QCD SYMMETRIES IN η- AND η'-MESIC NUCLEI*

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We discuss the role of QCD symmetries and confinement in understanding η- and η'-mesic nuclei. η and η' bound states in nuclei are sensitive to the flavour-singlet component in the meson. The bigger the singlet component, the more attraction and the greater the binding. Recent results on the η' mass in nuclei from the CBELSA/TAPS Collaboration are very similar to the prediction of the Quark Meson Coupling model. In the model, η–η' mixing induces a factor of two enhancement of the η-nucleon scattering length $a_{\eta N}$ relative to the prediction with a pure octet η with real part about 0.8 fm.

1. Introduction

Measurements of the η- and η'- (as well as pion and kaon) nucleus systems promise to yield valuable new information about dynamical chiral and axial U(1) symmetry breaking in low energy QCD. The quark condensate is modified in the nuclear environment which leads to changes in the properties of hadrons in medium including the masses of the Goldstone bosons [1]. While pions and kaons are would-be Goldstone bosons associated with chiral symmetry, the isosinglet η and η' mesons are too massive by about 300–400 MeV for them to be pure Goldstone states [2]. They receive extra mass from non-perturbative gluon dynamics associated with the QCD axial anomaly. How does this gluonic part change in nuclei?

The η- and η'-nucleon interactions are attractive suggesting that these mesons may form strong-interaction bound-states in nuclei. Medium modifications can be understood at the quark level through coupling of the scalar isoscalar σ (and also ω and ρ) mean-fields in the nucleus to the light quarks in the hadron [3]. The binding energies and in-medium masses of the η and η' are sensitive to the flavour-singlet component in the mesons and hence to the non-perturbative glue associated with axial U(1) dynamics [4]. There is presently a vigorous experimental programme to search for evidence of these bound states with ongoing experiments at COSY to look for possible η bound states in helium [5], and new experiments at ELSA [6] and GSI/FAIR [7] to look for possible η' bound states in carbon.

In this paper, we discuss the relation between QCD symmetries and possible medium effects in these mesons. Important considerations are confinement, chiral and axial U(1) symmetry, their behaviour in medium and the role of η–η' mixing. We focus on the Quark Meson Coupling model (QMC, for a review see [3]) and compare its predictions for the η and η' systems to chiral coupled channels, NJL and linear σ models.

Meson masses in nuclei are determined from the meson nucleus optical potential and the scalar induced contribution to the meson propagator evaluated at zero three-momentum, $\vec{k} = 0$, in the nuclear medium. Let $k = (E, \vec{k})$ and m denote the four-momentum, and mass of the meson in free space. Then, one solves the equation

$$k^2 - m^2 = \text{Re } \Pi\left(E, \vec{k}, \rho\right) \tag{1}$$

for $\vec{k} = 0$, where Π is the in-medium s-wave meson self-energy. Contributions to the in-medium mass come from coupling to the scalar σ field in the nucleus in mean-field approximation, nucleon–hole and resonance–hole excitations in the medium. For $\vec{k} = 0$, $k^2 - m^2 \sim 2m(m^* - m)$, where m^* is the effective mass in the medium. The mass shift $m^* - m$ is the depth or real part of the meson nucleus optical potential. The imaginary part of the potential measures the width of the meson in the nuclear medium. The s-wave self-energy can be written as [8]

$$\Pi\left(E, \vec{k}, \rho\right)\Big|_{\{\vec{k}=0\}} = -4\pi\rho\left(\frac{b}{1 + b\left\langle\frac{1}{r}\right\rangle}\right). \tag{2}$$

Here, ρ is the nuclear density, $b = a(1 + \frac{m}{M})$, where a is the meson–nucleon scattering length, M is the nucleon mass and $\langle\frac{1}{r}\rangle$ is the inverse correlation length, $\langle\frac{1}{r}\rangle \simeq m_\pi$ for nuclear matter density. Attraction corresponds to positive values of a. The denominator in Eq. (2) is the Ericson–Ericson–Lorentz–Lorenz double scattering correction.

What should we expect for the η and η'?

COSY searches are focussed on possible η bound states in ^{3}He and ^{4}He [5]. Eta bound states in helium require a large η-nucleon scattering length with real part greater than about 0.9 fm [9]. For clean observation of a bound state, one needs the real part of the optical potential to be much bigger than the imaginary part. We refer to [10] for a recent discussion of the η in light nuclei.

