Hamilton - Jacobi treatment of front-form Schwinger model

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Abstract

The Hamilton-Jacobi formalism was applied to quantize the front-form Schwinger model. The importance of the surface term is discussed in detail. The BRST-anti-BRST symmetry was analyzed within Hamilton-Jacobi formalism.

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1 Introduction

Quantum electrodynamics in one-space and one-time dimension with massless charged fermion is known as the Schwinger model. It is the one of the very few models of field theory which can be solved analytically [1, 2, 3]. The Fock-space content of the physical states depends crucially on the coordinate system and on the gauge. It is only in the front form that a simple constituent picture emerges [4] as well as it is an important example of the type of simplification that we hope will occur for QCD in physical space-time. The investigations of similar model with massive fermion and for non-abelian theory, where the fermion is in the fundamental and adjoint representation, revealed that many properties are unique to the Schwinger model [5]. During last years light-cone quantization of quantum field theory has emerged as a promising method for solving problems in the strong coupling regime [6]. The front-form Hamiltonian and BRST formulation [7] and recently the extended Hamiltonian formalism of the pure space-like axial gauge Schwinger model [8] were investigated. The Schwinger model in the front form possesses a set of three first-class constraints [9]. In the instant form it has two first-class constraints [10].

Hamilton-Jacobi formalism was subjected to various investigations during the last years. The formalism was applied for strings and p-Branes [11] and for strongly coupled gravitational systems [12] and in addition the quantum Hamilton-Jacobi formulation was obtained from the equivalence principle [13]. A new method of quantization of the system with constraints based on the *Carathéodory*'s equivalent Lagrangians method [14] was initiated [15, 16] by one of us.

Recently this formalism was generalized to the singular systems with higher order Lagrangians and to systems which have elements of the Berezin algebra [17, 18, 19]. The quantization of the systems with constraints was investigated using this approach [20, 21, 22]. Recently, the connection between the integrability conditions and Dirac's consistency conditions [23] were established [19]. Importance of the surface terms [24] was analyzed as well as the relation between Batalin-Fradkin-Tyutin [25] and Hamilton-Jacobi formalism [21]. Even more recently the formalism was applied to investigate the nonholonomic-constrained systems with second-class constraints [26] as well as Proca's model [27].

The advantage of the Hamilton-Jacobi formalism is that we have no difference between first and second class constraints and we do not need gauge-fixing term because the gauge variables are separated in the processes of constructing an integrable system of total differential equations. In addition the action provided by the formalism can be used in the process of path integral quantization method of the constrained systems.

The main aim of this paper is to investigate the quantization of the front-form Schwinger model and its BRST extension using Hamilton-Jacobi formalism.

The plan of the paper is the following:

In sec. 2 the Hamilton-Jacobi formalism is presented. In sect. 3 the front-form Schwinger model and its BRST extension are analyzed using Hamilton-Jacobi formalism. In sec. 4 conclusions are given.

2 Hamilton-Jacobi formalism

Let us assume that the Lagrangian L is singular and the Hessian supermatrix has rank n-r. The Hamiltonians to start with are

$$H_{\alpha}^{'} = H_{\alpha}(t_{\beta}, q_a, p_a) + p_{\alpha}, \tag{1}$$

where $\alpha, \beta = n-r+1, \cdots, n$,$a = 1, \cdots n-r$. The usual Hamiltonian H_0 is defined as

$$H_0 = -L(t, q_i, \dot{q}_{\nu}, \dot{q}_a = w_a) + p_a w_a + \dot{q}_{\mu} p_{\mu} \mid_{p_{\nu}=-H_{\nu}}, \nu = 0, n-r+1, \cdots, n. \tag{2}$$

which is independent of $\dot{q}_{\mu}$.Here $\dot{q}_a = \frac{dq_a}{d\tau}$,where τ is a parameter. The equations of motion are obtained as total differential equations in many variables as follows

