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TOWARDS NEW STATES OF MATTER

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Towards new states of matter

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A linear realization of flavor $SU(3) \times SU(3)$ symmetry is developped with scalars and pseudoscalars mesons coupled to baryons and massive vector mesons which may be also coupled to colored quarks and gluons (deconfined above a critical range of energy densities and seemingly inside the baryons). The coupling to vector fields may lead to finite density baryonic and anti-baryonic matter what may also occur by means of a modified chemical potential. The stability equation which yields bound systems is verified. A qualitative discussion of the possible resulting (QCD - type) phase diagram is discussed including the possibility of finding several kinds of superfluid (and eventually superconductive) states. Some bosonic fields are assumed to have non zero expected values, at least at low energies, corresponding to dynamical symmetry breakings. The scalar "condensate" or classical expectation value, related to the QCD scalar condensate $\bar{\sigma} \propto < \bar{q}q >$, seems to decrease as density increases although it may also increase until asymptotic freedom of the underlying theory (QCD) becomes relevant. Generalized symmetry radius is found and the masses of the particles are found to vary with density.

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I. INTRODUCTION AND $SU(3)$ LINEAR SIGMA MODEL

The believed fundamental theory for strong interacting systems, quantum chromodynamics (QCD), is expected to lead to the description of nuclear interacting systems with color confined, and the flavor (basically chiral) structure which remains at the hadronic level is far more relevant. However it seems to be fair to ask the following questions: is QCD a theory for one interaction? or does it provide an unifying picture of two fundamental interactions? For the light hadronic particles, chiral symmetry (and also with strangeness quantum number for $SU(3) \times SU(3)$) yields a convenient frame for classifying the hadrons and describing processes. Chiral symmetry is expected to be spontaneously broken down to isospin symmetry in the Nambu realization resulting in a intrincated vacuum with scalar condensate, in terms of the quarks [1]. It has been difficult to describe nuclear interactions departing from such picture and many attempts have hard partially achieved this [2]. Furthermore and as a consequence the phase diagram of matter states is not completely known.

In a series of papers i am proposing an unifying frame for the development of strong interacting physics at finite baryonic (and eventually quark) densities built over properties of hadrons expected to be grounded on QCD. In this work, which is nearly a resumé of part of them, it is discussed 1) possible role of anti-matter in the phase diagram; 2) the spontaneous symmetry breaking of $SU(3) \times SU(3)$ in an effective linear sigma model with baryons, (pseudo+)scalar mesons, vector mesons, which can be coupled to deconfing quarks and gluons at high energy densities. Properties of the hadrons at finite hadronic densities are described by "condensates" of bosonic fields. Phase diagram of strong interactions would include several superfluid and superconductive states and it may contain a further axis of anti-baryonic density which may be a third (in)dependent axis in this diagram.

The invariant Lagrangian density of the $SU(3) \times SU(3)$ Linear Sigma Model with three-component baryons, $N_i(\mathbf{x})$, scalars (which are being found and discussed in the literature and may form a quark and anti-quark and/or may be multi quarks states nonet or octet) and pseudoscalars mesons (which are denoted by (Σ, Π) respectively for both -flavor partner- nonets as defined below) covariantly coupled to massive gauge isovector-vector fields V_μ,$\vec{\rho}_\mu$ and $(\vec{A}_1)_\mu$ $(SU(2) \times SU(2))$ may be given by:

$$\begin{aligned}\mathcal{L} = \bar{N}_i(\mathbf{x})\left(i\gamma_\mu \mathcal{D}_t^\mu - g_s(\Sigma + i\gamma_5.\Pi)\right) N_i(\mathbf{x}) + \frac{1}{2}\left(\partial_\mu\Sigma.\partial^\mu\Sigma + \partial_\mu\Pi.\partial^\mu\Pi\right) + \frac{\mu^2}{2} Tr|\Sigma + i\Pi|^2 + \\ -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \lambda_1 Tr(|(\Sigma + i\Pi)|^2)^2 - \lambda_2 (Tr(|\Sigma + i\Pi|^2))^2 + \frac{1}{2} m_V^2 V_\mu V^\mu + \mathcal{L}_\rho + \mathcal{L}_{A_1} + \mathcal{L}_{QCD+int},\end{aligned} \quad (1)$$

