MENU 2007
11th International Conference
on Meson-Nucleon Physics and
the Structure of the Nucleon
September10-14, 2007
IKP, Forschungzentrum Jülich, Germany

SPONTANEOUS P-PARITY VIOLATION IN DENSE BARYON MATTER

S.S. Afonin[⋆,1], A.A. Andrianov[$], V.A. Andrianov[⋆], D. Espriu[$]
[⋆]St. Petersburg State University, St. Petersburg, Russia
[$]University of Barcelona, Barcelona, Spain

Abstract

We investigate possibilities for dynamical P-parity violation in dense baryon matter in the framework of effective quark models. Dynamical P-parity violation can appear in models with at least two scalar and two pseudoscalar fields, where both scalar fields are condensed at normal conditions. At special configurations of coupling constants, one of pseudoscalar fields can then also condense at some value of baryon density, the phenomenon results in mixing of the scalar and pseudoscalar physical degrees of freedom, hence, giving rise to P-parity violation. We discuss the implications and possible experimental signatures for P-parity violation in strong interactions in future experiments with heavy-ion collisions.

1 Introduction

Presently the issue of dense baryon matter is attracting a lot of interest as long as some striking physical phenomena are expected to occur in certain regimes, such as the phase transition to chirally symmetric hadron matter. The message we would like to convey is that before any phase transition the P-parity in cold dense baryon matter could undergo spontaneous breaking. At zero baryon density (chemical potential) this phenomenon is precluded by the Vafa-Witten theorem [1]. However, the conditions under which this theorem was proven (positivity of the measure of partition function in vector-like theories) do not hold anymore at finite baryon density (see [2] for further discussions).

We shall report some important results of ongoing work along this line. In short, at certain value of quark chemical potential and in the physical range of model parameters, the phenomenon of spontaneous parity breaking (SPB) has been recently observed in extensions of popular low-energy models of

[1]E-mail address: afonin24@mail.ru

QCD, namely in a generalized Nambu–Jona-Lasinio model [3] (the so-called Quasilocal Quark Model (QQM)), in extended chiral quark model [4], and in a generalized sigma-model [2]. In all cases, the underlying mechanism turned out to be rather similar, we are going to describe briefly the relevant general features.

2 General analysis

The possibility of SPB arises when two different scalar fields condense with a relative phase between their v.e.v.'s. Let us consider a model with two multiplets of scalar/pseudoscalar fields

$$H_j = \sigma_j \mathbf{I} + i\hat{\pi}_j, \quad j = 1,2; \quad H_j H_j^\dagger = (\sigma_j^2 + (\pi_j^a)^2), \tag{1}$$

here $\hat{\pi}_j \equiv \pi_j^a \tau^a$ with τ^a being a set of Pauli matrices. We shall deal with scalar systems globally symmetric in respect to $SU(2)_L \times SU(2)_R$ rotations working in the exact chiral limit. We should think of these two chiral multiplets as representing the two lowest-lying radial states for a given J^{PC}. The introduced degrees of freedom possess all the necessary ingredients to study SPB.

The effective potential of the models considered has, in general, the following form at zero quark chemical potential μ (after specifying the v.e.v. $\langle H_1 \rangle = \langle \sigma_1 \rangle$),

$$\begin{aligned} V_{\text{eff}} = \frac{1}{2}\text{tr}\Bigg\{ &- \sum_{j,k=1}^{2} H_j^\dagger \Delta_{jk} H_k + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 \\ &+ \frac{1}{2}\lambda_4 (H_1^\dagger H_2 H_1^\dagger H_2 + H_2^\dagger H_1 H_2^\dagger H_1) + \frac{1}{2}\lambda_5 (H_1^\dagger H_2 + H_2^\dagger H_1) H_1^\dagger H_1 \\ &+ \frac{1}{2}\lambda_6 (H_1^\dagger H_2 + H_2^\dagger H_1) H_2^\dagger H_2 \Bigg\} + \mathcal{O}\left(\frac{|H|^6}{\Lambda^2}\right), \end{aligned} \tag{2}$$

with 9 real constants Δ_{jk}, λ_i. QCD bosonization rules indicate that $\Delta_{jk} \sim \lambda_i \sim N_c$. The neglected terms will be suppressed by inverse power of the chiral symmetry breaking scale $\Lambda \simeq 1.2$ GeV. If we assume the v.e.v. of H_j to be of the order of the constituent mass $0.2 \div 0.3$ GeV, it is reasonable to neglect these terms.

