WEINBERG MODEL AND THE "HOT" UNIVERSE

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Submitted 17 May 1972
ZhETF Pis. Red. 15, No. 12, 745 - 748 (20 June 1972)

Much interest was aroused recently by attempts to construct a renormalized theory of weak interaction [1]. In the corresponding Weinberg model (W.m.) the masses of the intermediate boson, electron, etc., which hinder the unification of weak interaction with electromagnetism, arise as the consequence of spontaneous symmetry breaking. In the present article the W.m. is applied to a large system of weakly-interacting particles at nonzero temperature. Such a system is dealt with, for example, in cosmology, where the "hot" model of the universe is now assumed.

1. There has been frequent mention of the analogy between the W.m. and the theory of superconductivity, bearing in mind the conversion of the phonon (massless) spectrum of collective excitations in a superconductor into a plasmon (massive) spectrum on going over to charged particles. However, a more direct analogy is connected with the Meissner effect (cf., e.g., [2]): the magnetic field H is pushed out of the superconductor precisely because Bose condensation of Cooper pairs takes place in it (the "wave function" of the pairs is $\Psi \sim \langle \psi^+\psi^+ \rangle$), the theory becomes non-invariant relative to the phase transition, and the photon acquires a nonzero mass $\kappa \sim |\Psi|$. Formally the matter reduces to the substitution $\Delta\vec{A} \to (\Delta - \kappa^2)\vec{A}$ in the equation for the vector potential $\vec{A}$, where $1/\kappa$ is the depth of penetration of the field into the superconductor.

Under certain assumptions, the Meissner effect is described by the Ginzburg-Landau theory [3, 2], based on the expression for the free energy

$$F + F_0 + H^2/8\pi + |(\nabla - 2ie\mathbf{A})\Psi|^2/2m - \alpha|\Psi|^2 + \beta|\Psi|^4. \quad (1)$$

Here $F_0$ is the free energy of the normal metal in the absence of a field, and $\alpha$ and $\beta$ are phenomenological parameters. The expression (1) is fully analogous to the boson part of the W.m. Lagrangian; this, in the simplest model [4]

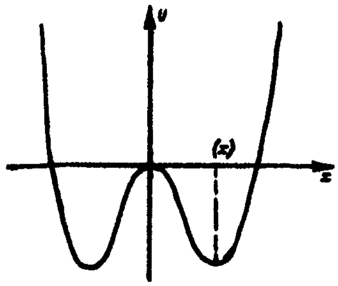
$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + |(\partial_\mu - 2igB_\mu)\phi|^2 + \mu^2|\phi|^2 - \lambda|\phi|^4, \quad (2)$$

where B and $\phi$ are the vector and scalar fields. The violation of the symmetry is connected with the fact that $\langle\phi\rangle$ is not equal to zero, i.e., with the Bose condensation of the field $\phi$.

2. It is well known that the quantity $|\Psi|$ in (1), and with it also the photon mass in the superconductor, decreases with increasing temperature and vanishes when $T \geq T_c$, where $T_c$ is the critical temperature. This is a common property of all the ordered systems (with broken symmetry) known to us. It is connected in final analysis with the fact that when T increases the minimum of the free energy F = E - TS is more and more favored by the increase of the entropy S, i.e., by the violation of the order.

There are all grounds for assuming that a similar property will be possessed also by the quantity $\langle\phi\rangle$. The concrete symmetry breaking at low temperatures and its restoration at high temperatures can be seen, as applied to the theories of [1] and [2], from the model of the anharmonic oscillator with imaginary frequency. The corresponding Hamiltonian

$$H = \frac{1}{2}(p^2 - \mu^2 x^2) + \lambda x^4,$$




and the potential energy U is shown in the figure. At low temperatures the particle is located in one of the potential wells and has $\langle x \rangle \neq 0$. At large T (high excitation energies), however, the particle leaves the well and its motion becomes fully symmetrical ($\langle x \rangle = 0$). Then the critical temperature is obviously of the order of the depth of the well.

It is difficult to estimate this quantity in the W.m., since we do not know the dimensionless coupling constant $\lambda$. Assuming it to be of the order of unity, we have $\langle\phi\rangle \sim \mu$ and $T_c \sim \mu^4/n$, where n is the equilibrium concentration of the $\phi$-particles, $n \sim \langle\phi\rangle^2$. From this, according to Weinberg [1],

$$T_c \sim \langle \phi \rangle \sim G^{-1/2}, \qquad (3)$$

i.e., the critical temperature is of the order of the "unitary limit" of the weak-interaction theory, $10^3$ Gev $\sim 10^{16}$ deg.

