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THE LIGHT-CONE GAUGE IN THE THEORY OF RELATIVISTIC SURFACES

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ԼՈՒՍԱՅԻՆ ԿՈՆԻ ՏՐԱՄԱՉԱՓՈՒԹՅՈՒՆԸ ՌԵԼՅԱՏԻՎԻՍՏԱԿԱՆ ՄԱԿԵՐԵՎՈՒՅԹՆԵՐԻ ՏԵՍՈՒԹՅՈՒՆՈՒՄ

Ռելյատիվիստական մակերևույթների տեսությունում կառուցվում է լուսակերպ տրամաչափություն: Այս տրամաչափությունում տեսության քվանտացման ժամանակ համիլտոնյանը որոշված է դրականորեն, չնայած կապերը լրիվ լուծված չեն՝ ինդեֆինիտ չափաղրումով վիճակներ չկան: Ի դեպ, հնարավորություն կա ստուգել կովարիանտությունը:

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Г.К.САВВИДИ

КАЛИБРОВКА СВЕТОВОГО КОНУСА В ТЕОРИИ РЕЛЯТИВИСТСКИХ ПОВЕРХНОСТЕЙ

Строится светоподобная калибровка в теории релятивистских поверхностей. При квантовании теории в этой калибровке гамильтониан положительно определен, хотя связи решены не полностью, состояний с индефинитной метрикой нет, причем есть возможность проверить ковариантность.

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THE LIGHT-CONE GAUGE IN THE THEORY OF RELATIVISTIC SURFACES

A light-like gauge is constructed in the theory of open relativistic surfaces within which part of constraint equations can be solved. In the quantization of the theory in this gauge the Hamiltonian is positively defined, states with negative norm are absent and there arises a real possibility to check up covariance.

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Yerevan 1987

1. Introduction.

The string theory attracts great attention because it successfully solves the main problems of grand unification theory. The fundamental particles in this theory may be regarded as one-dimensional objects - strings - contrary to points in usual field theory. At present, there exist only six string theories for quite definite groups and space-time dimensions, consistent with quantum mechanics and Lorentz invariance.

If originally the string theory was formulated in the light-cone gauge, at present essential progress is achieved in the construction of the covariant string field theory, perturbation theory and calculation of loop corrections. Presumably, the covariant approach will enable one to obtain the nonperturbative results too.

Consider the string theory from another viewpoint. Let us regard as before that fundamental are the point material objects which by some dynamical laws may form objects of finite dimensions. Clearly, their number must be continuum, since it is impossible to form a finite-dimensional object with the use of a countable set of such point objects. The dynamics of this system is given by the well-known "gauge" principle, according to which the string action is proportional to the area of the surface swept out by the string 1 .

From this viewpoint, it is natural to ask why the point objects must form one-dimensional strings contrary to extended higher-dimension objects. In the string, already from the very beginning, there is "squeezed" a part of degrees of freedom. Therefore, it is quite natural to give freedom to all degrees and consider objects of arbitrary dimensions. The principle of minimal "area" may, as before, serve as "gauge" principle, although one may, of course, consider also other geometric constructions that depend on curvature tensor too.

Do there exist theories consistent with quantum mechanics and relativity for objects with large number of dimensions [2,3] ? If no, then string is really a unique object. If yes, then string is none other than a limit of more general objects.

On this way, there arises a serious problem connected with the gauge invariance of the theory and, as its consequence, constraints between the variables. There exist several approaches to the quantization of systems with constraints. In a first of them the constraints are ignored, the Poisson brackets are introduced between all variables, and only then constraints are imposed. This Dirac quantization [4,5] possesses explicit covariance; however one needs an additional study of states with negative norm [6,7] . In a second approach, the constraint equations are explicitly solved, after which the Poisson brackets are imposed only on independent dynamical variables [8,9,[illegible]] . In this approach one should check the covariance, since the Poincaré group is realized here nonlinearly [5] . In a third one, the phase space is extended with the use of anticommuting ghost-variables which compensate nonphysical degrees of freedom [10,11] . In the large phase space, in the classical limit, there exists a supersymmetric transformation - BRST, whose nilpotency in quantization should be specially checked [12] . There exist also other quantization methods; however, the condition of absence of some or other anomalies in them brings to the restriction on the space-time dimensions.

