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FINITE BRST-ANTIBRST TRANSFORMATIONS FOR THE THEORIES WITH GAUGE GROUP

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Following our recent results [P. Yu. Moshin, A. A. Reshetnyak, Nucl. Phys. B 888 (2014) 92], we discuss the notion of finite BRST-antiBRST transformations, with a doublet λ_a, $a = 1, 2$, of anticommuting (both global and field-dependent) Grassmann parameters. We find an explicit Jacobian corresponding to this change of variables in the theories with gauge group. Special field-dependent BRST-antiBRST transformations for the Yang-Mills path integral with s_a-potential (functionally-dependent) parameters $\lambda_a = s_a\Lambda$ generated by a finite even-valued functional Λ and the anticommuting generators s_a of BRST-antiBRST transformations, amount to a precise change of the gauge-fixing functional. This proves the independence of the vacuum functional under such BRST-antiBRST transformations and leads to presence of modified Ward identities. The form of transformation parameters that induces a change of the gauge in the path integral is found and is exactly evaluated for connecting two arbitrary R_ξ-like gauges. The finite field-dependent BRST-antiBRST transformations are used to generalize the Gribov horizon functional h_0, in the Landau gauge in BRST-antiBRST setting, in the Gribov–Zwanziger model and to find h_ξ corresponding to general R_ξ-like gauges in the form compatible with gauge-independent S-matrix.

Keywords: *gauge theories, BRST-antiBRST Lagrangian quantization, Yang-Mills theory, Gribov–Zwanziger model, field-dependent BRST-antiBRST transformations.*

1 Motivations

The principles of the special supersymmetries known as BRST symmetry [1, 2] and BRST-antiBRST symmetry [3–5] compose a basis of the modern quantization methods for gauge theories [6, 7]. Their peculiarities involve in the presence of a Grassmann-odd parameter μ and two Grassmann-odd parameters $(\mu, \bar{\mu})$, respectively. The latter parameters within the Sp (2)-covariant schemes of generalized Hamiltonian [8] and Lagrangian [9, 10] quantizations (see [11] as well) $(\mu, \bar{\mu}) \equiv (\mu_1, \mu_2) = \mu_a$ form an Sp (2)-doublet. These infinitesimal odd-valued parameters may be regarded both constants and field-dependent functionals to be used respectively for derivation of the Ward identities and for establishing of the gauge-independence of the corresponding partition function in the path integral approach.

In [12] the BRST transformations with a finite field-dependent parameter (FFDBRST) in the gauge theories with gauge group, i.e. Yang-Mills (YM) theories, whose quantum action is constructed by the Faddeev–Popov (FP) rules [13], were first introduced by means of a functional equation for the parameter in question, and used to provide the path integral with such a change of variables that would allow one to relate the quantum action given in a certain gauge with the one given in a different gauge however without it solving in the general setting. The problem of establishing a relation of the FP action in a certain gauge with the action in a different gauge, by using a change of variables induced by a FFDBRST transformation was solved in [14], thereby providing an exact relation between a finite parameter and a finite change of the gauge-fixing condition in terms of the gauge Fermion. In particular, this result implies the conservation of the number of physical degrees of freedom in a given YM theory with respect to FFDBRST transformations, which means the impossibility of relating the Yang-Mills theory to another theory, whose action may contain, in addition to the FP action, certain non-BRST invariant terms (such as the Gribov horizon functional [15] in the Gribov–Zwanziger theory [16]) in the same configuration space[1].

Note, first, the solution of a similar problem for arbitrary constrained dynamical systems in the generalized Hamiltonian formalism [22, 23] has been recently proposed in [24], second, for the general gauge theories, (possessing by reducible gauge symmetry and/or an open gauge algebra) an exact Jacobian generated by FFDBRST transformations in the path integral constructed according to the BV procedure [25] was obtained in [26] with resolution of the consistency of *soft BRST symmetry breaking* [27] problem.