3. From the statement concerning the reconstruction of the broken symmetry at high temperature there follow conclusions of importance in cosmology[1)]. A temperature on the order of (3) corresponds to a time $\sim 10^{-12}$ sec from the start of the expansion of the world and to a density of matter $\sim 10^{29}$ g/cm$^3$ (cf., e.g., [5]). In this epoch and in the preceding ones the intermediate boson, electron, etc., were massless particles. Accordingly the weak interaction, like the electromagnetic one, had a long-range character.

The presence of uncompensated interactions of this kind on a macroscopic scale would mean the occurrence of colossal repulsion forces (absence of saturation). It is therefore necessary to stipulate besides macroscopic electroneutrality of the universe also an analogous neutrality condition in the "weak charge" sense. The latter condition, a detailed analysis of which will be the subject of a separate article, is of the form

$$\sum_i k_i (n_i - \bar{n}_i) = 0,$$

where $n_i$ is the concentration of the weakly interacting particles of sort i, $\bar{n}_i$ is the same for antiparticles, and $k_i$ are constants of the order of unity. The condition (4) determines in principle the quantity $n_\nu - \bar{n}_\nu$ for the neutrino from the known concentrations of heavy weakly-interacting particles.

The authors is grateful to V.L. Ginzburg for a discussion and to E.S. Fredkin for discussions and stimulating criticism.

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[1)] We do not take into account the possibility, discussed in the literature, of the existence of an upper temperature limit (see [5] concerning this question). We note also that the condensate should vanish also at high intensity of the B-field, i.e., at a high density of matter. This corresponds to the vanishing of the superconductivity in a strong magnetic field.

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# POSSIBLE STUDY OF BOUND $\bar{p}n$ STATES IN EXPERIMENTS ON THE ANNIHILATION OF $\bar{p}$ ON d


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Submitted 18 May 1972
ZhETF Pis. Red. 15, No. 12, 748 - 751 (20 June 1972)


An earlier study [1] of the annihilation of stopped $\bar{p}$ in a deuterium bubble chamber has suggested that a bound state of n and $\bar{p}$ exists. A comparison of the experimental results with the theoretically expected spectrum of the recoil-nucleon momenta in the reaction

$$\bar{p} + d \to p + X, \tag{1}$$

where X is the bound $\bar{p}n$ state, was carried out in [2]. It was shown that, owing to the relatively large annihilation level widths, the form of this spectrum, and particularly the position and width of the maxima in it, are determined not only by the conservation laws and by the masses of the bound states, but also by their quantum numbers, and primarily by the orbital momenta. The maximum observed in [1] corresponded to an appreciable contribution of the d-state of the $\bar{p}n$ system. The maxima corresponding to the S- and p-waves of the relative motion of $\bar{p}$ and n, as noted in the analogous experiments at different energies of the incoming p, since in this case they turn out to be in the observable region of the recoil-proton spectrum (150 MeV/c < q < 800 MeV/c).

In this article we present the theoretically expected form of the momentum spectrum of the recoil protons in reaction (1) for different p energies. An analysis shows that a study of the spectra for different recoil-proton emission angles makes it possible to determine experimentally the nonzero orbital momenta of the bound states of $\bar{p}$ and n.

Just as in [2], we start out in the analysis of the reactions (1) from the pickup mechanism, which is well known in nuclear physics. We note that the choice of the concrete mechanism of the peripheral process is immaterial for the conclusions presented below, although the form of the spectrum can change in some way on going for example from pickup to the substitution reaction.

The differential cross section of reaction (1), corresponding to pickup, can be written in the form (we assume that $\hbar = c = 1$):

$$\frac{k}{m}\frac{d\sigma}{dq\,d\Omega} = \frac{2I+1}{2\pi}\;\frac{q^2(q^2+\alpha^2)^2\,F_d^2(q)\,F_{N\bar{N}}^2(s)\,\Gamma}{(q^2+\alpha^2-s^2-\kappa^2)^2+\Gamma^2 m^2/4}\,. \tag{2}$$

Here $\vec{k}$ and $\vec{q}$ are the momenta of $\bar{p}$ and of the recoil proton, $d\Omega$ is the element of solid angle in the direction of $\vec{q}$, $\vec{s} = (\vec{k} + \vec{q})/2$, and I, $\kappa^2/m$, and $\Gamma$ are respectively the total angular momentum, the binding energy, and the annihilation width of the considered state of the $N\bar{N}$ system, $\alpha^2/m$ is the deuteron binding energy, m is the mass of the nucleon, and F(a) are the Fourier components of the radial wave functions

$$F(a) = \int_0^\infty \chi_\ell(r)\, j_\ell(ar)\, r\, dr, \tag{3}$$