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Topologically massive gauge theories and their dual factorized gauge-invariant formulation

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Abstract
There exists a well-known duality between the Maxwell–Chern–Simons theory and the 'self-dual' massive model in $(2+1)$ dimensions. This dual description may be extended to topologically massive gauge theories (TMGT) for forms of arbitrary rank and in any dimension. This communication introduces the construction of this type of duality through a reparametrization of the 'master' theory action. The dual action thereby obtained preserves the full gauge symmetry structure of the original theory. Furthermore, the dual action is factorized into a propagating sector of massive gauge-invariant variables and a decoupled sector of gauge-variant variables defining a pure topological field theory. Combining the results obtained within the Lagrangian and Hamiltonian formulations, a completed structure for a gauge-invariant dual factorization of TMGT is thus achieved.

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1. Introduction

A manifest realization of the gauge invariance principle implies that the original fields used to define any gauge theory do not generate physical configurations, since these fields are not gauge-invariant degrees of freedom. As a matter of fact, two general approaches to

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isolate genuine physical degrees of freedom are available. The first involves some gauge-fixing procedure in order to effectively remove the contributions of redundant gauge-variant degrees of freedom. However such gauge fixings usually suffer Gribov problems, except in some exceptional cases. The second approach consists of constructing a factorized dual formulation. Indeed, following a convenient redefinition of the gauge fields within the Lagrangian formulation, gauge-variant degrees of freedom are decoupled from the physical ones. There exists quite a number of examples of gauge theories where this kind of technique has been developed (and which is sometimes referred to as a 'dual projection' [1, 2]). The main difficulty arising for such a programme is the rare existence of such reparametrizations while at the same time being local and conserving the number of degrees of freedom. Moreover, field redefinitions within the covariant Lagrangian formulation are not necessarily associated with equivalent canonical transformations within the corresponding Hamiltonian formulation while preserving at each step gauge invariance.

Actually, the covariant extension from the Hamiltonian formulation to the Lagrangian first-order field theory turns out to be trivial in the infrared limit, namely when only the global sector of zero momentum modes is retained. In that case, any factorization or soldering technique is associated with a corresponding canonical transformation within the Hamiltonian formulation. However this feature does not necessarily survive for field theories. As an example, the soldering that fuses self-dual and anti-self-dual Lagrangians into the Maxwell–Chern–Simons–Proca theory cannot be associated with a canonical transformation within the Hamiltonian formulation [3], although it is the case in the infrared limit [4]. However, as is to be discussed presently, topologically massive gauge theories (TMGT) in which a topological term preserving exact gauge invariance generates a mass gap, do not encounter such restrictions. Through a local and linear field redefinition within the first-order Lagrangian formulation, or the associated canonical transformation within the Hamiltonian formulation, the dual action possesses the same gauge symmetry structure as the original theory and is factorized into a propagating sector of massive physical variables and a decoupled sector with gauge-variant variables defining a pure topological field theory (TFT, for a review see [5]).

In the following section, it is shown that in (2+1) dimensions the canonical transformation introduced in [6] within the Hamiltonian formulation is complementary to a dual projection for the Lagrangian first-order formulation of the Maxwell–Chern–Simons theory [2]. In the same way, the covariant extension of the factorization identified within their Hamiltonian formulation [6] leads to a dual projection for topologically massive gauge theories in any dimension and for all tensorial ranks, which has not been considered previously. These results hence provide a complete understanding of a novel general structure for TMGT, referred to as 'topological-physical' (TP) factorization, which involves both the Lagrangian and Hamiltonian formulations.

2. Dual factorization of the MCS theory

A topological Chern–Simons term generates mass [7] for a propagating spin one vector field A of which the Lagrangian density reads,

$$\mathcal{L}_{\mathrm{MCS}} = -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} + \frac{1}{4} \kappa \epsilon^{\mu\nu\rho} F_{\mu\nu} A_\rho, \qquad (1)$$

where the field scaling parameter e is real while κ is a real multiplicative constant. The reduction of a 'master' Lagrangian [8] accounts for the common origin of both the MCS and 'self-dual' Lagrangians [9]. The master Lagrangian is the first-order form of the MCS

Lagrangian after the introduction of gauge-invariant auxiliary fields f_μ, readily reducible through Gaussian integration,

$$\mathcal{L}^{2+1}_{\text{master}} = \tfrac{1}{2}e^2 f_\mu f^\mu + \tfrac{1}{4}\epsilon^{\mu\nu\rho}F_{\mu\nu}(2f_\rho + \kappa A_\rho). \qquad (2)$$

However, to a certain extent the reduction of the master Lagrangian as introduced in [8] is analogous to a procedure of gauge fixing. Indeed, the reduction of gauge-variant variables within the Lagrangian formulation is analogous to the resolution of the associated first-class 'Gauss' constraint within the Hamiltonian formulation.

