Schwinger model in the light-cone gauge

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The Schwinger model, defined in the space interval $-L \leq x \leq L$, with (anti)periodic boundary conditions, is canonically quantized in the light-cone gauge $A_\perp = 0$ by means of equal-time (anti)commutation relations. The transformation diagonalizing the complete Hamiltonian is explicitly constructed, thereby giving spectrum, chiral anomaly, and condensate. The structures of Hilbert spaces related both to free and to interacting Hamiltonians are completely exhibited. Besides the usual massive field, two chiral massless fields are present, which can be consistently expunged from the physical space by means of a subsidiary condition of a Gupta-Bleuler type. The chiral condensate does provide the correct nonvanishing value in the decompactification limit $L \to \infty$.

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I. INTRODUCTION

The Schwinger model [1] is a celebrated theoretical laboratory, possessing many nontrivial properties [2]. The literature is so copious that we refrain from providing further references.

The reduction to two dimensions entails tremendous simplifications in quantum electrodynamics and, as a consequence, the Schwinger model turns out to be the only local gauge theory with non-trivial coupling, where exact operational solutions can be found. In addition, it is believed that some interesting features that this model exhibits persist in more realistic field theories.

As an example, all the problems related to the spontaneous breakdown of the chiral symmetry, and the corresponding chiral anomaly, are very similar to the ones in four-dimensional QCD (QCD$_4$), with the obvious advantage that, in this simplified two-dimensional world, these phenomena appear in a much more transparent way. Moreover, the infinite degeneracy of the vacuum state due to chiral symmetry is analogous to that found in QCD$_4$ so that one is naturally led to introduce $\theta$-vacua.

Nevertheless, it should be emphasized that, although similar, the intimate reasons of the appearance of these phenomena are deeply different in the two theories. It is common belief that the infrared behavior of QCD$_4$ is at the root of the confining force between quarks and antiquarks. In the Schwinger model, such a confining force is a “free bonus” of the theory: electrodynamics naturally confines in 1+1 dimensions, due to the linear rise of the Coulomb potential. Consequently, the Schwinger model is a formidable laboratory to study the effects of confinement, but certainly not the causes.

The aim of this paper is to develop a rigorous operatorial treatment of the Schwinger model, when considered in the space interval $-L \leq x \leq L$, with periodic boundary conditions for the vector field and antiperiodic ones for fermions. The compactification of the spatial dimension will naturally provide an infrared regulator of the theory, without spoiling gauge invariance.

We choose to quantize the model in the “strong” light-cone gauge (LCG) $A_\perp = 0$, by imposing an equal-time canonical algebra [3,4]. There are several reasons that make the LCG particularly interesting. First of all, contrary to a common prejudice, this gauge is not manifestly unitary when the theory is quantized on spacelike surfaces. In addition, the direction in which the theory is compactified has to be carefully chosen. We recall indeed that axial gauges cannot be defined on compact manifolds (i.e., compactifying both space and time) without introducing singularities in the vector potentials, due to Singer’s theorem; nevertheless, partial compactifications are possible, provided they occur in a direction different from the one specifying the gauge choice: in the present case, to compactify the range of $x^+$ would be inconsistent. On the other hand, equal-time quantization suggests to regularize the theory with respect to infrared singularities by compactifying the space direction.

In the Schwinger model, a manifestly unitary formulation can instead be obtained in the Coulomb gauge. Thus, as far as the content of physical degrees of freedom is concerned, LCG can be seen as an intermediate choice between Coulomb and Lorentz gauges, but with the great advance that the Faddeev-Popov sector decouples in the non-Abelian gener-
alization of the model, making the transition to the non-Abelian case smoother.

When the theory in LCG is quantized by equal-time commutation relations, Gauss’ law does not hold strongly; rather, the Gauss operator obeys a free-field equation and entails the presence in the Fock space of unphysical degrees of freedom. The vanishing of Gauss’ operator has to be imposed weakly, by a mechanism that is reminiscent of the Gupta-Bleuler quantization scheme for electrodynamics in Feynman gauge, but with the great advantage that it can be naturally extended to the non-Abelian case.

In the present case, thanks to compactification of the spatial dimension, we have an even richer structure of the Hilbert space, as topological excitations (zero modes) come into the game.

The plan of the paper is as follows.

In Sec. II we review the canonical quantization in LCG; we define the space of states for the free theory as the direct product of a Fock space $\mathcal{F}_A$ containing the frequency modes, obtained through repeated action of creation operators on a Fock vacuum, times a ’’quantum-mechanical’’ $L^2$ space of the zero-mode sector. Then we introduce the interaction, namely we consider the Schwinger model in LCG and provide the relevant equal-time commutation relations.

Section III is devoted to quantization at $t = 0$; products of quantum operators are defined and regularized by means of gauge-invariant point splitting techniques. In particular, the expressions for the currents and for the kinetic terms occurring in the Hamiltonian are carefully discussed.

Section IV deals with the diagonalization of the complete Hamiltonian. The unitary transformation, which diagonalizes the Hamiltonian, relating free and interacting fields, is explicitly exhibited. This is made possible by the partially compact nature of the manifold (cylinder). The free-fields sector contains, besides the ’’physical’’ massive scalar field with mass $\sqrt{\frac{\alpha}{4\pi}}$, two additional ’’unphysical’’ chiral massless fields, with the same chirality, but opposite signs in the commutators. Consequently, the Fock space will have an indefinite metric.

In Sec. V we discuss the temporal evolution of the fields. All the operatorial solutions are explicitly exhibited and we check that they satisfy the correct Euler-Lagrange equations of motion. In the same section, it is also shown that Gauss’ law is implemented by defining a physical Hilbert space in which the total charge vanishes and by selecting a suitable zero-norm combination of ghostlike and ’’longitudinal’’ degrees of freedom, in the same way as the Gupta-Bleuler formalism in the Feynman gauge.

The structure of the ’’physical’’ Hilbert space is discussed in Sec. VI. We show that the same unitary operator diagonalizing the Hamiltonian performs the mapping between free and interacting Fock spaces. A set of degenerate vacua is obtained, all of them being related by a residual gauge transformation. Then, the requirement of gauge invariance naturally leads to the definition of $\theta$-vacua. Moreover a positive definite inner product is derived, and it is shown that the specific ghost-particle combinations forced by the (weakly) vanishing of Gauss’ operator always have vanishing norm.

The physical Hilbert space is eventually defined as a quotient space. Finally, chiral anomaly and chiral condensate are discussed. As a final check it is shown that the chiral condensate reproduces the correct nonvanishing result of the continuum in the decompactification limit $L \rightarrow \infty$.

II. THE SCHWINGER MODEL

A. The free-fermion model

We start by recalling the treatment of free massless fermions in the space interval $[-L, L]$. We assume antiperiodic boundary conditions $\psi(t, -L) = -\psi(t, L)$. The classical Lagrangian is given by

$$\mathcal{L} = i \overline{\psi}(x) \partial_\mu \gamma^\mu \psi(x).$$

Here $\psi$ is a two-component field:

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}.$$

$\gamma^0$ and $\gamma^1$ are $2 \times 2$ matrices such that the algebra

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}$$

is fulfilled.

The action is invariant under global phase and chiral transformations leading to the well-known classical expression for the conserved vector and axial vector currents.

When performing the canonical quantization the classical variable $\psi_a(x)$ and its conjugate momentum

$$\pi_a(x) = \frac{\partial \mathcal{L}}{\partial (\partial_0 \psi_a(x))} = i \psi^+_a(x)$$

become operators, obeying the canonical anticommutation relations

$$\{\psi_a(t, x), \psi^+_B(t, y)\} = \delta_{aB} \delta(x-y), \quad \alpha, \beta = 1, 2,$n

$$\{\psi_a(t, x), \psi_B(t, y)\} = \{\psi^+_a(t, x), \psi^+_B(t, y)\} = 0,$$

where $\delta(x-y)$ denotes the periodic $\delta$-distribution.

Using the explicit representation for the gamma matrices $\gamma^\mu$, $\mu = 0, 1$:

$$\gamma^0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \gamma^1 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix},$$

we get the equations of motion

$$\partial_- \psi_1(x) = 0, \quad \partial_+ \psi_2(x) = 0,$$

where

$$x^-=\frac{t-x}{\sqrt{2}}, \quad x^+=\frac{t+x}{\sqrt{2}}, \quad \partial_- = \frac{\partial}{\partial x^-} = \frac{\partial_0 - \partial_1}{\sqrt{2}}, \quad \partial_+ = \frac{\partial}{\partial x^+} = \frac{\partial_0 + \partial_1}{\sqrt{2}}.$$

The most general solution fulfilling the condition

$$\psi(t, x) = -\psi(t, x + 2L)$$

(2)
is
\[ \psi_1(t,x) = \frac{1}{\sqrt{2L}} \sum_{n=0}^{\infty} \left( b_n e^{-i(n+1/2)(\pi L)(t+x)} + d_n^+ e^{i(n+1/2)(\pi L)(t+x)} \right), \]
\[ \psi_2(t,x) = \frac{1}{\sqrt{2L}} \sum_{n=-\infty}^{-1} \left( b_n e^{i(n+1/2)(\pi L)(t-x)} + d_n^+ e^{-i(n+1/2)(\pi L)(t-x)} \right). \]
(“left” and “right” movers).

