quad \text{or} \quad X_{j+} = \mathbb{R}_+ = [0, \infty).
\]

Likewise, denote the \( j \)-positive subspace of \( \mathbf{X} \) by

\[
\mathbf{X}_{j+} = X_1 \times \cdots \times X_{j+} \times \cdots \times X_d.
\]

The reflection of the coordinate \( x_j \) is the transformation

\[
\pi_j : x \rightarrow \pi_j x, \text{ where } (\pi_j x)_i = \begin{cases} x_i, & \text{if } i \neq j \\ -x_j, & \text{if } i = j \end{cases}.
\]

We denote \( \varrho \) by \( \pi_0 \), so we treat time reflection and spatial reflection on an equal footing. The Fock space \( \mathcal{E} \) over \( \mathcal{K} \) and the \( j \)-positive subspaces \( \mathcal{E}_{j+} \) will now refer to the one-particle space \( \mathcal{K} = L_2(\mathbf{X}) \), and the \( j \)-positive subspace \( \mathcal{K}_{j+} = L_2(\mathbf{X}_{j+}) \).

**Definition 3.** The operator \( D \) is doubly-reflection-positive with respect to \( \pi_j \) if both

\[
0 \leq \pi_j D \quad \text{and} \quad 0 \leq D \pi_j \quad \text{on} \quad L_2(\mathbf{X}_{j+}).
\]

This is equivalent to both

\[
0 \leq \pi_j D \quad \text{and} \quad 0 \leq D \pi_j \quad \text{on} \quad L_2(\mathbf{X}_{j-}),
\]

or to

\[
0 \leq \pi_j D \quad \text{on both} \quad L_2(\mathbf{X}_{j\pm}).
\]

Recall that symmetry of the operator \( D \) with integral kernel \( D(x, x') \) means \( D(x, x') = D(x', x) \). Moreover, a covariance for classical fields that is reflection-positive with respect to the reflection \( \pi \) must be symmetric and satisfy \( \pi D \pi = D^* \).
Proposition 14. Suppose $D$ is symmetric on $L_2(X)$, and

$$\pi D \pi = D^*$$

for a reflection $\pi$. Then double-reflection-positivity and reflection-positivity with respect to $\pi$ on $L_2(X_+)$ are equivalent.

Proof. Double RP is a stronger condition, so one only needs to show that RP ensures double RP. Since $\pi X_\pm = X_\mp$ and $\pi$ is self-adjoint and unitary, the condition (49) is equivalent to the other two conditions. Thus, it is sufficient to show that $0 \leq \pi D$ on $L_2(X_+)$ implies $0 \leq D\pi$ on the same subspace.

Using $\pi D \pi = D^*$, one infers

$$D(x, x') = (\pi D^* \pi)(x, x') = (D^*)(\pi x, \pi x') = \overline{D(\pi x', \pi x)},$$

so symmetry ensures that $D(x, x') = D(\pi x, \pi x')$. This is the operator relation $D = \overline{D} = \pi D \pi$, as $\pi$ is real, so also $D\pi = \pi D$. Therefore

$$\langle f, D\pi f \rangle_{L_2(X)} = \langle \overline{f}, D\pi f \rangle_{L_2(X)} = \langle f, \pi D f \rangle_{L_2(X)},$$

(50)

Complex conjugation leaves $L_2(X_+)$ invariant, so reflection-positivity ensures $0 \leq \langle f, \pi D f \rangle_{L_2(X)}$. Therefore $0 \leq \langle f, D\pi f \rangle_{L_2(X)}$ for $f \in L_2(X_+)$, as claimed. $\Box$

Let $e_j$ denote a unit vector in the $j$th coordinate direction. Define $T_j$ as the unitary translation operator on spacetime that translates by one period $\ell_j$ in the coordinate direction $j$, namely

$$(T_j f)(x) = f(x - \ell_j e_j),$$

with $T_j : L_2(X_+) \to L_2(X_+)$. In addition,

$$\left( \pi_j T_j^{-1/2} f \right)(x) = \left( T_j^{-1/2} f \right)(\pi_j x) = f(\pi_j x + \frac{1}{2} \ell_j e_j).$$

Now assume that $D(x - x')$ decreases sufficiently rapidly so that the sum

$$D^{cj}(x, x') = \sum_{n=\infty}^{\infty} \left( T_j^{-n} D \right)(x - x') = \sum_{n=-\infty}^{\infty} D(x - x' + n \ell_j e_j)$$

(51)

converges absolutely. Then (51) defines the operator $D^{cj}$ on the space $X^{cj}$.

