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# Changes of symmetry in weak interactions at large transverse momenta

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The weak reaction $l + p \to l' + X$ is treated at high energies in the framework of field theories at finite temperature $T$, where $T$ is proportional to the average transverse momentum $\langle p_\perp \rangle$ of the outgoing lepton $l'$. In models with spontaneous symmetry breaking, we find a restoration of symmetry (e.g., parity) with increasing $\langle p_\perp \rangle$. The following simple relation between the depolarization $R = \mathcal{P}(\langle p_\perp \rangle)/\mathcal{P}(\langle p_\perp \rangle = 0)$ of leptons, the mass of the Higgs particle $M_H$, and the coupling $\lambda$ is derived: $M_H/\lambda \geq 9\langle p_\perp \rangle/32(1-R)^{1/2}$.

## I. INTRODUCTION

Spontaneous symmetry breaking is playing a major role in theoretical particle physics. However, there is so far no direct experimental evidence that the various symmetry breakings we are seeing are indeed of a spontaneous nature.[1] In many-body physics the situation is much clearer from this point of view, since there the symmetries can be changed by heating the system (e.g., superconductivity), which probes the spontaneous character of the breaking. If in high-energy physics, conditions could be created similar to the heating of a many-body system, one could hope to be able to check the nature of the breakdown of symmetries.

Kirzhnits and Linde[2] and other authors considered the change of symmetry for an elementary-particle system in a heat bath of macroscopic (astrophysical) dimensions, but apparently there is no way cosmologically to distinguish between spontaneously broken symmetrics and other types of symmetries.[3]

Some time ago, we suggested that one should see the restoration of strong-interaction symmetries [SU(3)] at high energies and large momentum transfers[4] which correspond to high temperatures. Salam and Strathdee[5] considered the problem of symmetry restoration in the presence of strong magnetic and electric fields.

Thermodynamical and hydrodynamical approaches to large transverse momenta $p_\perp$ in strong interactions suggest[6] the existence of hot regions in hadronic matter excited by the projectile, and therefore in Ref. 7 we put forward the idea that inside such a hot region elementary fields (particles) are to be described according to field theory at finite temperature. This can be understood, e.g., within a partonlike model where the gluon condensate and quark-antiquark sea constitute a medium in which elementary fields interact. As an application in Ref. 8, we have suggested that the polarization of leptons produced in neutrino reactions might decrease with the average transverse momentum $\langle p_\perp \rangle$ of the outgoing lepton. As will be shown below, in deep-inelastic interactions induced by leptons rather high effective temperatures are obtained so that the changes of symmetries expected as a consequence of phase transitions might begin to show up already at present accelerator energies. Therefore, in the present paper, a more quantitative investigation of the spontaneous-symmetry-breaking effects at high energies is made. In Sec. II, we derive among other things a relation between $M_H/\lambda$ and the decrease of symmetry breaking at high energies. $M_H$ is the mass of a Higgs particle, and $\lambda$ is the corresponding (scalar)[4] coupling. In Sec. III, we discuss the experimental implications of the relations obtained in Sec. II and compare them with the predictions of theories containing right-handed currents.

## II. RELATION BETWEEN THE VACUUM EXPECTATION VALUE AND HIGGS-PARTICLE PARAMETERS

We start with a Goldstone theory based on the group O($n$) with a single vector multiplet of scalar fields. It is easy to generalize our approach to gauge theories for any Lie group.[1,8] The potential in the Lagrangian is of the form

$$V_0(\phi) = \tfrac{1}{2}\alpha\phi^2 + \tfrac{1}{4}\lambda^2\phi^4\,, \tag{2.1}$$

with $\lambda > 0$ and $\alpha < 0$ in order to have a spontaneously broken theory. At temperature $T \neq 0$ the vacuum expectation value is defined by

$$\hat{\phi}(T) = \frac{\sum \langle E_i | \phi | E_i \rangle e^{-E_i/T}}{\sum e^{-E_i/T}}\,, \tag{2.2}$$

