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Symmetries and in-medium effects

Chiral symmetry breaking and modification of meson properties in a strongly interacting medium

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Abstract. Chiral symmetry is a fundamental symmetry of Quantum Chromodynamics (QCD) in the limit of vanishing quark masses. In the hadronic sector chiral symmetry is broken; otherwise chiral partners - hadronic states with the same spin but opposite parity - should be degenerate in mass which is not observed in nature. It has been suggested that chiral symmetry might at least be partially restored in a strongly interacting environment. As a consequence, properties of hadrons, encoded in their mass and width, may be modified when embedded in a nucleus. These ideas have motivated widespread theoretical and experimental activities. As an example, recent experimental results on the in-medium properties of the η' meson are presented.

1 Introduction

Eugene P. Wigner received the Nobelprize in Physics in 1963 *"for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles"*. Also today, in modern Quantum Chromodynamics (QCD), symmetries and symmetry breaking play a fundamental role. In the limit of vanishing quark masses, QCD exhibits chiral symmetry. This implies that - as shown in figure 1 left - left-handed and right-handed quarks, interacting through gluon exchange, retain their handedness, left-handed quarks stay left-handed, right-handed quarks stay right-handed, i.e. chirality is conserved.

The QCD ground state does, however, not share chiral symmetry. The QCD vacuum is populated with $\bar{q}q$ pairs in $^3P_0$ states with $J^\pi = 0^+$ as indicated in figure 1 right a.), giving rise to the chiral condensate $<0|\bar{q}q|0>$. In the presence of the chiral condensate chiral symmetry is broken since - as shown in figure 1 right b.) - a left-handed quark can be converted into a right-handed quark by annihilating with the left-handed antiquark of the $^3P_0$ pair.

Chiral symmetry is broken in the hadronic sector. If chiral symmetry were to hold, chiral partners, i.e. hadronic states with the same spin but opposite parity - should be degenerate in mass: m(J^π) = m($J^{-\pi}$). This is not observed experimentally. As indicated in figure 2 left, chiral partners in the excitation energy spectrum of the nucleon or scalar and vector mesons show mass splits almost comparable to their mass. Figure 2 right illustrates the importance of symmetry breaking for understanding the masses of the known pseudo-scalar mesons. All 9 pseudo-scalar mesons would be degenerate in mass

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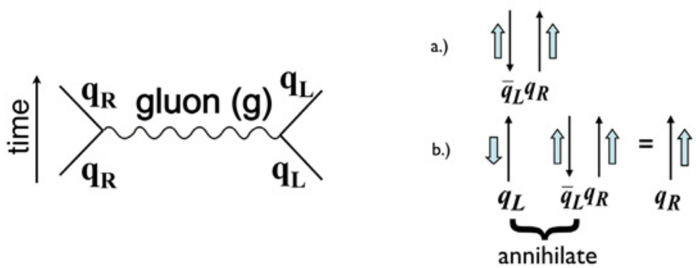

Figure 1. Left: Interaction of a right-handed and left-handed quark by gluon exchange, retaining their handedness. Right: a.) scalar quark-antiquark pairs in a $^3P_0$ state, making up the chiral condensate; b.) breaking of chiral symmetry in the presence of a chiral condensate: interacting with a scalar quark-antiquark pair, a left handed quark is converted into a right handed quark.