Proposition 15 (Compactification of Reflection Positivity). Let $D$ be translation-invariant and symmetric on $L_2(X)$ and let $D$ be doubly-reflection-positive with respect to $\pi_j$. Define $D^{ci}$ by the integral kernel (51). Then $D^{ci}$ is doubly-reflection-positive with respect to $\pi_j$.

Remark. If $i = j$, the proposition states that reflection positivity for a coordinate $x_j \in \mathbb{R}$ extends to the case of a compactified coordinate $x_j \in S^1$. However, for $i \neq j$ the proposition says that reflection positivity in the $j$th-direction remains unaffected by the compactification of spacetime along a different coordinate direction $x_i$. 
Proof. The Case $i = j$. We first show that $0 \leq \langle f, \pi_j D^{cj} f \rangle_{L_2(X^{cj})}$ for all $f \in L_2(X^{cj})$. Here, $f$ depends on the coordinate $x_j \in [-\frac{1}{2} \ell_j, \frac{1}{2} \ell_j]$ and is supported in the positive half interval. Imbed $L_2(X^{cj})$ in $L_2(X)$ in the natural way, so that translations $T_j$ on $L_2(X)$ translate the support of $f$ by $\ell_j e_j$. Then

$$\langle f, \pi_j D^{cj} f \rangle_{L_2(X^{cj})} = \left\langle f, \pi_j D^{cj} f \right\rangle_{L_2(X)} = \sum_{n=-\infty}^{\infty} \left\langle f, \pi_j T_j^{-n} Df \right\rangle_{L_2(X)}. \quad (52)$$

For the moment, let us suppress the variables $x_i$ for $i \neq j$. Thus, we write

$$\left\langle f, \pi_j T_j^{-n} Df \right\rangle_{L_2(X)} = \int_0^{1/2 \ell_j} \int_0^{1/2 \ell_j} \overline{f(x_j)} D(-x_j - x'_j + n \ell_j) f(x'_j) dx_j dx'_j \quad (53)$$

We now show that each term in the sum (52) is positive. These terms are of the form given in (53). In case $n \leq 0$, the operator $T_j^{-n/2}$ maps $L_2(X_{j+})$ into itself. Thus, reflection positivity of $\pi_j D$ ensures positivity, i.e.,

$$0 \leq \left\langle f, \pi_j T_j^{-n} Df \right\rangle_{L_2(X)} \quad \text{for} \quad n \leq 0. \quad (54)$$

On the other hand, if $n \geq 1$, then $T_j^{-n/2}$ maps $L_2(X_{j+})$ into $L_2(X_{j-})$. Hence, $\pi_j T_j^{-n/2}$ maps $L_2(X_{j+})$ into itself. Thus, for $f \in L_2(X_{j+})$,

$$\left\langle f, \pi_j T_j^{-n} Df \right\rangle_{L_2(X)} = \left\langle T_j^{-n/2} \pi_j f, DT_j^{-n/2} f \right\rangle_{L_2(X)} = \left\langle \pi_j T_j^{-n/2} f, (D\pi_j) \pi_j T_j^{-n/2} f \right\rangle_{L_2(X)}. \quad (55)$$

The positivity of $D\pi_j$ on $L_2(X_{j+})$ now ensures that

$$0 \leq \left\langle f, \pi_j T_j^{-n} Df \right\rangle_{L_2(X)} \quad \text{for} \quad 1 \leq n. \quad (56)$$

The relations (54) and (55) show that (52) is a sum of non-negative terms. Thus, $0 \leq \pi_j D^{cj}$ on $L_2(X^{cj})$, as claimed.

