Gauge Theories for Target Spaces with Degenerate Metrics

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Abstract

Some gauge theories for fiber target spaces with degenerate metrics are regarded. The gauge theory with Galilei group $G(2)$ is obtained as a contraction of $SO(2)$ gauge theory with Higgs mechanism. The analogue of the standard electroweak theory for contracted $SU(2)$ group is considered. It is shown that the gauge field theory with degenerate metrics in target (matter) field space describe the same set of fields and particle mass as initial one, if Lagrangians in the base and in the fiber both are taken into account. Such theory based on non-semisimple contracted group provide more simple field interactions as compared with initial one. The conjecture is advanced that Higgs boson being an artefact of the Higgs mechanism is unobservable.

1 Introduction

Gauge field theory was suggested by Yang and Mills [1] and is regarded now as most powerfull method for unified description of fundamental interactions in particle physics, where the compact semisimple Lie groups seem to play the most fundamental roles. For example, in the standard Weinberg-Salam model [2], [3] of electroweak theory, the gauge group is $SU(2) \times U(1)$.

It was realized by Nappi and Witten [4] that one can also construct gauge theories for some non-semisimple groups (which admit a nondegenerate invariant bilinear form ) and such theories have much simpler structure than the standard theories with semisimple groups. Later the gauge theories, $\sigma$-models and solitonic hierarchies for different non-semisimple groups was investigated [5]–[8].

The aim of this talk is to regard some gauge theories based on non-semisimple Cayley-Klein groups. Such Cayley-Klein groups are invariance groups of spaces with degenerate metrics and can be obtained from the classical simple groups by contractions.

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2 Gauge theory for $SO(2)$ group

Let $\mathbb{R}_4$ is Minkowski space-time: $x_\mu x_\mu = x_0^2 - x_1^2 - x_2^2 - x_3^2$, $\mu = 0, 1, 2, 3$ and $\Phi_2$ is the target space, i.e. the space of fundamental representation of $SO(2)$ group, that elements named matter fields depend on $x \in \mathbb{R}_4$. Gauge transformations: $\phi'(x) = \omega(\alpha(x)) \phi(x)$, $\omega(\alpha(x)) \in SO(2)$ or

$$
\begin{pmatrix}
\phi'_1(x) \\
\phi'_2(x)
\end{pmatrix} =
\begin{pmatrix}
\cos \alpha(x) & \sin \alpha(x) \\
-\sin \alpha(x) & \cos \alpha(x)
\end{pmatrix}
\begin{pmatrix}
\phi_1(x) \\
\phi_2(x)
\end{pmatrix}
\tag{1}
$$

leave invariant the form $\phi^t \phi = \phi_1^2(x) + \phi_2^2(x)$ and define Euclid metrics in $\Phi_2$.

The Lagrangian is written as [9]

$$
L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} (D_\mu \phi)^t D_\mu \phi + \frac{\mu^2}{2} \phi^t \phi - \frac{\lambda}{4} (\phi^t \phi)^2,
\tag{2}
$$

where covariant derivatives are

$$
D_\mu \phi_1 = \partial_\mu \phi_1 + e A_\mu \phi_2, \quad D_\mu \phi_2 = \partial_\mu \phi_2 - e A_\mu \phi_1.
\tag{3}
$$

Here $e$ is the coupling constant, $A_\mu(x)$ is the gauge field and the field tensor is defined in the standard way $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.

Higgs mechanism [10] is the method of generation mass for gauge fields. A Lagrangian ground state is such configuration of fields $A_\mu, \phi_1, \phi_2$, that minimize theirs energy. There are a set of ground states

$$
(\phi_1^{\text{vac}})^2 + (\phi_2^{\text{vac}})^2 = \phi_0^2, \quad A_\mu^{\text{vac}} = \partial_\mu \alpha, \quad \phi_0 = \frac{\mu}{\sqrt{\lambda}},
\tag{4}
$$

which can be obtained by gauge transformations from one of them:

$$
A_\mu^{\text{vac}} = 0, \quad \phi^{\text{vac}} = \begin{pmatrix} \phi_0 \\ 0 \end{pmatrix}, \quad \phi_0 = \frac{\mu}{\sqrt{\lambda}},
\tag{5}
$$

as it is shown on Fig. 1.

