Physics Letters B 757 (2016) 405–411

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Derivative self-interactions for a massive vector field

Jose Beltrán Jiménez [a], Lavinia Heisenberg [b,*]

[a] CPT, Aix Marseille Université, UMR 7332, 13288 Marseille, France
[b] Institute for Theoretical Studies, ETH Zurich, Clausiusstrasse 47, 8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 19 February 2016
Received in revised form 5 April 2016
Accepted 6 April 2016
Available online 11 April 2016
Editor: M. Trodden

ABSTRACT

In this work we revisit the construction of theories for a massive vector field with derivative self-interactions such that only the 3 desired polarizations corresponding to a Proca field propagate. We start from the decoupling limit by constructing healthy interactions containing second derivatives of the Stueckelberg field with itself and also with the transverse modes. The resulting interactions can then be straightforwardly generalized beyond the decoupling limit. We then proceed to a systematic construction of the interactions by using the Levi–Civita tensors. Both approaches lead to a finite family of allowed derivative self-interactions for the Proca field. This construction allows us to show that some higher order terms recently introduced as new interactions trivialize in 4 dimensions by virtue of the Cayley–Hamilton theorem. Moreover, we discuss how the resulting derivative interactions can be written in a compact determinantal form, which can also be regarded as a generalization of the Born-Infeld lagrangian for electromagnetism. Finally, we generalize our results for a curved background and give the necessary non-minimal couplings guaranteeing that no additional polarizations propagate even in the presence of gravity.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

1. Introduction

The discovery of the cosmic acceleration of the universe triggered a plethora of attempts to unveil the physical mechanism behind it. The simplest explanation comes about in the form of a cosmological constant, but its required small value, although not inconsistent, seriously challenges our theoretical understanding. A natural approach to these somewhat related problems, namely the cosmological constant and the cosmic acceleration, is resorting to infrared (IR) modifications of gravity. Since a gravitational theory based on a massless spin 2 particle needs to coincide with General Relativity (GR) at low energies, modifications of gravity on large distances inevitably lead to the introduction of additional degrees of freedom (dof). In numerous cases, IR modifications of gravity eventually boil down to one additional scalar mode. In the simplest scenarios, it corresponds to a canonical scalar field with a given potential and some couplings to matter. However, in more interesting frameworks, like e.g. the DGP model [1], the additional scalar field gives rise to a novel class of theories characterized by the presence of second order derivative interactions of the scalar field, while the field equations remain of second order, avoiding that way the rise of Ostrogradski instabilities. The properties of this scalar field were then generalized in [2] resulting in the class of Galileon theories. These theories are remarkable on their own right because of a number of features, namely: their field equations are explicitly second order even though second derivatives of the fields appear in the action, there is only a finite number of them and are invariant (up to a total derivative) under a constant shift of the field and its gradient, with important consequences for their naturalness under quantum corrections [3]. Interestingly, they have been shown to arise in a natural manner in IR modifications of gravity and played an important role in the construction of a consistent theory of massive gravity [4,5]. Moreover, although they modify gravity on large scales, there is a higher scale where new effects come in which is known as Vainshtein radius [6]. This is in fact a crucial property for the viability of these theories since the scalar field is screened below this scale.[1] The generalization of

* Corresponding author.
E-mail addresses: jose.beltran@cpt.univ-mrs.fr (J. Beltrán Jiménez), lavinia.heisenberg@eth-its.ethz.ch (L. Heisenberg).

[1] It is worth mentioning that for certain sub-classes of theories, the existence of a Vainshtein screening is not sufficient to avoid conflict with local gravity tests [7,8].

http://dx.doi.org/10.1016/j.physletb.2016.04.017
0370-2693/© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

these theories to include curvature effects led to the (re-)discovery of Horndeski actions as the most general actions for a scalar-tensor theory with second order equations of motion [9]. There exists also an interesting link between massive gravity and these interactions [10]. The Horndeski interactions are however not the most general theories propagating the 2 dof's of the graviton plus 1 additional dof in a scalar-tensor theory [11].

The construction of Galileon and/or Horndeski actions roots in the same structure found in the Lovelock invariants built by using the symmetry properties of the Levi–Civita tensor and the Bianchi identities. This is actually the reason why the Galileons are typically found in modifications of gravity in higher dimensional setups including Gauss–Bonnet or higher order Lovelock terms [12]. This line of reasoning was used in [13] to build Galileon-like lagrangians for arbitrary p-forms. There it was argued that Galilean interactions are not possible for massless spin 1 fields in 4 dimensions. A more exhaustive classification of Galilean interactions for arbitrary p-forms and in arbitrary dimension has been recently performed in [14], where it was confirmed the non-existence of massless vector Galileons in 4 dimensions. This no-go theorem does not extend however to the case of massive spin 1 fields where it is possible to build non-gauge invariant derivative self-interactions of the vector field while keeping the desired 3 propagating degrees of freedom. The key property of these theories is that the Stueckelberg field has the class of Galileon/Horndeski interactions so it only propagates one dof. Interestingly, this type of vector-tensor theories also arise naturally in some modifications of gravity with Gauss–Bonnet terms in Weyl geometries [15,16]. A classification of derivative vector self-interactions keeping 3 propagating degrees of freedom was carried out in [17]. A subclass of these with a coupling of the vector field to the Einstein tensor had been considered in [18] as a potential mechanism to generate cosmic magnetic fields. The case where the longitudinal model has Galilean self-interactions was considered in [19] and its covariantised version in [17,19,20]. Recently, it has been claimed in [21] that new derivative self-interactions different from those already found in literature exist and opened the possibility for an infinite series of such terms. This would mean that the massive vector field case is crucially different from its scalar counterpart where Galilean (or, more generally, Horndeski) terms form a finite set of lagrangians. In this note, we revisit this result and argue that the vector field case does resemble the scalar case and a finite series of terms (in a sense that will be made more explicit below) are allowed.