To guess the typical values of couplings, it is instructive to consider a specific model. Let us take the QQM [3] as an example. The relevant form of Lagrangian is defined as follows,

$$\mathcal{L}_{\text{QQM}} = \bar{q}(i\partial\!\!\!/)q + \sum_{k,l=1}^{2} a_{kl}\left[\bar{q} f_k(s) q\, \bar{q} f_l(s) q - \bar{q} f_k(s)\tau^a\gamma_5 q\, \bar{q} f_l(s)\tau^a\gamma_5 q\right]. \tag{3}$$

Here a_{kl} represents a symmetric matrix of real coupling constants and $f_k(s)$, $s \equiv -\partial^2/\Lambda^2$ are the polynomial form factors specifying the quasilocal (in momentum space) interaction. The form factors are orthogonal on the unit interval and the results of calculations do not depend on a concrete choice of form factors in the large-log approximation. A convenient choice is $f_1(s) = 2 - 3s$, $f_2(s) = -\sqrt{3}s$. The values of couplings λ_i in Eq. (2) are then fixed for $i = 2, \ldots, 6$: $\lambda_2 = \frac{9N_c}{32\pi^2}$, $\lambda_3 = \frac{3N_c}{8\pi^2}$, $\lambda_4 = \frac{3N_c}{16\pi^2}$, $\lambda_5 = -\frac{5\sqrt{3}N_c}{8\pi^2}$, $\lambda_6 = \frac{\sqrt{3}N_c}{8\pi^2}$.

We shall assume that the scalars under consideration are generated in the quark sector of QCD. The baryon chemical potential is transmitted to the meson sector via a quark-meson coupling. Without loss of generality we can assume that only the first field H_1 has local coupling to quarks; this actually defines the chiral multiplet H_1. Thus finite density is transmitted to the boson sector via $\Delta\mathcal{L} = -(\overline{q}_R H_1 q_L + \overline{q}_L H_1^\dagger q_R)$, where $q_{L,R}$ are assumed to be constituent quarks. Then the one-loop contribution to V_{eff} is

$$\Delta V_{\text{eff}}(\mu) = \frac{\mathcal{N}}{2}\Theta(\mu - |H_1|)\left[\mu|H_1|^2\sqrt{\mu^2 - |H_1|^2} - \frac{2\mu}{3}(\mu^2 - |H_1|^2)^{3/2}\right.$$
$$\left. -|H_1|^4 \ln\frac{\mu + \sqrt{\mu^2 - |H_1|^2}}{|H_1|}\right] \times \left(1 + O\left(\frac{\mu^2}{\Lambda^2}; \frac{|H_1|^2}{\Lambda^2}\right)\right), \quad (4)$$

where $\mathcal{N} \equiv \frac{N_c N_f}{4\pi^2}$ and μ is the chemical potential. The higher-order contributions of chiral expansion in $1/\Lambda^2$ are not considered. This effective potential is normalized to reproduce the baryon density for quark matter $\rho_B = \frac{N_f}{3\pi^2}p_F^3$, where the quark Fermi momentum is $p_F = \sqrt{\mu^2 - |\langle H_1\rangle|^2}$. Normal nuclear density is $\rho_B \simeq 0.17$ fm^{-3} $\simeq$ $(1.8$ fm$)^{-3}$ that corresponds to the average distance 1.8 fm between nucleons in nuclear matter.

Our analysis of the mass-gap equations and mass spectrum based on potential (2) supplemented with the in-medium contribution (4) resulted in a generic picture which is graphically displayed in Fig. 1 and Fig. 2.