One can reduce the proof of positivity of $D^{cj} \pi_j$ on $L_2(X^{cj})$ to the previous case. In fact, one can replace $n$ by $-n$ in (51) and write

$$\left\langle f, D^{cj} \pi_j f \right\rangle_{L_2(X)} = \sum_{n=-\infty}^{\infty} \left\langle f, T_j^n D\pi_j f \right\rangle_{L_2(X)} = \sum_{n=-\infty}^{0} \left\langle T_j^{-n/2} f, (D\pi_j) T_j^{-n/2} f \right\rangle_{L_2(X)} + \sum_{n=1}^{\infty} \left\langle \pi_j T_j^{-n/2} f, (\pi_j D) \pi_j T_j^{-n/2} f \right\rangle_{L_2(X)}. \quad (57)$$
We have already shown that these matrix elements are positive. Thus, $0 \leq D^{c_i} \pi_j$ on $L_2(X_+^{c_j})$.

**The case** $i \neq j$. For $f \in L_2(X_+^{c_i})$ one has, for any $n' \in \mathbb{Z}$,

$$\left\langle f, \pi_j D^{c_i} f \right\rangle_{L_2(X^{c_j})} = \sum_{n=-\infty}^{\infty} \left\langle f, \pi_j T^{-n}_i f \right\rangle_{L_2(X^{c_i})} = \sum_{n=-\infty}^{\infty} \left\langle f, \pi_j T^{-n+n'}_i f \right\rangle_{L_2(X^{c_j})}.$$  

Using the fact that $T_i$ commutes with both $\pi_j$ and $D$, one arrives at

$$\left\langle f, \pi_j D^{c_i} f \right\rangle_{L_2(X^{c_j})} = \lim_{N \to \infty} \left\langle g_N, \pi_j D g_N \right\rangle_{L_2(X^{c_i})}, \quad (56)$$

where

$$g_N = \frac{1}{\sqrt{2N+1}} \sum_{n=-N}^{N} T^{-n}_i f \in L_2(X_+). \quad (57)$$

Observe that the translations $T_i$ act in the $i$th-coordinate direction, orthogonal to the $j$th-coordinate direction, so they map $L_2(X_+)$ into itself. As $\pi_j D$ is positive on $L_2(X_+)$, one concludes that

$$0 \leq \left\langle g_N, \pi_j D g_N \right\rangle_{L_2(X_+)} \Rightarrow \left\langle f, \pi_j D^{c_i} f \right\rangle_{L_2(X^{c_j})}.$$  

Thus, $0 \leq \pi_j D^{c_i}$ on $L_2(X_+)$, as claimed. The argument to show that $0 \leq D^{c_i} \pi_j$ on $L_2(X_+)$ is similar, so we omit the details.  

**7. Summary of Positivity Conditions**

We now summarize the various positivity conditions that we have discussed in this paper in the case $X = \mathbb{R}^d$. We state the conditions the characteristic function $S(f)$ of the field is subject to, and—for the Gaussian case—the conditions the covariance of the characteristic function has to obey.

**7.1. Neutral fields.** We use the unitary time-reflection operator $\vartheta$, the unitary reflection $\pi_n$ in the plane orthogonal to $n$, and in the Gaussian case the covariance $D$.

**Measure positivity.** The condition

$$0 \leq \sum_{j,j'=1}^{N} \overline{c_j} c_{j'} S(f_{j'} - f_j), \quad (58)$$

leads to the existence of a positive measure as the Fourier transform of $S(f)$. In the Gaussian case $S(f) = e^{-\frac{1}{2} \langle f, D f \rangle_{L_2}}$, and condition (58) is equivalent to

$$0 \leq D \text{ on } L_2(\mathbb{R}^d). \quad (59)$$
Time-reflection positivity. The condition of time-reflection positivity is

\[ 0 \leq \sum_{j,j'=1}^{N} \bar{c}_j c_{j'} S(f_{j'} - \vartheta f_j) \quad \text{for } f_j \in L_2(\mathbb{R}^d). \tag{60} \]

In the Gaussian case this is equivalent to

\[ 0 \leq \vartheta D \quad \text{on } L_2(\mathbb{R}^d). \tag{61} \]

