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дубна

E2-85-103

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SU(2) LATTICE GAUGE-HIGGS MODEL

Submitted to "Z.für Phys. C"

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1985

1. INTRODUCTION

The present paper is devoted to the investigation of the SU(2) gauge-Higgs model phase structure. The Higgs fields are transformed over the fundamental group representation, and the radial mode of the Higgs field is active.

In recent years many papers have been aimed at studying the gauge-Higgs theories (see, for instance [1-5]). In most of the papers the radial fluctuations of the Higgs field Φ_i were neglected, i.e., it was assumed that $|\Phi_i| = \text{const}$. The refusal of this strongly simplifying assumption changes completely the phase picture of the theory. As we know, the first investigations of the phase diagrams taking into account radial fluctuations have been made in papers [2] for the Z_2-symmetric theory. The active radial mode has been also used in papers [3-5] for the models with symmetry groups Z_N, U(1), SU(2), SU(3).

In the present paper we investigate the nature of phase transitions by the Monte-Carlo method as well as by approximate calculations using an effective potential of the Coleman-Weinberg-type. A special attention has been paid to the end points of phase diagrams.

The paper is organized as follows: The second section is devoted to the formulation of the model; in the third section the effective potential of the Coleman-Weinberg-type is constructed and used to analyse the type of phase transitions by one of the order parameters and the dependence of the points of phase transitions on the parameters of the action; the fourth section contains the results of the Monte-Carlo calculations and their comparison with those obtained with the help of the effective potential.

2. FORMULATION OF THE PROBLEM

We choose the action for a gauge field with the symmetry group SU(2) interacting with Higgs fields in the fundamental representation of the gauge group in the form

$$S = \beta \sum_{\square} S_{\square} + \Sigma S_L . \qquad (2.1)$$

where

$$S_{\square} = 1 - \frac{1}{2} \mathrm{Sp}\, U_{\square} , \qquad (2.2)$$

$U_{\square} \equiv U_{ij} U_{jk} U_{k\ell} U_{\ell i}$ and the gauge field $U_{ij} \equiv U_L$ is defined on the link $L \equiv (i, j)$ outgoing from the site i and ending on the site j. The second term in (2.1) is the sum over all links and S_L has the form

$$S_L = \frac{1}{4}\left(\frac{m^2}{2} \Phi_i^* \Phi_i + \lambda (\Phi_i^* \Phi_i)^2\right) + (\Phi_i^* \Phi_i - \mathrm{Re}\, \Phi_i^* U_{i,i+\mu} \Phi_{i+\mu}). \qquad (2.3)$$

The Higgs field Φ_i is defined in each site i and Φ_i is the column of two rows. It is convenient to represent the field Φ_i by a pair of variables (R_i, ϕ_i), where $R_i = \sqrt{\Phi_i^* \Phi_i}$ and ϕ_i is the unitary matrix 2x2:

$$\phi_i = \frac{1}{R_i} \left\| \begin{matrix} \Phi_i^{(1)} & -\Phi_i^{(2)*} \\ \Phi_i^{(2)} & \Phi_i^{(1)*} \end{matrix} \right\| \subseteq SU(2) .$$

Then the action S_L can be rewritten as

$$S_L = \frac{1}{4}\left(\frac{m^2}{2} R_i^2 + \lambda R_i^4\right) + \left(R_i^2 - R_i R_{i+\mu} \frac{1}{2} \mathrm{Sp}(\phi_i U_{i,i+\mu} \phi_{i+\mu}^*)\right). \qquad (2.4)$$

Now we use the Higgs "polar" variables $(R_i ; \phi_i)$ to determine the partition function

$$Z = \int \prod_i d\mu(R_i)\, d\phi_i \prod_L dU_L\, e^{-S[\{R_i\};\{\phi_i\};\{U_L\}]} , \qquad (2.5)$$

where dU_L and $d\phi_i$ are the Haar measures on group SU(2), and the radial measure $d\mu(R)$ is chosen in the form $d\mu(R) \sim R^3 dR$. In our paper we calculated the following order parameters:

$$\langle R^2 \rangle = Z^{-1} \int \prod_i d\mu(R_i) d\phi_i \prod_L dU_L R_i^2\, e^{-S} ,$$

$$\langle 1 - \square \rangle = Z^{-1} \int \prod_i d\mu(R_i) d\phi_i \prod_L dU_L\, \mathrm{Re}(1 - \frac{1}{2} \mathrm{Sp}\, U_{\square}) e^{-S} . \qquad (2.6)$$

If $m^2 \to \infty$ or $\lambda \to \infty$, the radial fluctuations of the Higgs field become negligible and we are left with a pure SU(2) gauge theory with a crossover in the order parameter $\langle 1 - \square \rangle$ at $\beta \simeq 2.2$.