Recently, we have proposed an extension of BRST-antiBRST transformations to the case of finite (both

[1] For some aspects in study of the Gribov copies problem in YM theories in covariant, Landau, maximal Abelian gauges see [17–21].

global and field-dependent) parameters for Yang-Mills in [28] and general gauge theories [29–31] within the BRST-antiBRST Lagrangian and generalized Hamiltonian quantization methods (obtained also in [32]). Here, we review the origin of the concept of finite BRST-antiBRST transformations, and study on a base of their properties its influence on the quantum structure of YM theory in the framework of BRST-antiBRST setting.

We use the conventions introduced in [28]. In particular, unless otherwise specified by an arrow, derivatives with respect to the fields are taken from the right, and those with respect to the corresponding antifields are taken from the left. The raising (lowering) of Sp (2) indices, $s^a = \varepsilon^{ab}s_b$, $s_a = \varepsilon_{ab}s^b$, is fulfilled by a constant antisymmetric metric tensor ε^{ab}, $\varepsilon^{ac}\varepsilon_{cb} = \delta^a_b$, subject to the normalization, $\varepsilon^{12} = 1$.

2 Proposal for Finite Field-Dependent BRST-antiBRST transformations

The generating functional of Green's functions for irreducible gauge theories with closed algebra within BRST-antiBRST Lagrangian quantization [9, 10] is given by

$$Z_F(J) = \int d\phi \ \exp\left\{\tfrac{i}{\hbar}\left[S_F(\phi) + J_A\phi^A\right]\right\} \ , \qquad (1)$$

depending on sources J_A with BRST-antiBRST-invariant quantum action

$$\begin{aligned} S_F(\phi) &= S_0(A) + 1/2 s^a s_a F(A,C) \\ &= S_0(A) + S_{\rm gf}(A,B) + S_{\rm gh}(A,C) + S_{\rm add}(C) \ , \end{aligned} \qquad (2)$$

determined on the total configuration space parameterized respectively by the classical, $Sp(2)$-duplet of ghost-antighost, Nakanishi-Lautrup fields $\phi^A = (A^i, C^{\alpha a}, B^\alpha)$ (subject to Grassmann parity $\varepsilon(\phi^A) \equiv \varepsilon_A$, $\varepsilon_A = (\varepsilon(A^i), \varepsilon(B^\alpha), \varepsilon(C^{\alpha a})) \equiv (\varepsilon_i, \varepsilon_\alpha, \varepsilon_\alpha + 1)$ in condensed notations and being the same as in FP method. The quantities S_0, F appear by classical gauge-invariant action and admissible gauge-fixing Bosonic functional chosen here in quadratic approximation, in case of YM theory (with $A^i = A^{\mu n}(x)$ given on d-dimensional Minkowski space and taking its values in the algebra Lie of $SU(N)$ gauge group for $\eta_{\mu\nu} = diag(-,+,...,+)$

$$S_0 = -1/4 \int d^dx F^n_{\mu\nu}F^{\mu\nu n}, n = 1,...,N^2-1, \qquad (3)$$

given in terms of the strength $F^{\mu\nu n} = \partial^{[\mu}A^{\nu]n} + f^{nop}A^{\mu 0}A^{\nu p}$ and

$$F_\xi(A,C) = -\frac{1}{2}\int d^dx \ \left(A^m_\mu A^{m\mu} - \xi/2\varepsilon_{ab}C^{ma}C^{mb}\right) \quad (4)$$

corresponding to R_ξ-family of the gauges (with $\chi_\xi(A,B) = \partial_\mu A^{\mu a} + \frac{\xi}{2}B^a = 0$) within FP rules for YM theories. The rest terms in (2) the gauge-fixing term $S_{\rm gf}$, the ghost term $S_{\rm gh}$, and the interaction term $S_{\rm add}$, quartic in C^{ma} are determined by,

$$\begin{aligned} S_{\rm gf} &= \int d^dx \left[\left(\partial^\mu A^m_\mu\right) + \xi/2B^m\right]B^m, \\ S_{\rm gh} &= \frac{1}{2}\int d^dx \left(\partial^\mu C^{ma}\right) D^{mn}_\mu C^{nb}\varepsilon_{ab}, \\ S_{\rm add} &= -\tfrac{\xi}{48}\int d^dx \ \ f^{mnl}f^{lrs}C^{sa}C^{rc}C^{nb}C^{md}\varepsilon_{ab}\varepsilon_{cd}. \end{aligned} \qquad (5)$$