In the theory of extended objects the above-described quantization schemes are difficult to realize because at covariant quantization it is impossible to prove the absence of states with negative norm or to construct a gauge which could allow one to solve explicitly the constraint equations and to check up covariance, and in case of BRST quantization its nilpotency [13] .

Since in the general form the problem still seems to be sufficiently complex, in this work, just as in Ref. [3] , we consider the theory of open two-dimensional surface whose action is proportional to the swept volume. Using the method of construction of time-like gauge for relativistic surfaces [3] , in this work we construct a light-like gauge in which one can solve a part of constraint equations. A single equation, which remains unsolved, reflects the symmetry that was left in that gauge, analogous to the Weyl gauge $A_0 = 0$ in the Yang-Mills theory. At quantization of theory in this gauge, the Hamiltonian is positively defined; although the constraints are solved incompletely, states with negative norm are absent, and there exists a real possibility to check up covariance, since, though the Poincare group is realized nonlinearly, yet is not as much "nonlinearly" as at solving all constraints.

2. Light-Like Gauge.

The light-like gauge in the string theory enables one to solve explicitly all constraint equations in such a way that there remain D-2 independent transverse coordinates which then can be quantized canonically [5] . A considerable part of loop calculations was performed in this gauge [14] . Therefore, the construction of a gauge suitable for quantization in the surface theory is necessary for its successful study.

Consider a two-dimensional open surface M, whose action is proportional to the volume swept by its motion in the D-dimensional space-time [1,2,3] :

$$S = -T\int d\tau\, d\sigma_1 d\sigma_2\, \mathrm{Det}^{1/2} g = \int d\tau\, d\sigma_1 d\sigma_2 \mathcal{L} \tag{1}$$

where $g_{\alpha\beta} = x^{\mu}_{\alpha}\, x_{\mu\beta}$, $x^{\mu}_{\alpha} = \partial x^{\mu}/\partial \xi^{\alpha}$, $\xi^{\alpha} = (\tau, \sigma_1, \sigma_2)$, $\alpha, \beta = 0, 1, 2$; $x_{\mu}(\xi)$ is parametric representation of the swept volume, $\xi \in \Omega \times [\tau_{in}, \tau_{fin}]$. The motion equations have the form:

$$\partial_{\tau} P^{\tau}_{\mu} + \partial_{\sigma_a} P^{\sigma_a}_{\mu} = 0 \quad , \qquad a = 1,2 \tag{2}$$

where P^{τ}_{μ} and $P^{\sigma_a}_{\mu}$ are components of energy momentum current:

$$P^{\alpha}_{\mu} = -\partial \mathcal{L}/\partial x^{\mu}_{\alpha} = T g^{1/2} g^{\alpha\beta} x_{\mu\beta} \tag{3}$$

The constraint equations

$$P^{\tau}_{\mu} x^{\mu}_{\sigma_a} = 0 \; , \quad P^{\tau}_{\mu} P^{\tau\mu} = T^2 \left\{ x^2_{\sigma_1} x^2_{\sigma_2} - (x_{\sigma_1} x_{\sigma_2})^2 \right\}$$

$$P^{\tau}_{\mu} x^{\mu}_{\tau} + \mathcal{L} = 0 \tag{4}$$

are a consequence of invariance of action (1) under reparametrization transformation group $\bar{\xi} = \bar{\xi}(\xi)$:

$$M^{\alpha}_{\beta} = \partial \bar{\xi}^{\alpha}/\partial \xi^{\beta} \, , \qquad \bar{P}^{\mu\beta} = \frac{M^{\beta}_{\alpha}}{\det M} P^{\mu\alpha} . \tag{5}$$

So long as we consider the open surface theory, then the boundary conditions must hold [3] :

$$d\sigma_2 P_\mu^{\sigma_1} - d\sigma_1 P_\mu^{\sigma_2} \Big|_{\partial\Omega} = 0 \qquad (6)$$

while the surface boundary ∂M itself must be invariant under reparametrization transformations (5).