3. THE EFFECTIVE POTENTIAL METHOD

An approach developed in this section for investigating phase transitions by the strong coupling expansion for an effective potential of the Coleman-Weinberg-type turns out to be a useful supplement to the numerical Monte-Carlo method. In spite of a narrow region of applicability of this expansion, the effective potential method provides an elegant interpretation of the specific features of the behaviour of order parameters observed in the numerical modeling, and in particular, understanding of the nature of phase transition in the so-called end point.

Let us represent the partition function as

$$Z = \int \prod_i d\mu(R_i)\tilde{Z}\{R_i\}, \qquad (2.7)$$

where

$$\tilde{Z}\{R_i\} = e^{-\tilde{S}\{R_i\}} = \int \prod_i d\phi_i \prod_L dU_L \cdot e^{-S} \qquad (2.8)$$

and the action S is defined by (2.1)-(2.3). Now we expand the quantity in powers of β (strong coupling expansion):

$$\tilde{S} = \tilde{S}_0\{R_i\} + \beta\tilde{S}_1\{R_i\} + \beta^2\tilde{S}_2\{R_i\} + \ldots$$

whose coefficients $\tilde{S}_0, \tilde{S}_1, \tilde{S}_1, \ldots$ are related with $\tilde{Z}$ by

$$\tilde{S}_0 = -\ln\tilde{Z}|_{\beta=0}, \quad \tilde{S}_1 = -\tilde{Z}^{-1}\frac{d}{d\beta}\tilde{Z}|_{\beta=0}, \quad \tilde{S}_2 = \frac{1}{2}\left(\tilde{S}_1^2 - \tilde{Z}^{-1}\frac{d^2}{d\beta^2}\tilde{Z}\right)\Big|_{\beta=0} \qquad (2.9)$$

and so on.

Using (2.9) and definition (2.8) we get the quantities

$$S_0 = \sum_i [(4 + \frac{m^2}{2})R_i^2 + \lambda R_i^4] - \sum_\ell \ln\frac{2I_1(x_\ell)}{x_\ell}, \quad \tilde{S}_1 = [N_\Box - \sum_\Box \prod_{\ell\subset\Box}\frac{I_2(x_\ell)}{I_1(x_\ell)}],$$

$$\tilde{S}_2 = -\frac{1}{2}\sum_\Box [1 - 3\sum_{i\subset\Box}\cdot\frac{I_2(x_i)}{x_i I_1(x_i)} + 12\sum_{i<j\subset\Box}\frac{I_2(x_i)}{x_i I_1(x_i)}\frac{I_2(x_j)}{x_j I_1(x_j)} -$$

$$- 48\sum_{i<j<k\subset\Box}\frac{I_2(x_i)}{x_i I_1(x_i)}\cdot\frac{I_2(x_j)}{x_j I_1(x_j)}\cdot\frac{I_2(x_k)}{x_k I_1(x_k)} + 192\prod_{\ell\subset\Box}\frac{I_2(x_\ell)}{x\ I\ (x_\ell)}] -$$

$$-\frac{1}{2}\sum_{\substack{\Box,\Box' \\ \Box\cap\Box' = L}}[1 - \frac{3I_2(x_L)}{x_L I_1(x_L)}]\prod_{i\subset\Box\cup\Box'/L}\frac{I_2(x_i)}{I_1(x_i)} + \frac{1}{2}\sum_{\substack{\Box,\Box' \\ \Box\cap\Box'\neq\emptyset}}\prod_{i\subset\Box}\frac{I_2(x_i)}{x_i I_1(x_i)}$$

