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LYCEN 2000-131
CERN-Th 2000-339
November, 2000

**Role of mesons in chiral symmetry
restoration and associated signals**

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International Symposium on Nuclei and Nucleons – Darmstadt –
October, 2000

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Role of mesons in chiral symmetry restoration and associated signals

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Chiral symmetry is partly restored in the nuclear medium, with a decrease of the order parameter, i.e., of the magnitude of the quark condensate, by about 40 % at normal density. The virtual nuclear pions are an important component of this restoration, acting in the same way as the real ones of a heat bath. Among the other mesons the scalar-isoscalar one, the σ meson, is expected to play a special role since it has the same quantum numbers as the condensate. It is thus the only meson which can directly dissolve into the condensate. We give the expression of its contribution to the restoration process in the framework of the linear sigma model, displaying the difference with the pionic contribution.

We also discuss the various signals associated with these two components of the restoration. The signal associated with the pion is the 'mixing of the axial and vector correlators', taken not literally but in the sense that will be defined. For the scalar meson, it is the reduction of the hadron masses in the nuclear medium. This perspective leads naturally to the description of the mean scalar field of QHD, the quantum hadrodynamics theory of nuclei. We discuss, in particular, how it appears in the linear sigma model. This demonstrates how QHD is incorporated in chiral theories.

To Achim Richter as a token of my friendship and my admiration for his career.

1. INTRODUCTION

Chiral symmetry, which is spontaneously broken in the QCD vacuum, is partly restored in a dense medium, heat bath or nuclear medium. The simplest case is that of the heat bath at moderate temperatures, $T < 100$ MeV, where only pions are thermally excited. Their presence modifies the order parameter according to

$$\frac{\langle \bar{q}q(T) \rangle}{\langle \bar{q}q(0) \rangle} = 1 - \frac{\rho_\pi^S(T)}{2f_\pi^2 m_\pi}, \quad (1)$$

where $\rho_\pi^S(T)$ is the scalar density of thermally excited pions. In the nuclear medium the condensate evolution is as easily evaluated, utilising the σ -commutator of the nucleon, Σ_N , which fixes the amount of restoration induced by each nucleon:

$$\Sigma_N = 2m_\pi \int d\vec{x} [\langle N | \bar{q}q(x) | N \rangle - \langle \bar{q}q(0) \rangle]. \quad (2)$$

Its value is known to be about 50 MeV. For non-interacting nucleons, adding their effect, the evolution of the condensate writes:

$$\frac{\langle \bar{q}q(\rho) \rangle}{\langle \bar{q}q(0) \rangle} = 1 - \frac{\Sigma_N \rho}{f_\pi^2 m_\pi^2}. \quad (3)$$

This expression leads to a decrease of the order parameter by $\approx 40\%$ at normal nuclear density. However the origin of the restoration is more complex than in the heat bath and is due to several sources. One originates from the presence of the virtual pions of the nuclear cloud. They act in a similar way as the real ones of the heat bath, modifying the condensate value by the same expression as given in Eq. 1. The scalar density of the virtual pions is related to the expectation value in the nuclear ground state of the squared pion field by

$$\rho_s^\pi = m_\pi \langle A | \phi^2 | A \rangle. \quad (4)$$

The evolution of pionic origin of the quark condensate is thus governed by the average value of the ratio $\phi^2/2f_\pi^2$ as in the heat bath. Evaluations of this quantity at normal density give values of about .15 to .20, while the total amount of restoration is .4, which means that nearly one half of the restoration comes from the pion cloud. What is the origin of the rest? It is normal to investigate the role of the non-pionic meson cloud. Now among the mesons the sigma plays a special role: it has the same quantum numbers, $S = I = 0$, as the condensate and thus can directly dissolve into it.