The classical energy-momentum tensor
\[ \Theta^{\mu\nu} = \frac{\partial L}{\partial \left( \partial_\mu \psi_\alpha \right)} \partial_\nu \psi_\alpha - L g^{\mu\nu} \]
leads to the corresponding conserved quantities
\[ P^0 = H = \int_{-L}^{L} dx \Theta^{00}(x); \quad P^1 = \int_{-L}^{L} dx \Theta^{01}(x). \]

We get a quantum description by defining the products as normal-ordered and introducing creation and annihilation operators:
\[ H = -\int_{-L}^{L} dx :i \bar{\psi}(x) \gamma^1 \partial_1 \psi(x): \]
\[ = \sum_{n=-\infty}^{\infty} k_0[n+1/2] \left( b_n^+ b_n + d_n^+ d_n \right), \]
\[ P_1 = \int_{-L}^{L} dx :i \bar{\psi}^+(x) \partial_1 \psi(x): \]
\[ = \sum_{n=-\infty}^{\infty} k_1[n+1/2] \left( b_n^+ b_n + d_n^+ d_n \right), \]
where
\[ k_0[n+1/2] = \left| n + \frac{1}{2} \right| \frac{\pi}{L}, \quad k_1[n+1/2] = \left( n + \frac{1}{2} \right) \frac{\pi}{L}. \]
Electric charge \( Q \) and chiral charge \( Q_5 \) are given by the following operators:
\[ Q = e \int_{-L}^{L} dx: \psi^+(x) \psi(x):, \]
\[ Q_5 = -e \int_{-L}^{L} dx: \psi^+(x) \gamma^5 \psi(x):. \]

With \( \gamma^5 = \gamma^0 \gamma^1 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \), \( Q \) and \( Q_5 \) become
\[ Q = e \sum_{n=-\infty}^{\infty} (b_n^+ b_n - d_n^+ d_n), \]
\[ Q_5 = e \sum_{n=0}^{\infty} (b_n^+ b_n - d_n^+ d_n) - e \sum_{n=-\infty}^{-1} (b_n^+ b_n - d_n^+ d_n). \]

We are now ready to introduce the bosonization. From the fermionic currents
\[ j^- = \frac{j^0 - j^1}{\sqrt{2}} = e \sqrt{2} \psi^1 \psi_1^1, \]
\[ j^+ = \frac{j^0 + j^1}{\sqrt{2}} = e \sqrt{2} \psi^2 \psi_2^1, \]
we get
\[ j^- = \frac{e}{\sqrt{2L}} \sum_{p=1}^{\infty} \left( C_p e^{-i(\pi L)p(t+x)} + C_p^+ e^{i(\pi L)p(t+x)} \right) \]
\[ + \frac{e}{\sqrt{2L}} \sum_{n=0}^{\infty} \left( b_n^+ b_n - d_n^+ d_n \right), \]
\[ j^+ = \frac{e}{\sqrt{2L}} \sum_{n=-\infty}^{-1} \left( C_p e^{i(\pi L)p(t-x)} + C_p^+ e^{-i(\pi L)p(t-x)} \right) \]
\[ + \frac{e}{\sqrt{2L}} \sum_{n=-\infty}^{-1} \left( b_n^+ b_n - d_n^+ d_n \right), \]
where
\[ C_n = \sum_{m=0}^{n-1} d_m b_{n-m-1} \]
\[ + \sum_{m=0}^{\infty} (b_m^+ b_{m+n} - d_m^+ d_{m+n}), \]
for \( n > 0 \),
\[ C_n = \sum_{m=-n}^{-1} d_m b_{n-m-1} \]
\[ + \sum_{m=-\infty}^{-1} (b_m^+ b_{m+n} - d_m^+ d_{m+n}), \]
for \( n < 0 \).

One can easily verify that the fusion operators \( C_n \) obey the following bosonic commutation rules.
\[ [C_n, C_m^+] = |n| \delta_{m,n}, \]
\[ [C_n, C_m] = [C_n^+, C_m^+] = 0. \]

We notice that the operators \( Q, Q_5, C_n \), act on the fermionic Fock space \( \mathcal{F} \) obtained starting from a vacuum state \( |0\rangle \) annihilated by the operators \( b_n \) and \( d_n \), and that
\[ [C_n, Q] = [C_n, Q_5] = [Q, Q_5] = 0. \]

Let us now consider a peculiar set of states \( |M,N\rangle \). The state \( |M,N\rangle \) represents \( M \) particles \((M<0)\) or antiparticles \((M>0)\) of the left type in the lowest \( M \) energetic levels and \( N \) particles \((N<0)\) or antiparticles \((N>0)\) of the right type in the lowest \( N \) levels; namely
\[
|M,N\rangle = b_{M-1}^+ \cdots b_0^+ b_{-N}^+ \cdots b_{-1}^+ |0\rangle, \quad \text{for } M<0, \ N<0, \\
|M,N\rangle = d_{M-1}^+ \cdots d_0^+ d_{-N}^+ \cdots d_{-1}^+ |0\rangle, \quad \text{for } M>0, \ N>0, \\
|M,N\rangle = d_{M-1}^+ \cdots d_0^+ b_{-N}^+ \cdots b_{-1}^+ |0\rangle, \quad \text{for } M>0, \ N<0, \\
|M,N\rangle = b_{M-1}^+ \cdots b_0^+ d_{-N}^+ \cdots d_{-1}^+ |0\rangle, \quad \text{for } M<0, \ N>0.
\]

Since
\[
Q |M,N\rangle = - e(M + N) |M,N\rangle, \\
Q_5 |M,N\rangle = - e(M - N) |M,N\rangle,
\]
any given state \( |M,N\rangle \) can be identified by means of the eigenvalues of \( Q \) and \( Q_5 \).

It can be verified that for any state \( |M,N\rangle \)
\[ C_n |M,N\rangle = 0. \]

Moreover, as the operators \( C_n^+ \) commute with the charges, the eigenvalues of \( Q \) and \( Q_5 \) are not modified by applying \( C_n^+ \) on the states \( |M,N\rangle \).

In Ref. [6] it has been shown that the fermionic Fock space \( \mathcal{F} \) can be decomposed as an infinite direct sum of irreducible Fock representations of the algebra (15), which coincide with the eigenspaces of \( Q \) and \( Q_5 \).

The Hamiltonian and the momentum [Eqs. (7) and (8)] can be expressed in terms of the charges and of the fusion operators through
\[
H = \frac{\pi}{4L^2} (Q^2 + Q_5^2) + \frac{\pi}{L_{\pi} \sigma_2} C_n^+ C_n, \\
P_1 = \frac{\pi}{2L^2} Q Q_5 + \frac{\pi}{L_{\pi} \sigma_2} \sum e(n) \ C_n^+ C_n.
\]

In order to express the fermionic operators in terms of the fusion operators, it is useful to introduce the quantities
\[
\varphi_1^{(+)}(t,x) = - \sum_{n=1}^{+\infty} \frac{1}{n} C_n e^{-i(n/L)(x + t)}, \\
\varphi_1^{(-)}(t,x) = \sum_{n=1}^{+\infty} \frac{1}{n} C_n^* e^{-i(n/L)(x + t)}, \\
\varphi_2^{(+)}(t,x) = \sum_{n=-\infty}^{-1} \frac{1}{n} C_n e^{i(n/L)(t - x)}, \\
\varphi_2^{(-)}(t,x) = - \sum_{n=-\infty}^{-1} \frac{1}{n} C_n^* e^{-i(n/L)(t - x)}.
\]

Then we can define the operators
\[
\sigma_a(t,x) = \sqrt{2L} e^{tQ_5} \psi_a(t,x) e^{-tQ_5},
\]
which carry the fermionic charge. One can easily derive the relations [5]
\[
\sigma_a(t,x)\sigma_a(t,x) = \sigma_a(t,x)\sigma_a(t,x) = 1, \\
\{\sigma_1(t,x), \sigma_2(t,y)\} = \{\sigma_1(t,x), \sigma_2(t,y)\} = 0, \\
[Q, \sigma_a(t,x)] = - e\sigma_a(t,x), \\
[Q_5, \sigma_a(t,x)] = (-1)^a e\sigma_a(t,x), \\
[C_n, \sigma_a(t,x)] = [C_n^+, \sigma_a(t,x)] = 0.
\]

The quantities \( \sigma_a(0,0) \) are usually called spurious. Using Eqs. (20), (21), (26), and (27), it can be shown that
\[
\sigma_a(t,x) = e^{\Lambda_a(t,x)} \sigma_a e^{-\Lambda_a(t,x)},
\]
where
\[
\Lambda_a(t,x) = - \frac{i\pi}{4Le} [Q - (-1)^a Q_5][t - (-1)^a x].
\]