$$\prod_{j\subset\Box'}\frac{I_2(x_j)}{x_j I_1(x_j)}, \qquad (2.10)$$

where I_n are the modified Bassel functions, $x_\ell = R_i R_{i+\hat{\mu}}$, $\ell = (i,\hat{\mu})$. Now we apply to $\tilde{S}\{R_i\}$ a standard procedure for obtaining an effective potential of the Coleman-Weinberg-type [6,8]. For our purpose it is sufficient to use only the lowest order approximation for the effective potential V_{eff} which is defined as

$$V_{eff}(\bar{R}) = \frac{1}{N_L}\tilde{S}\{R_i\}|_{R_i=\bar{R}} = \sum_{k\geq 0}\beta^k V_{eff}^{(k)}(\bar{R}), \qquad (2.11)$$

where

$$V_{eff}^{(0)}(\bar{R}) = (1 + \frac{m^2}{8}\bar{R}^2) + \frac{\lambda}{4}\bar{R}^4 - \ln\frac{2I_1(\bar{R}^2)}{\bar{R}^2} - \frac{3}{2}\ln R^2.$$

$$V_{eff}^{(1)}(\bar{R}) = \frac{3}{2}[1 - \frac{I_2^4(\bar{R}^2)}{I_1^4(\bar{R}^2)}], \qquad (2.12)$$

$$V_{eff}^{(2)}(\bar{R}) = -\frac{3}{2}\{\frac{21}{2}[1 - \frac{I_2^8(\bar{R}^2)}{I_1^8(\bar{R}^2)}] - 36\frac{I_2(\bar{R}^2)}{\bar{R}^2 I_1(\bar{R}^2)} +$$

$$+ 36[\frac{I_2(\bar{R}^2)}{\bar{R}^2 I_1(\bar{R}^2)}]^2 - 96[\frac{I_2(\bar{R}^2)}{\bar{R}^2 I_1(\bar{R}^2)}]^3 + 96[\frac{I_2(\bar{R}^2)}{\bar{R}^2 I_1(\bar{R}^2)}]^4\}.$$

The last term in $V_{eff}^{(0)}(\bar{R})$ allows for the structure of the measure of integration over R_i: $d\mu(R_i) = R_i^3 dR_i$ in (2.5). In further calculations we shall use only the first three terms of expansion (2.11) for V_{eff} defined in (2.12). The region of applicability in β of an approximate expression for V_{eff} is rather small ($|\beta| \leq 0.3$) that follows from the estimate of a relative contribution of corrections (2.12) to the expansion (2.11). However, this turns out to be sufficient for our aims.

The shape of the effective potential for different values of β, m^2 and λ helps us to understand the nature of the phase transitions with the change of these parameters. Figure 1 shows the typical behaviour of the effective potential for different values of m^2 and fixed β and λ. For small values of m^2 the effective potential has only one minimum (fig.1a). With increasing $|m^2|$ ($m^2 < 0$) V_{eff} acquires a second minimum (see fig.1b) lying above the first and then the values of V_{eff} in both minima become equal (fig.1c). With further increasing $|m^2|$ the value of the effective potential in the right minimum becomes less than in the left (fig.1d) and eventually the left minimum vanishes at all (fig.1e). The left minimum of V_{eff} in fig.1b corresponds to a stable phase whereas the right to a metastable and the situation is reversed in fig.1d). At $m^2 = m_c^2$, where the minima become equal (fig.1c), there occurs a phase transition of the first order. With the help of V_{eff} one can recover the β-dependence of m^2 for not very large values of β. The dependence of m_c^2 on β at different values of λ is shown in fig.2. We see that the effective potential predicts a shift with increasing λ of the lines of fase transitions to the right and upward. The circles indicate that the lines of the first order phase transitions have end points (at least for not very small λ). Near the end point $m_c^2(\lambda)$; $\beta_c(\lambda)$ of the line of the first order phase transitions the minima of the effective potential move nearer to each other and the local maximum between them disappears. Figure 3 exemplifies the behaviour of the effective potential near an end point ($\beta = \beta_c$) for different values of $m = -m_c^2$. At some values of $|m^2| < |m_c^2|$, near the end point the effective potential has, in addition to the minimum at some relatively small value of $\bar{R}^2$, also an inflection point to the right of the minimum (see fig.3a). With increasing $|m^2|$ the minimum and the inflection point approach each other and at some value of $m^2 = m_c^2$ "coincide" (fig.3c). With further increasing $|m^2|$ the inflection point shifts to the left of the minimum (fig.3d). and with further increasing $|m^2|$ the minimum shifts to the right towards large values of $\bar{R}^2$ (fig.3e).