In contradistinction to the master Lagrangian method [8], the dual factorized theory is constructed through a local and linear field redefinition, hence of a field-independent path-integral Jacobian, leading to a redefinition of the master action $S_{\text{master}}[A, f] \to S_{\text{SD}}[E, \mathcal{A}]$, namely

$$E_\mu(A_\mu, f_\mu) = f_\mu, \qquad \mathcal{A}_\mu(A_\mu, f_\mu) = \frac{1}{\kappa}f_\mu + A_\mu. \qquad (3)$$

This transformation resulting from the Lorentz covariant extension of the phase-space canonical transformation introduced in [6] is equivalent to that used in [2] and so the dual projection technique is recovered. Note that this field redefinition is well defined provided only the topological mass parameter κ is non-vanishing, $\kappa \neq 0$. Upon reduction through Gaussian integration, the gauge-invariant variables E_μ are found to correspond to the electric and magnetic field components,

$$E_i \equiv \varepsilon_{ij}E^j_{\text{elec}}, \qquad E_0 \equiv B_{\text{mag}}.$$

Consequently, a coherent reparametrization of configuration space is achieved. In fact, it factorizes the action into two decoupled contributions,

$$\mathcal{L}^{2+1}_{\text{fact}} = \mathcal{L}_{\text{SD}}[E_\mu, \partial_\mu E_\nu] + \mathcal{L}_{\text{CS}}[\mathcal{A}_\mu, \partial_\mu \mathcal{A}_\nu].$$

In deriving this expression, a total surface term mixing the two field variables has been ignored, since it does not contribute for any appropriate choice of boundary conditions. It may, however, play a role when the quantum field theory is defined on a manifold with boundaries.

The physical self-dual part $\mathcal{L}_{\text{SD}}$ consists of Proca and topological mass terms,

$$\mathcal{L}_{\text{SD}} = \frac{1}{2}e^2 E_\mu E^\mu - \frac{1}{2\kappa}\epsilon^{\mu\nu\rho}\partial_\mu E_\nu E_\rho.$$

This part describes a single propagating spin one free excitation of mass $m = \hbar\kappa e^2$ and violates parity. The second part $\mathcal{L}_{\text{CS}}$ consists of gauge-variant variables defining a purely topological Chern–Simons theory,

$$\mathcal{L}_{\text{CS}} = \tfrac{1}{2}\kappa\epsilon^{\mu\nu\rho}\partial_\mu \mathcal{A}_\nu \mathcal{A}_\rho.$$

This last part, already expected within the path-integral quantization approach [10], is absent from the dual Lagrangian when the master action method [8] is used in which case all the topological content inherited from the original Chern–Simons term is lost. In particular, non-trivial topological features become manifest in the presence of external sources, or when the space manifold Σ has non-trivial topology (see [11] and references therein). It is also noteworthy to mention that in the infrared limit dual projection techniques bring to the fore the existence of the Z_2 quantum anomaly of topological origin [4, 12].

As far as the local part of the theory is concerned, the fact that the pure Chern–Simons theory describes gauge fields of flat connection implies, in combination with (3), that

$$\kappa\varepsilon^{\mu\nu\rho}\partial_\mu \mathcal{A}_\nu = \kappa\varepsilon^{\mu\nu\rho}\partial_\mu A_\nu + \varepsilon^{\mu\nu\rho}\partial_\mu f_\nu \approx 0.$$

One recovers of course the condition for the reduction of the master action in [8], but in the present approach this condition is required as a weak constraint preserving the gauge content between the original and dual formulations.

3. Dual factorization of general TMGT

The equivalence between gauge non-invariant first-order mass generating theories for any p-form and TMGT has so far been shown in diverse dimensions through the Hamiltonian embedding due to Batalin, Fradkin and Tyutin (BFT), either partial [13] or complete [14], through the covariant gauge embedding method [15, 16] within the Lagrangian formulation, through the master action [17], etc. All methods developed so far share a common characteristic, namely that, in fact, the dual action does not possess the same gauge symmetry content as the original formulation. Hence at the quantum level, the equivalence between the two dual formulations applies only for pure theories defined on space manifolds of trivial topology.