The action (3) is invariant with respect to infinitesimal gauge transformations $\delta A^m_\mu = D^{mn}_\mu\zeta^n$ with arbitrary functions $\zeta^\alpha \equiv \zeta^n$ ($\varepsilon(\alpha) = 0$) on $R^{1,d-1}$, whereas the infinitesimal BRST-antiBRST transformations, $\delta\phi^A = s^a\phi^A\mu_a$, for YM theories in terms of anticommutiong generators s^a: $s^a s^a b + s^b s^a = 0$,

$$\begin{aligned} & s^a A^m_\mu = D^{mn}_\mu C^{na} \ , \\ & s^a\delta B^m = 1/2 f^{nml}\left(B^l C^{na} + (1/6) f^{lrs}C^{sb}C^{ra}C^{nc}\varepsilon_{cb}\right), \\ & s^b C^{ma} = \left(\varepsilon^{ab}B^m - (1/2)f^{mnl}C^{la}C^{nb}\right), \end{aligned} \qquad (6)$$

leave the action S_F and integrand $\mathcal{I}^F_\phi$ in $Z_F(0) =\equiv \int \mathcal{I}^F_\phi$ by invariant only in the 1-st order in μ_a.

To restore the total BRST-antiBRST invariance of S_F and $\mathcal{I}^F_\phi$ in the whole orders in μ_a we introduced in [28] finite transformations of ϕ^A with a doublet λ_a of anticommuting parameters, $\lambda_a\lambda_b + \lambda_b\lambda_a = 0$,

$$\phi^A \to \phi'^A = \phi^A + \Delta\phi^A = \phi'^A\left(\phi|\lambda\right) : \phi'\left(\phi|0\right) = \phi, \quad (7)$$

as the solution of the functional equation

$$G\left(\phi'\right) = G\left(\phi\right) \ \ \texttt{if} \ \ s^a G\left(\phi\right) = 0 \qquad (8)$$

for any regular functional $G(\phi)$ invariant under infinitesimal BRST-antiBRST transformations. The general solution of (8) permits to restore *finite BRST-antiBRST transformations* in a unique way $\phi^A \to \phi'^A$,

$$\phi'^A = \phi^A\left(1 + \overleftarrow{s}^a\lambda_a + \tfrac{1}{4}\overleftarrow{s}^2\lambda^2\right) \equiv \phi^A\exp\{\overleftarrow{s}^a\lambda_a\}, \quad (9)$$

where a set of elements $\{g(\lambda)\} = \{\exp\{\overleftarrow{s}^a\lambda_a\}\}$ forms Abelian two-parametric supergroup with odd generating elements λ_a. The BRST-antiBRST invariance of $\mathcal{I}^F_\phi$ means the validity of the relation,

$$\mathcal{I}^F_{\phi g(\lambda)} = \mathcal{I}^F_\phi, \qquad (10)$$

where we have used the fact established in [28] that under global finite transformations, corresponding to $\lambda_a = \text{const}$, the integration measure remains invariant.

3 Jacobian for Finite BRST-antiBRST transformations

As we have mentioned above the Jacobian of the change of variables generated by global finite transformations, is equal to 1:

$$\Im\left(\phi\right) = 0 \Longrightarrow \text{Sdet}\left(\frac{\delta\phi'}{\delta\phi}\right) = 1 \,\text{and}\, d\phi' = d\phi. \qquad (11)$$