It is obvious that at $m^2 = m_c^2$ the derivative of the order parameter $\frac{d}{dm^2}\langle R^2\rangle(m^2)$ has a singularity. Indeed, let be the solution of the equation

$$\frac{d}{\bar{R}} V_{eff}(\bar{R}, m^2) = 0, \qquad (2.13)$$

i.e., $\bar{R}_c(m^2)$ is the value of the order parameter at a given value of m^2. By differentiating eq. (2.13) with respect to m^2, we get

$$0 = \frac{d}{dm^2} V'_{eff}[R_c(m^2), m^2] = \frac{\partial}{dm^2} V'_{eff}[\bar{R}_c(m^2), m^2] + \frac{d}{dm^2}\bar{R}_c(m^2)\, V''_{eff}$$

or

$$\frac{d}{dm^2}\bar{R}_c(m^2) = -\frac{\bar{R}_c(m^2)}{4V''_{eff}[\bar{R}_c(m^2), m^2]}.$$

Since $V''_{eff} \to 0$ as $m^2 \to m_c^2$ we get from (2.14) $\frac{d}{dm^2}\bar{R}_c(m^2) \to \infty$

(the solid line in fig.4).

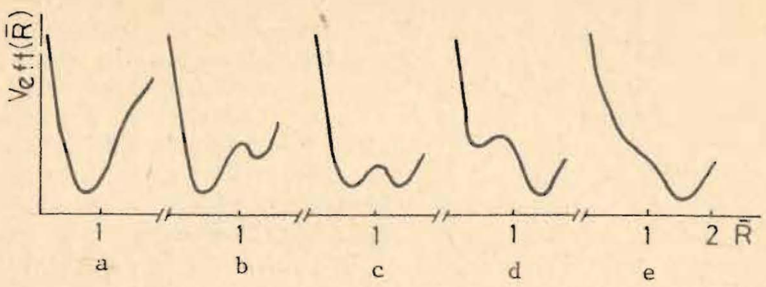


Fig.1. Behaviour of the effective potential as a function of $\bar{R}$ at fixed λ and β around the point of the phase transition of first order. Curves a-e correspond to growing values of $|m^2|$.

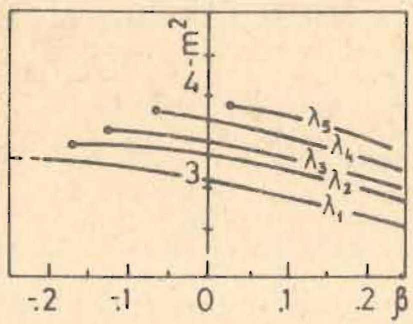


Fig.2. The displacement of lines of the phase transitions of first order and its end point in the plane (β; m^2) with growing λ ($\lambda_1 < \lambda_2 < \lambda_3 < \lambda_4 < \lambda_5$). The results are obtained by analysing the effective potential V_{eff}.

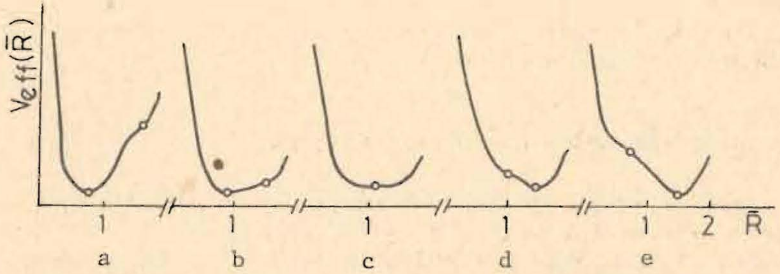


Fig.3. Dependence of the effective potential on $\bar{R}$ at different values of m^2 and fixed λ and $\beta = \beta_c$. Circles denote the minimum and point of inflexion of V_{eff}.