Figure 1: Lagrangian ground states for $SO(2)$ gauge theory.
For small (linear) field excitations with respect to vacuum $A_\mu(x), \phi_1(x) = \phi_0 + \chi(x), \phi_2(x)$ Lagrangian (2) can be written as

$$L = L^{(2)} + L^{(3)} + L^{(4)},$$

where quadratic in fields $A_\mu, \chi, \phi_2$ Lagrangian

$$L^{(2)} = -\frac{1}{4}B_{\mu\nu}B_{\mu\nu} + \frac{e^2}{2}\phi_0^2B_{\mu\nu} + \frac{1}{2}(\partial_\mu\chi)^2 - \mu^2\chi^2,$$

$$B_\mu = A_\mu - \frac{1}{e\phi_0}\partial_\mu\phi_2, \quad F_{\mu\nu} = B_{\mu\nu}$$

describe massive vector field $B_\mu$, $m_V = e\phi_0 = \frac{e\mu}{\sqrt{\lambda}}$ — gauge field and massive scalar field $\chi$, $m_\chi = \sqrt{2}\mu$ — matter field (Higgs boson). Field interactions are given by $L^{(3)}$ and $L^{(4)}$

$$L^{(3)} = eA_\mu(\phi_2\partial_\mu\chi - \chi\partial_\mu\phi_2) + \phi_0\chi \left[ e^2A_\mu^2 - \lambda \left( \chi^2 + \phi_2^2 \right) \right],$$

$$L^{(4)} = \frac{1}{2} \left( \chi^2 + \phi_2^2 \right) \left[ e^2A_\mu^2 - \frac{\lambda}{2} \left( \chi^2 + \phi_2^2 \right) \right],$$

which include terms of third and fourth order in fields.

### 3 Gauge theory for Galilei group.

#### 3.1 Galilei group and Galilei geometry

Galilei space $\Phi_2(\iota)$ and Galilei group $G_2 = SO(2;\iota)$ can be obtained from $\Phi_2$ and $SO(2)$ by substitution: $\phi_2 \to j\phi_2, \alpha \to j\alpha$, where contraction parameter takes two values $j = 1, \iota$, $\iota^2 = 0, \iota/\iota = 1$. Gauge transformations

$$\begin{pmatrix} \phi'_1(x) \\ j\phi'_2(x) \end{pmatrix} = \begin{pmatrix} \cos j\alpha(x) & \sin j\alpha(x) \\ -\sin j\alpha(x) & \cos j\alpha(x) \end{pmatrix} \begin{pmatrix} \phi_1(x) \\ j\phi_2(x) \end{pmatrix}$$

leave invariant the form $\phi'(j)\phi(j) = \phi_1^2 + j^2\phi_2^2$, which for $j = 1$ define Euclid metrics in $\Phi_2$.

For $j = \iota$ Galilei (degenerate) metrics $\phi'(\iota)\phi(\iota) = \phi_1^2 + \iota^2\phi_2^2$ in the 2-dim fiber space $\Phi_2(\iota)$ is obtained, where $\{\phi_1\}$ is 1-dim base and $\{\phi_2\}$ is 1-dim fiber. There are **two invariants**: $\text{inv}_1 = \phi_1^2$ under the general transformations $\phi'(\iota) = \omega(\iota\alpha)\phi(\iota)$, where

$$SO(2;\iota) \ni \omega(\iota\alpha) = \begin{pmatrix} 1 & \iota\alpha \\ -\iota\alpha & 1 \end{pmatrix}, \alpha \in \mathbb{R}, \omega'(\iota\alpha)\omega(\iota\alpha) = 1$$

(10)
and \( \text{inv}_2 = \phi_2^2 \) under transformations in the fiber \((\phi_1 = 0)\). Therefore there are two metrics: one in the base and another in the fiber.

A bundle of lines through a point on this two planes has different properties relative to the plane automorphism \([\Pi]\). On Euclid plane, any two lines of the bundle are transformed to each other by rotation around the point. On Galilei plane, there is one isolated line that do not superposed with any other line of the bundle by Galilei boost.