$$\begin{aligned} dq_a &= (-1)^{P_a + P_a P_{\alpha}} \frac{\partial_r H_{\alpha}^{'}}{\partial p_a} dt_{\alpha}, dp_a = -(-1)^{P_a P_{\alpha}} \frac{\partial_r H_{\alpha}^{'}}{\partial q_a} dt_{\alpha}, \\ dp_{\mu} &= -(-1)^{P_{\mu} P_{\alpha}} \frac{\partial_r H_{\alpha}^{'}}{\partial t_{\mu}} dt_{\alpha}, \mu = 1, \cdots, r, \end{aligned} \tag{3}$$

$$dz = (-H_{\alpha} + (-1)^{P_a + P_a P_{\alpha}} p_a \frac{\partial_r H_{\alpha}^{'}}{\partial p_a}) dt_{\alpha}, \tag{4}$$

where $z = S(t_{\alpha}, q_a)$ and P_i represents the parity of a_i.

Determination of the degrees of freedom in the Hamilton-Jacobi formulation really needs elaboration. Although one starts with a system of n degrees of freedom the theory forces to reduce it due to the integrability conditions. In other words, variations of constraints may cause new constraints and again their variations leads one to a degree of freedom which is less than n. If the variations vanish identically, of course degrees of freedom do not change.

3 The front-form Schwinger model

The Lagrangian density of the Schwinger model in one-space, one -time dimension is

$$L^{'} = \psi \gamma^{\mu} (i\partial_{\mu} + gA_{\mu}) \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \tag{5}$$

where $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$.

The bosonised version has the following Lagrangean density [10, 28].

$$L^{''} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu\phi)^2 - g\epsilon^{\mu\nu}\partial_\mu\phi A_\nu, \tag{6}$$

where $g^{\mu\nu} = diag(1, -1)$, $\epsilon^{01} = -\epsilon^{10} = 1$, or in the component form (6) becomes

$$L^{'''} = \frac{1}{2}(\dot\phi^2 - \phi^{'2}) + g(\phi^{'}A_0 - \dot\phi A_1) + \frac{1}{2}(\dot A_1 - \dot A_0^{'})^2. \tag{7}$$

The light-cone coordinates are defined as

$$x^\pm = \frac{1}{\sqrt{2}}(x^0 \pm x^1). \tag{8}$$

The Lagrangian (7) in the light-cone coordinate form becomes

$$L = (\partial_+\phi)(\partial_-\phi) + g(\partial_+\phi)A^+ - g(\partial_-\phi)A^- + \frac{1}{2}(\partial_+A^+ - \partial_-A^-)^2. \tag{9}$$

Here $A_\pm = \frac{1}{\sqrt{2}}(A_0 \pm A_1)$ and $\partial_\pm\phi = \frac{1}{\sqrt{2}}(\dot\phi \pm \phi^{'})$.

¿From (9) we calculate the canonical momenta as

$$\Pi^+ = 0, \Pi^- = \partial_+A^+ - \partial_-A^-, \Pi = \partial_-\phi + gA^+, \tag{10}$$

where Π^+, Π^- and Π are conjugate to A^-, A^+ and ϕ respectively. ¿From (10) the Hamiltonian densities to start with are

$$H_1^{'} = \Pi^+, H_2^{'} = \Pi - \partial_-\phi - gA^+ \tag{11}$$

The canonical Hamiltonian density is

$$H_c = \frac{1}{2}(\Pi^-)^2 + \Pi^-(\partial_-A^-) + g(\partial_-\phi)A^-. \tag{12}$$

In Hamiltonian-Jacobi formalism we have , at this stage, three Hamiltonians densities

$$\begin{aligned} H_1^{'} &= \Pi^+, H_2^{'} = \Pi - \partial_-\phi - gA^+, \\ H_0^{'} &= p_0 + \frac{1}{2}(\Pi^-)^2 + \Pi^-(\partial_-A^-) + g(\partial_-\phi)A^- \end{aligned} \tag{13}$$