and is determined by minimizing the effective potential $V$,

$$\frac{\partial V}{\partial \phi}=0 \text{ at } \phi=\hat{\phi}\,, \tag{2.3}$$

where

$$V=V_0+V_1\,. \tag{2.4}$$

$V_1$ is the one-loop contribution[1,8]

$$V_1=\frac{n+2}{3\pi^2}T^4 \times \int_0^\infty dx\,x^2 \ln\{1-\exp[-(x^2+a^2)^{1/2}]\}\,, \tag{2.5}$$

where

$$a^2=M^2(T)/T^2\,, \tag{2.6}$$

$$M^2(T)=\left.\frac{\partial^2 V_0}{\partial\phi^2}\right|_{\phi=\hat{\phi}}=\alpha+3\lambda^2\hat{\phi}^2(T)\,. \tag{2.7}$$

The critical temperature is defined by the condition

$$\hat{\phi}(T_c)=0\,, \tag{2.8}$$

yielding

$$T_c=\left(\frac{12}{n+2}\right)^{1/2}\frac{(|\alpha|)^{1/2}}{\lambda}=\left(\frac{6}{n+2}\right)^{1/2}\frac{M_H}{\lambda}\,. \tag{2.9}$$

The mass of the Goldstone-Higgs particle is given by

$$M_H^2=M^2(0)=-2\alpha\,. \tag{2.10}$$

From Eq. (2.3) we get

$$-\tfrac{1}{2}+\lambda^2\varphi^2+\frac{n+2}{2\pi^2}\lambda^2 t^2 I(a)=0\,, \tag{2.11}$$

where

$$\varphi(t)=\hat{\phi}/M_H\,, \tag{2.12}$$

$$t=T/M_H\,, \tag{2.13}$$

are dimensionless quantities and

$$I(a)=\int_0^\infty \frac{x^2dx}{(x^2+a^2)^{1/2}}\left[\exp(x^2+a^2)^{1/2}-1\right]^{-1} \equiv I(0)Z(a^2)\,, \tag{2.14}$$

where

$$I(0)=\pi^2/6\,,$$

and $Z$ is a monotonically decreasing function of $a^2$ with

$$Z(a^2)\leqslant 1\,, \tag{2.15}$$

and $a^2$ is given by (2.6).

The solution of Eq. (2.11) gives the temperature dependence of the vacuum expectation value of the scalar fields. The symmetry-breaking effects are proportional to $\varphi$ and Eq. (2.11) contains all the information we are interested in. For convenience we rewrite this equation in the form

$$\varphi^2=\frac{1}{2\lambda^2}-\frac{n+2}{12}t^2 Z[a^2(\varphi^2)]\,. \tag{2.16}$$

For $a^2>0$ which corresponds to low temperatures $t$, the integral $I(a^2)$ is real and using Eqs. (2.6), (2.7) and (2.15), (2.16) we find that $\varphi$ and $t$ are restricted to the following domains:

$$\begin{aligned} &a^2\geqslant 0:\ \ 0\leqslant t^2\leqslant\frac{4}{(n+2)\lambda^2}\equiv t_0^2\,,\\ &\varphi^2(t=t_0)=\frac{1}{6\lambda^2}\leqslant\varphi^2\leqslant\frac{1}{2\lambda^2}=\varphi^2(t=0)\,. \end{aligned} \tag{2.17}$$

$\varphi(0)$ is the maximum value of $\varphi(t)$ in most models[1] including the present one.