Alternative time-reflection positivity. The alternative condition of time-reflection positivity is

\[ 0 \leq \sum_{j,j'=1}^{N} \bar{c}_j c_{j'} S(f_{j'} - \vartheta f_j) \quad \text{for } f_j \in L_2(\mathbb{R}^d^+). \tag{62} \]

In the Gaussian case this is equivalent to

\[ 0 \leq D \vartheta \quad \text{on } L_2(\mathbb{R}^d^+). \tag{63} \]

Spatial-reflection positivity. The condition for spatial-reflection positivity is

\[ 0 \leq \sum_{j,j'=1}^{N} \bar{c}_j c_{j'} S(f_{j'} - \pi_n f_j) \quad \text{for } f_j \in L_2(\mathbb{R}^d^+_n). \tag{64} \]

In the Gaussian case this is equivalent to

\[ 0 \leq \pi_n D \quad \text{on } L_2(\mathbb{R}^d^+_n). \tag{65} \]

Alternative spatial-reflection positivity. The alternative condition for spatial-reflection positivity is

\[ 0 \leq \sum_{j,j'=1}^{N} \bar{c}_j c_{j'} S(f_{j'} - \pi_n f_j) \quad \text{for } f_j \in L_2(\mathbb{R}^d^-_n). \tag{66} \]

In the Gaussian case this is equivalent to

\[ 0 \leq D \pi_n \quad \text{on } L_2(\mathbb{R}^d^-_n). \tag{67} \]

7.2. Charged fields. In the case of the charged field we use the charge conjugation operator \( \mathcal{C} \), the unitary time-reflection operator \( \vartheta \), and the unitary reflection \( \pi_n \) in the plane orthogonal to \( n \). In the Gaussian case we also use the matrix covariance \( D \).

Measure positivity. The positivity condition

\[ 0 \leq \sum_{j,j'=1}^{N} \bar{c}_j c_{j'} S(f_{j'} - \mathcal{C} f_j), \tag{68} \]

leads to the existence of a positive measure as the Fourier transform of \( S(f) \). In the Gaussian case this positivity is equivalent to

\[ 0 \leq \mathcal{C} D \quad \text{on } L_2. \tag{69} \]
**Time-reflection positivity.** The condition of time-reflection positivity is

\[ 0 \leq \sum_{j,j'}^{N} \overline{c_j} c_{j'} S(f_{j'} - \vartheta \overline{C f_j}) \quad \text{for} \quad f_j \in L_{2+}. \tag{70} \]

In the Gaussian case this is equivalent to

\[ 0 \leq \vartheta C D \quad \text{on} \quad L_{2+}. \tag{71} \]

**Alternative time-reflection positivity.** The alternative condition of time-reflection positivity is

\[ 0 \leq \sum_{j,j'}^{N} \overline{c_j} c_{j'} S(f_{j'} - C \vartheta f_j) \quad \text{for} \quad f_j \in L_{2-}. \tag{72} \]

In the Gaussian case the alternative condition is equivalent to

\[ 0 \leq D \vartheta C \quad \text{on} \quad L_{2+}. \tag{73} \]

**Spatial-reflection positivity.** The condition for spatial-reflection positivity is

\[ 0 \leq \sum_{j,j'}^{N} \overline{c_j} c_{j'} S(f_{j'} - \pi_n C f_j) \quad \text{for} \quad f_j \in L_{2,n+}. \tag{74} \]

Here, \( L_{2,n+} = L_2(\mathbb{R}^d_{n+}) \oplus L_2(\mathbb{R}^d_{n-}) \) and \( L_{2,n-} = \pi_n L_{2,n+} \). In the Gaussian case (74) is equivalent to

\[ 0 \leq \pi_n C D \quad \text{on} \quad L_{2,n+}. \tag{75} \]

**Alternative spatial-reflection positivity.** The alternative condition for spatial-reflection positivity is

\[ 0 \leq \sum_{j,j'}^{N} \overline{c_j} c_{j'} S(f_{j'} - \pi_n C f_j) \quad \text{for} \quad f_j \in L_{2,n-}. \tag{76} \]

In the Gaussian case this is equivalent to

\[ 0 \leq C D \pi_n \quad \text{on} \quad L_{2,n+}. \tag{77} \]

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