At the same time for finite field-dependent transformations, we show in [28] that for the particular case of functionally dependent parameters $\lambda_a = \Lambda \overleftarrow{s}_a$, $(s^1\lambda_1 + s^2\lambda_2 = -s^2\Lambda)$ with a certain even-valued potential, $\Lambda = \Lambda(\phi)$, which is inspired by infinitesimal field-dependent BRST-antiBRST transformations with the parameters

$$\mu_a = \frac{i}{2\hbar}\varepsilon_{ab}\left(\Delta F\right)_{,A} X^{Ab} = \frac{i}{2\hbar}\left(s_a \Delta F\right) , \qquad (12)$$

for which with accuracy up to linear in ΔF terms the gauge independence of the integrand (therefore of the vacuum functional $Z_F(0)$) follows $\mathcal{I}^F_{\phi g(\mu(\Delta F))} = \mathcal{I}^{F+\Delta F}_\phi + o(\Delta F)$. In case of finite field-dependent transformations with group element $g(\Lambda\overleftarrow{s}_a)$ a set of which forms now non-Abelian 2-parametric supergroup, the superdeterminant of the change of variables takes the form

$$\mathrm{Sdet}\left(\frac{\delta(\phi g(\Lambda\overleftarrow{s}_a))}{\delta\phi}\right) = \left[1 - \frac{1}{2}s^2\Lambda\left(\phi\right)\right]^{-2} , \qquad (13)$$

$$d\phi' = d\phi \ \exp\left\{\tfrac{i}{\hbar}\left[i\hbar \ln\left(1 - \tfrac{1}{2}s^2\Lambda\right)^2\right]\right\} . \qquad (14)$$

4 Compensation equation for Yang-Mills actions in different gauges

In view of the invariance of the quantum action $S_F(\phi)$ under (9), the change $\phi^A \to \phi'^A = \phi^A g(\lambda(\phi))$ induces in (1) the following transformation of the integrand $\mathcal{I}^F_\phi$

$$\mathcal{I}^F_{\phi g(\lambda(\phi))} = d\phi \exp\left\{\tfrac{i}{\hbar}\left[S_F\left(\phi\right) + i\hbar \ln(1 - \tfrac{1}{2}s^2\Lambda)^2\right]\right\} .$$

Due to the explicit form of the initial quantum action $S_F = S_0 - (1/2)\,F\overleftarrow{s}^2$, the BRST-antiBRST-exact contribution $i\hbar \ln\left(1 + s^a s_a \Lambda/2\right)^2$ to the action S_F, resulting from the transformation of the integration measure, can be interpreted as a change of the gauge-fixing functional made in the original integrand $\mathcal{I}^F_\phi$,

$$i\hbar \ln\left(1 + s^a s_a \Lambda/2\right)^2 \ = \ s^a s_a\left(\Delta F/2\right) \qquad (15)$$

$$\Longrightarrow \mathcal{I}^F_{\phi g(\lambda(\phi))} = \mathcal{I}^{F+\Delta F}_\phi , \qquad (16)$$

for a certain $\Delta F\left(\phi|\Lambda\right)$, whose relation to $\Lambda\left(\phi\right)$ is established from (15) called in [28] as well as *compensation equation* on unknown parameter $\Lambda(\phi)$ to provide gauge independence of the vacuum functional, $Z_F(0) = Z_{F+\Delta F}(0)$. The explicit solution of (15) (which satisfies to the solvability condition because of BRST-antiBRST exactness of its both hand-sides) up to BRST-antiBRST-exact terms is given by the relations,

$$\Lambda\left(\phi|\Delta F\right) = 2\Delta F\left(s^a s_a \Delta F\right)^{-1}\left[\exp\left(\tfrac{1}{4i\hbar}s^b s_b \Delta F\right) - 1\right]$$
$$= \frac{1}{2i\hbar}\Delta F \sum_{n=0}^{\infty}\frac{1}{(n+1)!}\left(\frac{1}{4i\hbar}s^a s_a \Delta F\right)^n . \qquad (17)$$

And visa-verse having considered the equation (15) for unknown ΔF with given Λ we obtain

$$\Delta F\left(\phi\right) = -2i\hbar \ \Lambda\left(s^2\Lambda\right)^{-1}\ln\left(1 - s^2\Lambda/2\right)^2 \ . \qquad (18)$$