The gauge variables are A^- and Φ and the independent one is A^+. The equations of motion corresponding to (13) are

$$dA^+ = \frac{\partial H_0^{'}}{\partial \Pi^-}d\tau = (\Pi^- + \partial_-A^-)d\tau,$$

$$d\Pi^- = -\frac{\partial H_0^{'}}{\partial A^+}d\tau - \frac{\partial H_2^{'}}{\partial A^+}d\Phi = gd\Phi. \tag{14}$$

¿From $dH_1^{'} = 0$ we find that

$$H_3^{'} = \partial_-\Pi^- - g\partial_-\Phi = 0. \tag{15}$$

Constraint (15) is not suitable for Hamilton-Jacobi but if we consider it as a density the contribution to the action is zero. At this point we can see the main difference between Dirac's formulation and Hamilton-Jacobi formalism for fields. To keep the physical interpretation in Hamilton-Jacobi formulation we must have all the constraints in the form of $p_\alpha + H_\alpha$. In our concrete case the constraints are not in the form required but they are first class. The system is integrable on the surface of constraints, in other words when $H_1^{'} = H_2^{'} = H_3^{'} = 0$. For this model the reduced phase-space is suitable in the Hamilton-Jacobi formalism. In this case we have

$$H_0^{'} = p_0 + \frac{1}{2}(\Pi^-)^2. \tag{16}$$

3.1 BRST Invariance

The main aim of this section is to find a way to relate BRST transformation [29] to the Hamilton-Jacobi formulation. The first problem is the Lagrangian to start with. The starting point is the BRST invariant Lagrangian [7]

$$\begin{aligned} L^{'} &= \Pi^-\partial_+A^+ + \Pi_u\partial_+u + \Pi_v\partial_+v - \frac{1}{2}(\Pi^-)^2 - \Pi^-(\partial_-A^-) - gA^-(\partial_-\phi) \\ &+ (\partial_-\phi + gA^+)\partial_+\phi. \end{aligned} \tag{17}$$

obtained from the total Hamiltonian

$$H_T = \frac{1}{2}(\Pi^-)^2 + \Pi^-(\partial_-A^-) + g(\partial_-\phi)A^- + \Pi^+u + (\Pi - \partial_-\Phi - gA^+)v. \tag{18}$$

Here Π_u and Π_v are the momenta corresponding to Lagrange's multipliers u and v.

The BRST and anti- BRST symmetries for Schwinger model have the forms

$$\begin{aligned} \delta\phi = 0 \quad &, \delta A^+ = \partial_-c, \delta A^- = \partial_+c, \delta u = \partial_+\partial_+c, \delta v = 0, \\ \delta\Pi = g\delta_-c \quad &, \delta\Pi^+ = 0, \delta\Pi^- = 0, \delta\Pi_u = 0, \delta\Pi_v = 0 \\ \delta c = 0 \quad &, \delta\bar{c} = 0, \delta b = 0, \end{aligned} \tag{19}$$

$$\begin{aligned} \bar{\delta}\phi = 0 \quad &, \bar{\delta}A^+ = -\partial_-\bar{c}, \bar{\delta}A^- = -\partial_+\bar{c}, \bar{\delta}u = -\partial_+\partial_+\bar{c}, \bar{\delta}v = 0, \\ \bar{\delta}\Pi = -g\bar{\delta}_-\bar{c} \quad &, \bar{\delta}\Pi^+ = 0, \bar{\delta}\Pi^- = 0, \bar{\delta}\Pi_u = 0, \bar{\delta}\Pi_v = 0 \end{aligned}$$

$$\bar{\delta}\bar{c} = 0 \qquad , \bar{\delta}\bar{c} = 0, \bar{\delta}b = 0, \tag{20}$$

where c, $\bar{c}$ are Grassmann variables, b is a bosonic variable and in addition $\delta^2 = 0$, $\bar{\delta}^2 = 0$.

