The eta and etaprime in medium

Steven Bass

Chiral symmetry, eta and eta´ physics:
the masses of these mesons are 300-400 MeV too big for them to be pure Goldstone bosons

→ Famous axial U(1) problem of QCD

Additional mass is associated with non-perturbative gluon dynamics

→ How should the eta and eta-prime masses be modified in nuclei ?

→ Possible bound states and eta(-prime) nucleon scattering lengths

→ New developments from experiments @ ELSA and WASA (+GSI)

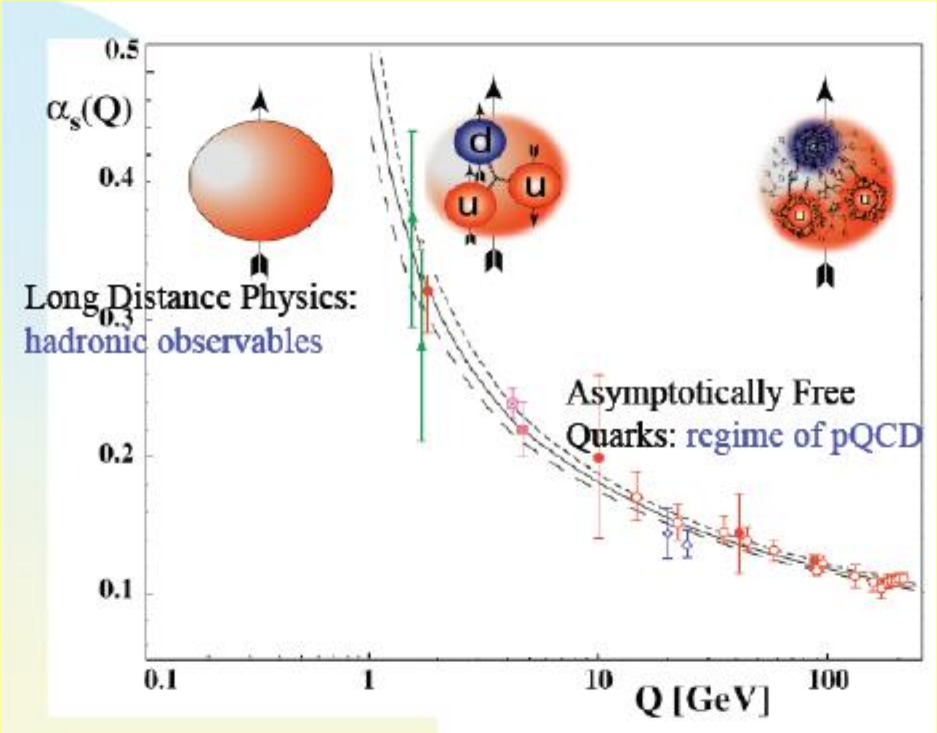
Recent developments in eta´ physics: the eta´ in nuclear matter and odd l-wave exotics from CERN

Krakow, June 10 2015

SMI

ÖAW Austrian Academy of Sciences

From Quarks to Hadrons



- Confinement

- Dynamical chiral symmetry breaking:
  - » Chiral condensate, pions, kaons, ... Goldstone bosons

- Axial U(1) Symmetry breaking ... Big masses for eta and etaprime

- Using nuclei to probe symmetries and possible restoration (both quark and gluonic effects)

Chiral symmetry

- QCD Lagrangian with massless quarks exhibits chiral symmetry

$$\mathcal{L}_{QCD} = \bar{\psi}_L\left(i\hat{\partial} + g\hat{A}\right)\psi_L + \bar{\psi}_R\left(i\hat{\partial} + g\hat{A}\right)\psi_R - m_q\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right) - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \mapsto e^{i\frac{1}{2}\vec{\alpha}.\vec{\tau}\gamma_5}\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad , \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix} \mapsto e^{i\frac{1}{2}\vec{\beta}.\vec{\tau}\gamma_5}\begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