The following relation can be verified:
\[
|\mathcal{M}, \mathcal{N}\rangle = \sigma_1^M \sigma_2^N |0\rangle,
\]
where \( \sigma_2^{-1} = \sigma_2^+ \). It is useful to rescale the fusion operators
\[
C_n = i\sqrt{|n|} \gamma_n, \quad C_n^+ = - i\sqrt{|n|} \gamma_n^+, \quad \text{so that}
\]
\[
[\gamma_n, \gamma_m] = \delta_{m,n}, \quad [\gamma_n, \gamma_m] = [\gamma_n^+, \gamma_m^+] = 0.
\]

Defining the bosonic field
\[
\varphi(x) = \frac{i}{2\sqrt{\pi}} (\varphi_1^{(+)} + \varphi_1^{(-)} - \varphi_2^{(+)} - \varphi_2^{(-)}) \\
= - \frac{1}{\sqrt{2L_{\pi} \sigma_2}} \sum_{n=0}^{-1} \frac{1}{\sqrt{2k_0}} (\gamma_n e^{-ikx} + \gamma_n^+ e^{ikx}),
\]
the fermionic currents can be rewritten as
\[ j^- = \frac{Q + Q_5}{2\sqrt{2}L} - \frac{e}{\sqrt{\pi}} \partial_+ \varphi, \quad (32) \]

\[ j^+ = \frac{Q - Q_5}{2\sqrt{2}L} - \frac{e}{\sqrt{\pi}} \partial_- \varphi, \quad (33) \]

where \( \varphi \) is a "quasiscalar" field, as it has no zero mode.

**B. The free Maxwell field at \( t=0 \)**

As we are considering the theory on the cylinder, we can assume that the algebra of interacting fields at a given time \( t=0 \) is isomorphic to the free-fields algebra.\(^1\)

The free Maxwell field is described by the Lagrangian

\[ \mathcal{L} = -\frac{1}{4} F_{\mu
u} F^{\mu\nu}. \quad (34) \]

In order to quantize it we have to choose a gauge; we choose the light-cone gauge by adding to the classical Lagrangian the following "gauge-fixing" term

\[ \mathcal{L}_{gf} = \lambda^{(0)} n_\mu A^\mu, \]

where \( n_\mu = (1/\sqrt{2})(1,1) \) and \( \lambda^{(0)} \) is a Lagrange multiplier enforcing the gauge condition \( n_\mu A^\mu = 0 \).

We define

\[ A = A_+ = \frac{A_0 + A_1}{\sqrt{2}}, \quad F = F_{01}. \]

The Euler–Lagrange equations are

\[ \partial_\mu F^{\mu\nu} + n^\nu \lambda^{(0)} = 0, \quad (35) \]

which, in turn, imply

\[ \partial_- \lambda^{(0)} = 0. \quad (36) \]

Following the standard Dirac procedure, we can derive the following independent equal-time commutation relation:

\[ [A(t,x), F(t,y)] = i \sqrt{2} \delta(x-y). \quad (37) \]

At variance with the Coulomb gauge choice, equal-time quantization in the light-cone gauge entails the presence of unphysical degrees of freedom \([4]\). Strictly speaking, in order to recover Maxwell’s equations, one should impose the condition \( \lambda^{(0)} = 0 \). However, as \( \lambda^{(0)} \) does not commute with \( A \), to impose \( \lambda^{(0)} = 0 \) in an operatorial sense would be inconsistent with quantization. In analogy with the Gupta-Bleuler formalism, this condition will be imposed weakly.

We start considering the quantization of the bosonic field at \( t=0 \).

The Fourier expansion of \( A(0,x) \) and \( F(0,x) \) is

\[ A(0,x) = \sqrt{2} A_1(0,x) = \frac{1}{\sqrt{L}} \sum_{n \neq 0} a_n e^{i n (\pi/L) x} + \frac{a_0}{\sqrt{L}}, \quad (38) \]

\[ F(0,x) = \frac{1}{\sqrt{2L}} \sum_{n \neq 0} b_n e^{i n (\pi/L) x} + \frac{b_0}{\sqrt{2L}}, \quad (39) \]

\[ a_+^* = a_-, \quad b_+^* = b_- . \]

From the canonical commutation relations of \( A \) and \( F \) it follows that

\[ [a_n, b_m] = i \delta_{n,m}, \quad (40) \]

\[ [a_0, b_0] = i, \quad (41) \]

all other commutators vanishing.

As far as zero modes are concerned, we represent Eq. (41) in a \( L^2 \)-space by means of the relations

\[ a_0 \psi(a_0) = a_0 \psi(a_0), \quad b_0 \psi(a_0) = -i \frac{d}{da_0} \psi(a_0), \quad \psi \in \mathcal{L}^2. \]

For the frequency modes we shall consider a Fock space \( \mathcal{F}_A \) representation in terms of suitable creation and annihilation operators. The free bosonic Hamiltonian is

\[ H(0) = \int_{-L}^L dx \left( \frac{1}{2} F^2(0,x) - \frac{A(0,x)}{\sqrt{2}} \partial_1 F(0,x) \right). \]

The operator ordering in this equation is irrelevant in obtaining the commutators that follow. From Eqs. (38) and (39) we get

\[ H^r(0) = \frac{1}{2} \sum_{n \neq 0} b_n b_+ - \frac{i}{2} \sum_{n \neq 0} k_1 a_- b_+ + \frac{1}{2} b_0^2 \]

and thereby

\[ [H(0), b_n] = k_0 b_n, \quad \text{for } n > 0, \]

\[ [H(0), b_n] = -k_0 b_n, \quad \text{for } n < 0, \]

which suggest an interpretation of \( b_n \) as an annihilation operator for \( n < 0 \) and as a creation operator for \( n > 0 \). The commutators for \( a_n \) follow from analogous considerations. \( \mathcal{F}_A \) is now constructed by means of the following creation and annihilation operators:

\[ A_n = a_n \sqrt{k_0/2} + i \frac{b_n}{\sqrt{2k_0}}, \quad A_n^+ = a_n \sqrt{k_0/2} - i \frac{b_n}{\sqrt{2k_0}}, \quad \text{for } n < 0, \quad (42) \]

\[ A_n = a_- \sqrt{k_0/2} - i \frac{b_-}{\sqrt{2k_0}}, \quad A_n^+ = a_+ \sqrt{k_0/2} + i \frac{b_+}{\sqrt{2k_0}}, \quad \text{for } n > 0. \quad (43) \]

From Eq. (40) it follows that

\[ 1\]We recall that this assumption would not be allowed in the continuum, owing to Haag’s theorem.
all other commutators vanishing.

We notice that, since \( A_n \) is an annihilation operator and \( A_n^\dagger \) is a creation one, the negative sign in Eq. (45) entails the presence of negative norm states in the Fock space \( \mathcal{F}_A \). On the other hand, we know that redundant degrees of freedom are present, as we have to impose the vanishing of \( \lambda^{(0)} \), the superscript \( (0) \) denoting free fields. As a consequence we have to consistently define a physical Hilbert space. Let us consider the time evolution of the Gauss operator

\[
\lambda^{(0)}(t,x) = -\sqrt{2} \delta_i \partial_i F^{(0)}(t,x) = -\sqrt{2} e^{-iH\phi^i} \partial_i F(0,x)e^{iH\phi^i}.
\]

We get

\[
\lambda^{(0)}(t,x) = \frac{1}{\sqrt{2L}} \left\{ \sum_{n=-\infty}^{-1} k_0 \sqrt{k_0} (A_n - A_{-n}) e^{-ik_0(t+x)} \\
- \sum_{n=1}^{+\infty} k_0 \sqrt{k_0} (A_n^\dagger - A_{-n}^\dagger) e^{ik_0(t+x)} \right\}.
\]

The physical states are defined by

\[
\lambda^{(0)}(+,1)_{\text{phys}} = 0,
\]

namely

\[
(A_n - A_{-n})_{\text{phys}} = 0, \quad \forall n < 0,
\]

which is reminiscent of the Gupta-Bleuler condition in the Feynman gauge.

In the vector space of linear combinations of products of creation operators acting on the vacuum, we introduce a positive-definite inner product \( \langle \cdot, \cdot \rangle \) such that \( [A_n, A_m^\dagger] = \delta_{nm}, \) where \( A_n^\dagger \) is the adjoint of \( A_n \) with respect to the inner product \( \langle \cdot, \cdot \rangle \). A Fock space can be constructed by a Cauchy completion with respect to this inner product, which is related to the product \( \langle \cdot, \cdot \rangle \) compatible with Eq. (45), by

\[
\langle \cdot, \cdot \rangle = \langle \cdot, \eta \cdot \rangle,
\]

where

\[
\eta = (-1)^N, \quad N = - \sum_{n<0} A_n^\dagger A_{-n}.
\]

In turn the inner product \( \langle \cdot, \cdot \rangle \) in the physical subspace defined by Eq. (46) turns out to be semi-positive-definite. The physical Hilbert space is eventually obtained as the quotient space.