The supercharges corresponding to (19) and (20) are

$$Q = \int dx^-[ic(\partial_-\Pi^- - g\partial_-\phi) - i\partial_+ c(\Pi^+ + \Pi - \partial_-\phi - gA^+)], \tag{21}$$

$$\bar{Q} = \int dx^-[-i\bar{c}(\partial_-\Pi^- - g\partial_-\phi) + i\partial_+\bar{c}(\Pi^+ + \Pi - \partial_-\phi - gA^+)], \tag{22}$$

After adding a gauge-fixing term to (17) we obtain [7]

$$L_{BRST} = L' + \delta(\bar{c}(\partial_+ A^+ + \frac{1}{2}b - gA^+ + \Pi)) \tag{23}$$

or

$$\begin{aligned} L_{BRST} &= \Pi^-\partial_+ A^+ + \Pi_u\partial_+ u + \Pi_v\partial_+ v - \frac{1}{2}(\Pi^-)^2 - \Pi^-(\partial_- A^-) \\ - &\quad gA^-(\partial_-\phi) + (\partial_-\phi + gA^+)\partial_+\phi + \frac{1}{2}b^2 + b(\partial_+ A^- - gA^+ + \Pi) \\ + &\quad (\partial_+\bar{c})(\partial_+ c). \end{aligned} \tag{24}$$

Since the Lagrangian (24) is degenerate on the extended phase-space, we can apply Hamilton-Jacobi formulation.

The Hamiltonian densities corresponding to (24) are

$$\begin{aligned} H_1^{''} &= \Pi^+ - b, H_2^{''} = \Pi_c - \partial_+\bar{c}, H_3^{''} = \Pi_{\bar{c}} - \partial_+ c, H_4^{''} = \Pi - \partial_-\Phi - gA^+, \\ H_0^{''} &= p_0 + \frac{1}{2}(\Pi^-)^2 + \Pi^-(\partial_- A^-) + g(\partial_-\phi)A^- + \Pi_c\Pi_{\bar{c}} \\ - &\quad \Pi^+(\Pi - gA^+) - \frac{1}{2}(\Pi^+)^2 \end{aligned} \tag{25}$$

We mention that in (25) all Hamiltonians are BRST- anti- BRST invariant if $\delta p_0 = \bar{\delta} p_0 = 0$.

The corresponding equations of motion for independent variables are

$$d\Pi^- = -g\Pi^+ dx^+ - gd\Phi, dA^+ = (\Pi^- + \partial_- A^-)dx^+ \tag{26}$$

The variations of $H_1^{''}, H_2^{''}, H_3^{''}, H_4^{''}$ gives

$$d\Pi^+ = db, d\Pi = \partial_- d\Phi + gdA^+ \tag{27}$$

$$d\Pi_c = \partial_+ d\bar{c}, d\Pi_{\bar{c}} = \partial_+ dc, \tag{28}$$

¿From (28) we obtain

$$\partial_+(\partial_+ c) = 0, \partial_+(\partial_+\bar{c}) = 0, \tag{29}$$

On the other hand $d\Phi = -g\Pi^+ dx^+ - gd\Phi$, then $\Pi^+ = 0$. From (27) we obtain $b = 0$. The equation of motion corresponding to Π^+ is

$$d\Pi^+ = \partial_-\Pi^- - g\partial_-\Phi \tag{30}$$

As a consequence a new constraint appears and it is considered as a new Hamiltonian density

$$H_5^{''} = \partial_-\Pi^- - g\partial_-\Phi. \tag{31}$$

Solving $H_2^{''} = 0, H_3^{''} = 0$ we obtain c and $\bar{c}$ as

$$c(x^+) = Ax^+ + B, \bar{c}(x^+) = A^{'}x^+ + B^{'}. \tag{32}$$

Let $\mid \psi >$ be the physical state of the model. All Hamiltonians from (25) annihilate the physical state. We mention that this condition is the same as