The dual factorization approach of this communication readily applies to topological mass generation in any dimension and for all tensorial ranks. Given a real-valued p-form field A in $\Omega^p(\mathcal{M})$ and a $(d-p)$-form field B in $\Omega^{d-p}(\mathcal{M})$ over a $(d+1)$-dimensional spacetime manifold $\mathcal{M}$ endowed with a Lorentzian metric structure, the general action for TMGT reads

$$S[A,B] = \int_{\mathcal{M}} \frac{\sigma^p}{2e^2} F \wedge *F + \frac{\sigma^{d-p}}{2g^2} H \wedge *H + \kappa \int_{\mathcal{M}} (1-\xi) F \wedge B - \sigma^p \xi A \wedge H, \tag{4}$$

where $\sigma = (-1)$. The arbitrary real and dimensionless variable ξ introduced in order to parametrize any possible surface term is physically irrelevant for an appropriate choice of boundary conditions on $\mathcal{M}$. The field scaling parameters e and g are real. The action (4) is invariant under two independent classes of finite Abelian gauge transformations acting separately on either the A or B fields,

$$A' = A + \alpha, \qquad B' = B + \beta, \tag{5}$$

where α and β are, respectively, closed p- and $(d-p)$-forms, while the derived quantities $F = \mathrm{d}A$ and $H = \mathrm{d}B$ are the gauge-invariant field strengths of A and B, respectively. The last term in (4) is a topological 'BF' coupling between the two dynamical fields A and B. In $(3+1)$ dimensions, one recovers the Cremmer–Scherk action [18].

In order to construct the dual factorized action of TMGT, the original action (4) must be written in its first-order form after the introduction of gauge-invariant auxiliary $(d-p)$- and p-form fields $\mathfrak{f}$ and $\mathfrak{h}$, respectively,

$$S_{\text{master}} = \frac{e^2}{2}(\mathfrak{f})^2 + \frac{g^2}{2}(\mathfrak{h})^2 + \int_{\mathcal{M}} F \wedge \mathfrak{f} + H \wedge \mathfrak{h} + \kappa \int_{\mathcal{M}} (1-\xi) F \wedge B - \sigma^p \xi A \wedge H. \tag{6}$$

In (6), the inner product on $\Omega^k(\mathcal{M}) \times \Omega^k(\mathcal{M})$ is defined as

$$(\omega_k, \eta_k) = \int_{\mathcal{M}} \omega_k \wedge *\eta_k,$$

with the convenient notation $(\omega_k)^2 = \sigma^{d+1-k}(\omega_k, \omega_k)$. A simple local and linear transformation in the master action (6) of field-independent path-integral Jacobian and inducing the redefinition $S_{\text{master}}[A, B, \mathfrak{f}, \mathfrak{h}] \to S_{\text{fact}}[E, G, \mathcal{A}, \mathcal{B}]$, namely

$$\begin{aligned} E &= \mathfrak{f}, \qquad & \mathcal{A} &= A - \frac{1}{\kappa}\sigma^{p(d-p)}\mathfrak{h}, \\ G &= \mathfrak{h}, \qquad & \mathcal{B} &= B + \frac{1}{\kappa}\mathfrak{f}, \end{aligned} \tag{7}$$

enables the factorization of the theory into two decoupled sectors,

$$S_{\text{fact}}[E, G, \mathcal{A}, \mathcal{B}] = S_{\text{dyn}}[E, G] + S_{BF}[\mathcal{A}, \mathcal{B}]. \tag{8}$$

Once again this transformation is well defined provided the topological coupling κ does not vanish. The two total divergences mixing the variables $\mathcal{A}$ and $\mathcal{B}$ with E and G, respectively, are again parametrized by ξ.

The first contribution $S_{\rm dyn}[E, G]$ consisting of dynamical gauge-invariant variables reads as

$$S_{\rm dyn} = \frac{e^2}{2}(E)^2 + \frac{g^2}{2}(G)^2 + \frac{1}{\kappa}\int_{\mathcal{M}} \sigma^{d-p}\xi\, E \wedge {\rm d}G - (1-\xi)\,{\rm d}E \wedge G. \qquad (9)$$

The gauge-independent 'self-dual' action generalized to any dimension of [16, 17] is recovered. Depending on the value of the parameter ξ, the Proca action for a p- or $(d-p)$-form field is then readily identified through Gaussian integration. Indeed, by setting $\xi = 1$ and integrating out the then Gaussian auxiliary $(d-p)$-form field E, one derives the action of a p-form field G of mass $m = \hbar\mu$, with $\mu = \kappa e g$. Alternatively, one may also obtain the action of a $(d-p)$-form field E of mass $m = \hbar\mu$, by fixing $\xi = 0$ and eliminating the Gaussian p-form field G.