**C. The Schwinger model in the light-cone gauge**

The Schwinger model is defined by the following Lagrangian:

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{i}{2} (\bar{\psi} \gamma^\mu \partial_\mu \psi - \partial_\mu \bar{\psi} \gamma^\mu \psi) - j_\mu A_\mu.
\]

In order to quantize it we have to choose a gauge; we choose the light-cone gauge by adding to the classical Lagrangian the following "gauge-fixing" term

\[
\mathcal{L}_{gf} = \lambda n_\mu A^\mu,
\]

where \( n_\mu = (1/\sqrt{2})(1,1) \) and \( \lambda \) is a Lagrange multiplier enforcing the gauge condition \( n_\mu A^\mu = 0 \).

The classical gauge-fixed Hamiltonian is

\[
H = \int_{-L}^{L} dx \left( \frac{1}{2} F^2(x) - \frac{A^2}{\sqrt{2}} + \frac{1}{2} \left( i \bar{\psi}(x) \gamma^1 \partial_1 \psi(x) \right) + A(x) j^z(x) \right),
\]

where, again,

\[
A = A_0 + A_1, \quad F = F_0.
\]

The Euler-Lagrange equations are

\[
\partial_\mu F^{\mu\nu} - j^\nu + n_\nu \lambda = 0,
\]

which, in turn, imply

\[
\partial_\cdot \lambda = 0.
\]

Following the standard Dirac procedure, one can derive the following independent equal-time (anti)commutation relations:

\[
[A(t,x), F(t,y)] = i \sqrt{2} \delta(x-y),
\]

\[
\{ \psi(t,x), \psi^+(t,y) \} = e^{i\pi/2} \delta(x-y),
\]

all other (anti)commutators vanishing.

Again, as \( \lambda \) does not commute with \( A \) and \( \psi \), the condition \( \lambda = 0 \) will be imposed weakly.

**III. REGULARIZATION OF COMPOSITE QUANTUM OPERATORS AT EQUAL TIME**

**A. Point splitting regularization**

Products of operators are plagued by ultraviolet singularities that need to be regularized. In the following we shall use the standard point splitting technique. To preserve gauge invariance, the following bosonic string

\[
e^{-i\int_{-}\int_{+} dy^t dx^t A_\mu(x,y)}
\]

will be inserted in the fermionic bilinears. The exponential involves products of operators at the same point, which in turn have to be suitably regularized. This problem will be carefully discussed when needed. For the time being, we formally define [7]
\[ j^\mu(x) = e \lim_{\epsilon \to 0} [ \bar{\psi}(x + \epsilon) \gamma^\mu e^{-ie j^\mu_{x+y} A_\nu(y)} \psi(x) + \bar{\psi}(x) \gamma^\mu e^{-ie j^\mu_{x+y} A_\nu(y)} \psi(x + \epsilon) ], \]
\[ e^2 < 0 \] (51)
and
\[ [i \bar{\psi}(x) \gamma^\mu \partial_\mu \psi(x) - i \partial_\mu \bar{\psi}(x) \gamma^\mu \psi(x),]_R = \lim_{\epsilon \to 0} (i \bar{\psi}(x + \epsilon) \gamma^\mu e^{-ie j^\mu_{x+y} A_\nu(y)} \partial_\mu \psi(x) - i \partial_\mu \bar{\psi}(x) \gamma^\mu e^{-ie j^\mu_{x+y} A_\nu(y)} \psi(x + \epsilon) \epsilon \epsilon = 0, \] (52)
where the vacuum considered here is the one of the fully interacting theory. The regularized quantum Dirac equation is
\[ i \gamma^\mu \partial_\mu \psi(x) - e \gamma^\mu [A_\mu(x) \psi(x)]_R = 0, \] (53)
where [2]
\[ [A_\mu(x) \psi(x)]_R = \frac{1}{2} \lim_{\epsilon \to 0} \{ A_\mu(x + \epsilon) \psi(x) + \psi(x) A_\mu(x - \epsilon) \}, \quad e^2 < 0. \]

**B. Regularized current**

We are now in the position of giving an explicit expression for the quantum fermionic currents. We recall the definition
\[ j^-(0,x) = \frac{1}{2} \lim_{\epsilon \to 0} [ \sqrt{2} e \bar{\psi}^-_1(0,x + \epsilon) e^{-ie j^\mu_{x+y} A_\nu(y)} \times \psi_1(0,x) + H.c.]. \]
As \( A_1 \) and \( \psi_1 \) commute at equal time, we can write
\[ j^-(0,x) = \frac{1}{2} \lim_{\epsilon \to 0} [ j^-(0,x; e) e^{-ie j^\mu_{x+y} A_\nu(y)} + H.c.], \]
where
\[ j^-(0,x; e) = e \sqrt{2} \bar{\psi}^-_1(0,x + \epsilon) \psi_1(0,x). \] (54)
Using
\[ \psi_1(0,x) = e^{-\phi^{-1}_1(0,x)} e^{A_1(0,x)} \sigma e^{A_1(0,x)} e^{-\phi^{-1}_1(0,x)} \]
and
\[ \Lambda_1(0,x) = \frac{i \pi}{4L} e^{Q + Q_x}, \]
it follows that
\[ [\phi^{-1}_1] = -\phi^{(+)}_1, \quad \Lambda_1 = -\Lambda_1, \]
and hence
\[ J^{(0)} = \frac{e}{\sqrt{2L}} \bar{\psi}^-(0,x + e) e^{-\Lambda_1(0,x + e)} \sigma \]
\[ \times e^{-\Lambda_1(0,x + e)} e^{\phi^{(+)}_1}(0,x + e) e^{\phi^{-1}_1}(0,x) e^{\Lambda_1(0,x)} \]
\[ \times \sigma e^{\Lambda_1(0,x)} e^{-\phi^{(+)}_1(0,x)}. \]
By recalling Eqs. (24)-(27) and the relation
\[ e^A B = B e^A e^c, \]
if \([A,B] = cB\), with \( c \) being a constant number, (55) we obtain
\[ J^{(0)} = \frac{e}{\sqrt{2L}} e^{-i(\pi/2L)e} e^{-2\Lambda_1(0,e)} e^{\phi^{-1}_1(0,x + e)} \]
\[ \times e^{\phi^{(+)}_1(0,x + e)} e^{-\phi^{-1}_1(0,x)} e^{\phi^{(+)}_1(0,x)}. \]
From the identity
\[ e^{A} e^{B} = e^{B} e^{A} e^{[A,B]}, \] if \([A,B] = c \) number, (56) we can write
\[ e^{\phi^{(+)}_1(0,x + e)} e^{-\phi^{-1}_1(0,x)} = e^{-\phi^{-1}_1(0,x)} e^{\phi^{(+)}_1(0,x + e)} \]
\[ \times e^{\phi^{(+)}_1(0,x + e) - \phi^{-1}_1(0,x)}. \]
Using the decomposition for the quasi-scalar field \( \phi \), we get
\[ [\phi^{(+)}_1(0,x + e), -\phi^{-1}_1(0,x)] \]
\[ = \sum_{n = 1}^{\infty} \frac{2}{n} e^{-in(\pi/2L)e} \]
\[ = -\ln(1 - e^{-in(\pi/2L)e}), \] (57)
and therefore
\[ J^{(0)} = \frac{e}{\sqrt{2L}} \frac{e^{-i(\pi/2L)e}}{1 - e^{-i(\pi/2L)e}} e^{-2\Lambda_1(0,e)} e^{\phi^{-1}_1(0,x + e)} \]
\[ \times e^{\phi^{(+)}_1(0,x + e) - \phi^{-1}_1(0,x)}. \] (58)
Neglecting terms that vanish in the limit \( e \to 0 \) we get
$$j_-(0,x;\varepsilon) = \frac{e}{i\pi e^{\sqrt{i}}} + \frac{Q + Q_5}{2\sqrt{2}L} + \frac{e}{i\pi e^{\sqrt{i}}} \times (\partial_1 \psi_1^{(-)}(0,x) + \partial_1 \psi_1^{(+)}(0,x)).$$