For $a^2<0$ the integral and therefore the solution of (2.11) are complex. We assume, as suggested by Weinberg,[1] that the physical solution corresponds to the real part of $\varphi$; the imaginary part is canceled by higher-order loop contributions. In this case one gets

$$\begin{aligned} &a^2\leqslant 0:\ \ \frac{4}{(n+2)\lambda^2}\leqslant t^2\leqslant t_c^2=\frac{6}{(n+2)\lambda^2}\,,\\ &\varphi^2(t_c)=0\leqslant\varphi^2\leqslant\frac{1}{6\lambda^2}=\varphi^2(t_0)\,. \end{aligned} \tag{2.18}$$

For $t\gg 1$ we have $Z\simeq 1$, and the solution of Eq. (2.16) is

$$\varphi^2(t)/\varphi^2(0)\simeq 1-\tfrac{1}{6}(n+2)\lambda^2t^2\,. \tag{2.19}$$

In Fig. 1, we represent $\varphi^2(t)/\varphi^2(0)$ as a function of $t^2$, for $n=1$ and for two values of $\lambda$ ($\lambda=\frac{1}{3}$ and $\lambda=\frac{1}{2}$). Our approach is limited to $\lambda<1$ because we use perturbation theory in the expansion of $V$. It is seen that the larger $\lambda$ becomes, the sooner the restoration of symmetry is observable. If we denote the parameter describing the restoration of symmetry by

$$\delta=1-\varphi(t)/\varphi(0)\,, \tag{2.20}$$

so that $\delta(T_c)=1$ and $\delta(0)=0$, (2.19) yields

$$\delta=1-\left[1-\frac{(n+2)\lambda^2T^2}{6M_H^2}\right]^{1/2}\,, \tag{2.21}$$

which for small $\delta$ reduces to

$$\delta\simeq\frac{(n+2)\lambda^2T^2}{12M_H^2}\,. \tag{2.22}$$

## III. EXPERIMENTAL IMPLICATIONS

The temperatures reached in strong interactions at present accelerator energies might already exceed the value of $m_\pi\simeq 140$ MeV considered to be

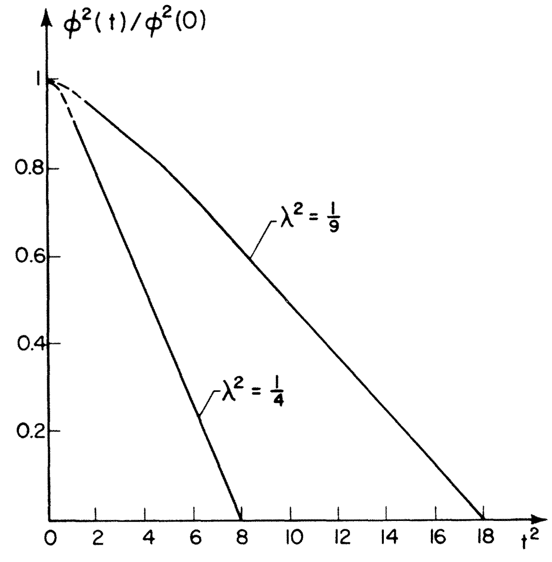


FIG. 1. Dependence of $\varphi^2(t)/\varphi^2(0)$ on $t^2$ according to Eq. (2.19) for $n=1$. The dashed parts of the curves correspond to the region of $t^2$ where the deviation from the linear approximation (2.19) is still important. However, the scale is here much increased.

a critical temperature for this type of interaction, so that it is of no surprise that phase-transition-like effects are apparently already being seen[7] in hadronic physics (e.g., the cutoff of $p_\perp$ of secondaries[10]). At first glance, one might be tempted to expect no similar effects for weak interactions in the present energy regime since the critical weak temperatures $T_c^W$ are known[1,2] to be much higher than the strong ones $T_c^S$.