For the η', new experiments are planned to look for possible bound states in carbon using the (p, d) reaction at GSI [7] and in photoproduction at ELSA [6]. Recent measurements of the transparency ratio for η' photo-production from nuclear targets have been interpreted to mean a small η' width in nuclei 20±5.0 MeV at nuclear matter density ρ_0 [11] that might give rise to relatively narrow bound η'-nucleus states accessible to experiments.

In addition to bound state searches, meson mass shifts can also be investigated through studies of excitation functions in photoproduction experiments from nuclear targets. The production cross section is enhanced with the lower effective mass in the nuclear medium. When the meson leaves the nucleus it returns on-shell to its free mass with the energy budget conserved at the expense of the kinetic energy so that excitation functions and momentum distributions can provide essential clues to the meson properties in medium [12]. Using this physics, a first (indirect) estimate of the η' mass shift has recently been deduced by the CBELSA/TAPS Collaboration [13]. The η'-nucleus optical potential $V_{\text{opt}} = V_{\text{real}} + iW$ deduced from these photoproduction experiments is

$$V_{\text{real}}(\rho_0) = m^* - m = -37 \pm 10(\text{stat.}) \pm 10(\text{syst.}) \text{ MeV} ,$$
$$W(\rho_0) = -10 \pm 2.5 \text{ MeV} \tag{3}$$

at nuclear matter density. These numbers suggest that bound states may be within reach of forthcoming experiments. The mass shift, Eq. (3), is also very similar to the expectations of the Quark Meson Coupling model, see below.

2. QCD symmetries and the η and η'

Low energy QCD is characterised by confinement and dynamical chiral symmetry breaking. The absence of parity doublets in the hadron spectrum tells us that the near-chiral symmetry for light u and d quarks is spontaneously broken. Scalar confinement implies dynamical chiral symmetry breaking. For example, in the Bag model the Bag wall connects left- and right-handed quarks leading to quark–pion coupling and the pion cloud of the nucleon [14]. Spontaneous chiral symmetry breaking in QCD is associ-

ated with a non-vanishing chiral condensate[1]

$$\langle \mathrm{vac}|\bar{\psi}\psi|\mathrm{vac}\rangle < 0 \,. \tag{4}$$

This spontaneous symmetry breaking induces an octet of Goldstone bosons associated with SU(3) and also (before extra gluonic effects in the singlet channel) a flavour-singlet Goldstone boson. The Goldstone bosons P couple to the axial-vector currents which play the role of Noether currents through

$$\langle \mathrm{vac}|J_{\mu5}^k|P(p)\rangle = -if_P^k \, p_\mu e^{-ip.x} \tag{5}$$

with f_P^k the corresponding decay constants and satisfy the Gell-Mann–Oakes–Renner relation

$$m_\pi^2 f_\pi^2 = -m_q \left\langle \bar{\psi}\psi \right\rangle \,. \tag{6}$$

The pion and kaon fit well in this picture.

The isosinglet η and η' masses are about 300–400 MeV too heavy to be pure Goldstone states. One needs extra mass in the flavour-singlet channel associated with non-perturbative topological gluon configurations [16, 17], related perhaps to confinement [18] or instantons [19]. SU(3) breaking generates mixing between the octet and singlet states yielding the massive η and η' bosons.

With increasing density chiral symmetry is partially restored corresponding to a reduction in the value of the quark condensate and pion decay constant f_π. Experiments with pionic atoms give a value $f_\pi^{*2}/f_\pi^2 = 0.64 \pm 0.06$ at nuclear matter density ρ_0 [1]. This suggests changes in the meson masses in the medium and also the coupling of the Goldstone bosons to the constituent quarks and the nucleon — for reviews of the QCD phase diagram and medium modifications at finite density, see [3, 20, 21]. These medium modifications need to be understood self-consistently within the interplay of confinement, spontaneous chiral symmetry breaking and axial U(1) dynamics. In the limit of chiral restoration, the pion should decouple from the physics, the pion decay constant f_π go to zero and (perhaps) with scalar confinement the pion constituent-quark and pion nucleon coupling constants should vanish with dissolution of the pion wavefunction.

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[1] Spontaneous symmetry breaking and phase transitions give changes in the vacuum energy which couples to gravity. It is interesting that the QCD quark condensate gives a contribution 10^{44} times larger (and the electroweak Higgs condensate 10^{56} times larger) than the nett vacuum energy extracted from the cosmological constant without additional physics, see *e.g.* [15]. Further, the vacuum energy extracted from the cosmological constant is small and positive whereas the QCD and Higgs contributions come with a negative sign.