First of all, we identify τ with some combination of time and space coordinates:

$$nx = \lambda\tau \qquad (7)$$

where n is an arbitrary constant vector, such that $n^2 \geqslant 0$, and λ will be defined some later. From (5) we have

$$n\bar{P}^{\beta} = \frac{M_{\alpha}^{\beta}}{\det M} \, nP^{\alpha} \qquad (8)$$

and like in Ref. [3] we can construct such surface parametrization in which the momentum density in the direction $n - nP^{\tau}$ will be constant and proportional to total momentum:

$$nP^{\tau} = \frac{nP}{\pi^2} \qquad (9)$$

where total momentum is

$$P_\mu = \int d\sigma_1 \, d\sigma_2 \, P_\mu^{\tau} \qquad (10)$$

With the help of remained arbitrariness in the choice of parametrization we can attain a fulfilment of equality between components nP^{σ_1} and nP^{σ_2}:

$$nP^{\sigma_1} = nP^{\sigma_2} \qquad (11)$$

After fixing gauge conditions (7), (9) and (11), matrix M_α^β in (8) is determined yet ambiguously, since there are transformations, under which the conditions (7), (9), (11) remain unchanged. Indeed, to preserve conditions $nx = \lambda\tau$ and $nP^\tau = \text{const}$, it is necessary that the upper line of matrix M_α^β should have the form of (1, 0, 0), and its determinant should equal unity, det M = 1 [3], the second and third lines should preserve equality of components nP^{σ_1} and nP^{σ_2} :

$$\begin{pmatrix} nP^\tau \\ n\bar{P}_0^{\bar{\sigma}_1} \\ n\bar{P}_0^{\bar{\sigma}_2} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ g_t & g_{\sigma_1} & g_{\sigma_2} \\ h_t & h_{\sigma_1} & h_{\sigma_2} \end{pmatrix} \begin{pmatrix} nP^\tau \\ nP_0^{\sigma_1} \\ nP_0^{\sigma_2} \end{pmatrix}, \qquad \begin{matrix} nP^{\sigma_1} = nP^{\sigma_2} \\ n\bar{P}^{\bar{\sigma}_1} = n\bar{P}^{\bar{\sigma}_2} \end{matrix} \tag{8'}$$

where $\bar{\sigma}_1 = g(\sigma_1 \sigma_2 \tau)$, $\bar{\sigma}_2 = h(\sigma_1 \sigma_2 \tau)$. One may readily be convinced that here we have nontrivial solutions for g and h .

Consider a projection of motion equations (2) on the direction n :

$$\partial_\tau (nP^\tau) + \partial_{\sigma_a}(nP^{\sigma_a}) = \partial_{\sigma_a}(nP^{\sigma_a}) = (\partial_{\sigma_1} + \partial_{\sigma_2})\, nP^{\sigma_a} = 0 \tag{12}$$

whose solution has the form $nP^{\sigma_a} = \chi(\sigma_1 - \sigma_2)$, and in virtue of boundary conditions (6) $\chi = 0$ [3], i.e.