The singularity of the derivative of the order parameter $\langle R^2\rangle(m^2)$ with respect to m^2 at the end point allows one to as-

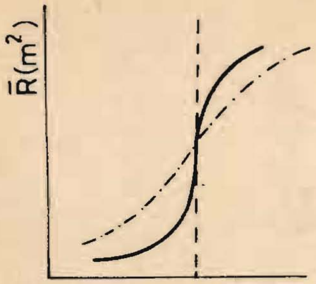


Fig.4. Behaviour of $\bar{R}(m^2)$ at $\beta = \beta_c$ (solid curve) and for $\beta < \beta_c$ (dotted curve).

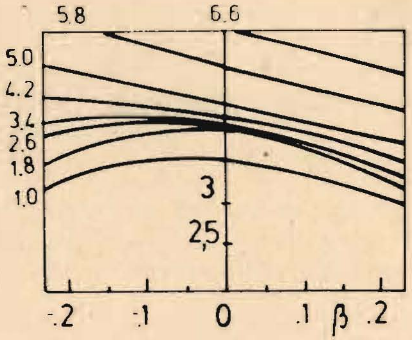


Fig.5. The level lines of the function $\bar{R}(\beta; m^2)$ for λ = 0,12.

sert that it is a point of the second order phase transition. To the left of this point, i.e., at $\beta < \beta_c$, we observe a change of regime (crossover) without singularities in the behaviour of the derivative of the order parameter $\langle R^2 \rangle (m^2)$ (see the dashed line in fig.4). The lines of the level of the order parameter $\langle R^2 \rangle$ in the plane (m^2, β) at λ = 0,12 are shown in fig.5. There occurs a discontinuity, i.e., the first order phase transition, where two lines of the level almost coincide. At the end point $(m_c^2; \beta_c)$ the level lines diverge (in fig.5 these are lines with the values of the order parameter 1,8 and 2,6), however, they are still at a relatively short distance from each other. This proximity of two different lines of the level indicates a sharp change of regime. We may say that the "line" of crossovers is the trail of the end point. Obviously, an analogous situation occurs in the phase plane (β, β_A) in the pure SU(2) gauge theory with mixed action [9].

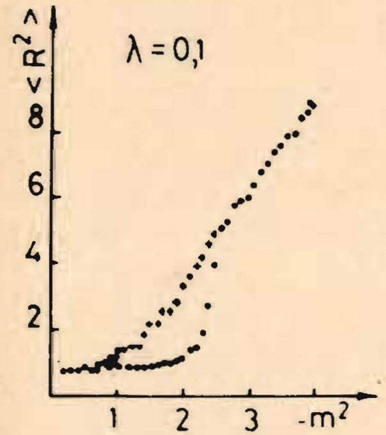
4. RESULTS OF THE MONTE-CARLO CALCULATIONS

The model (2.1)-(2.3) has been numerically investigated by the Monte-Carlo method with the use of the Metropolis algorithm [7]. 4-5 updates of the field variables in each site and on each link of the lattice have been optimised. To update the gauge field variables which are the elements of the SU(2) group, the old value of the field variable has been multiplied by a random $\tilde{U}$ element of the group SU(2) which is close to unity. The Φ_i field has been updated in two stages. First, an attempt was made to update the radial variable R_i and then the angular variable ϕ_i. The degree of proximity of a random group element $\tilde{U}$ to the unit

one and the interval $R_i \pm \Delta R$ of the new value of the radial variable R_i have been choosen so as to provide the probability of updating ~50%. The sequence of renewing of variables on links and at sites was chosen in a random way (stochastic sweeps). We have employed the Monte-Carlo method to calculate the following order parameters $\langle 1 - \square \rangle$ and $\langle R^2 \rangle$, defined by (2.6). The behaviour of the order parameters near the phase transition points has been studied by two different methods:

i) Thermal cycles

One of the parameters (β or m^2) was being slowly changed in a given interval, first in one direction and then back. At each point the final configuration from the preceding point is used as an initial configuration. 7-10 iterations were made at each step and the averaging was performed over the last 4 iterations. The typical step of changing $\beta(m^2)$ was equal to 0.05-0.1. At the beginning of the thermal cycle ~100 iterations were made