If one interpret these planes in some physical context, then on Euclid plane all lines must have the same physical dimension \([\phi_1] = [\phi_2]\). On Galilei plane, there are infinite many lines with physical dimension identical with dimension of the base \([\phi_1]\) and one isolated line in the fiber with some different physical dimension \([\phi_2] \neq [\phi_1]\) (see [12] for details).

### 3.2 Gauge theory for Galilei group \(G_2\).

Gauge theory for \(SO(2;\iota) = G_2\) can be obtained from those for \(SO(2)\) by the substitution

\[
\phi_1 \rightarrow \phi_1, \quad \phi_2 \rightarrow j\phi_2, \quad A_\mu \rightarrow jA_\mu, \quad F_{\mu\nu} \rightarrow jF_{\mu\nu}, \quad \text{with } j = \iota. \tag{11}
\]

Full Lagrangian is split on the Lagrangian in the base

\[
L_b = \frac{1}{2} (\partial_\mu \phi_1)^2 + \frac{\mu^2}{2} \phi_1^2 - \frac{\lambda}{4} \phi_1^4, \tag{12}
\]

the Lagrangian in the fiber \((\approx j^2)\)

\[
L_f = -\frac{1}{4} F_{\mu\nu}^2 + \frac{1}{2} (\partial_\mu \phi_2)^2 + \frac{\mu^2}{2} \phi_2^2 + \frac{1}{2} \phi_1^2 (e^2 A_\mu^2 - \lambda \phi_2^2) + eA_\mu (\phi_2 \partial_\mu \phi_1 - \phi_1 \partial_\mu \phi_2), \tag{13}
\]

and higher order part \((\approx j^4)\)

\[
L_h = \frac{1}{2} \phi_2^2 \left( e^2 A_\mu^2 - \frac{\lambda}{2} \phi_2^2 \right), \tag{14}
\]

which disappear for \(j = \iota\).

Higgs mechanism is realized in three steps:

(i) the Lagrangian in the base \(L_b\) is maximal and the Lagrangian in the fiber is equal to zero \(L_f = 0\) at

\[
\phi_1 = \phi_0, \quad \phi_2 = 0, \quad A_\mu = \frac{1}{e} \partial_\mu \alpha, \quad F_{\mu\nu} = 0, \quad \lambda \phi_0^2 = \mu^2, \tag{15}
\]
where point $M(\phi_0, 0) \in \Phi_2(\iota)$ is one of the ground states;

(ii) gauge transformations

\[
\phi_1' = \phi_1, \quad \phi_2' = \phi_2 + \alpha \phi_1, \quad A'_\mu = A_\mu + \frac{1}{e} \partial_\mu \alpha, \quad F'_{\mu\nu} = F_{\mu\nu}, \quad (16)
\]

applied to $M$ define the set of ground states $\{\phi_1^2 = \phi_0^2, \phi_2 \in \mathbb{R}, A'_\mu = \frac{1}{e} \partial_\mu \alpha\}$ as sphere in $\Phi_2(\iota)$ (see Fig. 2);

(iii) field excitations around ground state $M$ are

\[
\phi_1(x) = \phi_0 + \chi(x), \quad \phi_2(x), \quad A_\mu(x). \quad (17)
\]

As a result we obtain the Lagrangian in the base

\[
L_b = \frac{1}{2} (\partial_\mu \chi)^2 - \mu^2 \chi^2 + L^{(3)}_b + L^{(4)}_b,
\]

\[
L^{(3)}_b = -\lambda \phi_0 \chi^3, \quad L^{(4)}_b = -\frac{\lambda}{4} \chi^4, \quad (18)
\]

which describe massive scalar field $\chi$, $m_\chi = \sqrt{2}\mu$ (Higgs boson) and its self interaction $L^{(3)}_b$, $L^{(4)}_b$ and the Lagrangian in the fiber

\[
L_f = -\frac{1}{4} B^2_{\mu\nu} + \frac{e^2 \phi_0^2}{2} B_\mu^2 + L^{(3)}_f + L^{(4)}_f,
\]