$$nP^{\sigma_1} = nP^{\sigma_2} = 0 \qquad (13$$

Now using the explicit form of $P_\mu^{\sigma_a}$ (3) and the condition (13), we obtain:

$$(x_\tau x_{\sigma_a}) = 0\,, \qquad a = 1, 2 \tag{14}$$

Thus, from (14) we have

$$P^{\tau}_{\mu} = T \frac{X^{\tau}_{\mu} (X^2_{\sigma_1} X^2_{\sigma_2} - (X_{\sigma_1} X_{\sigma_2})^2)}{\sqrt{X^2_{\tau} (X^2_{\sigma_1} X^2_{\sigma_2} - (X_{\sigma_1} X_{\sigma_2})^2)}} , \tag{15}$$

$$P^{\sigma_a}_{\mu} = T \frac{X^{\sigma_a}_{\mu} X^2_{\tau} X^2_{\sigma_{a+1}} - X^{\sigma_{a+1}} X^2_{\tau} (X_{\sigma_1} X_{\sigma_2})}{\sqrt{X^2_{\tau} (X^2_{\sigma_1} X^2_{\sigma_2} - (X_{\sigma_1} X_{\sigma_2})^2)}} . \tag{16}$$

From (15) and (9) it follows that

$$\lambda^2 \left(\frac{\pi^2 T}{(nP)} \right)^2 \left\{ X^2_{\sigma_1} X^2_{\sigma_2} - (X_{\sigma_1} X_{\sigma_2})^2 \right\} = X^2_{\tau} \tag{17}$$

and if we put

$$\lambda = \frac{nP}{(\pi^2 T)^{2/3}} \tag{18}$$

then in this gauge (7), (9), (11) we have

$$X^2_{\sigma_1} X^2_{\sigma_2} - (X_{\sigma_1} X_{\sigma_2})^2 = (\pi^2 T)^{-2/3} X^2_{\tau} ; \tag{19}$$

$$P^{\tau}_{\mu} = (\pi^2 T)^{-1/3} T X^{\tau}_{\mu} \tag{20}$$

$$P^{\sigma_a}_{\mu} = (\pi^2 T)^{1/3} T \left\{ X^{\sigma_a}_{\mu} X^2_{\sigma_{a+1}} - X^{\sigma_{a+1}}_{\mu} (X_{\sigma_1} X_{\sigma_2}) \right\} \tag{21}$$

3. Hamiltonian Formalism.

The time-like gauge in Ref. [3] is equivalent to the choice $n =$ $= (1, 0,\ldots)$; however, just like in the string theory [2] , we choose the vector n as light-like $n = (1, 1, 0, \ldots, 0)$, i.e. $n_- = 1$, $n_+ = 0$. Then the additional condition (9) means that

$$p_+^\tau = \frac{P_+}{\pi^2} \tag{22}$$

and condition (7) means that x^+ is proportional to τ :

$$x_+ = \frac{P_+}{(\pi^2 T)^{2/3}}\tau \tag{23}$$

Constraints (4) will be rewritten as

$$\frac{P_+}{\pi^2} x^-_{\sigma_1} = p_i^\tau x^i_{\sigma_1} \tag{24a}$$

$$\frac{P_+}{\pi^2} x^-_{\sigma_2} = p_i^\tau x^i_{\sigma_2} \tag{24b}$$

$$2\frac{P_+}{\pi^2} p_-^\tau = p^i_\tau p^\tau_i + T^2\left\{(x^i_{\sigma_1})^2 (x^i_{\sigma_2})^2 - (x^i_{\sigma_1} x^i_{\sigma_2})^2\right\} \tag{24c}$$

where $i = 2, \ldots, D$. Introduce the barycentric coordinate of surface M:

$$q_-(\tau) = \frac{1}{\pi^2}\int d\sigma_1 d\sigma_2 x_-(\sigma_1, \sigma_2, \tau) \tag{25}$$

Integrate (24a) over σ_1 :

$$x_- = c(\sigma_2, \tau) + \int_0^{\sigma_1} p_i^\tau x^i_\tau d\sigma_1' \tag{26}$$