Thus, the field-dependent transformations with the parameters $\lambda_a = s_a\Lambda$ amount to a precise change of the gauge-fixing functional. E.g. to relate $Z_{F_\xi}(J)$ with $Z_{F_{\xi+\Delta\xi}}(J)$ in R_ξ- family of the gauges we should to fulfill FFDBRST-antiBRST transformations with parameters,

$$\lambda_a = \tfrac{\Delta\xi}{4i\hbar}\varepsilon_{ab}\int d^dx \ \left(B^n C^{nb}\sum_{n=0}^{\infty}\tfrac{1}{(n+1)!}\right)\left[\tfrac{\Delta\xi}{4i\hbar}\int d^dy\right.$$
$$\left.\times\left(B^u B^u - \frac{1}{24}f^{uwt}f^{trs}C^{sc}C^{rp}C^{wd}C^{uq}\varepsilon_{cd}\varepsilon_{pq}\right)\right]^n \qquad (19)$$

5 Gauge Dependence Problem and modified Ward identities

The property (16) leads in [30], first, to a so-called modified Ward identity, depending on field-dependent parameters $\lambda_a = \Lambda\overleftarrow{s}_a$ and therefore on finite change of the gauge due to (17),

$$\left\langle\left\{1 + \tfrac{i}{\hbar}J_A\left[X^{Aa}\lambda_a(\Lambda) - \tfrac{1}{2}Y^A\lambda^2(\Lambda)\right] - \tfrac{1}{4}\left(\tfrac{i}{\hbar}\right)^2\varepsilon_{ab}\right.\right.$$
$$\left.\left.\times J_A X^{Aa} J_B X^{Bb}\lambda^2(\Lambda)\right\}\left(1 - \tfrac{1}{2}\Lambda\overleftarrow{s}^2\right)^{-2}\right\rangle_{F,J} = 1, \ (20)$$

for $(s^a\phi^A, s^2\phi^A) \equiv (X^{Aa}, -2Y^A)$ and, second, to a relation which describes the gauge dependence of $Z_F(J)$ for a finite change of the gauge $F \to F + \Delta F$:

$$\Delta Z_F(J) = Z_F(J)\left\langle\tfrac{i}{\hbar}J_A\left[X^{Aa}\lambda_a\left(\phi| - \Delta F\right)\right.\right.$$
$$\left. -\tfrac{1}{2}Y^A\lambda^2\left(\phi| - \Delta F\right)\right] - (-1)^{\varepsilon_B}\left(\tfrac{i}{2\hbar}\right)^2 J_B J_A$$
$$\left.\times\left(X^{Aa}X^{Bb}\right)\varepsilon_{ab}\lambda^2\left(\phi| - \Delta F\right)\right\rangle_{F,J} . \qquad (21)$$

In (20), (21) the symbol "$\langle\mathcal{A}\rangle_{F,J}$" for a quantity $\mathcal{A} = \mathcal{A}(\phi)$ stands for the source-dependent average expectation value corresponding to a gauge-fixing $F(\phi)$

$$\langle\mathcal{A}\rangle_{F,J} = Z_F^{-1}(J)\int d\phi \ \mathcal{A}\left(\phi\right)\exp\left\{\tfrac{i}{\hbar}\left[S_F + J\phi\right]\right\}$$

with $\langle 1\rangle_{F,J} = 1$. Note, for constant λ_a from (20) follows an Sp(2)-doublet of the usual Ward identities at the first order in λ_a: $J_A\left\langle X^{Aa}\right\rangle_{F,J} = 0$ and a derivative identity at the second order in λ_a:

$$\left\langle J_A\left[2Y^A + (i/\hbar)\,\varepsilon_{ab}X^{Aa}J_B X^{Bb}\right]\right\rangle_{F,J} = 0 \ . \qquad (22)$$

6 Gribov-Zwanziger theory in BRST-antiBRST formulation in Landau and Feynman gauges

Because of the gauge-fixing functional F_0 corresponds to Landau gauge we introduce Gribov horizon functional in the same manner as in [16] in the FP procedure in Euclidian space

$$h(A) = \int d^dx \, \big(d^dy \; f^{mrl} A^r_\mu(x) K^{mn\,-1}(x;y) \; f^{nsl} A^{\mu s}(y) + d(N^2-1)\big). \tag{23}$$

with γ^2, $K^{mn}(x;y)$ being a Gribov mass parameter determined from implied gap equation and FP matrix. Proper not BRST-antiBRST-invariant action in F_0 reference frame looks as