The paper is organized as follows. In the next section we start from the decoupling limit and construct general interactions for the Stueckelberg field containing up to its second derivatives. From this we will then construct theories beyond the decoupling limit. In Section 3 we will proceed to a systematic construction of the interactions for the massive vector field directly in the unitary gauge by making use of the Levi–Civita tensor. Along with this construction we will show that the higher order derivative self-interactions introduced in [21] vanish in 4 dimensions due to a non-trivial cancellation provided by the Cayley–Hamilton theorem. We will then show how the interactions can be nicely rewritten in a determinantal form, which allows to interpret the derivative self-interactions as a generalization of Born-Infeld electromagnetism. Finally, we consider the case of a curved spacetime and give the counter-terms that are needed to avoid additional propagating polarizations when gravity is turned on.

2. Decoupling limit of generalized Proca

Historically, the decoupling limit has proven to be advantageous in order to construct healthy theories. Its power lies in its ability to isolate a given degree of freedom and capture its relevant interactions. For instance, in the case of interacting gauge fields, this limit allows to decouple the longitudinal modes together with their self-interactions and study the processes in which they are involved without caring about the remaining transverse modes. The very same idea helped with the construction of a non-linear covariant theory of massive gravity without introducing the Boulware-Deser ghost [22]. In a bottom-up approach, the decoupling limit allowed to isolate the problematic interactions of the helicity-0 mode of the graviton and construct them in a healthy way [4]. Once the decoupling limit was under control, it was possible to extend it to a fully non-linear theory. In this section we shall follow an analogous course of action for the case of a Proca field with derivative self-interactions.

Similarly to the massive gravity case, the non-gauge invariant derivative self-interactions of the vector field might introduce an additional ghostly degree of freedom. In order to be more precise, let us resort to the Stueckelberg trick in order to restore the explicitly broken gauge invariance of a Proca field with mass M^2 so that we replace $A_\mu \to A_\mu + \partial_\mu \pi/M$ with π the Stueckelberg field, which will play the role of the longitudinal mode of the massive vector field. If we (carefully) take the limit when the mass goes to zero we can completely decouple π and study that sector separately. In the simplest case of a purely massive vector field with $U(1)$ couplings to matter, this limit simply leads to usual electromagnetism with the longitudinal mode being a completely decoupled free massless scalar field. Things are different when considering more general potentials or non-abelian gauge fields, which lead to non-linear sigma models.

It is the Stueckelberg field which we need to keep under control and make sure that it only propagates the one dof associated to the longitudinal polarization. Since this field does not contribute to the gauge invariant field strength tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, terms built out of $F_{\mu\nu}$ will not introduce the undesired mode. Similarly, since purely potential terms of the form $V(A^2)$ will only introduce first derivatives of the Stueckelberg, they will not add a fourth polarization either. However, when considering non-gauge invariant derivative terms like $(\partial_\mu A^\mu)^2$, the Stueckelberg field will generally acquire higher order derivatives and, thus, an additional mode suffering from the Ostrogradski instability will be present. This pathology can however be bypassed by properly constructing such terms. To that end, we will require the following conditions:

- The pure Stueckelberg field sector belongs to the Galileon/Horndeski class of lagrangians. Due to the origin of π, only the subclass with shift symmetry can be present.
- The couplings of second derivatives of π to the transverse modes must also lead to second order field equations.

The first condition will be relevant for the leading order in the decoupling limit with interactions purely constructed out of the Stueckelberg field. The second condition will be important for the terms with non-trivial couplings between the transverse modes and the Stueckelberg field. More explicitly, we will consider lagrangians depending on the vector field A_μ and its first derivatives $\partial_\mu A_\nu$. Since we want to explicitly separate the derivative interactions with non-trivial contributions for π, we will express the lagrangian as $\mathcal{L} = \mathcal{L}(A_\mu, F_{\mu\nu}, S_{\mu\nu})$ with $S_{\mu\nu} = \partial_\mu A_\nu + \partial_\nu A_\mu$. Moreover, we will introduce a given scaling for each object so that the corrections with respect to the pure Proca action admit an expansion of the form

$$\mathcal{L} \sim \sum_{m,n,p} c_{m,n,p} \left(\frac{A}{\Lambda_M}\right)^m \left(\frac{F}{\Lambda_F^2}\right)^n \left(\frac{S}{\Lambda_S^2}\right)^p , \tag{1}$$

Download English Version:

https://daneshyari.com/en/article/1848732

Download Persian Version:

https://daneshyari.com/article/1848732

Daneshyari.com