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VACUUM INSTABILITY, COSMOLOGY AND CONSTRAINTS ON
PARTICLE MASSES IN THE WEINBERG-SALAM MODEL

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VACUUM INSTABILITY, COSMOLOGY AND CONSTRAINTS ON PARTICLE
MASSES IN THE WEINBERG-SALAM MODEL.

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Abstract

A set of constraints on the masses of particles in the Weinberg-Salam model is obtained. It is shown in particular, that in the absence of superheavy fermions ($m_f \lesssim 100$ GeV) the mass of the Higgs meson should exceed 9 GeV. It is noted that for certain relations between particle masses symmetry breaking in gauge theories is determined not by the usual energetical considerations but by the lepton asymmetry of the Universe.

Some years ago it was shown that at certain relations between particle masses radiative corrections may lead either to the absence of spontaneous symmetry breaking in gauge theories [1,2], or vice versa to an extremely strong dynamical symmetry breaking [3,4]. This effect can be easily understood e.g. in the Weinberg-Salam model [5], where ^{the} effective potential $V(\varphi)$ at the classical level is given by

$$V(\varphi) = -\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{4}\varphi^4, \quad (1)$$

where φ is the classical Higgs scalar field, μ_0 and λ_0 are some constants, see Fig. 1, curve A. In the one-loop approxi-

$$V(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \frac{1}{64\pi^2} \left(\sum_H m_H^4 \ln \frac{m_H^2}{\mu^2} + 3 \sum_V m_V^4 \ln \frac{m_V^2}{\mu^2} - 4 \sum_F m_F^4 \ln \frac{m_F^2}{\mu^2} \right), \quad (2)$$

where μ and λ are some new (calculable) constants, m_H , m_V and m_F are respectively the masses of the Higgs mesons, vector particles and fermions [1,2,4]. As it was shown in [1,2], the masses of vector particles being much greater than the masses of the Higgs mesons and fermions, the effective potential (2) has an additional minimum at $\varphi = 0$, and (in the theory with one Higgs meson) this minimum becomes even more deep than the ordinary minimum at $\varphi = \sigma \neq 0$ for

$$m_H^2 < \frac{1}{16\pi^2\sigma^2} \left(3 \sum_V m_V^4 - 4 \sum_F m_F^4 \right), \quad (3)$$

see Fig. 1, curve B. In the Weinberg-Salam model without very heavy fermions and with $\sin^2\theta_W \sim 0.22$ (θ_W is the Weinberg angle) the condition $V(\sigma) < V(0)$ leads to a constraint [1,2]

$$m_H \geq 6.8 \text{ GeV} . \quad (4)$$

On the other hand, if superheavy fermions do exist, then from (2) it follows, that the effective potential at $\varphi \rightarrow \infty$ becomes unbounded from below, Fig. 1, curve G. For the vacuum stability at $\varphi = \sigma$ it is necessary that $V(\sigma) < V(\infty)$, from which with the account taken of the equality

$$m_H^2 = 3\lambda\varphi^2 - \mu^2 \quad \text{it follows that}$$

$$\frac{3}{4} m_H^4 > 4 \sum_F m_F^4 - 3 \sum_V m_V^4 . \quad (4)$$

At $\varphi \rightarrow \infty$ one-loop expression (2) becomes unreliable, but nevertheless one can show, that for

$$m_H^4 \ll 4 \sum_F m_F^4 - 3 \sum_V m_V^4 \quad (5)$$

there exist such large values of φ for which the one-loop approximation is still reliable, and $V(\varphi) < V(\infty)$. Therefore the existence of superheavy fermions satisfying inequality (5) would imply vacuum instability with respect to a superstrong dynamical symmetry breaking. This result has been first obtained by Krive and the author in the context of the linear σ -model [3], and has been further generalized for the theories of a more general type, including the Weinberg-Salam model, in ref. [4]. Some years later the same results together with numerical estimates have been obtained independently by Krasnikov [6], by Phan Quang Hung [7] and by Politzer and Wolfram [8]. Quite recently a very similar investigation has been carried out by Cabibbo, Maiani, Parisi and Petronzio in application to the grand unified theories [9]. However