\[
L^{(3)}_f = e A_\mu(\phi_2 \partial_\mu \chi - \chi \partial_\mu \phi_2) + \phi_0 \chi (e^2 A^2_\mu - \lambda \phi_2^3),
\]

\[
L^{(4)}_f = \frac{1}{2} (e^2 A^2_\mu - \frac{\lambda}{2} \phi_2^2), \quad B_\mu = A_\mu - \frac{1}{e \phi_0} \partial_\mu \phi_2, \quad (19)
\]

which describe massive vector gauge field $B_\mu$, $m_V = e \phi_0 = \frac{\sqrt{2} \mu}{\sqrt{\lambda}}$ and field interactions.

So in the theory with Galilei gauge group $G_2$ matter field (Higgs boson) $\chi$ in the base and gauge field $B_\mu$ in the fiber have different physical dimensions. Nevertheless, the mass dimension of Higgs boson $m_\chi = \sqrt{2}\mu$ and vector boson $m_V = e \phi_0 = \frac{e \mu}{\sqrt{\lambda}}$ are identical and are the same as for $SO(2)$ gauge theory. More simple field interactions are provided by Galilei gauge theory as compared to $SO(2)$ one.

Figure 2: Ground states for Galilei gauge theory.
4 Electroweak theory and its contraction

4.1 Standard electroweak theory

Standard electroweak theory is constructed for gauge group $SU(2) \times U(1)$. Gauge fields $A^a_\mu$ ($a = 1, 2, 3$) correspond to $SU(2)$ and field $B_\mu$ correspond to $U(1)$. There are two coupling constants: $g$ for $SU(2)$ and $g'$ for $U(1)$. The fundamental representation space of $SU(2)$ is interpreted as the target space $\Phi_2(\mathbb{C})$. Matter fields $\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \in \Phi_2(\mathbb{C})$ are now complex ones $\phi_1, \phi_2 \in \mathbb{C}$.

Standard bosonic Lagrangian is written in the form

$$L = -\frac{1}{4} F^a_\mu F^a_\mu - \frac{1}{4} B_\mu B_\mu + (D_\mu \phi)^\dagger D_\mu \phi - \lambda \left( \phi^\dagger \phi - \frac{v^2}{2} \right)^2,$$  \hspace{1cm} (20)

where $D_\mu$ is covariant derivative

$$D_\mu \phi = \partial_\mu \phi - ig^a_2 \tau^a A^a_\mu \phi - ig'_2 B_\mu \phi,$$

$$\tau^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \tau^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \tau^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$ \hspace{1cm} (21)

Matrices $T^a = \frac{1}{2} \tau^a$ and $Y = \frac{1}{2}$ are generators of $SU(2) \times U(1)$. One of the Lagrangian ground states

$$\phi^{vac} = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}, \quad A^a_\mu = B_\mu = 0$$ \hspace{1cm} (22)

is taken as the vacuum. The matrix $Q = Y - T^3 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$ is generator of $U(1)_{em}$ subgroup, which annihilate ground state $Q \phi^{vac} = 0$. Linear field excitations with respect of vacuum

$$\phi_1(x) = \frac{1}{\sqrt{2}} (v + \chi(x)), \quad \frac{1}{\sqrt{2}} \phi_2(x), \quad A^a_\mu(x), \quad B_\mu(x)$$ \hspace{1cm} (23)

are regarded and new fields are introduced

$$W^\pm_\mu = \frac{1}{\sqrt{2}} (A^1_\mu \mp i A^2_\mu),$$

$$Z_\mu = \frac{1}{\sqrt{g^2 + g'^2}} (g A^3_\mu - g' B_\mu), \quad A_\mu = \frac{1}{\sqrt{g^2 + g'^2}} (g A^3_\mu + g' B_\mu),$$ \hspace{1cm} (24)
where $W^\pm_\mu$ are the complex fields $(W^-)^* = W^+_\mu$ and $Z_\mu, A_\mu$ are the real fields.