In nuclear physics the scalar-isoscalar meson also plays a special role. It provides the attraction which binds the nucleons in the nucleus. The existence of a mean scalar field, together with a vector one (which plays no special role in the condensate problem), is the essence of quantum hadrodynamics, QHD, the relativistic theory of nuclei. The mean scalar field is responsible for the lowering of the nucleon mass in the medium. The hadron mass reduction in the nuclear medium can be seen as a precursor signal of chiral symmetry restoration since the vanishing of the hadron masses is a way of reaching the Wigner realization of the symmetry. This was the suggestion made by Brown and Rho[1] of a link between the in-medium hadron masses and the in-medium condensate. They suggested the following law, based on scaling arguments, for the hadron mass evolution:

$$\frac{M_h^*}{M_k} = \frac{f_\pi^*}{f_\pi} = \left[\frac{\langle \bar{q}q(\rho) \rangle}{\langle \bar{q}q(0) \rangle} \right]^{1/3}, \quad (5)$$

which clearly establishes the precursor character of the mass reduction. However Birse[2] pointed out the problems associated with such a relation. As mentioned previously, part of the condensate evolution comes from the pion density. But its influence cannot be reflected on the masses because it would violate the constraints of chiral perturbation theory. Indeed, the expectation value of ϕ^2 , which governs the pionic part of the condensate evolution, contains a term (linked to the non-analytical part of the nucleon σ commutator) proportional to the pion mass. If the mass were to follow the condensate evolution it would also contain such a term. However this is forbidden by chiral perturbation theory: no term of order m_π is allowed in the nucleon-nucleon potential. The

pion cloud, which largely controls the condensate evolution, cannot influence the mass. Nevertheless a link between the mass and the rest of the condensate evolution is allowed. On the other hand the pion leads to another precursor signal, the mixing of the axial and vector correlator, a concept first introduced in the heat bath by Dey et al. [3] and adapted to nuclei by Chanfray et al.[4]. The possibility thus emerges that different factors of restoration lead to different types of signals. This is the theme which will be developed in this talk.

It is divided into two parts. In section II, the notion of mixing induced by the pions will be discussed. Section III deals with the role of scalar isoscalar meson in the restoration process and in the in- medium mass reduction.

2. AXIAL-VECTOR MIXING IN NUCLEI

The concept of correlator mixing induced by thermal pions is simple: the emission or absorption of an s-wave pion changes the parity of a system. A photon can convert into the A1 meson, a process forbidden at zero temperature, if a thermal pion is simultaneously produced or absorbed. This simple fact translates into the expression for the mixing of axial and vector (isovector) correlators, given by Dey et al. [3], valid in the chiral limit and for small temperatures, i.e., for soft pions.

$$\Pi_A(T) = (1 - \varepsilon)\Pi_A(T = 0) + \varepsilon\Pi_V^{I=1}(T = 0), \quad (6)$$

$$\Pi_V^{I=1}(T) = (1 - \varepsilon)\Pi_V^{I=1}(T = 0) + \varepsilon\Pi_A(T = 0). \quad (7)$$

The mixing parameter ε is linked to the change of the quark condensate $\delta < \bar{q}q(T) >$

$$\varepsilon = \frac{4}{3} \frac{\delta < \bar{q}q(T) >}{< \bar{q}q(0) >} \approx \frac{T^2}{9f_\pi^2}. \quad (8)$$

The mixing is accompanied by a depletion effect (factor $1-\varepsilon$) both being a signal of the restoration process. In nuclei pions are also present, from the pion cloud and they participate in the restoration process. But a virtual pion does not belong to an external source such as the heat reservoir. It comes from one nucleon and is re-absorbed by the same or another nucleon. In such a situation there is no genuine mixing. However, the notions of depletion and mixing can be adapted, though not trivially, to the nuclear situation. When looked in detail the mixing arises from contact couplings involving the photon (or the axial current), an s-wave pion and a hadron or system of hadrons. An example of such terms is provided by the coupling in $\vec{\phi} \times \partial_\mu \vec{\phi}$ of the photon to the pion or the Kroll-Ruderman term in pion photoproduction. We define as mixing-cross- sections the ones generated by such terms. An example is provided by the quasi-deuteron cross-section in the photo-absorption. This cross-section fills in the dip between the cross section at the giant resonance and the pion threshold. It arises from a 2p2h excitation induced by the two contact terms, as shown in fig. 1. According to our definition this is a mixing cross-section. Such a definition is useful if we can show that this type of mixing is a signal for the restoration and if there is a depletion effect associated with it.