However, this point of view might be misleading since at the same energy $E$, in weak interactions much higher energy densities $\epsilon_w \equiv E/V_w \simeq E/R_w^3$ are reached than the energy densities $\epsilon_s \equiv E/V_s \simeq E/R_s^3$ in strong interactions; here $V$ and $R$ are the interaction volume and radius, respectively. Since $R_w \sim m_W^{-1}$ and $R_s \sim m_\pi^{-1}$ one has

$$\frac{\epsilon_w}{\epsilon_s} \simeq \left(\frac{m_W}{m_\pi}\right)^3 \gg 1\,,$$

where $m_W$ and $m_\pi$ are the masses of the intermediate boson and pion, respectively. It is reasonable to assume that the local temperature obtained in high-energy reactions is an increasing function of $\epsilon$ so that $T^w \gg T^s$. This is confirmed by the experimental observation that the average momentum transfer $\langle q^2\rangle$ in the weak reaction

$$\nu + p \to \mu + X \tag{3.1}$$

is much larger than the corresponding $\langle q^2\rangle$ in strong reactions. For (3.1) one has found[12] for $E<12$ GeV,

$$\langle q^2\rangle \simeq 0.21 + 0.22E\,,$$

where $E$ is the neutrino laboratory energy in GeV, and $q^2$ is in GeV$^2$. Since $\langle p_\perp\rangle$ is expected to increase with $\langle q^2\rangle$ it is reasonable to assume that $\langle p_\perp\rangle_{\text{weak}} \gg \langle p_\perp\rangle_{\text{strong}}$. On the other hand, it is easy to see that $\langle p_\perp\rangle$ is proportional to the temperature $T$. Indeed we have

$$\langle p_\perp\rangle = \int f\,dp_\parallel p_\perp^2\,dp_\perp \tag{3.2}$$

where for $f$ we take a Boltzmann distribution

$$f = \exp[-(p_\perp^2 + p_\parallel^2)^{1/2}/T] \Big/ \int f\,dp_\parallel p_\perp\,dp_\perp\,,$$

and where we neglect the (lepton) mass. An elementary calculation yields

$$\langle p_\perp\rangle = \frac{T}{8\pi}\int_0^\infty x^3 K_1(x)\,d_x = \tfrac{16}{9}\,T\,. \tag{3.3}$$

Thus we conclude again that $T^w \gg T^s$. By using Eqs. (3.3) and (2.21) we get the following relation between the symmetry-restoration parameter $\delta$ and $\langle p_\perp\rangle$:

$$\delta = 1 - \left[1 - \frac{27(n+2)\,\lambda^2\,\langle p_\perp\rangle^2}{512 M_H^2}\right]^{1/2}\,. \tag{3.4}$$

If we define by $\delta_{\text{exp}}$ the experimental upper limit of $\delta$ we find for small $\delta$ a lower limit for $M_H/\lambda$:

$$\frac{M_H}{\lambda} \geq \frac{[27(n+2)]^{1/2}}{32}\,\frac{\langle p_\perp\rangle}{(\delta_{\text{exp}})^{1/2}}\,. \tag{3.5}$$

At CERN an experiment[13] is in preparation in which the polarization of muons produced in reaction (3.2) by high-energy neutrinos will be measured. If parity is a spontaneously broken symmetry, we predict a parity restoration proportional to the $\delta$ of Eq. (3.4) and hence a decrease in the polarization $\mathcal{P}$ of the muon with $\langle p_\perp\rangle$. This decrease can be parametrized as follows:

$$R_1 \equiv \frac{\mathcal{P}(\mu)}{\mathcal{P}(\mu)_{\langle p_\perp\rangle=0}} = 1-\delta = \left[1 - \frac{27(n+2)\lambda^2\langle p_\perp\rangle^2}{512 M_H^2}\right]^{1/2}. \tag{3.6}$$

It is interesting to compare this prediction with that of models containing $V+A$ currents.[14] In those models one has

$$R_1 = 1 - \frac{m_1^2 - q^2}{m_2^2 - q^2}\,, \tag{3.7}$$

where $m_1$ and $m_2$ are the mass eigenstates of the intermediate $W_L$ and $W_R$ bosons; the $V-A$ limit corresponds to $m_1/m_2 \to 0$. In order to make a comparison possible, we assume that $\mathcal{P}(\langle p_\perp\rangle = 0)$ corresponds to a pure $V-A$ theory. The main difference between the two types of theories relies upon the fact that parity is completely restored in $V+A$ theories ($R_1 \to 0$) only at $q^2 \to \infty$, while in the temperature-dependent model this happens at finite

$$\langle p_\perp \rangle_c = \left(\frac{6}{n+2}\right)^{1/2} \frac{16}{9} \frac{M_H}{\lambda} \tag{3.8}$$

corresponding to the phase transition at $T_c$.