To see the effect of the gluonic mass contribution consider the η–η' mass matrix for free mesons (at leading order in the chiral expansion)

$$M^2 = \begin{pmatrix} \frac{4}{3}m_K^2 - \frac{1}{3}m_\pi^2 & -\frac{2}{3}\sqrt{2}\left(m_K^2 - m_\pi^2\right) \\ -\frac{2}{3}\sqrt{2}\left(m_K^2 - m_\pi^2\right) & \left[\frac{2}{3}m_K^2 + \frac{1}{3}m_\pi^2 + \tilde{m}_{\eta_0}^2\right] \end{pmatrix}. \tag{7}$$

Here $\tilde{m}_{\eta_0}^2$ is the flavour-singlet gluonic mass term.

The masses of the physical η and η' mesons are found by diagonalizing this matrix, *viz.*

$$\begin{aligned} |\eta\rangle &= \cos\theta \, |\eta_8\rangle - \sin\theta \, |\eta_0\rangle, \\ |\eta'\rangle &= \sin\theta \, |\eta_8\rangle + \cos\theta \, |\eta_0\rangle, \end{aligned} \tag{8}$$

where

$$\eta_0 = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right), \qquad \eta_8 = \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right). \tag{9}$$

One obtains values for the η and η' masses

$$m_{\eta',\eta}^2 = \left(m_K^2 + \tilde{m}_{\eta_0}^2/2\right) \pm \frac{1}{2}\sqrt{\left(2m_K^2 - 2m_\pi^2 - \frac{1}{3}\tilde{m}_{\eta_0}^2\right)^2 + \frac{8}{9}\tilde{m}_{\eta_0}^4}. \tag{10}$$

The gluonic mass term is obtained from summing over the two eigenvalues in Eq. (10)

$$m_\eta^2 + m_{\eta'}^2 = 2m_K^2 + \tilde{m}_{\eta_0}^2. \tag{11}$$

Substituting the physical values of m_η, $m_{\eta'}$ and m_K gives $\tilde{m}_{\eta_0}^2 = 0.73 \text{ GeV}^2$ [22]. The gluonic mass term has a rigorous interpretation in terms of the Yang–Mills topological susceptibility, see *e.g.* [16, 23].

In the OZI limit of no gluonic mass term the η would be approximately an isosinglet light-quark state ($\frac{1}{\sqrt{2}}|\bar{u}u + \bar{d}d\rangle$) with mass $m_\eta \sim m_\pi$ degenerate with the pion and the η' would be a strange-quark state $|\bar{s}s\rangle$ with mass $m_{\eta'} \sim \sqrt{2m_K^2 - m_\pi^2}$ — mirroring the isoscalar vector ω and ϕ mesons.

Phenomenological studies of various decay processes give a value for the η–η' mixing angle between $-15°$ and $-20°$ [24]. This mixing means that non-perturbative glue through axial U(1) dynamics plays an important role in both the η and η' and their interactions [2]. Treating the η as a pure octet would-be Goldstone boson risks losing essential physics. Processes associated with the flavour-singlet 1^{-+} channel are characterized by OZI violation. The anomalous glue that generates the large η and η' masses also drives OZI violating η and η' production and decay processes [24–28], enters in the η'-nucleon interaction [29] and the flavour-singlet Goldberger–Treiman relation [30] associated with the proton spin puzzle [31, 32].

The gluonic mass term is related to the QCD axial anomaly in the divergence of the flavour-singlet axial-vector current. While the non-singlet axial-vector currents are partially conserved (they have just mass terms in the divergence), the singlet current $J_{\mu 5} = \bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d + \bar{s}\gamma_\mu\gamma_5 s$ satisfies the anomalous divergence equation

$$\partial^\mu J_{\mu 5} = 6Q + \sum_{k=1}^{3} 2im_k \bar{q}_k \gamma_5 q_k \,, \qquad (12)$$

where $Q = \partial^\mu K_\mu = \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$ is the topological charge density. The integral over space $\int d^4 z\, Q = n$ measures the gluonic winding number [17] which is an integer for (anti-)instantons and which vanishes in perturbative QCD.

Within the low energy effective chiral Lagrangian for QCD the gluonic mass term is introduced via a flavour-singlet potential involving the topological charge density Q which is constructed so that the Lagrangian also reproduces the axial anomaly [22]. In this approach, the medium dependence of $\tilde{m}_{\eta_0}^2$ is introduced through coupling to the σ (correlated two-pion) mean-field in the nucleus through the interaction term $\mathcal{L}_{\sigma Q} = g_{\sigma Q}\, Q^2\, \sigma$, where $g_{\sigma Q}$ denotes coupling to the σ mean-field. One finds the gluonic mass term decreases in-medium $\tilde{m}_{\eta_0}^{*2} < \tilde{m}_{\eta_0}^2$ independent of the sign of $g_{\sigma Q}$ and the medium acts to partially neutralise axial U(1) symmetry breaking by gluonic effects [4].