Moreover,

$$e^{-ie_{f_{a}} x \phi_i(0,y)dy} = 1 - ie\varepsilon A_1(0,x) + \ldots$$

and therefore

$$j_-(0,x;\varepsilon) e^{-ie_{f_{a}} x A_1(0,y)dy} = \frac{e}{i\pi e^{\sqrt{i}}} - \frac{e^2 A_1(0,x)}{2\sqrt{2}\pi} + \frac{Q + Q_5}{2\sqrt{2}L}$$

$$+ \frac{e}{i\pi e^{\sqrt{i}}} (\partial_1 \psi_1^{(0)}(0,x)$$

$$+ \partial_1 \psi_1^{(+)}(0,x)).$$

From the definition of $j_-(0,x)$ it follows that

$$j_-(0,x) = -\frac{e^2 A_1(0,x)}{2\sqrt{2}\pi} + \frac{Q + Q_5}{2\sqrt{2}L}$$

$$+ \frac{e}{\sqrt{2}L_{n-1}} (i\sqrt{\frac{n}{\pi L}} \psi_1^{e^{in(\pi/L)x}}$$

$$- i\sqrt{\frac{n}{\pi L}} \psi_1^{e^{in(\pi/L)x})}. \tag{59}$$

An analogous calculation gives, taking

$$[ \psi_1^{0,x} \psi_1^{(-)} + \psi_1^{(-)} \psi_1^{0,x} ]$$

$$= \sum_{\sigma=1}^{\infty} \frac{1}{n} e^{in(\pi/L)x}$$

$$= -\ln(1 - e^{i\pi/L})$$

into account,

$$j_+(0,x) = \lim_{\varepsilon \rightarrow 0} [\sqrt{2} e^{\psi_1^{0,x} + \psi_1^{0,x}} e^{-ie_{f_{a}} x A_1(0,y)dy}$$

$$\times \psi_2(0,x) + \text{H.c.}]$$

$$= \frac{e^2 A_1(0,x)}{2\sqrt{2}\pi} + \frac{Q + Q_5}{2\sqrt{2}L}$$

$$+ \frac{e}{\sqrt{2}L_{n-1}} (i\sqrt{\frac{n}{\pi L}} \psi_1^{e^{in(\pi/L)x}}$$

$$- i\sqrt{\frac{n}{\pi L}} \psi_1^{e^{in(\pi/L)x})}. \tag{60}$$

**C. Regularized kinetic term**

The fermionic kinetic term entering the quantum Hamiltonian is

$$H_\psi = -\frac{1}{2} \int_{-L}^{L} dx [i\bar{\psi}(0,x) \gamma^0 \partial_1 \psi(0,x)$$

$$- i\partial_1 \bar{\psi}(0,x) \gamma^0 \psi(0,x) \right]_{R}$$

$$= \lim_{\varepsilon \rightarrow 0} \left\{ \frac{1}{2} \int_{-L}^{L} dx [i\psi_1^{+}(0,x) \partial_1 \psi_1(0,x)$$

$$- i\psi_2^{+}(0,x) \partial_1 \psi_2(0,x) + \text{H.c.}]\right\}_{R}.$$
By expanding in Taylor series one finds

\[
\psi_1'(0,x+\epsilon)\partial_1\psi_1(0,x) = \frac{i}{4\pi} \partial_1\psi_1(0,x)^2 + \frac{i\pi}{16L^2\epsilon^2} \times (Q+Q_5)^2 - \frac{Q+Q_5}{4Le} \partial_1\psi_1(0,x)
\]

\[
- \frac{i}{4\pi} \partial_1^2\psi_1(0,x) + \frac{1}{2i\pi\epsilon^2} + \text{const.}
\]

(62)

An analogous calculation gives

\[
\psi_2'(0,x+\epsilon)\partial_1\psi_2(0,x) = -\frac{i}{4\pi} \partial_1\psi_2(0,x)^2 + \frac{i\pi}{16L^2\epsilon^2} (Q-Q_5)^2 - \frac{Q-Q_5}{4Le} \partial_1\psi_2(0,x)
\]

\[
+ \frac{i}{4\pi} \partial_1^2\psi_2(0,x) - \frac{1}{2i\pi\epsilon^2} + \text{const.}
\]

(63)

In the previous formulas, positive and negative energy components \(\phi_1^+(\cdot)\) and \(\phi_1^-(\cdot)\) refer to the free fermion theory.

In the light-cone gauge the left component of the fermionic field does not interact: in the full Hamiltonian \(\phi_1\) is decoupled. The coupling with the gauge field only affects \(\phi_2=\phi_2^+(\cdot)+\phi_2^-(\cdot)\): the two frequencies mix under time evolution. The vacuum involved in the VEV subtraction refers to the interacting theory.

If we define

\[
H_{\phi}^{(0)} = \frac{1}{2} \int_{-L}^{L} dx \left[ i\psi_1'(0,x)\partial_1\psi_1(0,x) - i\psi_2'(0,x) \right]
\]

\[
\times \partial_1\psi_2(0,x) + \text{H.c.},
\]

where the dots denote normal ordering with respect to the above-mentioned frequencies, we easily get

\[
H_{\phi}^{(0)} = \frac{\pi}{4Le^2}(Q^2 + Q_5^2) + \frac{\pi}{2\pi^2} \sum_{n>0} |n|\gamma_n^+\gamma_n.
\]

The symbol \(N\) has been introduced because the products appearing there need to be regularized. Since the VEV involves the vacuum of the interacting theory, we shall see in the next section that the ordering \(N\) is nothing but the normal ordering with respect to the operators that diagonalize the full Hamiltonian.

### IV. DIAGONALIZATION OF THE INTERACTING HAMILTONIAN

We consider the classical Hamiltonian (48). Using Eqs. (61), (64), (38), and (39), we get the following quantum expression:
\( H = \frac{1}{2} b_0^2 + \frac{e^2}{2 \pi} a_0^2 + \frac{\pi}{4 Le^2} (Q^2 + Q_5^2) + \frac{1}{\sqrt{2L}} a_0 (Q - Q_5) \)

\[ + \mathcal{N} \left[ \sum_{n \neq 0} b_n b_{-n} + i \sum_{n \neq 0} k_1 a_n b_{-n} + \frac{e^2}{2 \pi} \sum_{n \neq 0} a_n a_{-n} \right. \]

\[ + \frac{i e}{\sqrt{\pi}} \sum_{n = -\infty}^{n = 0} \sqrt{2} k_0 (\gamma_n a_n - \gamma_n^+ a_{-n}) + \sum_{n \neq 0} k_0 \gamma_n^+ \gamma_n \right], \]

\( (65) \)

Setting \( m = e/\sqrt{\pi}, \omega = \sqrt{k_0^2 + m^2} \) and defining, for \( n < 0 \), the operators

\[ \chi_n = \gamma_n^+ - \frac{\sqrt{2 \pi k_0}}{e} b_n, \]

\[ \Sigma_n = \frac{1}{\sqrt{\omega}} \left( \frac{\sqrt{\pi}}{e} \sqrt{2} \omega + k_0 \right) b_n - \frac{i e}{\sqrt{2 \pi}} a_n - \sqrt{k_0} \gamma_n^+ \right), \]

\[ \Sigma_{-n} = \frac{1}{\sqrt{\omega}} \left( \frac{\sqrt{\pi}}{e} \sqrt{2} \omega - k_0 \right) b_n - \frac{i e}{\sqrt{2 \pi}} a_n + \sqrt{k_0} \gamma_n \right), \]

it is easy to check the following commutation relations:

\[ [\Sigma_n, \Sigma_m^+] = \delta_{mn}, \quad [\Sigma_{-n}, \Sigma_m^+] = \delta_{mn}, \]

\[ [\chi_n, \chi_m^+] = -\delta_{mn}, \]

all other commutators vanishing. In terms of these operators, the frequency part of the Hamiltonian \((65)\) takes the form

\[ H_1 = \mathcal{N} \left[ \sum_{n \neq 0} b_n b_{-n} + i \sum_{n \neq 0} k_1 a_n b_{-n} + \frac{e^2}{2 \pi} \sum_{n \neq 0} a_n a_{-n} \right. \]

\[ + \frac{i e}{\sqrt{\pi}} \sum_{n = -\infty}^{n = 0} \sqrt{2} k_0 (\gamma_n a_n - \gamma_n^+ a_{-n}) + \sum_{n \neq 0} k_0 \gamma_n^+ \gamma_n \right. \]

\[ + \sum_{n = 1}^{\infty} k_0 \gamma_n^+ \gamma_n - \sum_{n = 0}^{\infty} k_0 \chi_n \chi_n + \sum_{n \neq 0} \sqrt{k_0^2 + m^2} \Sigma_n^+ \Sigma_n \]

\( H_1 \) takes the form of the Fock Hamiltonian of a massive boson field (apart from the zero mode) with \( m = e/\sqrt{\pi} \) and of two massless chiral bosons, one of which having commutation relations leading to an indefinite metric. We notice that the term with negative sign in \( H_1 \) and the commutator of \( \chi \) and \( \chi^+ \), entail that \( \gamma_n^+ \), for \( n > 0 \), and \( \chi_n \), both evolve in time with a positive frequency. As we shall see, this property allows us to express the selection of a physical subspace in terms of annihilation operators. Inserting in Eq. \((66)\) the expressions of \( a_n \) and \( b_n \) in terms of the creation and annihilation operators of the gauge fields, we obtain, for \( n < 0 \):

\[ \chi_n = \gamma_n^+ + \frac{ik_0 \sqrt{\pi}}{e} (A_n - A_{-n}), \]

\[ \Sigma_n = -\sqrt{\frac{k_0}{\omega}} \gamma_n^+ \frac{ie}{\sqrt{2 \pi k_0 \omega}} (A_n + A_{-n}) - \frac{i k_0 \sqrt{\pi k_0 \omega}}{2 e} \times \left( \frac{1}{\omega} + \frac{k_0}{\omega} \right) (A_n - A_{-n}), \]

\[ \Sigma_{-n} = \sqrt{\frac{k_0}{\omega}} \gamma_n - \frac{ie}{2 \sqrt{2 \pi k_0 \omega}} (A_n + A_{-n}) \]

\[ - \frac{i k_0 \sqrt{\pi k_0 \omega}}{2 e} \left( 1 - \frac{k_0}{\omega} \right) (A_{n} - A_{-n}). \]