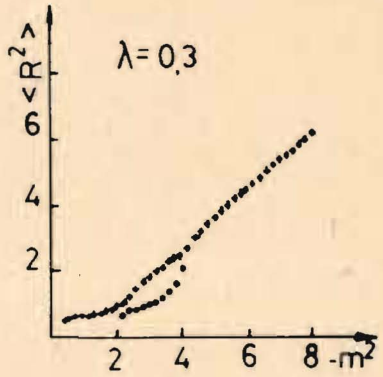
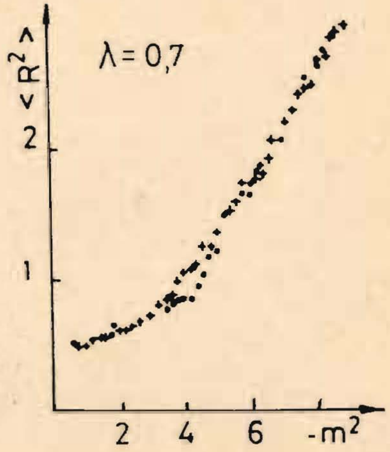


Fig.6. The results of thermal cycles in m^2 for order parameter $\langle R^2 \rangle$ at point $\beta = 2,2$ for different values of λ.



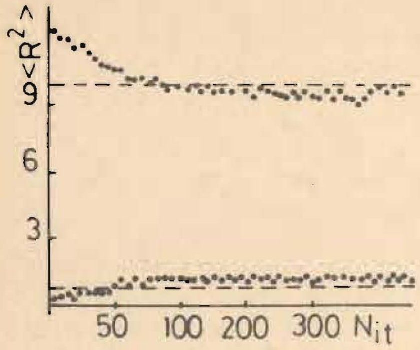


Fig.7. The dependence of order parameter $<R^2>$ on the number of Monte-Carlo iterations for $\beta=0$; $\lambda = 0{,}05$; $m^2 = -2{,}86$ and different initial configurations of variables U, ϕ and R. Dashed lines are calculated by formula (2.13).

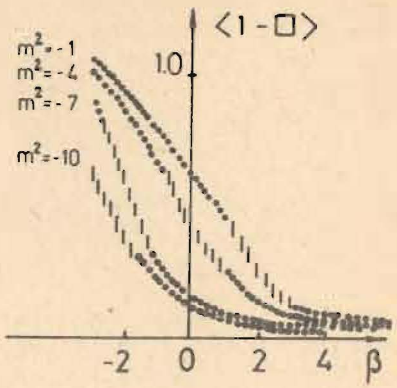


Fig.8. Results of thermal cycles in β at different values of m^2. Curves represent the behaviour of order parameter $<1-\Box>$. Verticas dashes denote the domain of slow convergence.

at constant values of β and m^2 to equilibrate the system. The appearance of a hysteresis loop (see, for instance, fig.6) may indicate a possible phase transition.

ii) The choice of different initial configurations (starts) both of the radial field variables $\{R_i\}$ and the fields $\{\phi_i\}$ and $\{U_\ell\}$.

As in the previous papers [3,5] we used mainly two types of starts: "hot", when all the values of field variables are chosen at random, and "cold", for which the initial distribution was chosen to be $U_\ell = \hat{1}$, $R_i = 0.1$, $\phi_i = \hat{1}$. The typical picture at the point of the first order transition (at $\lambda = 0{,}05$, $\beta = 0$, $m^2 = -2{,}86$) is shown in fig.7 and in terms of the effective potential V_{eff} it corresponds to the situation when the values V_{eff} of two minima coincide (fig.1c).