neither of these works has contained an investigation of the lifetime of the metastable vacuum states in the Weinberg-Salam model, which correspond to local but not absolute minima of $V(\varphi)$. This question is very important, since according to ref. [10] the lifetime of the metastable vacuum states may appear to be much greater than the age of the Universe, and in this case vacuum instability, which exists for certain relations between particle masses (3), (5)¹⁴, is not dangerous at all.

The first attempt to analyse this problem in the Weinberg-Salam model without heavy fermions is due to Frampton [11]. Unfortunately, however, the approximation, used in ref. [11], is not quite applicable to the problem, and (which is more important) the effects, connected with the high-temperature symmetry restoration in the early Universe [12] have not been considered. A more complete investigation of the decay of the metastable vacuum state with the account taken of the vacuum fluctuations, high-temperature effects and the effects connected with the Universe evolution, is contained in ref. [13] (see also [14]). The result is that even with the account taken of high-temperature thermodynamic fluctuations, stimulating tunneling from the metastable to the stable vacuum, the lifetime of the metastable vacuum is less than the age of the Universe only if the corresponding local minimum of $V(\varphi)$ is not deep and the curvature of the effective potential $\frac{d^2 V}{d\varphi^2}$ in the metastable vacuum state is not greater than $\sim 0.1 \text{ GeV}^2$ [13, 14].

This result makes it possible to obtain some new constraints on the Higgs meson mass. As it was mentioned above, the high-temperature effects lead to symmetry restoration in gauge theories (for a review see [14]). This means that at $t \rightarrow 0$, where t is the time from the beginning of the Universe evolution, the only minimum of the effective potential was at $\varphi = 0$ and the transition to the state $\varphi = \sigma \neq 0$ is possible only if the quantity $\mu^2 = \frac{d^2V}{d\varphi^2}|_{\varphi=0}$ at vanishing temperature is negative or extremely small ($\mu^2 \lesssim 0.1 \text{ GeV}^2$). This leads to a rather strong constraint on the Higgs meson mass

$$m_H > 9.6 \text{ GeV.} \quad (6)$$

for $\sin\theta_w \sim 0.22$ [13, 14].

One should realize that in several cases symmetry at $t \rightarrow 0$ could remain broken. This is possible if there

exists enormously large excess of neutrinos over antineutrinos, such that $L \gtrsim 10^8 B$, where L and B are lepton and baryon charge densities of the Universe [14]. Symmetry could remain broken at $t \rightarrow 0$ also in some theories with many heavy Higgs mesons with very special relations between their coupling constants [16]. In both cases initial vacuum state would correspond to $\varphi \neq 0$, and for the absence of the tunneling to the state $\varphi = 0$ the Higgs meson mass should exceed several hundred MeV [13, 14]. This is not a very strong constraint, but the both conditions, for which symmetry could remain broken at $t \rightarrow 0$, seem rather unnatural and unlikely. Therefore we believe that the most reasonable constraint on the Higgs meson mass is the one obtained above: $M_H > 9.6 \text{ GeV}$.

In the Weinberg-Salam model with superheavy fermions the problem of the metastable vacuum decay is more involved than in the case considered above. Some preliminary estimates indicate, that even with the account taken of the high-temperature thermodynamical fluctuations the lifetime of the vacuum state at $\varphi = 0$ is always much greater than the age of the Universe. Until this problem is not finally solved, the corresponding constraints on the fermion masses (5) should not be taken too seriously, though the possibility that for some unknown reasons we live on the top of the effective potential seems rather unlikely.