$$Q \mid \psi >= 0, \bar{Q} \mid \psi >= 0. \tag{33}$$

Taking into account (28) we obtain that the physical states are described by

$$\begin{aligned} \Pi^+ \mid \psi >= 0 \quad & , (\Pi - \partial_-\phi - gA^+) \mid \psi >= 0, \\ (\partial_-\Pi^- - g\partial_-\phi) \mid \psi > \quad & = 0. \end{aligned} \tag{34}$$

The result is the same as obtained in [7].

4 Conclusions

Despite of many attempts to clarify the Hamilton-Jacobi formalism for the systems with constraints a lot of problems remained unsolved. In this paper we analyzed the front-form Schwinger model with Hamilton-Jacobi and the results are the same as those obtained with Dirac's formalism. Using the consistency conditions we found three first class constraints but one of them is not in a form required by Hamilton-Jacobi formalism. As a consequence in this case we cannot calculate the action. To solve the problem we find the reduced phase-space. We mention that $H_3^{'}$ becomes a total divergence in Hamilton-Jacobi formalism. This model is an example of a constrained system such that all the constraints are first class but its physical interpretation from Hamilton-Jacobi point of view is missing. In the second part of the paper we started with a BRST invariant Lagrangian. Since the Lagrangian is singular on the extended phase-space we apply Hamilton-Jacobi formalism. All Hamiltonian densities are BRST- anti- BRST invariant provided that $\delta p_0 = \bar{\delta} p_0 = 0$. The equations for c and $\bar{c}$ were obtained and the results are in agreement with those obtained in literature.

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6 Appendix

Let us consider the Lagrangian $L(q,\dot{q})$ be an even function of N variables q^I that are elements of Berezin algebra. The variation of $S = \int Ldt$ leads us to the equations of motion

$$\frac{\delta_r S}{\delta q^i} = \frac{\partial_r L}{\partial q^i} - \frac{d}{dt}\frac{\partial_r L}{\partial \dot{q}^i} = 0, \tag{35}$$

The Hamiltonian becomes

$$H = p_i \dot{q}^i - L, \tag{36}$$

where the momenta are defined using the right derivatives

$$p_i = \frac{\partial_r L}{\partial \dot{q}^i}, \tag{37}$$

and Hamilton's equations are

$$\dot{q}^i = \frac{\partial_l H}{\partial p_i} = (-1)^{P_{(i)}} \frac{\partial_r H}{\partial p_i}, \dot{p}^i = \frac{-\partial_r H}{\partial q_i} = -(-1)^{P_{(i)}} \frac{\partial_l H}{\partial q_i}. \tag{38}$$

The Berezin bracket is defined as

$$\{F, G\}_B = \frac{\partial_r F}{\partial q^i}\frac{\partial_l G}{\partial p_i} - (-1)^{P_{(F)}P_{(G)}} \frac{\partial_r G}{\partial q^i}\frac{\partial_l F}{\partial p_i} \tag{39}$$

and has the following properties

$$\{F, G\}_B = -(-1)^{P_{(F)}P_{(G)}} \{G, F\}_B, \tag{40}$$

$$\{F, GK\}_B = \{F, G\}_B K + (-1)^{P_F P_G} \{F, K\}_B, \tag{41}$$

$$\begin{aligned}(-1)^{P_{(F)}P_{(K)}} \{F, \{G, K\}_B\}_B \quad &+ \quad (-1)^{P_{(G)}P_{(F)}} \{G, \{K, F\}_B\}_B \\ &+ \quad (-1)^{P_{(K)}P_{(G)}} \{K, \{F, G\}_B\}_B = 0.\end{aligned} \tag{42}$$

Here (42) represents the Jacobi's identity.

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