Assuming spontaneous violation of $CP$, strangeness, etc., one expects restoration of these symmetries at large $\langle p_\perp \rangle$ along the same lines as in Eq. (3.4). In particular the restoration of strangeness conservation in weak interactions would correspond to the vanishing of the Cabibbo angle at large $\langle p_\perp \rangle$, i.e., the ratio

$$R_2 = \frac{\sigma(\nu + p \to \mu + \Lambda)}{\sigma(\nu + p \to \mu + n)} \tag{3.9}$$

should decrease with $\langle p_\perp \rangle$.[15]

Some of these effects are striking, and an experimental test is highly desirable. A positive result would confirm not only the spontaneous character of the symmetry breakdown but also the applicability of a statistical approach to weak interactions. Both these assumptions are at present only conjecture.

## IV. DISCUSSION

Although for the sake of definiteness we considered a global O($n$) symmetry, our approach to the restoration of spontaneously broken symmetries is general and applies also to gauge groups. In this way through relations of type (3.5) direct experimental information about $M_H/\lambda$ can be obtained which at present is not available by other methods. This is in particular true also for unified models of weak and electromagnetic interactions with the exception of the standard SU(2) × U(1) model where there is one single Higgs field with $\langle \phi \rangle = M_H/\lambda \sim G_F^{-1/2} \simeq 300$ GeV (Ref. 16) and where there is no restoration of parity symmetry anyway.[17] This last model, however, is apparently in difficulty because of the smallness of the parity-violation effect in atomic physics. Indeed, in order to cope with this problem in a very recent paper Georgi and Weinberg[22] consider a larger symmetry group and postulate the existence of at least two intermediate neutral vector bosons, the mass of one of them being smaller than the usual value $m_Z \simeq 80$ GeV. In this way the atomic parity effect becomes much smaller. To achieve this one has to introduce another Higgs field with a vacuum expectation value smaller than 300 GeV. This leads to smaller values $M_H/\lambda$ which could make the parity-restoration effect in neutrino reactions, as discussed in this paper, observable.

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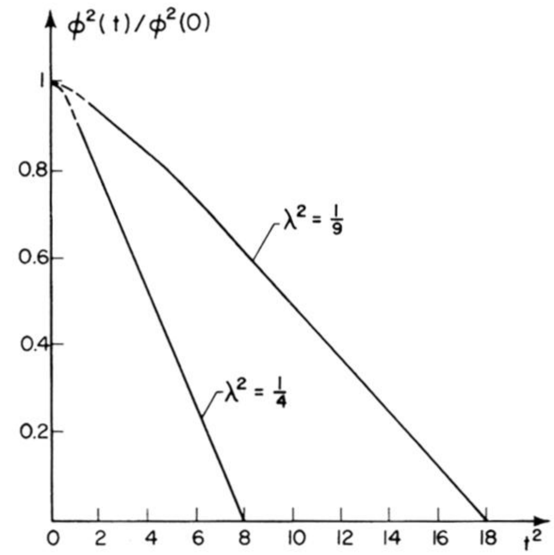


FIG. 1. Dependence of $\varphi^2(t)/\varphi^2(0)$ on $t^2$ according to Eq. (2.19) for $n = 1$. The dashed parts of the curves correspond to the region of $t^2$ where the deviation from the linear approximation (2.19) is still important. However, the scale is here much increased.