One can verify that the following unitary operator:

\[ U = e^{i \sum_n \left( k_0 (\gamma_n^+ A_n - A_{-n}^+) + \gamma_n (A_n - A_{-n}) \right)} \]

\[ \times e^{i \sum_n \theta (A_n^+ A_{-n}^+ - A_{-n}^+ A_n^+)} e^{i \pi/2} \sum_n (\gamma_n A_n - A_{-n}^+ \gamma_n^+), \]

with

\[ \theta = \ln \left( \frac{e}{\sqrt{\pi k_0 \omega}} \right), \]

maps creation and annihilation operators of the free original fields into new operators that diagonalize the interacting Hamiltonian. As a matter of fact, for \( n < 0 \), it can be checked that

\[ UA_{-n} U^{-1} = \chi_n, \]

\[ UA_n U^{-1} = i \Sigma_n, \]

\[ U \gamma_n U^{-1} = i \Sigma_{-n}, \]

\[ U \gamma_{-n} U^{-1} = \chi_n. \]

It is easy to realize that from

\[ A_p |M,N\rangle = \gamma_p |M,N\rangle = 0, \quad p \neq 0, \]

it follows that

\[ \Sigma_{\pm p} U |M,N\rangle = \chi_p U |M,N\rangle = -\chi_{-p} U |M,N\rangle = 0, \quad p < 0. \]

\( (69) \)

Therefore \( U \) maps the base vectors of the free-field Fock space obtained by repeated action of \( A_n^+ \) and \( \gamma_n^+ \) on the states \( |M,N\rangle \), in eigenstates of \( H_1 \) obtained by repeated action of \( \Sigma_{\pm p}, \chi_p^+ \), and \( \chi_{-p}^+ \) (\( p < 0 \)) on the states \( U |M,N\rangle \).

One obtains the zero mode of the massive boson by diagonalizing

\[ H_0 = \frac{1}{2} b_0^2 + \frac{e^2}{2 \pi} a_0^2 + \frac{\pi}{4 Le^2} (Q^2 + Q_5^2) + \frac{1}{\sqrt{2L}} a_0 (Q - Q_5). \]

By defining

\[ \Sigma_0 = \alpha + \frac{Q - Q_5}{2i \sqrt{Lm^2}} = \frac{1}{\sqrt{2}} \left( -i \sqrt{\frac{m}{e}} b_0^+ + \frac{Q - Q_5}{\sqrt{Lm^2}} \right), \]
\[ \Sigma_0^+ = \alpha^+ - \frac{Q - Q_5}{2i \sqrt{Lm^{3/2}}} = \frac{1}{\sqrt{2}} \left( i \sqrt{m} a_0^+ - \frac{Q - Q_5}{\sqrt{2} \sqrt{Lm^{3/2}}} \right), \]

(70)

the commutation relations \([\alpha, \alpha^+] = 1, [\Sigma_0, \Sigma_0^+] = 1\) follow and the Hamiltonian \(H_0\) can be written as
\[
H_0 = e^{i \pi \Sigma_0^+ \Sigma_0} + \frac{\pi}{2e^2 L} QQ_5.
\]

We are thus led to the following diagonal form of the complete Hamiltonian:
\[
H = \sum_{n=1}^{+\infty} k_n \gamma_+ \gamma_n - \sum_{n=-\infty}^{-1} k_n \gamma_+ \gamma_n + \sum_{n=1}^{+\infty} \sqrt{k_n^2 + m^2} \Sigma_n^+ \Sigma_n^-
\]
\[
+ \frac{\pi}{2e^2 L} QQ_5,
\]
\[\alpha\] and \(\Sigma_0\) being related by a unitary operator:
\[
\Sigma_0 = U_0 \alpha U_0^{-1},
\]

where
\[
U_0 = e^{i/2 Lm^{3/2}(Q - Q_5)(\alpha + \alpha^+)}. \]

We remark that \(Q, Q_5\) and the spurion \(\sigma_1\) commute with \(U_0\), whereas
\[
\sigma_2 = U_0 \sigma_2 U_0^{-1} = e^{-i \epsilon Lm^{3/2}(\alpha + \alpha^+) \sigma_2}.
\]

(71)

We have the following commutators between the operators \(\sigma_1, \sigma_2, Q, Q_5, \Sigma_0, \Sigma_0^+\):
\[
[\Sigma_0, \Sigma_0^+] = 1,
\]
\[
[\sigma_1, \sigma_2] = 0,
\]
\[
[Q, \sigma_1] = -e \sigma_1, \quad [Q_5, \sigma_1] = -e \sigma_1,
\]
\[
[Q, \sigma_2] = -e \sigma_2, \quad [Q_5, \sigma_2] = e \sigma_2,
\]

(72)

all other commutators vanishing.

Starting from the classical expression of the momentum
\[
P = \int_{-L}^{L} dx \Theta^{01} = \int_{-L}^{L} dx \left[ i \frac{\pi}{2} (\psi^-(0,x) \delta^1 \psi(0,x) \right.
\]
\[
- \delta^1 \psi^+(0,x) \psi(0,x)) + \frac{1}{\sqrt{2}} F(0,x) \delta^1 A(0,x) \right],
\]

the same transformation (66) leads to the following diagonal expression:
\[
P = \sum_{n=1}^{+\infty} k_n \gamma_+ \gamma_n + \sum_{n=-\infty}^{-1} k_n \gamma_+ \gamma_n + \sum_{n=0}^{+\infty} k_1 \Sigma_n^+ \Sigma_n^- + \frac{\pi}{2Le^2 QQ_5}.
\]

We notice that the modes \(\gamma\) and \(\chi\) have a negative momentum (owing to the negative sign in the \(\chi\) commutator). Therefore they describe bosonic degrees of freedom of the same left chirality.

V. THE TEMPORAL EVOLUTION

The temporal evolution can easily be determined, starting from the commutation relations
\[
[H, \Sigma_0, \Sigma_0] = -\omega \Sigma_0, \quad [H, \Sigma_0^+, \Sigma_0^+] = \omega \Sigma_0^+,
\]
\[
[H, \chi] = -k_0 \chi, \quad [H, \chi^+] = k_0 \chi^+,
\]
\[
[H, \gamma] = -k_0 \gamma, \quad [H, \gamma^+] = k_0 \gamma^+.
\]

(73)

\[
[H, \sigma_1] = -\frac{\pi}{4eL} [(Q + Q_5) \sigma_1 + \sigma_1 (Q + Q_5)],
\]
\[
[H, \sigma_2] = \frac{\pi}{4eL} [(Q - Q_5) \sigma_2 + \sigma_2 (Q - Q_5)],
\]
\[
[H, Q] = [H, Q_5] = 0.
\]

Setting
\[
\Sigma(t,x) = \frac{1}{\sqrt{2L}} \sum_{n=-\infty}^{+\infty} \frac{1}{\sqrt{2\omega}} (\Sigma_n e^{-i \omega t - k_1 x} + \Sigma_n^+ e^{i \omega t - k_1 x}),
\]

(74)

and
\[
\chi(t,x) = \frac{1}{\sqrt{2L}} \sum_{n=-\infty}^{+\infty} \frac{1}{\sqrt{2k_0}} (\chi_n e^{-ik_0 (t + x)} + \chi_n^+ e^{ik_0 (t + x)}),
\]

(75)

from Eq. (73) and the canonical commutation relations, it is easy to see that \(\Sigma(t,x)\) satisfies the Klein-Gordon equation:
\[
(\Box + m^2) \Sigma(t,x) = 0
\]

(76)

and
\[
[\Sigma(t,x), \partial_0 \Sigma(t,y)] = i \delta(x-y),
\]
\[
[\Sigma(t,x), \Sigma(t,y)] = [\partial_0 \Sigma(t,x), \partial_0 \Sigma(t,y)] = 0.
\]

Here \(\chi(t,x)\) is a massless chiral (left) field satisfying the algebra
\[
[
\chi(t,x), \partial_0 \chi(t,y)] = \frac{-i}{2L} \sum_{n=-\infty}^{+\infty} e^{-\epsilon k_0 \cos 0(x-y)}
\]

and
\[ \chi(t,x), \chi(t,y) = \frac{i}{2L} \sum_{n=-\infty}^{n=\infty} \frac{\sin k_0(x-y)}{k_0}, \]

\[ [\partial_0 \chi(t,x), \partial_0 \chi(t,y)] = \frac{i}{2L} \sum_{n=-\infty}^{n=\infty} k_0 \sin k_0(x-y). \]