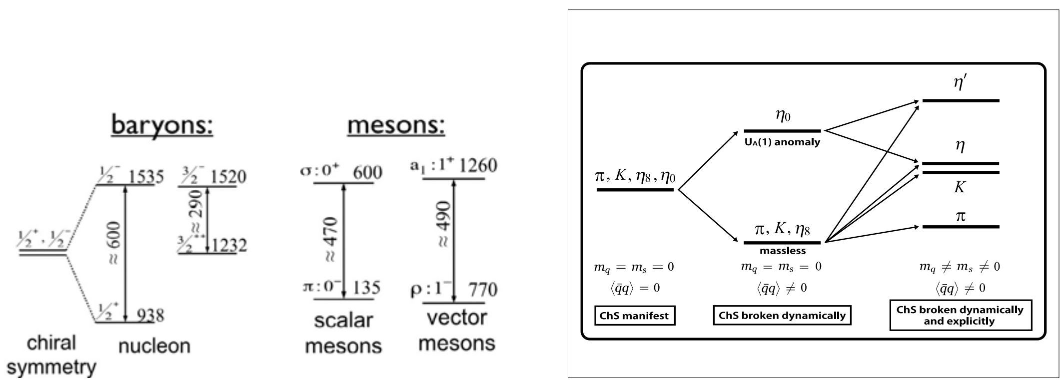

Figure 2. Left: mass splitting for chiral partners in the baryonic and mesonic sector. Right: mass spectrum of light pseudoscalar meson for no, dynamic, and additional explicit chiral symmetry breaking. The figure is taken from [1].

for massless quarks and in case of chiral symmetry. Due to the dynamical breaking of chiral symmetry ($<0|\bar{q}q|0> \neq 0$) and the $U_A(1)$ anomaly the singlet η_0 acquires mass. Introducing current quarks with non-zero masses and thereby breaking chiral symmetry explicitly leads to the experimentally established mass spectrum of pseudo-scalar mesons.

2 Theoretical predictions for in-medium modifications of meson properties

It has been argued that chiral symmetry may be restored in a strongly interacting medium, leading to modifications of meson properties such as masses and widths. The order parameter of chiral symmetry, the chiral condensate $<0|\bar{q}q|0>$ is expected to drop as a function of baryon density ρ and/or temperature T [2]. Unfortunately, the chiral condensate itself is not an observable quantity. However, QCD sum rules show that changes in the chiral and higher order condensates should have an impact on the integral over hadronic spectral functions [3, 4]. Although there is no direct relation between

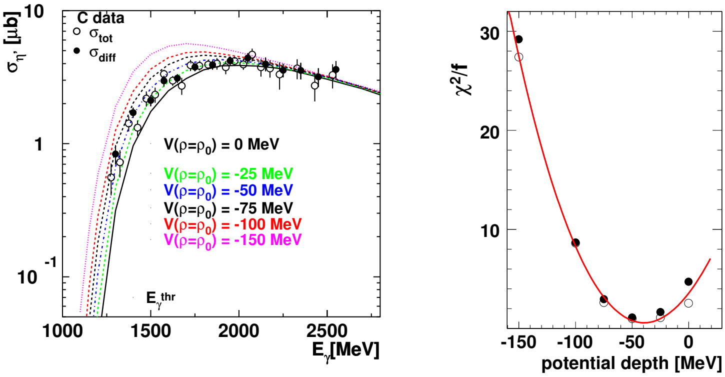

Figure 3. Left: Total cross section for η' photo-production off C [13] in comparison to calculations [15] assuming different depth of the real part of the η' optical potential. Right: χ^2- fit of the data with the calculated excitation functions for the different scenarios over the full incident photon energy range. The figure is taken from [13].

in-medium properties of hadrons and QCD condensates, QCD sum rules thus provide important constraints for hadronic models which are still needed for a quantitative comparison with experiments [5].

Calculations within the Nambu-Jona-Lasinio model predict that for high densities the singlet η' and the octet η become degenerate in mass. The calculations by Bernard and Meissner [6] exhibit only a very weak dependence of the η' mass on the baryon density while the calculations by Nagahiro et al. [7] show a much stronger variation of the η' mass with density, predicting a drop of the η' mass by about 150 MeV at normal nuclear matter density. More recently further theoretical studies of the in-medium mass of the η' meson in cold [8, 9] and also in heated hadronic matter [10] have been performed. These partially conflicting theoretical predictions and indirect evidence for strong in-medium mass changes of the η' meson, deduced from an analysis of RHIC data [11], have motivated our experimental studies [12, 13] of the in-medium properties of the η' meson.