The second point, concerning the existence of a depletion effect, is more easily dealt with. It implies a quenching of the coupling constants of the photon (or of the axial

Figure 1. Quasi-deuteron process

current) to the hadronic states in the nuclear medium. We take the example of the pion decay constant, f_π . In the heat bath its quenching arises from the thermal pion loops as shown in fig. 2. The vertex, where the axial current produces 3 pions, is imposed by chiral symmetry. Replacing the thermal pion by a virtual one does not change the expression of the in medium effect which writes in both cases:

$$\frac{f_\pi^*}{f_\pi} = 1 - \frac{\langle \phi^2 \rangle}{3f_\pi^2}. \quad (9)$$

This represents 2/3 of the condensate evolution from the pion, which is governed by the quantity $\langle \phi^2 \rangle / 2f_\pi^2$. This result agrees with the general expression of Dey et al. [3] (4/3 of the condensate evolution for the correlator, i.e., for f_π^2).

As for the link between the mixing-cross-section and the restoration, it has been established by Chanfray et al.[5]. They showed the existence of a sum rule linking the pion density to the integral over the energy of the mixing part of the photoabsorption cross-section, σ_γ^{mixing} :

$$\int d\vec{x} \langle \phi^2(x) \rangle = 3/(4\pi^2\alpha) \int d\omega \sigma_\gamma^{mixing}(\omega). \quad (10)$$

In the case of a single nucleon the mixing cross-section is the photoproduction-cross section, arising from the two contact pieces of the vector current, i.e., the Kroll-Ruderman term and the pion-in-flight one. In this case, σ_γ^{mixing} starts at the pion threshold. The mixing cross-section is not the physical cross-section, which contains other contributions such as the direct excitation of the Δ . But it includes, at larger energies, Δ -excitation accompanied by a pion through similar contact terms. The mixing-cross-section dominates the cross-section close to threshold, in both cases of a final nucleon or of a final Δ . An evaluation of the mixing cross-section guided by the threshold data[5] leads, through the

Figure 2. Renormalisation of f_π by pion loops in the heat bath and in the nuclear medium

relation 10, to a total pion number in the nucleon of the order of .4. It is consistent with the idea of a large participation of the nuclear pions to the restoration process.

The existence of mixing cross-sections represent the clearest signal of chiral symmetry restoration. While in the pure heat bath the experimental access is difficult, many examples of mixing cross-section exist in the nucleus. The quasi-deuteron process is one. Dilepton pair production in ultra relativistic heavy ion collisions is another interesting example. Their mass distribution of the pair produced provides the imaginary part of the vector correlator. The mass spectrum is much enhanced at low energies (around 500 MeV). The baryonic interpretation attributes the enhancement to the baryonic background, which allows the replacement of one pion of the $\pi^+\pi^-$ annihilation by a particle-hole state, in particular a Δ -hole one [6]. (The contact interactions with the photon are dominant at these energies) This is precisely the definition that we have given of a mixing cross-section for the process previously discussed of $\Delta\pi$ production. It is therefore an unambiguous signal for the restoration: it reflects the density of the pion cloud of the baryons present in the fireball.

Now this mechanism is not the only source of enhancement. Other ones have been discussed, such as resonance excitation[7,8], in particular the $N^*(1520 \text{ MeV})$ [9,10]. Do they also reflect the restoration process, as has been suggested [11]? The mechanism for this link is less transparent than in the case of the pion.