The temporal evolution of the original fields can now be obtained in the Heisenberg picture in the usual way; for instance

\[ A(t,x) = e^{iHt} A(0,x) e^{-iHt}, \]

and analogous ones for the other fields. We easily get

\[ A(t,x) = -\frac{2}{m} \partial_+ \left[ \Sigma(t,x) + \chi(t,x) - \frac{Q-Q_S}{\sqrt{2m^2L}} \right], \tag{77} \]

which in turn implies

\[ F(t,x) = m\Sigma(t,x). \tag{78} \]

Therefore the electric field \( F \) becomes massive

\[ (\Box + m^2) F(t,x) = 0. \]

We now turn our attention to the fermionic field. As far as the \( \psi_1 \) component is concerned, one immediately recovers a free temporal evolution:

\[ \psi_1(t,x) = \frac{1}{\sqrt{2L}} e^{-\phi_1^{(-)}(t,x)} e^{-i(\pi/4L)(Q+Q_S)(t+x)} \sigma_1 \]

\[ \times e^{-(i\pi/4L)(Q+Q_S)(t+x)} e^{-\phi_1^{(+))(t,x)},} \tag{79} \]

\[ \phi_1^{(-)}(t,x) = \sum_{n=1}^{+\infty} \frac{i}{\sqrt{n}} \gamma_n^+ e^{ik_0(t+x)}, \]

\[ \phi_1^{(+))(t,x) = \sum_{n=1}^{+\infty} \frac{i}{\sqrt{n}} \gamma_n e^{-ik_0(t+x)}. \]

For the \( \psi_2 \) component we get instead

\[ \psi_2(0,x) = \frac{1}{\sqrt{2L}} \exp \left[ \sum_{n=-\infty}^{n=\infty} \frac{1}{\sqrt{n}} \left[ \chi_n + \sqrt{k_0/\omega} (\Sigma_n + \Sigma_n^+) \right] e^{ik_1x} \right] \]

\[ \times e^{i(\pi/4L)(Q-Q_S)x} e^{i\pi mL \sum_0^\infty \sigma_1} e^{-i\pi mL \sum_0^\infty e^{i(\pi/4L)(Q-Q_S)x}} e^{-\phi_2^{(-)}(t,x)}, \]

\[ \times \exp \left[ \sum_{n=-\infty}^{n=\infty} \frac{1}{\sqrt{n}} \left[ \chi_n^+ e^{-ik_1x} + \sqrt{k_0/\omega} (\Sigma_n^+ - \Sigma_n) e^{-ik_1x} \right] \right] \]

\[ \times e^{i(\pi/4L)(Q-Q_S)x} e^{i\pi mL \sum_0^\infty \sigma_1} e^{-\phi_2^{(+))(t,x)},} \]

\[ \times e^{i\pi mL \sum_0^\infty e^{i(\pi/4L)(Q-Q_S)x}} \exp \left[ \sum_{n=-\infty}^{n=\infty} \frac{1}{\sqrt{n}} \left[ \chi_n e^{ik_1x} + \sqrt{k_0/\omega} (\Sigma_n^+ + \Sigma_n^+) e^{-ik_1x} \right] \right]. \]

where

\[ Z = -\frac{\pi}{2mL} \left[ \sum_{n=-\infty}^{n=\infty} \frac{1}{\sqrt{n}} \chi_n e^{i(\pi/L)x}, \sum_{p=-\infty}^{p=\infty} \frac{1}{\sqrt{p}} \chi_p e^{-i(\pi/L)x} \right] \]

\[ + \frac{\pi}{L} \left[ \sum_{n=-\infty}^{n=\infty} \frac{1}{\sqrt{\omega}} \Sigma_n e^{i(\pi/L)x}, \sum_{p=-\infty}^{p=\infty} \frac{1}{\sqrt{\omega}} \Sigma_p e^{-i(\pi/L)x} \right] \]

\[ = -\frac{\pi}{2mL} + \sum_{n=-\infty}^{n=\infty} \left( \frac{1}{\sqrt{n}} - \frac{\pi}{L} \frac{1}{\sqrt{\omega}} \right) \]

\[ = -\frac{\pi}{2mL} + \sum_{n=1}^{+\infty} \frac{m^2}{n \sqrt{(n \pi/L)^2 + m^2}} \left[ \frac{m^2}{n \sqrt{(n \pi/L)^2 + m^2}} + n \frac{\pi}{L} \right] \tag{80} \]
is a finite constant.² Using the relation
\[ e^{iHt} \psi_2 e^{-iHt} = e^{(i \pi/4Le)(Q - Q_3)t} \sigma_5 e^{(i \pi/4Le)(Q - Q_3)t}, \]
one can eventually find the temporal evolution of \( \psi_2 \):
\[ \psi_2(t, x) = e^{iHt} \psi_2(0, x) e^{-iHt} = \frac{e^{Z}}{\sqrt{2L}} e^{2i\sqrt{\pi} \chi(-)(t, x) + \Sigma^-(t, x)} e^{(i \pi/4Le)(Q - Q_3)(t + x)} \sigma_5 e^{(i \pi/4Le)(Q - Q_3)(t + x)} e^{2i\sqrt{\pi} \chi(+)^-(t, x) + \Sigma^+(t, x)} \]
(81)

where
\[ \chi^-(t, x) = \frac{1}{\sqrt{2L}} \sum_{n=\infty}^{-1} \frac{1}{\sqrt{2k_0}} \chi^+_n e^{ik_0(t + x)}, \]
\[ \chi^+(t, x) = \frac{1}{\sqrt{2L}} \sum_{n=\infty}^{-1} \frac{1}{\sqrt{2k_0}} \chi_n e^{-ik_0(t + x)}, \]
\[ \Sigma^-(t, x) = \frac{1}{\sqrt{2L}} \sum_{n=\infty}^{\infty} \frac{1}{\sqrt{2\omega}} \Sigma_n e^{i(\omega t - k_1 x)}, \]
\[ \Sigma^+(t, x) = \frac{1}{\sqrt{2L}} \sum_{n=\infty}^{\infty} \frac{1}{\sqrt{2\omega}} \Sigma_n e^{-i(\omega t - k_1 x)}. \]

It can be checked that the field \( \psi_2 \) satisfies the regularized Dirac equation (53).

Finally, for \( \lambda \) we get
\[ \lambda(t, x) = e^{iHt} \chi(0, x) e^{-iHt} \]
\[ = \frac{Q}{\sqrt{2L}} + \frac{m}{\sqrt{2L}} \sum_{n=\infty}^{-1} \sqrt{k_0} \left[ i(\gamma_n - \chi_n) e^{-ik_0(t + x)} - i(\gamma^+_n - \chi^+_n) e^{ik_0(t + x)} \right], \]
in agreement with both Euler-Lagrange equations for the electric field; \( \lambda \) cannot vanish strongly as it has nonvanishing commutators with \( A \) and \( \gamma \). In order to recover the correct Maxwell equations in the weak sense we have to define the physical states by imposing the following conditions:
\[ Q|\text{phys} \rangle = 0, \]  
(82)
\[ \lambda^{(+)}|\text{phys} \rangle = 0, \]  
(83)
\( \lambda^{(+)} \) being the positive frequency component of \( \lambda(x) \).

Equation (83) is equivalent to
\[ (\gamma_n - \chi_n)|\text{phys} \rangle = 0, \quad \forall n < 0. \]  
(84)

²We remark that, in the decompactification limit \( L \rightarrow \infty \), the factor \( e^{2i\sqrt{\pi} \chi} \) would diverge, producing an infinite renormalization constant for the field \( \psi_2 \).