Function C we shall find by differentiating (26) with respect to σ_2 and using (24b) and (25). Finally we have

$$x_- = q_-(\tau) + \frac{\pi^2}{P_+}\int_0^\pi d\sigma_1' d\sigma_2' \left\{\left(\frac{\sigma_1'}{\pi^2} - \theta(\sigma_1' - \sigma_1)\delta(\sigma_2' - \sigma_2)\right)\cdot p_i^\tau x^i_{\sigma_1'} + \right.$$

$$+\left(\frac{\sigma_2'}{\pi^2}-\delta(\sigma_1'-\sigma_2)\,\theta(\sigma_2'-\sigma_2)\right)P_i^{\tau}x^i_{\sigma_2'}\,-$$

$$-\frac{1}{2}\left(\frac{\sigma_1'\sigma_2'}{\pi^2}-\theta(\sigma_1'-\sigma_1)\,\theta(\sigma_2'-\sigma_2)\right)\left((P_i^{\tau}x^i_{\sigma_1'})_{\sigma_2'}+(P_i^{\tau}x^i_{\sigma_2'})_{\sigma_1'}\right)\Big\}. \tag{27}$$

After solving the constraint equations (24) we obtained D-2 variables x^i , P_i^{τ} instead of D-3 ones [3] . This is connected with the fact that the Frobenius condition [15] serves as the integrability condition of equations (24 a,b):

$$\varphi(\sigma_1\sigma_2)=P_i^{\tau}x^i_{\sigma_1}-P_i^{\tau}x_{\sigma_2}=0 \tag{28}$$

which remains as unsolved constraint. It reflects the fact that the gauge conditions (7), (9), (11) fix the gauge incompletely, being a consequence of residual symmetry (8').

With the help of the last equation in (4) and (24c) we can obtain the Hamiltonian:

$$H=P_i^{\tau}x^i_{\tau}-\mathcal{L}=2P_+P_-\frac{1}{(\pi^2T)^{2/3}}=$$

$$=\frac{\pi^2}{(\pi^2T)^{2/3}}\int d\sigma_1 d\sigma_2\left\{P_i^{\tau}P_i^{\tau}+T^2\left((x^i_{\sigma_1})^2(x^i_{\sigma_2})^2-(x^i_{\sigma_1}x^i_{\sigma_2})^2\right)\right\}. \tag{29}$$

If now, following Ref. [4] , we impose the Poisson brackets on all variables x^i and P_i^{τ}

$$\left\{x^i(\sigma),\,P_j^{\tau}(\sigma')\right\}=\delta_{ij}\,\delta(\sigma-\sigma') \tag{30}$$

then the Hamiltonian equations bring to correct equations of motion (2):

$$P_i^{\tau} = (\pi^2 T)^{-1/3} T x_{\tau}^{i} \,, \tag{31a}$$

$$\begin{aligned} T^{-1}(\pi^2 T)^{-1/3}\, \partial_{\tau} P_i^{\tau} &= \partial_{\sigma_1}\left(x^i_{\sigma_1}(x^j_{\sigma_2})^2 - x^i_{\sigma_2}(x^j_{\sigma_1} x^j_{\sigma_2})\right) + \\ &+ \partial_{\sigma_2}\left(x^i_{\sigma_2}(x^j_{\sigma_1})^2 - x^i_{\sigma_1}(x^j_{\sigma_1} x^j_{\sigma_2})\right) , \end{aligned} \tag{31b}$$

$$P_+ = \text{const} \,, \tag{31c}$$

$$\dot{q}_- = 2P_- = \frac{H}{P_+} \quad , \quad q_- = q_0^- + \frac{H}{P_+}\tau \tag{31d}$$