3 Experimental determination of the η' in-medium width and mass

Measuring the transparency ratio in photo-production experiments on a series of nuclei, an in-medium η' width of 15-25 MeV has been determined [12], corresponding to an imaginary part of the η'-nucleus potential of about 10 MeV, which is the smallest value reported so far for any meson. A possible in-medium mass shift of the η' meson can not be determined from an analysis of the η' line shape as almost all η' decays occur outside of the nucleus because of the long η' lifetime. As pointed out in [14, 15], indirect information on the in-medium meson mass can, however, be obtained from studying the excitation function and the momentum distribution of mesons. For a lower in-medium mass the phase space for meson production is increased leading to higher cross sections for incident beam energies near and below the production threshold on a free nucleon. Leaving the nucleus, a meson with a reduced in-medium mass has to generate its on-shell mass at the expense of its kinetic energy, leading to a downward shift in the meson momentum distribution.

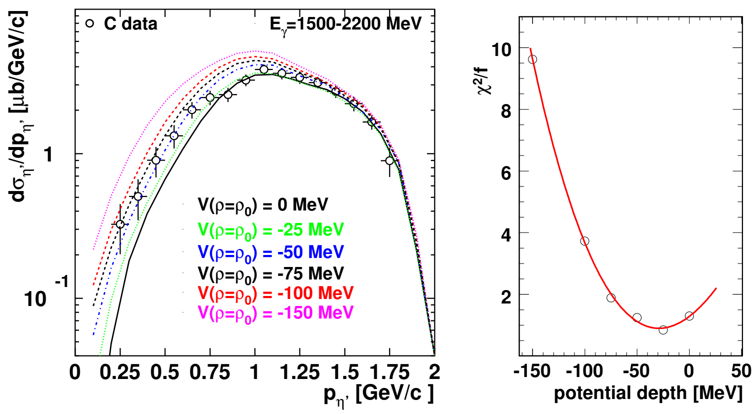

Figure 4. Momentum distribution of η' photoproduction off C for incident photons of 1500-2200 MeV [13] in comparison to calculations [15] assuming different depth of the real part of the η' optical potential. Right: χ^2- fit of the data with the calculated momentum distributions for the different scenarios. The figure is taken from [13].

Excitation functions and momentum distributions of the η' meson, measured in photo-production on C, are shown in Figs. 3,4 in comparison to calculations [15] for the experimentally determined imaginary part of the optical η'-nucleus potential, assuming different values for the real part. Fits to the data indicate a potential depth and thereby an in-medium mass drop of the η' meson of $(37 \pm 10(stat) \pm 10(syst))$ MeV at normal nuclear matter density and an average η' momentum of 1.1 GeV/c [13]. If confirmed by further experiments - data on η' photo production off Nb have recently been taken and are being analyzed - this result would imply the first (indirect) observation of a mass drop of a pseudoscalar meson at normal nuclear matter density. An in-medium mass shift of -40 MeV is in excellent agreement with predictions of the QMC model [8] and - considering the experimental systematic errors - close to the recent calculations by Sakai and Jido [9].

The relation between the potential depth and the η' scattering length has recently been investigated [16] for η' mesons at rest in a C nucleus. A possible momentum dependence of the scattering amplitude will have to be taken into account when comparing the potential depth reported in [13] to experimental limits on the η' scattering length deduced from an analysis of the η'-nucleon final-state-interaction in the $pp \rightarrow pp\eta'$ reaction [17, 18].

In view of the rather small in-medium width of the η' meson of about 20 MeV and the reported potential depth of about 40 MeV, the η' meson appears to be a promising candidate for a search for meson-nucleus bound states. Corresponding experiments are planned at the FRS spectrometer at GSI (Darmstadt) [1], the BGO-OD setup at ELSA (Bonn) [19], and the LEPSII spectrometer at RCNP (Osaka) [20].

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