VI. THE STRUCTURE OF THE HILBERT SPACE

A. The vacuum sector

The operators \( H, P, Q, \) and \( Q_5 \) commute pairwise. The common eigenstates can be obtained by the repeated action of the creation operators \( \Sigma^0_{0, \pm p}, \gamma^\pm_p, \chi^+_p \) \((p < 0)\) to the states
\[ |\Omega_{mn} \rangle = S \sigma^n_1 \sigma^n_2 |0 \rangle = \sigma_m^1 \sigma_m^2 |0 \rangle, \quad m, n = 0, \pm 1, \pm 2, \ldots , \]
where \( |0 \rangle \) is defined by the conditions
\[ \alpha|0 \rangle = \mathcal{A}_n|0 \rangle = \gamma_n|0 \rangle = Q|0 \rangle = Q_5|0 \rangle = 0 \]
and
\[ S = UU_0. \]

\( |\Omega_{mn} \rangle \) obeys the equations
\[ \Sigma_{0, \pm p} |\Omega_{mn} \rangle = \gamma_{-p} |\Omega_{mn} \rangle = \chi_{pn} |\Omega_{mn} \rangle = 0, \]
\[ \langle \Omega_{mn} |\mathcal{P}_{pq} \rangle = \langle 0 | \sigma^m_2 \sigma^n_1 S^+ \sigma^m_1 \sigma^n_2 |0 \rangle \]
\[ = (-1)^{p-m} \langle 0 | \sigma^m_2 \sigma^2^m_1 \sigma^n_2 \sigma^2^n_1 |0 \rangle \]
\[ = (-1)^{p-m} \langle 0 | p - m, q - n | \delta_{pq} |0 \rangle , \]
so that
\[ \langle \Omega_{mn} |\mathcal{P}_{pq} \rangle = \delta_{pq} \delta_{mn} , \quad \text{if} \quad \langle 0 |0 \rangle = 1, \]
and
\[ Q|\Omega_{mn} \rangle = -e(m + n)|\Omega_{mn} \rangle, \]
\[ Q_5|\Omega_{mn} \rangle = -e(m - n)|\Omega_{mn} \rangle, \]
\[ H|\Omega_{mn} \rangle = \frac{\pi}{2L} (m^2 - n^2)|\Omega_{mn} \rangle, \]
\[ P|\Omega_{mn} \rangle = -\frac{\pi}{2L} (m^2 - n^2)|\Omega_{mn} \rangle. \]

Among them, only the states
\[ |\Omega_{-n} \rangle = S \sigma^{n^2}_1 \sigma^{n^2}_2 |0 \rangle \]
satisfy the condition
\[ Q|\Omega_{-n} \rangle = 0, \]
and therefore are physical.

For such states

\[ Q_3 |\Omega_{-n}\rangle = 2n |\Omega_{-n}\rangle, \]

\[ H |\Omega_{-n}\rangle = P |\Omega_{-n}\rangle = 0. \]

An infinite set of vacua, labeled by the integer \( n \), are translation-invariant. Such states are related by a residual gauge transformation. As a matter of fact, if we define

\[ |\Omega_n\rangle = e^{i\pi(n+1)/2} |\Omega_{-n}\rangle = e^{i\pi(n+1)/2} \sigma_1^{n} \sigma_2{\bar{s}} |0\rangle = e^{i\pi(n+1)/2} \sigma_1^{n} \sigma_2{\bar{s}} |0\rangle, \]

we get

\[ T_1 |\Omega_n\rangle = |\Omega_{n+1}\rangle, \]

with

\[ T_1 = \sigma_1^{-1} \sigma_2. \]

The unitary operators \( T_m = (T_1)^m \) generate residual gauge transformations with winding number \( m \):

\[ T_mA(x)T_m^+ = A(x) - \frac{m \pi \sqrt{2}}{eL}, \]

\[ T_m \psi_\alpha(x)T_m^+ = (-1)^m e^{i m (\pi L)(t+x)} \psi_\alpha(x). \]

In order to construct gauge-invariant vacua (up to a phase factor), \( |\theta\rangle \) vacua are introduced:

\[ |\theta\rangle = \sum_{n=-\infty}^{+\infty} e^{in\theta} |\Omega_n\rangle, \]

which diagonalize the \( T_m \) operators

\[ T_m |\theta\rangle = e^{-im\theta} |\theta\rangle. \]

\( |\theta\rangle \) vacua are necessary to recover the validity of cluster decomposition. Different values of \( \theta \) give rise to inequivalent representations.

**B. The physical subspace**

We notice that the indefinite inner product \( \langle \cdot, \cdot \rangle \), which is preserved by the \( U \) operator, entails the presence of negative norm states. On the other hand, the scalar product \( \langle \cdot, \cdot \rangle \), is not preserved by \( U \) and the relations (67), (68) no longer hold for the scalar product \( \langle \cdot, \cdot \rangle \), if the adjoint operation is defined according to the indefinite inner product.

A Fock space \( \mathcal{V} \) can be constructed by repeated action of creation operators \( \Sigma^+_{n \geq 0}, \chi^+_n, \gamma^+_n (n < 0) \) on a \( |\theta\rangle \) vacuum, endowed with a positive-definite inner product \( \langle \cdot, \cdot \rangle_+ \), which preserves Eqs. (67) and such that the commutator (68) becomes canonical if \( \chi^+_n \) is replaced by the adjoint of \( \chi \) with respect to \( \langle \cdot, \cdot \rangle_+ \). In this case

\[ \langle \cdot, \cdot \rangle = \langle \cdot, \eta' \cdot \rangle_+, \text{ with } \eta' = (-1)^N \eta, \]

where

\[ N_x = - \sum_{n=-\infty}^{-1} \chi^+_n \chi_n. \]

If we select the physical space \( \mathcal{V}_p \) with the condition (84), we can easily see that the eigenstates \( |\phi_n\rangle \) of the operator

\[ N_{xy} = \sum_{n=-\infty}^{-1} (\gamma^+_n \gamma_n - \chi^+_n \chi_n), \]

\[ N_{xy} |\phi_n\rangle = n |\phi_n\rangle, \]

have vanishing norm for \( n \neq 0 \) and do not contribute to physical quantities. The physical Hilbert space can be defined as usual as a quotient space.

**C. Chiral anomaly and fermionic condensate**

From the temporal evolution of the fermion fields, it is easy to derive the expressions for the currents

\[ j^0(x) = j_3^1(x) = \frac{Q}{2L} + \frac{i e}{2 \sqrt{\pi L}} \sum_{n=-\infty}^{+\infty} \frac{k_1}{\sqrt{\omega}} (\Sigma_n e^{i(ut-k_1x)}) \]

\[ - \Sigma_n^+ e^{i(ut-k_1x)} + \frac{i e}{2 \sqrt{\pi L}} \]

\[ \times \sum_{n=-\infty}^{-1} \sqrt{k_0} [ (\gamma_n - \chi_n^*) e^{-ik_0(t+x)} - (\gamma_n^* - \chi_n^*) e^{ik_0(t+x)}], \]

\[ j^1(x) = j_3^0(x) = - \frac{Q}{2L} + \frac{i e}{2 \sqrt{\pi L}} \sum_{n=-\infty}^{+\infty} \sqrt{\omega} (\Sigma_n e^{i(ut-k_1x)}) \]

\[ - \Sigma_n^+ e^{i(ut-k_1x)} + \frac{i e}{2 \sqrt{\pi L}} \]

\[ \times \sum_{n=-\infty}^{-1} \sqrt{k_0} [ (\gamma_n - \chi_n^*) e^{-ik_0(t+x)} - (\gamma_n^* - \chi_n^*) e^{ik_0(t+x)}]. \]

Using Eqs. (74), (76), and (78), we get

\[ \partial_x \Sigma^0(x) = \frac{e^2}{\pi} F(x). \]

As a consequence the chiral charge

\[ q_5 = \int_{-\frac{L}{2}}^{\frac{L}{2}} dx j^0_5(x) = Q_5 + i m^{3/2} \sqrt{\Lambda} (\Sigma_0 e^{-imt} - \Sigma_0^* e^{imt}) \]

is not conserved and therefore cannot be the generator of
chiral transformations. Instead, the generator is the “free” chiral charge \( Q_5 \), which commutes with the Hamiltonian. On the other hand, \( q_5 \) is gauge-invariant, while \( Q_5 \) is not. The \( | \theta \rangle \) vacua are not invariant under the action of \( Q_5 \), leading to a spontaneous chiral symmetry breaking

\[
e^{i(\alpha + \alpha \alpha) | \theta \rangle} = | \theta + 2 \alpha \rangle.
\]

Let us now introduce the fermionic condensate

\[
\frac{\langle \theta | \bar{\psi}(x) \psi(x) \rangle | \theta \rangle}{\langle \theta | \theta \rangle} = \frac{1}{\langle \theta | \theta \rangle} \left[ \langle \theta | \psi_1^+(x) \psi_2(x) \rangle | \theta \rangle + \langle \theta | \psi_2^+(x) \psi_1(x) \rangle | \theta \rangle \right].
\]

Using Eqs. (79) and (81) it is easy to see that

\[
\langle \theta | \psi_1^+(x) \psi_2(x) \rangle | \theta \rangle = \frac{e^Z}{2L} \langle \theta | e^{i(\pi/2L)Q(t+x)} \sigma^+_1 \times \sigma_2 e^{i(\pi/2L)Q(t+x)} | \theta \rangle
\]

\[
= \frac{e^Z}{2L} \langle \theta | \sigma^+_1 | \theta \rangle
\]

\[
= \frac{e^Z}{2L} e^{-i \theta (\theta | \theta \rangle},
\]

and, therefore,

\[
\frac{\langle \theta | \bar{\psi}(x) \psi(x) \rangle | \theta \rangle}{\langle \theta | \theta \rangle} = \frac{e^Z}{L\cos \theta}.
\]

In the decompactification limit \( L \to \infty \) one recovers the well-known result [8]:

\[
\lim_{L \to \infty} e^Z \cos \theta = \frac{m}{2 \pi} e^y \cos \gamma,
\]

\( \gamma \) being the Euler-Mascheroni constant.

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