A complete set of constraints on M_H and M_F is plotted in Fig. 2 for the theory with one Higgs meson and one

fermion ²⁾. The region of absolutely forbidden values of m_H and m_F (region under the curve AB) is rather small. The region of the most probable values of m_H and m_F (see the discussion above) is plotted on Fig. 3, and to our opinion just this region should be considered when planning an experimental search for the Higgs mesons and heavy fermions.

In conclusion we would like to make a general observation, based on the analyses of the problem of symmetry breaking in the Weinberg-Salam model [13, 14]. As it can be seen by a comparison of Figs. 2 and 3, neither the region of the most probable values of m_H and m_F , nor the region of all possible values of m_H and m_F coincide with the region of the absolute vacuum stability AB'CD, Fig. 2. This means that symmetry breaking in a theory, in which metastable vacuum states are possible (in particular in the Weinberg-Salam model), is determined not by the usual energetical considerations, but by the physical processes at the early stages of the Universe evolution, at which the vacuum state of the theory has been formed.

Note added. After this work was written a paper of J.S.Kang [17] became known to the author. In this paper it is claimed

²⁾ For quarks the constraints on m_F plotted on fig. 2 should be divided by $\sqrt{3} \approx 1.73$, since there should exist three types of each quark with different colours. This means that for $m_H \ll m_W, m_Z$ the quark masses should not be greater than ~ 80 GeV.

that radiative corrections shift the position of the minimum of $V(\varphi)$ at $\varphi = \sigma$, and therefore strongly modify the masses of vector mesons and the lifetime of the muon decay if the Higgs meson mass is sufficiently small. This would lead to a rather strong constraint on the Higgs meson mass: $m_H \gtrsim 10-20$ Gev [17]. To our opinion, however, this constraint is an artifact of the renormalization prescription used in [17]. Indeed, in [17] the unphysical parameter $\frac{d^2V}{d\varphi^2} \big|_{\varphi=0}$ was fixed by the renormalization condition, and the value of σ was free to change. However σ is a physical quantity, $\sigma = 247$ Gev, and it should be fixed by a correct renormalization procedure in all orders of perturbation theory, like the value of the fine structure constant $\alpha \sim \frac{1}{137}$ in QED. Just such a renormalization procedure, fixing the position of the minimum of $V(\varphi)$ at $\sigma = 247$ Gev, is accepted in all the papers [1-9]. As a result the value of σ in the conventional renormalization procedure is not changed by radiative corrections (see Fig.1) and the abovementioned constraint on m_H , obtained in [17], disappears.

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Figure captions

Fig. 1. Effective potential $V(\varphi)$ in the Weinberg-Salam model.

A, $V(\varphi)$ at the classical level; B, modification of $V(\varphi)$ due to quantum corrections for $m_H^2 < \frac{1}{16\pi^2 G^2}$ ($3\sum_V m_V^4 - 4\sum_F m_F^4$); C, effective potential for $m_H^4 \ll 4\sum_F m_F^4 - 3\sum_V m_V^4$.

Fig. 2. Possible values of m_H and m_F in the theory with one

Higgs meson and one heavy fermion for $\sin \Theta_W \sim 0.22$. The dashed region AB'CD is the domain of the absolute vacuum stability, bounded by the lines AB and AD, corresponding to the constraints (3) and (5). More precisely, values of m_F in the region of absolute vacuum stability cannot be higher than the solid part of the line AD, and cannot be much higher than the broken part of AD.

The region of absolutely forbidden m_H and m_F is under the curve AB. If the Universe is not enormously charge asymmetric ($L \lesssim 10^8 B$), symmetry breaking takes place only for m_H and m_F in the region above the curve AB'CD.

Fig. 3. The dashed region AB'CD is the domain of the most probable values of m_H and m_F . In the theories with many Higgs mesons and fermions the line AD represents a constraint on the heaviest Higgs meson and the heaviest fermion,

Fig. 1.

Fig. 2.

Fig. 3.

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