In the previous section we have already mentioned a strong dependence of the shape of phase transitions on λ (see fig.2), which has been established by the effective potential. This fact is confirmed by the Monte-Carlo analysis. Thus, a sequence of thermal cycles at different λ at the point $\beta = 2.2$ (at the "cross-sover" point of a pure SU(2) gauge theory) indicates a sharp narrowing of the hysteresis loop with increasing λ from 0.1 to 0.7. A similar picture is observed for the order parameter $<1-\Box>$ which has a strong correlation with $<R^2>$. This fact is in agreement with a qualitative behaviour of an end point of first

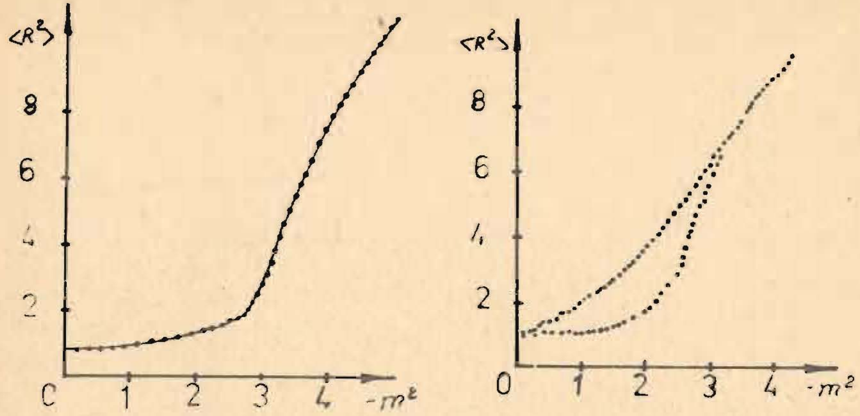


Fig.9. The dependence of $<R^2>$ on m^2 as a result of the thermal cycle for $\lambda = 0{,}1$ at a) $\beta = 0$ and b) $\beta = 1$.

order phase transitions (fig.2), which is shifted to the right-upward with increasing λ.

The vanishing of the radial fluctuations of the Higgs field ($<R^2> \to 0$) at $\lambda \to \infty$ or $m^2 \to \infty$ has already been given in sec.2. One can easily observe a first order phase transition at $\lambda = 0.1$ and $\beta = 2.2$ by the method of different starts (fig.7) which indicates the existence of two long-living configurations with highly different $<R^2>$. The Monte-Carlo analysis of the behaviour of the order parameter $<1-\Box>$ (fig.8a) provides a quantitative picture of such a "dying out" at fixed λ and with increasing m^2. Already at $m^2 = 10$ the dependence $<1-\Box>$ on β in the model (2.1)-(2.3) does not differ from that in the pure SU(2) gauge theory. By decreasing gradually m^2 up to zero and then passing to the region of negative, the Higgs fields effect actively the behaviour of an average plaquette $<1-\Box>$ (fig.8b) even at small λ. The behaviour of the order parameter $<R^2>$ with respect to m^2 at $\lambda = 0.1$, $\beta = 0$ and $\beta = 1$ is shown in fig.9; it indicates the existence of an end point of the line of the first order phase transition in the interval $0 < \beta < 1$. This is in complete correspondence with the picture obtained by the effective potential method in Sec.3. On the other hand, as has been pointed out in ref. [5], at fixed λ and increasing β a discontinuity of $<R^2>$ at the point of the first order phase transition as a function of m^2 decreases gradually up to zero (within $\beta \to \infty$) and there is no first order phase transition at β (fig.10). Thus for the lattice SU(2) gauge-Higgs theory the typical picture of the lines of a phase transition in the (β, m^2) plane (phase diagram) is shown in fig.11 corresponding to $\lambda = 0{,}1$. With increasing λ this line of phase transitions shifts to the right and upward.

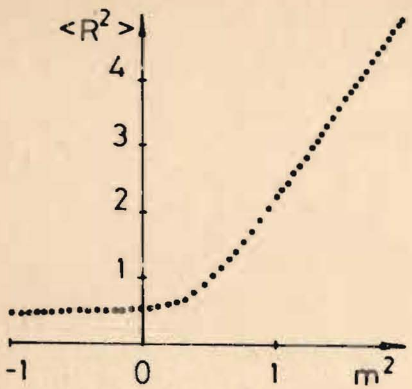


Fig.10. The dependence of order parameter $<R^2>$ on m^2 for $\beta = \infty$ and $\lambda = 0.1$.

