LORENTZ VIOLATION AND GRAVITY

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Gravitational theories with Lorentz violation must account for a number of possible features in order to be consistent theoretically and phenomenologically. A brief summary of these features is given here. They include evasion of a no-go theorem, connections between spontaneous Lorentz breaking and diffeomorphism breaking, the appearance of massless Nambu-Goldstone modes and massive Higgs modes, and the possibility of a Higgs mechanism in gravity.

1. Gravity and the SME

The Standard-Model Extension\(^1\) (SME) consists of the most general observer-independent effective field theory incorporating Lorentz violation. It is routinely used by both theorists and experimentalists to study and obtain bounds on possible forms of Lorentz violation.\(^2,3\) As an effective field theory, the SME can accommodate both explicit and spontaneous Lorentz breaking. However, there are differences in these two forms of symmetry breaking that arise in the context of gravity. This overview looks at these differences and what their primary consequences are.

In a gravitational theory with Lorentz violation it is useful to use a vierbein formalism. In this approach, both the local Lorentz frames and spacetime frames are accessible and linkage between the symmetries in these frames can be examined. The vierbein provides the connection between tensor components in local Lorentz frames and tensor components in the spacetime frame.

The Lagrangian in the SME is formed as the most general scalar function (under both local Lorentz and diffeomorphism transformations) using gravitational fields, particle fields, and Lorentz-violating SME coefficients. When the Lorentz breaking is explicit, the SME coefficients are viewed as fixed background fields. However, when the Lorentz breaking is spontaneous, the
SME coefficients are vacuum expectation values (vevs) of dynamical tensor fields.

In the gravity sector of the SME, a no-go theorem shows that with explicit Lorentz breaking an inconsistency can occur between conditions stemming from the field variations and symmetry considerations with geometrical constraints that must hold, such as the Bianchi identities. In contrast, the case of spontaneous Lorentz breaking was found to evade the no-go theorem. The main difference is that in a theory with explicit breaking the SME coefficients are not associated with dynamical fields, while with spontaneous Lorentz breaking they are, which creates a difference in the conditions that must hold. An important consequence of the no-go theorem is that the gravity sector of the SME can only avoid incompatibility with conventional geometrical constraints if the symmetry breaking is spontaneous.

2. Spontaneous symmetry breaking

The fact that the SME coefficients must be associated with vevs of dynamical fields that undergo spontaneous Lorentz violation leads to a number of effects that must be accounted for in the gravity sector of the SME. For example, when Lorentz symmetry is spontaneously broken, there is also spontaneous breaking of diffeomorphism symmetry. The spontaneous Lorentz breaking occurs when a nonzero tensor-valued vacuum occurs in the local Lorentz frames, which is necessarily accompanied by a vacuum value for the vierbein. When products of the vierbein vev act on the local tensor vevs, the result is that tensor vevs also appear in the spacetime frame. These tensor vevs spontaneously break local diffeomorphisms in the spacetime frame. Conversely, if a vev in the spacetime frame spontaneously breaks diffeomorphisms, then the inverse vierbein acting on it gives rise to vevs in the local frames. Consequently, spontaneous local Lorentz breaking implies spontaneous diffeomorphism breaking and vice versa.

With spontaneous symmetry breaking of both Lorentz and diffeomorphism symmetry, there are standard features in particle physics that need to be investigated. These include the possible appearance of massless Nambu-Goldstone (NG) modes and massive Higgs modes, or there is the possibility of a Higgs mechanism in which the NG modes are reinterpreted as additional degrees of freedom in a theory with massive gauge fields.

In the absence of a Higgs mechanism, there can be up to as many NG modes as there are broken spacetime symmetries. Since the maximal symmetry-breaking case would yield six broken Lorentz generators and four
broken diffeomorphisms, there can be as many as ten NG modes. A natural
gauge choice puts all of the NG modes into the vierbein. However, this will
in general lead to the appearance of ghosts, and it is for this reason that
most models involve breaking fewer than ten of the spacetime symmetries.

Spontaneous symmetry breaking is usually induced by a potential term
in the Lagrangian that has a degenerate minimum space. The NG modes
appear as excitations away from the vacuum that stay in the minimum
space, while massive Higgs modes are excitations that go up the potential
well away from the minimum. In conventional gauge theory, the potential
involves only scalar fields, and the massive Higgs modes are independent of
the gauge fields. However, with spontaneous Lorentz breaking, the metric
typically appears in the potential along with the tensor fields, and for this
reason massive Higgs modes can occur that include metric excitations. This
is an effect that has no analog in the case of conventional gauge theory.

In a Higgs mechanism, the would-be NG modes become additional de-
grees of freedom for massive gauge fields. The gauge fields associated with
diffeomorphisms are the metric excitations. However, a Higgs mechanism
involving the metric has been shown not to occur. This is because the
mass term that is generated by covariant derivatives involves the con-
nection, which consists of derivatives of the metric and not the metric itself.
However, for the broken Lorentz symmetry, where the relevant gauge fields
are the spin connection, a conventional Higgs mechanism can occur. This
is because the spin connection appears directly in covariant derivatives act-
ing on local tensor components, and when the local tensors acquire a vev,
quadric mass terms for the spin connection can be generated. Note, how-
ever, a viable Higgs mechanism involving the spin connection can only occur
if the spin connection is a dynamical field, which requires nonzero torsion
and that the geometry be Riemann-Cartan.

References
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