3. LINEAR σ -MODEL AND QUANTUM HADRODYNAMICS

I now come to the role of the scalar-isoscalar meson in the restoration process and in the nucleon mass modification, a work done in collaboration with G. Chanfray and P. Guichon. For this discussion we need a model. The linear σ model is well suited. It possesses chiral symmetry and describes the σ and the pion as chiral partners. In the application of this model we must face crucial question: what is the relation between the σ of this model and the one of QHD which provides the attraction between nucleons? Can we identify the mean scalar field of QHD, $\langle \sigma_{QHD} \rangle$, with the mean value of the chiral

partner of the pion, i.e., $\langle \sigma - f_\pi \rangle_{model}$ (the vacuum value must be subtracted)? The answer to this question is: Definitely not! They cannot be the same field. Indeed, in the model the quantity $\sigma - f_\pi$ is coupled to the squared pion field. Its expectation value thus depends on the pion density. If it is the same quantity which fixes the in-medium nucleon mass, the mass would depend on the expectation value of the squared pion field, which contains the linear term in the pion mass, forbidden by the chiral perturbation constraints. We are then left with two possibilities. Either the linear σ model is not suited to describe the nuclear attraction. Or there may exist within the model cancellations which make the nucleon- nucleon interaction independent of the pion density. In the usual formulation of the model cancellations are frequent and are needed in order to fulfil the soft pion theorems. We will explore the second possibility.

The cancellations are best implemented with a change of variables. Instead of the two chiral partners σ and π , we take two new fields. The scalar one is the radius of the chiral circle $\rho = f_\pi + s$, and for the pseudoscalar one, we introduce the chiral angle Φ/f_π . The relations between the two sets of field are

$$\sigma = (f_\pi + s) \cos(\phi/f_\pi); \quad (11)$$

$$\pi = \frac{\hat{\phi}}{(f_\pi + s)} \sin(\phi/f_\pi). \quad (12)$$

The quantity s represents the fluctuation of the radius. In the vacuum, the expectation value is $\langle \sigma \rangle = f_\pi$; hence $\langle s \rangle = 0$. The quantity s is manifestly a chiral invariant, while σ is not. We rewrite the Lagrangian in terms of the new fields. The interesting point is that s couples only derivatively to two pions. There is no term in $s\phi^2$. In this way the soft pion theorems are fulfilled without cancellations. The model allows the evaluation of various in-medium quantities. The first one is the quark condensate. Its expression is obtained from the following correspondence between the symmetry breaking Lagrangian of QCD and the one of the linear σ model:

$$\mathcal{L}_{sym. break.}^{QCD} = -2m_q \bar{q}q(x) \quad \leftrightarrow \quad \mathcal{L}_{sym. break.}^{\sigma model} = f_\pi m_\pi^2 \sigma(x). \quad (13)$$

The modification of the condensate is therefore given by that of the expectation value of the σ field, i.e., by $\langle \sigma - f_\pi \rangle$. For instance, for a single nucleon and expressing the field σ with the new variables, we have for the σ commutator:

$$\Sigma_N = f_\pi m_\pi^2 \int d\vec{x} \langle N | f_\pi - \sigma(x) | N \rangle = \quad (14)$$

$$\frac{1}{2} m_\pi^2 \int d\vec{x} \langle N | \phi^2(x) | N \rangle + f_\pi m_\pi^2 \int d\vec{x} \langle N | s(x) \left(1 - \frac{\phi^2(x)}{2f_\pi}\right) | N \rangle.$$

where only the lowest order terms in ϕ^2 have been retained. The first part is the pionic contribution to the restoration as discussed in the previous section. The second one is the contribution from the scalar meson. Notice that, to leading order, the scalar contribution is linear in the scalar field, while the pionic one depends on the squared pion field. The

Figure 3. Pion and scalar meson contributions to the condensate, represented by a cross.

difference, illustrated in the graphs of fig. 3, arises from the possibility, absent in the pion case, for the σ to dissolve in the condensate.