The second contribution $S_{BF}[\mathcal{A}, \mathcal{B}]$ to the dual factorized action (8) involves gauge-variant variables transforming as follows under the original Abelian gauge symmetries (5),

$$\mathcal{A}' = \mathcal{A} + \alpha, \qquad \mathcal{B}' = \mathcal{B} + \beta, \qquad (10)$$

and defines, in fact, once again a pure topological field theory of the BF type,

$$S_{BF} = \kappa \int_{\mathcal{M}} (1-\xi)\mathcal{F} \wedge \mathcal{B} - \sigma^p \xi \mathcal{A} \wedge \mathcal{H},$$

where $\mathcal{F} = {\rm d}\mathcal{A}$ and $\mathcal{H} = {\rm d}\mathcal{B}$. This decoupled TFT sector thus ensures that the gauge structure of the original theory is preserved through dual factorization. Moreover, as in the MCS case, the presence of this topological term, so far hardly evoked in the literature for very particular types of TMGT [19], has dramatic consequences. First, as described in [6] within the context of canonical quantization, this term controls the degeneracy of the physical spectrum of the original TMGT through topological invariants of the space manifold when it is of non-trivial topology. Second, this topological term could be of prime importance for theories where the p-form fields are connections coupled to extended objects carrying the associated relevant charges.

The transformation (7) is nothing other than the Lorentz covariant extension, in combination with the expressions for conjugate momenta, of the canonical transformation in the phase space of the original TMGT within their Hamiltonian formulation, as recently introduced in [6]. This covariant generalization emphasizes the universal character of the topological-physical factorization, whatever the formulation of the theory, hence leading to the following general and completed structure:

Lagrangian of TMGT (4)	Legendre transform $\Longleftrightarrow$ Constraints analysis	**Hamiltonian of TMGT**
$\Updownarrow$ Auxiliary fields		
Master Lagrangian		$\Updownarrow$ Canonical transformation
$\Updownarrow$ Factorization		
Factorized Lagrangian(8)	Legendre transform $\Longleftrightarrow$ Constraints analysis	**Factorized Hamiltonian [6]**

At first sight the introduction of the first-order form of the action (4) and thus the extension of the configuration space by auxiliary Gaussian fields seems artificial. As a matter of fact, to express directly the fields of the original Lagrangian formulation of TMGT as explicit functions of those of its dual formulation (8) turns out to be impossible because the two formulations do not possess the same numbers of degrees of freedom. Although the two formulations describe the same physics, there are extra auxiliary degrees of freedom in the dual formulation. Therefore, a convenient Lagrangian must be chosen among those leading to the same constrained Hamiltonian [20]. The convenient formulation is the first-order one (6) for which the comparison with the dual formulation is readily achieved from the local and linear transformation (7). This transformation simply redistributes the degrees of freedom, conserving the number of auxiliary fields and maintaining the gauge structure of the theory. In [6], where the dual topological-physical factorization was achieved within the Hamiltonian formulation, all second-class constraints are being reduced using Dirac brackets. Therefore, the two phase spaces possess already the same number of degrees of freedom at any given spacetime point and dualization is directly achieved. The first-order form of TMGT makes manifest the relation between the covariant field redefinitions within the Lagrangian formulation and the associated canonical transformations within the Hamiltonian formulation.

4. Conclusion

The possibility of the factorization introduced in this communication is intimately related to the fact that TMGT generate a mass gap. Indeed within the Hamiltonian formulation this mass gap involves the non-trivial dynamical global (or 'zero-mode') sector (which carries the structure of harmonic oscillators). It is then possible to factorize phase space through a canonical transformation which is obviously local, using the mass-gap parameter μ [6]. In this communication, this change of variables has been extended in a manifestly Lorentz covariant way by considering the first-order form of the original Lagrangian of TMGT. In comparison to other methods developed so far in the literature, the technique consisting in constructing the dual action for TMGT by a local and linear redefinition of the fields is, firstly, much more direct and, secondly, preserves the gauge symmetry content of the original action, while at each step maintaining manifest Lorentz covariance. In this sense, this type of dual projection method enables to isolate the physical content of the theory in a gauge-invariant way, the entire gauge-variant contributions residing only in the second sector of the action which reduces to a pure topological field theory. The relevance of our conclusions for general TMGT is confirmed by some results already achieved for particular types of TMGT within the path-integral framework [10, 19].

The appearance of this topological sector which ensures that the gauge symmetry content is maintained, has very intriguing consequences when TMGT are defined on topologically non-trivial manifolds [6] or are coupled to matter fields, whether of a fermionic or a bosonic character, since non-trivial topological effects then arise. The coupling to matter fields is currently under investigation. One result of interest established so far is that in the symmetry breaking phase, the effective Abelian Maxwell–Higgs Lagrangian is equivalent to a particular form of TMGT coupled to a real scalar 'Higgs' field in a very specific way [21].

Topological-physical factorization is the archetype of a more ambitious project whose basic ideas were suggested in a heuristic way in [22]. If this kind of technique is to turn out to be applicable to large classes of gauge-invariant theories generating a mass gap, it may offer perspectives in the development of new approximation schemes for non-perturbative dynamics.

In particular, it would be of great interest to understand whether similar considerations could apply to matter fields coupled to Yang–Mills theories in order to isolate the low-energy physical configurations coupled to the condensates of matter states which reside in the zero-mode sector.

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