3 Discussions

Let us mention several possible signatures of P-parity breaking ensuing from our analysis.

a) Decays of higher-mass meson resonances (radial excitations) into pions. Resonances do not have a definite parity and therefore the same resonance can decay both in two and three pions (in general into even and odd number of pions).

b) At the very point of the phase transition leading to parity breaking one has six massless pion-like states. After crossing the phase transition, in

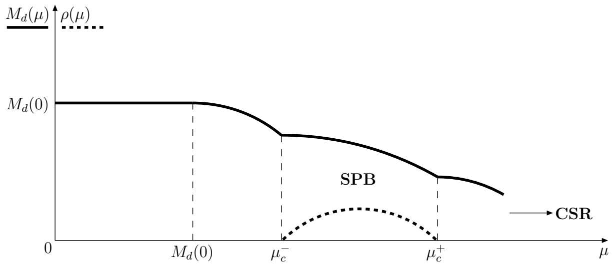

Figure 1: A qualitative dependence of dynamical quark mass M_d and pseudoscalar condensate ρ on quark chemical potential μ (usually $M_d(0) \simeq$ 300 MeV). In the points of entering and exiting the phase of spontaneous parity breaking (SPB) the derivatives on μ jump. The region close to the chiral symmetry restoration (CSR) is beyond the range of validity of chiral expansion.

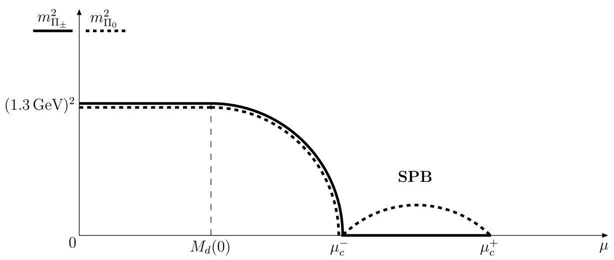

Figure 2: A qualitative behaviour of masses of isospin components for heavy pseudoscalar meson as a function of quark chemical potential μ when the SPB occurs.

the parity broken phase, the massless charged pseudoscalar states remain as Goldstone bosons enhancing charged pion production, whereas the additional neutral pseudoscalar state becomes massive.

c) Reinforcement of long-range correlations in the pseudoscalar channel (this effect could be hunted in lattice simulations).

d) Additional isospin breaking effects in the pion decay constant and substantial modification of the weak decay constant $F_{\Pi^\pm}$ for massless charged excited pions, giving an enhancement of electroweak decays.

Acknowledgments

This work is supported by research grants FPA2004-04582, SAB2005-0140 and RFBR 05-02-17477 as well as by Programs RNP 2.1.1.1112; LSS-5538.2006.2. The work is also done with support of the EU RTN networks FLAVIANET and ENRAGE.

References

[1] D. Weingarten, *Phys. Rev. Lett.* **51**, 1830 (1983); C. Vafa and E. Witten, *Phys. Rev. Lett.* **53** 535 (1984); S. Nussinov, *Phys. Rev. Lett.* **52**, 966 (1984); D. Espriu, M. Gross and J.F. Wheater, *Phys. Lett.* **B146**, 67 (1984); for a review see, S. Nussinov and M. Lambert, *Phys. Rept.* **362**, 193 (2002).

[2] A.A. Andrianov and D. Espriu, arXiv:0709.0049 [hep-ph].

[3] A.A. Andrianov and V.A. Andrianov, *Nucl. Phys. Proc. Suppl.* **39BC**, 257 (1995); hep-ph/9911383; A.A. Andrianov, V.A. Andrianov and V.L. Yudichev, *Theor. Math. Phys.* **108**, 1069 (1996); A.A. Andrianov, V.A. Andrianov and S.S. Afonin, hep-ph/0209260; *J. Math. Sci.* **143**, 2697 (2007).

[4] A.A. Andrianov, D. Espriu and R. Tarrach, *Nucl. Phys.* **B533**, 429 (1998); *Nucl. Phys. Proc. Suppl.* **86**, 275 (2000).