To estimate the size of the effect, we look to phenomenology and QCD motivated models. QCD inspired models of the η and η' nucleus systems are constructed with different selections of "good physics input": how they treat confinement, chiral symmetry and axial U(1) dynamics.

3. The η and η' in nuclei

The physics of η and η' mass shifts with η–η' mixing has been investigated by Bass and Thomas [4, 33] within the Quark Meson Coupling model of hadron properties in the nuclear medium [3, 34]. Here, the large η and η' masses are used to motivate taking an MIT Bag description for the meson wavefunctions. Gluonic topological effects are understood to be "frozen in", meaning that they are only present implicity through the masses and mixing angle in the model. The in-medium mass modification comes from coupling the light (up and down) quarks and antiquarks in the meson wavefunction to the scalar σ mean-field in the nucleus working in mean-field approximation [3]. The coupling constants in the model for the coupling of light-quarks to the σ (and ω and ρ) mean-fields in the nucleus are adjusted to fit the saturation energy and density of symmetric nuclear matter, and

the bulk symmetry energy. The strange-quark component of the wavefunction does not couple to the σ field and η–η' mixing is readily built into the model. Gluon fluctuation and centre-of-mass effects are assumed to be independent of density. The model results for the meson masses in medium and the real part of the meson–nucleon scattering lengths are shown in Table I for different values of the η–η' mixing angle, which is taken to be density independent[2]. The QMC model makes no claim about the imaginary part of the scattering length.

TABLE I

Physical masses fitted in free space, the bag masses in medium at normal nuclear-matter density, $\rho_0 = 0.15$ fm^{-3}, and corresponding meson–nucleon scattering lengths.

	m [MeV]	m^* [MeV]	Re a [fm]
η_8	547.75	500.0	0.43
η $(-10°)$	547.75	474.7	0.64
η $(-20°)$	547.75	449.3	0.85
η_0	958	878.6	0.99
η' $(-10°)$	958	899.2	0.74
η' $(-20°)$	958	921.3	0.47

Increasing the flavour-singlet component in the η at the expense of the octet component gives more attraction, more binding and a larger value of the η-nucleon scattering length, $a_{\eta N}$. Since the mass shift is approximately proportional to the η-nucleon scattering length, it follows that the physical value of $a_{\eta N}$ should be larger than if the η were a pure octet state. For the η' the opposite is true: the greater the mixing angle the smaller the singlet component in the η' and smaller the value of the η' binding energy and the η'-nucleon scattering length.

There are several key observations.

3.1. η bound states

η–η' mixing with the phenomenological mixing angle $-20°$ leads to a factor of two increase in the mass-shift and in the scattering length obtained in the model relative to the prediction for a pure octet η_8. This result may explain why values of $a_{\eta N}$ extracted from phenomenological fits to experimental data, where the η–η' mixing angle is unconstrained give larger values than those predicted in theoretical models, where the η is treated as a pure octet state.

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[2] The values of Re a_η quoted in Table I are obtained from substituting the in-medium and free masses into Eq. (2) with the Ericson–Ericson denominator turned-off (since we choose to work in mean-field approximation).

COSY-11 have studied the final state interaction (FSI) in measurements of η production in proton–proton collisions close to threshold based on the effective range approximation. The results are consistent with the scattering length $a_{\eta N} \simeq 0.7 + i\,0.4$ fm [35]. K-matrix fits to experimental data suggest a value close to 0.9 fm for the real part of $a_{\eta N}$ [36]. In contrast, smaller values of $a_{\eta N}$ with real part ~ 0.2 fm are predicted by chiral coupled channels, where the η meson is treated in pure octet approximation [37, 38]. These chiral models involve performing a coupled channels analysis of η and η' production after multiple rescattering in the nucleus with potentials obtained from the SU(3) chiral Lagrangian.

For the kaon nucleus system, similar results are obtained using the QMC and chiral coupled channels models, *e.g.* reduction in the K^- mass of about 100 MeV at nuclear matter density and interpretation of the $\Lambda(1405)$ resonance as dynamically generated in the kaon–nucleon system [37, 39]. An effective mass drop of the K^- to about 270 MeV at $2\rho_0$ has been observed in heavy-ion collisions [40], consistent with the predictions of the Quark Meson Coupling and chiral coupled channels model calculations.