where the three last terms stand for the isovector mesons, which for $SU(2)$ chiral picture are the rho and A_1, and the quarks and gluons with interactions also with hadrons which would be relevant for energy densities close to those of the deconfining phase transition with asymptotic freedom. The covariant derivative is: $\mathcal{D}^\mu_t = \partial^\mu - ig_V V^\mu - ig_3(A^\mu_L - A^\mu_R)$, with the "generalized right and left" combinations (in the SU(2): $A^\mu_{R,L} \propto A^\mu_\rho \pm A^\mu_{A_1}$) of the flavor partner isovector mesons [1]; g_V, g_S, g_3 and λ_i are the coupling constants The scalar (pseudoscalar) matrix was chosen to be written as: $\Sigma = \sum_a \lambda_a \sigma_a$ ($\Pi = \sum_a \lambda_a "\pi_a"$) where the λ_a are the Gell-Mann matrices in the adjoint representation and σ_a ("π_a") the scalar (pseudoscalar) fields.

The minimization of the spin zero potential for the $SU(3)$ symmetric limit results in a strange-chiral radius v_3 that can be defined with a "mixed" coupling: $\lambda_3 = \lambda_2 + \lambda_1/2$, reading: $v_3^2 = \mu^2/(4\lambda_3)$, where μ^2 is the mass from the Lagrangian. This is the analogous to the chiral radius in $SU(2) \times SU(2)$. The Lagrangian term would be written as: $-\lambda_3(Tr|\Sigma^2 + \Pi^2| - v_3^2)^2$.

II. CHARACTERIZING POSSIBLE STATES

The averaged energy density is calculated for quantized baryons initially considered to form a Fermi liquid and all bosonic variables are condensated states, for the spin zero bosons the quantum fluctuations taken into account with a variational approach with Gaussian wavefunctionals [3, 4], such that the averaged energy reads:

$$\mathcal{H}^{tot} = \rho_f + g_V V_0 \rho_B - \frac{1}{2}\tilde{m}_V^2 V_0^2 + \lambda_3 (Tr|\tilde{\Sigma}^2 + \tilde{\Pi}^2| - \tilde{v}_3^2)^2, \tag{2}$$

Where $\tilde{m}$ is an "effective mass" for the vector field (temporal component) and $\tilde{v}_3$ a modified chiral radius due to quantum fluctuations (also considered to shift the spin zero fields classical values with tilde) which are not calculated explicitely. We perform a truncation of the effective potential which corresponds to: 1) equate all the quantum two point functions which shift the classical values, 2) neglect further terms in the above expression of the energy density as proposed in [4]. From now on, ρ_B (and eventually ρ_f) are to depend on the classical values of spin zero variables (like $\tilde{\sigma}$, $\tilde{\pi}$) and V_0, as variational parameters. Correlations and many-body effects of the fermions for the bosonic fields are considered such that the baryonic density depend on them and vice versa. From this consideration the equations of the system are derived [4].

The stability condition of the bound system can be written as:

$$\frac{d\mathcal{H}}{d\rho_B} == \frac{\mathcal{H}}{\rho_B}\bigg|_{\rho_B=\rho_0} = -\frac{E}{A} < 0. \tag{3}$$

Where $-E/A$ is the binding energy per baryon. To look for solution for this expression we consider that each kind of hadrons satisfy it nearly independently [4]. A solution for this prescription [4] for the fermion density which reproduces usual values for ρ_f is given by [4]:

$$\rho_f = K\frac{\rho_B}{9} Ln\left(\frac{\rho_B}{\rho_0} e^{\frac{34.3}{K} - \frac{\rho_B}{\rho_0}}\right), \tag{4}$$

where K is the usual incompressibility modulus and 34.2 (in fm^{-1}) was adjusted to fit the usual value of ρ_f at ρ_0. A solution for the spin zero bosons part of stability equation is given by:

$$(Tr|\bar{\Sigma} + \bar{\Pi}|^2 - \tilde{v}_3^2) = \tilde{D}\sqrt{\rho_B}\ ||_{\rho_B=\rho_0}. \tag{5}$$

Where the "condensates" of the scalar and pseudo scalar bosons (whenever they occur - like in [4]) are denoted by $\bar{a}$. A detailed comparison of this prescription with the exact result will be shown elsewhere. The solutions for these (stability) equations do obey the equations of motion. The above expression is, in principle, valid at zero density and at ρ_0 but seems to be also valid at different ρ_B. $\tilde{D}$ is a constant to be fixed by this boundary condition [4]. The scalar condensate or classical expectation value, related to the QCD scalar condensate $\bar{\sigma} \propto < \bar{q}q >$, seems to decrease as density increases (from the vaccum) although it may also increase [4] until asymptotic freedom of the underlying theory (QCD) becomes relevant and chiral symmetry is restored.