Equations of motion for X_- and P_-^{τ} are satisfied identically owing to (24c) and (27). It is necessary, just like in the string theory [5], to postulate the Poisson bracket between the independent variables q_-^0 and P_+:

$$\left\{ q_-^0 \,,\, P_+ \right\} = -1 \tag{32}$$

while the other Poisson brackets are taken zero. The Poisson bracket of the Hamiltonian (29) with constraint (28) vanishes:

$$\left\{ H \,,\, \varphi \right\} = 0 \tag{33}$$

so φ is a generator of infinitesimal transformations that remained after imposing additional conditions (7), (9), (11) (see transformation (8')). The action of this transformation on variables X^i and P_i^{τ} is given by the formula:

$$\delta x^{i}=\left\{x^{i},\varphi\varepsilon\right\}=\varepsilon_{\sigma_1}x^{i}_{\sigma_2}-\varepsilon_{\sigma_2}x^{i}_{\sigma_1}\,,$$

$$\delta P^{\tau}_{i}=\left\{P^{\tau}_{i},\varphi\varepsilon\right\}=\varepsilon_{\sigma_1}P^{\tau}_{i,\sigma_2}-\varepsilon_{\sigma_2}P^{\tau}_{i,\sigma_1}\,. \qquad (34)$$

4. Quantization.

At quantization of the theory in the light-like gauge (7), (9), (11), (22), (23) it is necessary to take into account the fact that not all initial constraints were solved. The Poisson brackets (30), (32) we shall replace by equal-time commutators [5]:

$$[x^{i}(\sigma),P^{\tau}_{j}(\sigma')]=i\,\delta^{i}_{j}\,\delta(\sigma-\sigma') \qquad (35a)$$

$$[x^{i}(\sigma),x^{j}(\sigma')]=[P^{\tau}_{i}(\sigma),P^{\tau}_{j}(\sigma')]=0 \qquad (35b)$$

$$[q^{-}_{o},P_{+}]=-i\,;[q^{-}_{o},x^{i}]=[q^{-}_{o},p^{i}]=[P_{+},x^{i}]=[P_{+},p^{i}]=0 \qquad (35c)$$

where $\sigma=(\sigma_1,\sigma_2)$, $i=2,\dots,D$. The other operators, X^{-} , P^{τ}_{-} , P^{τ}_{+} and X^{+} , are expressed through X^{i} , P^{τ}_{i} , q^{-}_{o} , P_{+} by means of relations (22), (23), (24c), (27). So long as between X^{i} and P^{τ}_{i} operators we have the constraint (28), then in quantization the latter must be taken into account in such a way that it should define subspace of physical states of the system:

$$\hat{\varphi}\,|\,\Psi_{Phys}\rangle=0 \qquad (36)$$

Such quantization scheme is intermediate between noncovariant [8,9,5] and covariant [4,5,6,7] ones and resembles the quantization of Yang-Mills fields in the Weyl gauge $A_0^a = 0$, since after imposing the gauge conditions $A_0^a = 0$ there remain gauge transformations depending only on space coordinates whose generators are constraints.

In this quantization scheme, contrary to the covariant one, where $[x^\mu(\sigma), p^\nu(\sigma')] = i g^{\mu\nu} \delta(\sigma - \sigma')$, the states with negative norm are absent, since only spatial components participate in (35a). Therefore, there is no need to solve eq. (36) either. On the other hand, just like in noncovariant string quantization, the invariance under the Poincare group may turn out violated, since operators x^-, P_-^τ are expressed nonlinearly through operators x^i and P_i^τ; so the invariance must be specially checked. In contrast with the string, here the covariance should be checked on subspace of physical states (36).

In quantum theory there arise ambiguities due to the transition to noncommuting quantities. These ambiguities, at noncovariant quantization, are eliminated in string theory by the requirement of hermiticity and Lorentz invariance of theory. The similar arguments may be used here too.

The work devoted to the verification of Lorentz invariance will be published elsewhere.

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Г.К.САВВИДИ
КАЛИБРОВКА СВЕТОВОГО КОНУСА В ТЕОРИИ РЕЛЯТИВИСТСКИХ ПОВЕРХНОСТЕЙ
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