- Noether currents

$$J^{(3)}_{\mu 5} = \left[\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d\right] \qquad \partial^\mu J^{(3)}_{\mu 5} = 2m_u\bar{u}i\gamma_5 u - 2m_d\bar{d}i\gamma_5 d$$

- No parity doublets in hadron spectrum → Spontaneous Chiral symmetry breaking: non zero condensate $\langle \text{ vac } | \bar{q}q | \text{ vac } \rangle < 0$ spontaneously breaks the symmetry

→ Nonet of near massless Goldstone bosons with $J^P = 0^-$

- Identify with pion, kaon, eta with meson mass squared proportional to m_q

$$m^2_{\eta_8} = \frac{4}{3}m^2_{\mathrm{K}} - \frac{1}{3}m^2_\pi$$

… where is the singlet boson ?

Eta and Etaprime masses

- Mass matrix

$$M^2_{\eta-\eta'} = \begin{pmatrix} \frac{4}{3}m^2_{\rm K} - \frac{1}{3}m^2_\pi & -\frac{2}{3}\sqrt{2}(m^2_{\rm K} - m^2_\pi) \\ -\frac{2}{3}\sqrt{2}(m^2_{\rm K} - m^2_\pi) & [\frac{2}{3}m^2_{\rm K} + \frac{1}{3}m^2_\pi + \tilde{m}^2_{\eta_0}] \end{pmatrix}$$

- Diagonalize

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

- Eigenvalues

$$m^2_{\eta',\eta} = (m^2_{\rm K} + \tilde{m}^2_{\eta_0}/2) \pm \frac{1}{2}\sqrt{(2m^2_{\rm K} - 2m^2_\pi - \frac{1}{3}\tilde{m}^2_{\eta_0})^2 + \frac{8}{9}\tilde{m}^4_{\eta_0}}.$$

$$m^2_\eta + m^2_{\eta'} = 2m^2_K + \tilde{m}^2_{\eta_0}.$$

- With no glue:
  chiral symmetry „predicts" eigenstates with masses 300 MeV „too small"
  - „eta" $(\frac{1}{\sqrt{2}}|\bar{u}u + \bar{d}d\rangle)$ degenerate with the pion
  - „etaprime" $|\bar{s}s\rangle$ with mass $\sqrt{2m^2_K - m^2_\pi}$

Glue in etaprime physics

- Glue enters through the anomaly equation …

$$\partial^\mu J^{GI}_{\mu 5} = 2f\partial^\mu K_\mu + \sum_{i=1}^{f} 2im_i\bar{q}_i\gamma_5 q_i$$

- Etaprime has a strong affinity to glue

- SU(3) breaking means the gluon anomaly is important to both the eta and eta´

- Three important places glue can contribute [Acta Phys Pol B45 (2014) 2455]
  - » Gluonic potential in the QCD vacuum gives the etaprime a big mass … How is this modified in the nuclear medium ?
  - » The etaprime has a large singlet component
    → coupling to gluonic intermediate states (OZI violation)
  - » Gluonic Fock components in the etaprime wavefunction

U(1) extended chiral Lagrangian

- Low energy effective Lagrangian
  - constructed to reproduce the axial anomaly in the anomalous divergence equation and the gluonic mass term for the singlet boson

$$\mathcal{L} = \frac{F_\pi^2}{4}\mathrm{Tr}\left(\partial^\mu U \partial_\mu U^\dagger\right) + \frac{F_\pi^2}{4}\mathrm{Tr}\, M\left(U + U^\dagger\right) + \frac{1}{2}\mathrm{i}Q\,\mathrm{Tr}\left[\log U - \log U^\dagger\right] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2}Q^2.$$

$$U = \exp\{\mathrm{i}(\phi/F_\pi + \sqrt{2/3}\,\eta_0/F_0)\}$$

- Q is the topological charge density and the gluonic potential yields the gluonic contribution to the etaprime mass term

$$\frac{1}{2}\mathrm{i}Q\,\mathrm{Tr}\left[\log U - \log U^\dagger\right] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2}Q^2 \mapsto -\frac{1}{2}\tilde{m}_{\eta_0}^2\eta_0^2.$$