The averaged value of the Lagrangian yields massive fermions without breaking the flavour symmetry explicitely as long as the three scalar fields Σ_{ii}, diagonal elements of the matrix Σ, acquires classical values in the vacuum already. In the medium it yields:

$$M^*_{a,b;s} = g_S < \Psi|. < N_{a,s}|(\bar{\sigma}_a + \bar{\xi} + i\gamma_5 \vec{\tau}.\vec{\pi})|N_{b,s} > .|\Psi > \simeq g_S \sum_a \bar{\Sigma}_{a,a}\delta_{a,b}. \tag{6}$$

In this expression a, b stands for the flavor index (1,2,3). These three scalar condensates would appear due to a spontaneous symmetry breaking of $SU(3) \times SU(3)$ down to $SU(3)$. As the density varies so do the condensates and onsequentely the hadronic masses and properties. Experimental value of $E/A, \rho_0, K$ and masses are considered for inding other variables. The corresponding results for quark bound system with hadron-quark states will be shown lsewhere.

III. MATTER AND ANTI-MATTER STATES

The resulting Dirac equation for the baryons coupled to the classical bosons (the vector V_μ and scalars and pseu-loscalars) with a modified chemical potential, considered to be included as $\gamma_\mu \mu$, is given by:

$$\left[\gamma_\mu(\partial_\mu - ig_V V^\mu + \mu\gamma^0 - ig_3 B^\mu) - ig_s(\bar{\Sigma} + i\gamma_5.\bar{\Pi})\right]\Psi(\mathrm{x}) = 0. \tag{7}$$

Vhere B_μ is the contribution of the isovector mesons which may develop classical values and are more appropriate for he description of isospin/flavor asymmetric processes and systems, like neutron-proton asymmetric nuclear systems. The solution for this equation is a mixture of baryons and anti-baryons which yield finite baryon density and anti-aryon density state(s). These densities (including current densities) can be defined as: $\bar{N}\gamma_\mu N$ and $N^T\gamma_\mu\bar{N}^T$ with Nambu-Gorkov spinors [5]. However the spectra of the (positive and negative energy) solutions are not the same nymore due to the classical temporal component of the vector field and to the chemical potential, as expected. If he vector field component V_0 becomes negative the eingenvalues associated to anti-matter may be favored leading referentially to anti-matter (bound) states eventually. Anti-matter bound states could be considered in the phase liagram of our Universe, constituted rather of matter, as a third axis (besides density and temperature) eventually ssociated to the matter density - as to be linear independent or not. This may occur in relativistic heavy ions ollisions under execution and being prepared in RHIC and CERN [6]. These finite density systems may be expected o have relevant dynamical effects. In [5] the effect of classical tensor and vector fields were considered to the formation of superconductive states at very high densities yielding condensates of di-antifermions besides the usual di-fermions di-quarks) condensates due to the breakdown of gauge symmetries which would occur after the consideration of nti-matter fields, like shown above.

IV. SUMMARY

The linear sigma model with strange particles for baryons and bosons with spin zero and one particles was developped o describe finite density hadronic systems below the energies in which deconfinement and chiral/flavor symmetries estoration(s) take place. An *in medium* symmetry radius was defined and other properties were suggested including xtensions for the phase diagram of strong interacting systems. Relevance for aspects of relativistic heavy ions ollisions was briefly commented and will be discussed elsewhere at length.

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[2] See for example references in: B.D. Serot and J.D. Walecka, Int. Jour. of Mod. Phys. **E 6**, 515 (1997).
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[4] F.L. Braghin, submitted to publication (2001-2003)
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[6] See for example in: Quark Matter 2002; *International Workshop on Relativistic Aspects of Nuclear Physics*, Caraguatatuba, Brazil, Ed. by T. Kodama *et al*, World Scientific, (2001).