The pion contributes instead only through the fluctuations (which also exist for the scalar field). Notice that the scalar contribution to the condensate also depends on the pion field squared. This to be expected since the condensate is not a chiral invariant object.

A similar decomposition holds in a uniform nuclear medium with

$$\frac{\langle \bar{q}q(\rho) \rangle}{\langle \bar{q}q(0) \rangle} = 1 - \frac{\langle \Phi^2 \rangle}{2f_\pi^2} + \langle \frac{s(1 - \Phi^2/2f_\pi^2)}{f_\pi} \rangle, \quad (15)$$

where the expectation values are taken with respect to the nuclear ground state. To zeroth order in the pion loops, the scalar part is governed by the expectation value of the field $\langle s \rangle$, as given, to lowest order in the density, by the model value:

$$\langle s \rangle = -\frac{g\rho}{m_\sigma^2}. \quad (16)$$

Here $g = M/f_\pi = 10$ is the σ -nucleon coupling constant. We will discuss numerical values later.

The model allows the evaluation of other in-medium quantities, such as the nucleon mass for which we obtain:

$$M^* - M = -g \langle s \rangle = -g^2 \rho / m_\sigma^2. \quad (17)$$

It is governed by the chiral invariant field s and not by the σ field. It has no dependence at all on ϕ^2 , which insures the compatibility between this expression and the chiral constraints. The cancellations, that I mentioned above, are indeed present in the mass problem. With this formulation of the model they are built in. The identification with quantum hadrodynamics becomes trivial since in QHD the mass modification is given by a similar expression, We should therefore identify the σN coupling constant of quantum

hadrodynamics with the quantity g . On the other hand the identification of the scalar mean field of QHD should be made with the chiral invariant quantity $\langle s \rangle$.

Concerning the precursor character of the reduction of the nucleon mass, it is a signal of the restoration induced by the scalar meson. Both are driven by the mean scalar field. However the mass does not follow the corresponding quark evolution since the last quantity depends on the pion loops. It is only to zero order in the pion density that the correspondence holds. This result must apply to any model, where the mass evolution is related to the condensate one, since it is a requirement of the chiral symmetry constraints.

For the numerical values, we have seen that the value of the σN coupling constant is $M/f_\pi = 10$, consistent with the QHD phenomenology. For the other in-medium values the parameters of the model are fixed by the pion mass and decay constant and the sigma mass. The last quantity is not well known and we take it as a free parameter of the model. We evaluate the in-medium quantities for two values, $m_\sigma = 1.0$ and $.8$ GeV. The corresponding values for the nucleon mass modification are -150 and -220 MeV, respectively; these magnitudes are compatible with the QHD phenomenology. For the relative amount of restoration from the scalar field we obtain 15% and 22%. Equivalently, the contribution to the nucleon σ commutator from the scalar meson is 18 and 28 MeV, respectively, as compared to a total value of 50 MeV. An appreciable amount of the restoration originates from the scalar meson exchange.

In conclusion, two mesons play an essential role in chiral symmetry restoration in nuclei. Firstly the pion, as a Goldstone boson. Its field is long ranged and the pionic fluctuations play a major role. Second, since the σ meson has the quantum numbers, 0^{++} , it becomes possible for it to dissolve into the condensate. These two mesons give rise to distinct precursor signals: the so-called correlator mixing for the pion and the mass reduction for the scalar. We have also seen that the scalar meson, which lowers the mass, is a chiral invariant, i. e., it is dressed by the pion loops, while the condensate evolution is driven by the bare scalar particle. Because of this difference, the difficulty to incorporate quantum hadrodynamics in a chiral theory has been eliminated and our results are fully consistent with the constraints of chiral perturbation theory.

4. Acknowledgements

This talk reports of works done in collaboration with J. Delorme, G. Chanfray and P. Guichon. It is a pleasure to acknowledge their contribution to the understanding of these problems. I am grateful to the organisers of this meeting for giving me the opportunity to participate in this tribute to Achim Richter.

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