The second order Lagrangian

$$L^{(2)} = -\frac{1}{2} W^\pm_\mu W^{\pm}_\mu + m^2 W^+_\mu W^-_\mu - \frac{1}{4} F^\mu_\nu F_\mu^\nu - \frac{1}{4} Z^\mu_\nu Z^{\mu}_\nu + \frac{1}{2} m^2 Z^2 - \frac{1}{2} m^2 \chi^2$$

(25)

describe massive vector fields $W^\pm_\mu$, $m_W = \frac{1}{2} g v$ (W-bosons), massless vector field $A_\mu$, $m_A = 0$ (photon), massive vector field $Z_\mu$, $m_Z = \frac{g}{2} \sqrt{g^2 + g'^2}$ (Z-boson) and massive scalar field $\chi$, $m_\chi = \sqrt{2} \lambda v$ (Higgs boson). W- and Z-bosons are connected with the weak interaction, photon – with electromagnetic one.

W- and Z-bosons was experimentally observed: $m_W = 80\, GeV, \quad m_Z = 91\, GeV$. Higgs boson is unobserved up to now. $W^\pm_\mu, Z_\mu, A_\mu$ are the gauge fields, $\chi$ is the matter field. Higgs boson is arised in gauge theory with Higgs mechanism for any gauge group. Taking into account these arguments we advance the following

**Conjecture:**

Higgs boson is an artefact of the Higgs mechanism and therefore is unobservable.

### 4.2 Contraction of the electroweak theory to $SU(2; \iota) \times U(1)$ group

Compact simple group $SU(2)$ is defined as transformation group of $\Phi_2(\mathbb{C}) \equiv \mathbb{C}_2$

$$\omega \phi = \begin{pmatrix} \alpha & -\beta^* \\ \beta & \alpha^* \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \quad \omega \in SU(2), \quad \phi_1, \phi_2 \in \mathbb{C},$$

(26)

which leave invariant the form $\phi^\dagger \phi = |\phi_1|^2 + |\phi_2|^2$. Here $|\alpha|^2 + |\beta|^2 = 1$.

Non-compact non-semisimple contracted group $SU(2; \iota)$ and fiber complex space $\Phi_2(\iota)$ can be obtained from $SU(2)$ and $\Phi_2$ by the substitution:

$$\phi_2 \rightarrow j \phi_2, \quad \beta \rightarrow j \beta, \quad j = \iota,$$

(27)

then $|\alpha|^2 + \iota^2 |\beta|^2 = |\alpha|^2 = 1$, i.e.

$$SU(2; \iota) \ni \omega(\iota) = \begin{pmatrix} e^{i\phi} & -i \beta^* \\ i \beta & e^{-i\psi} \end{pmatrix}, \quad \psi \in [0, 2\pi), \quad \beta \in \mathbb{C}.$$ 

(28)

The fundamental representation of $SU(2; \iota)$ group is unitary $\omega(\iota) \omega(\iota)^\dagger = 1$. The space $\Phi_2(\iota)$ is 2-dim complex fiber space with degenerate metrics

$$\phi^\dagger(\iota) \phi(\iota) = |\phi_1|^2 + \iota^2 |\phi_2|^2,$$

(29)
where \( \{ \phi_1 \} \) is the complex base and \( \{ \phi_2 \} \) is the complex fiber. There are two invariants: \( \text{inv}_1 = |\phi_1|^2 \) under the general transformations
\[
\phi_1' = e^{i\psi}\phi_1, \quad \phi_2' = e^{-i\psi}\phi_2 + \beta \phi_1
\]
and \( \text{inv}_2 = |\phi_2|^2 \) under the transformations in the fiber \( \phi_1 = 0, \, \phi_2' = e^{-i\psi}\phi_2 \). Therefore there are two metrics: one in the base and another in the fiber.