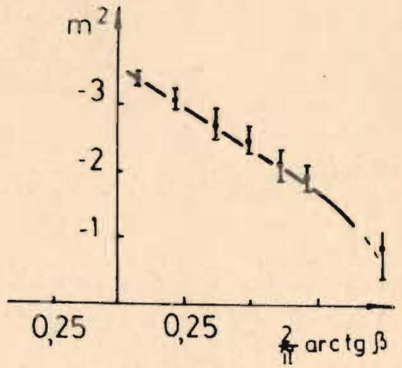


Fig.11. Phase diagram in the plane (β, m^2) at $\lambda = 0.1$, calculated by the Monte-Carlo method. The solid line represents the phase transition of first order; the thin dashed line denotes the region where the type of phase transition is not yet established. Errors in the determination of transition points are indicated.

How far the lines of the first order phase transitions extend to the region of large β is not yet clear and should be further investigated.

CONCLUSION

Thus, we have investigated the phase structure of the lattice SU(2) gauge-Higgs theory. For the construction of phase diagrams we have used both the numerical approach, the Monte-Carlo method, and an approximate analytical method based on the use of an effective potential of the Coleman-Weinberg-type. In both approaches the radial mode of the Higgs field was thought to be frozen out. We have detected the lines of first order phase transitions in the (β, m^2) plane at fixed λ, which have end points corresponding to second order phase transitions. This result follows from the numerical as well as from the analytical analysis which show a good qualitative and quantitative agreement. At first sight, our results do not agree with the result of ref. [4] in which only second order phase transitions have been observed. A more thorough investigation shows that the discrepancy of our results with those of ref. [4] is only seeming, caused by a different choice of the model parameters [11]. The comparison of the formulae (2.3)-(2.4) with analogous from

ref. [4] leads to the following relations between the parameters β, λ, and m^2 in our paper and those of paper [4], which are denoted by $\tilde\beta, \tilde\lambda$, and k $\beta = \tilde\beta$, $\lambda = \tilde\lambda/4k^2$, $m^2 = (1 - 2\tilde\lambda - 8k)/k$.

To define the type of a phase transition the authors of paper [4] have studied the region of parameters $\tilde\beta, \tilde\lambda$, and k, which is beyond the region of parametric space studied. In particular, they studied in detail the point $\tilde\lambda = 0.5$, $\tilde\beta = 2.25$, $k = 0.27$ which corresponds to $\lambda = 1.715$, $\beta = 2.25$, and $m^2 = -8$.

Our investigation shows however that at $\lambda \gtrsim 1$ both minima of the model effective potential are so close to each other that become indistinguishable in the Monte-Carlo analysis. This is the reason for the conclusion on the second order phase transition made in ref. [4].

The existence of an end point on the line of the first order phase transition, we have established, testifies to the complementarity principle suggested in refs. [10]. This end point is a critical point analogous to a phase diagram of the type "gas-liquid-ice"; in the phase diagram the crossover line is the "trail" of this end point. In particular, the existence of this line explains a crossover in the pure gauge SU(2) theory at $\beta \simeq 2,2$.

ACKNOWLEDGEMENT

The authors are indebted to N.N.Govorun, V.A.Matveev, M.G.Meshcheryakov, A.N.Sissakian, and D.V.Shirkov for useful discussions and interest in this work.

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Received by Publishing Department
on February 21, 1985.

Гердт В.П. и др. E2-85-103
SU(2) -Хиггс-калибровочная теория на решетке

Исследуются фазовые диаграммы в SU(2) -симметричной хиггс-калибровочной теории с размороженной радиальной модой. Хиггсовские поля рассматриваются в функциональном представлении. Построены фазовые диаграммы для различных значений константы скалярного самодействия. Показано, что линии фазовых переходов 1-го рода имеют концевые точки, которые являются критическими точками, аналогично тому, как это имеет место на фазовых диаграммах типа "газ-жидкость-лед".

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1985

Gerdt V.P. et al. E2-85-103
SU(2) Lattice Gauge-Higgs Model

Phase diagrams are investigated in the SU(2) gauge-Higgs theory with a defrost radial mode. The Higgs fields are considered in the fundamental representation. Phase diagrams are determined for different values of the scalar self-action constants. It is shown that the lines of first order phase transitions have end points which are critical points, analogous to a phase diagram of the type "gas-liquid-ice".

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1985