$$S_h\,(\phi) = S_{F_0}\,(\phi) + \gamma^2 h\,(\phi)\ . \tag{24}$$

We determine the Gribov-Zwanziger theory in any F_ξ gauge (R_ξ-gauge) in a way compatible with gauge-independent property for generating functional of Green's functions in F_0 where Gribov Horizon in F_ξ gauge should be determined as

$$h_\xi = h\Big(1 + \frac{1}{2i\hbar}\,(\overleftarrow{s}^a)\,(\Delta F_\xi \overleftarrow{s}_a) \sum_{n=0}^{\infty} \frac{1}{(n+1)!} \times \Big(-\frac{1}{4i\hbar}\Delta F_\xi \overleftarrow{s}^2\Big)^n - \frac{1}{16\hbar^2}\,(\overleftarrow{s}^2)\,(\Delta F_\xi)^2 \times \Big[\sum_{n=0}^{\infty} \frac{1}{(n+1)!}\Big(-\frac{1}{4i\hbar}\Delta F_\xi \overleftarrow{s}^2\Big)^n\Big]^2\Big), \tag{25}$$

where ΔF_ξ is readily determined with account taken of (19); for details, see [28].

7 Conclusion

We have proposed the concept of finite BRST-antiBRST and FFDBRST-antiBRST transformations for Yang-Mills theories in the Sp(2)-covariant Lagrangian quantization. The Jacobian of the change of variables generated by FFDBRST-antiBRST transformations with functionally dependent parameters is exactly calculated. It is established that quantum YM action in different gauges is related to each other by means of FFDBRST-antiBRST transformations with functionally dependent parameters obtained as the solution of the compensation equation. The new Ward identity and gauge dependence problem for finite change of the gauge for generating functional of Green's functions is derived and studied. The Gribov-Zwanziger theory in BRST-antiBRST formulation is suggested and Gribov horizon functional in the way compatible with S-matrix gauge independence in the Feynman and arbitrary gauges is suggested.

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КОНЕЧНЫЕ БРСТ-АНТИБРСТ ПРЕОБРАЗОВАНИЯ ДЛЯ ТЕОРИЙ С КАЛИБРОВОЧНОЙ ГРУППОЙ

Следуя нашим результатам [P. Yu. Moshin, A. A. Reshetnyak, Nucl. Phys. B 888 (2014) 92], мы обсуждаем понятие конечных БРСТ-антиБРСТ преобразований с дуплетом λ_a, $a = 1, 2$, антикоммутирующих (как глобальных, так и зависящих от полей) грассмановых параметров. Мы непосредственно вычисляем якобиан, соответствующий этой замене переменных для теорий с калибровочной группой. Специальные зависящие от полей БРСТ-антиБРСТ преобразования для функционального интеграла полей Янга–Миллса с s_a-потенциальными (функционально-зависимыми) параметрами $\lambda_a = s_a\Lambda$, порожденными конечным Грассманово-четным функционалом Λ и антикоммутирующими генераторами s_a БРСТ-антиБРСТ преобразований, обеспечивают точную замену функционала, фиксирующего калибровку. Это доказывает независимость вакуумного функционала относительно таких БРСТ-антиБРСТ преобразований и приводит к наличию модифицированных тождеств Уорда. Найден вид параметров преобразований, которые индуцируют замену калибровки в функциональном интеграле, и они точно оцениваются для связи двух произвольных R_ξ-подобных калибровок. Конечные зависящие от полей БРСТ-антиБРСТ преобразования используются для обобщения функционала горизонта Грибова h_0, в калибровке Ландау в БРСТ-антиБРСТ постановке, в модели Грибова-Цванцигера для нахождения функционала h_ξ соответствующего общим R_ξ-подобным калибровкам в виде, совместном с калибровочной независимостью S-матрицы.

Ключевые слова: *калибровочные теории, БРСТ-антиБРСТ лагранжево квантование, теории Янга-Миллса, модель Грибова-Цванцигера, зависящие от полей БРСТ-антиБРСТ преобразования.*

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