Contraction of the standard electroweak theory to \( SU(2;\iota) \times U(1) \) gauge group is obtained by the substitution:
\[
\phi_1 \rightarrow \phi_1, \quad \phi_2 \rightarrow j\phi_2, \quad A^3_{\mu} \rightarrow A^3_{\mu}, \quad A^1_{\mu} \rightarrow jA^1_{\mu}, \quad A^2_{\mu} \rightarrow jA^2_{\mu},
\]
(31)
or for new fields:
\[
\chi \rightarrow \chi, \quad A_{\mu} \rightarrow F_{\mu\nu}, \quad Z_{\mu} \rightarrow Z_{\mu} \Rightarrow Z_{\mu
u} \rightarrow Z_{\mu\nu}, \quad W_{\mu} \rightarrow jW_{\mu} \Rightarrow W_{\mu\nu} \rightarrow jW_{\mu\nu}.
\]
(32)

The second order Lagrangian
\[
L^{(2)}(j) = \frac{1}{4} F_{\mu\nu}F_{\mu\nu} - \frac{1}{4} Z_{\mu\nu}Z_{\mu\nu} + \frac{1}{2} m_Z^2 Z_{\mu} Z_{\mu} + \frac{1}{2} (\partial_{\mu}\chi)^2 - \frac{1}{2} m_\chi^2 \chi^2 + j^2 \left[ -\frac{1}{2} W^+_{\mu\nu} W^-_{\mu\nu} + m_W^2 W^+_{\mu\nu} W^-_{\mu\nu} \right]
\]
(33)
for \( j = \iota \) is split on the Lagrangian in the base
\[
L^{(2)}_b = -\frac{1}{4} F_{\mu\nu}F_{\mu\nu} - \frac{1}{4} Z_{\mu\nu}Z_{\mu\nu} + \frac{1}{2} m_Z^2 Z_{\mu} Z_{\mu} + \frac{1}{2} (\partial_{\mu}\chi)^2 - \frac{1}{2} m_\chi^2 \chi^2,
\]
(34)
which describe the gauge fields \( A_{\mu}, Z_{\mu} \), as well as the matter field \( \chi \) (Higgs boson) and the Lagrangian in the fiber \( (\approx \iota^2) \)
\[
L^{(2)}_f = -\frac{1}{2} W^+_{\mu\nu} W^-_{\mu\nu} + m_W^2 W^+_{\mu\nu} W^-_{\mu\nu},
\]
(35)
which describe the gauge fields \( W^\pm_{\mu} \).

As regards the field interactions, then, for example, in the interactions of all fields with electromagnetic field
\[
-\frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} = -\frac{1}{4} (F_{\mu\nu} \sin \theta_w + Z_{\mu\nu} \cos \theta_w)^2 - \frac{j^2}{2} \left[ |D_{\mu} W^-_{\nu} + ig \left( Z_{\mu} W^-_{\nu} - Z_{\nu} W^-_{\mu} \right) |^2 + +ig (F_{\mu\nu} \sin \theta_w + Z_{\mu\nu} \cos \theta_w) \left( W^-_{\mu\nu} W^+_{\nu\mu} - W^+_{\mu\nu} W^-_{\nu\mu} \right) \right] + j^4 \frac{1}{4} g^2 \left( W^-_{\mu\nu} W^+_{\nu\mu} - W^+_{\nu\mu} W^-_{\nu\mu} \right)^2,
\]
(36)
the terms \( (\approx j^4) \) disappear under contraction \( j = \iota \), whereas those \( (\approx j^2) \) are included in \( L_f \).

Similar to the Galilei gauge theory, in the contracted electroweak theory the same fields with the same particle mass spectrum as for standard theory are reproduced but more simple field interactions are provided.
5 Conclusion

Single contracted Cayley-Klein group is the motion group of its fundamental representation space, which has two metrics: one in the base and another in the fiber. This means that for the complete description of a physical system in such space it is necessary to regard two Lagrangians. The gauge field theory with degenerate metrics in target (matter) field space describe the same set of fields and particle mass as initial one, if Lagrangians in the base and in the fiber both are taken into account.

Since it is the structure constants that determine the interactions and since under contractions of Lie group some structure constants of its algebra turn to zero, the gauge field theory based on non-semisimple contracted group provide more simple field interactions as compared with initial one.

The experimental observation of the gauge field particles predicted by the standard electroweak theory and unobservation of the single matter field as well as the presence of Higgs boson in any gauge theory with Higgs mechanism suggests the following

**Conjecture:**

*Higgs boson is an artefact of the Higgs mechanism and therefore is unobservable.*

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