The η-nucleon interaction is characterised by a strong coupling to the $S_{11}(1535)$ nucleon resonance. For example, η-meson production in proton–nucleon collisions close to threshold is known to proceed via a strong isovector exchange contribution with excitation of the $S_{11}(1535)$. Recent measurements of η' production suggest a different mechanism for this meson [41]. Experiments in heavy-ion collisions [42] and η photoproduction from nuclei [43, 44] suggest little modification of the $S_{11}(1535)$ excitation in-medium. In quark models the S_{11} is interpreted as a 3-quark state: $(1s)^2(1p)$. In QMC, the excitation energy is ~ 1544 MeV, consistent with observations, with the scalar attraction compensated by repulsion from coupling to the ω mean-field to give the excitation energy [4]. Small mass shift is also reported in the coupled channels models where the S_{11} is instead interpreted as a $K\Sigma$ quasi-bound state, with the η instead treated as a pure octet state [45].

3.2. η' bound states

From Table I, the QMC prediction for the η' mass in medium at nuclear matter density is 921 MeV with mixing angle of $-20°$. This value is in excellent agreement with the mass shift $-37 \pm 10 \pm 10$ MeV deduced from photoproduction data [13]. For the η'-nucleon scattering length a conservative upper bound $|\mathrm{Re}\,a_{\eta'N}| < 0.8$ fm has been deduced by COSY-11 [46] by comparing the FSI in π^0 and η' production in proton–proton collisions close to threshold.

If we assume the mass, formula (11) holds also in symmetric nuclear matter at finite density and substitute the QMC predictions for the η, η' and kaon masses in medium ($m_K^* = 430.4$ MeV), then we obtain $\tilde{m}_{\eta_0}^{*2}(\rho_0) = 0.68$ GeV$^2 < 0.73$ GeV^2 with η–η' mixing angle equal to $-20°$.

Mixing increases the octet relative to singlet component in the η', reducing the binding through increased strange quark component in the η' wavefunction. Without the gluonic mass contribution, the η' would be a strange quark state after η–η' mixing. Within the QMC model there would be no coupling to the σ mean-field and no mass shift, so that any observed mass shift is induced by the QCD gluon anomaly that generates part of the η' mass.

New coupled channels model calculations have appeared with mixing and vector meson channels included, fitted to a range of possible values of $a_{\eta'N}$ [47]. In both QMC and coupled channels calculations the η and η' masses decrease in medium and confinement is inbuilt in the models, either through the Bag wavefunction with QMC or using hadron degrees of freedom in coupled channels models.

In an alternative approach, large binding energies for the η' up to 150 MeV were obtained in recent chiral NJL model calculations [48]. In this model, the medium dependence of the η mass depends strongly on the axial U(1) breaking. The η mass (and also pion mass) increases in medium as chiral symmetry is partially restored without axial U(1) breaking or with density independent axial U(1) breaking. Any decreasing η mass depends on the density dependence of the axial U(1) breaking term which is put in through instantons. There is no confinement in the model and nuclear matter is treated as a Fermi gas of quarks (instead of a Fermi gas of nucleons). Similar results for the mass shifts (about 100 MeV reduction for the η' and 50 MeV increase for the η) were also found in linear sigma model based calculations in an hadronic basis with the difference between the η' and η masses taken to be proportional to the quark condensate [49, 50].

These different theoretical results raise interesting questions about the role of confinement, the representation of chiral symmetry (whether the σ is better treated as a two pion resonance or as a quark–antiquark state) and how massive the light 0^- states can be for their wavefunctions to be treated as pure Goldstone bosons in the models.

4. Summary and open questions

Medium modifications of hadron properties are determined by chiral and flavour symmetries in QCD. The η and η' are sensitive to flavour-singlet axial U(1) degrees of freedom. QCD inspired models including confinement, chiral and axial U(1) dynamics yield a range of predictions for the η and η'

binding in nuclei. The QMC prediction for the η' mass shift is very similar to the recent value determined by CBELSA/TAPS from photoproduction experiments, and the real part of the η-nucleon scattering length to values extracted from phenomenological fits to low-energy scattering data. The positive results for the η and η' suggest one might also look at charmed mesons in nuclei, *e.g.* charmed mesic nuclei [51], where large binding energies are also predicted. New data on possible η and η' bound states is expected soon from running and planned experiments at COSY, ELSA and GSI, and will help to pin down the dynamics of axial U(1) symmetry breaking in low-energy QCD.

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