- Couple to sigma mean field and repeat …

$$\mathcal{L}_{\sigma Q} = Q^2 g_\sigma^Q \sigma$$

$$\tilde{m}_{\eta_0}^2 \mapsto \tilde{m}_{\eta_0}^{*2} = \tilde{m}_{\eta_0}^2 \frac{1+2x}{(1+x)^2} < \tilde{m}_{\eta_0}^2$$

where

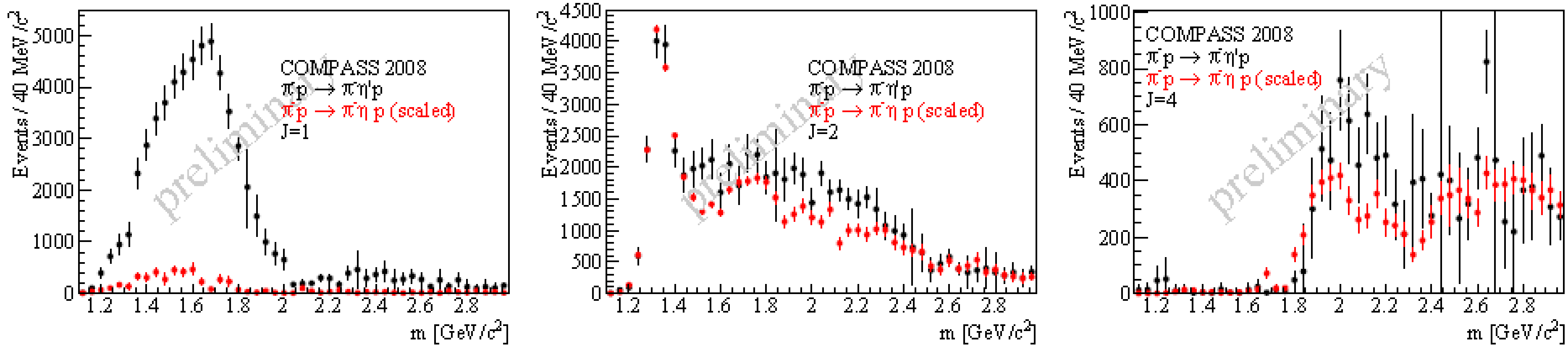
$$x = \frac{1}{3} g_\sigma^Q \sigma \tilde{m}_{\eta_0}^2 F_0^2.$$

New Compass results

- Iterate $\mathcal{L}_{m2Q} \; = \; \lambda \; Q^2 \; \mathrm{Tr} \; \partial_\mu U \partial^\mu U^\dagger$ in Bethe Salpeter equation

dynamicaly generates 1^{-+} exotic resonance with mass ~ 1400 MeV

[SDB and E Marco, PRD 65 (2002) 057503]



(a) P-wave, $J=1$ (b) D-wave, $J=2$ (c) G-wave, $J=4$

Compass, hep-ex 1408.4286, Phys Lett B740 (2015) 303

J	1	2	3	4	5	6
$\frac{I_J(\eta\pi^-)}{I_{\rm total}(\eta\pi)}$ [%]	4.4	81.9	0.3	6.9	0.1	0.7
$\frac{I_J(\eta'\pi^-)}{I_{\rm total}(\eta'\pi)}$ [%]	41.7	42.3	3.7	8.4	0.9	1.2
$R_{\rm corr}$	0.17 ± 0.01	0.94 ± 0.02	0.16 ± 0.05	0.83 ± 0.07	0.15 ± 0.12	0.68 ± 0.15

Eta(prime) bound states in nuclei

[SDB + AW Thomas, Phys Lett B634 (2006) 368,
Acta Phys Pol B 45 (2014) 627]

- New experiments + big effort ...
- Binding energies and effective masses in nuclei are sensitive to
  - Coupling to scalar sigma field in the nuclei in mean field approx.
  - Nucleon-nucleon and nucleon-hole excitations in the medium
- TH: Solve for the meson self-energy in the medium

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

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

$$b = a(1 + \frac{m}{M})$$

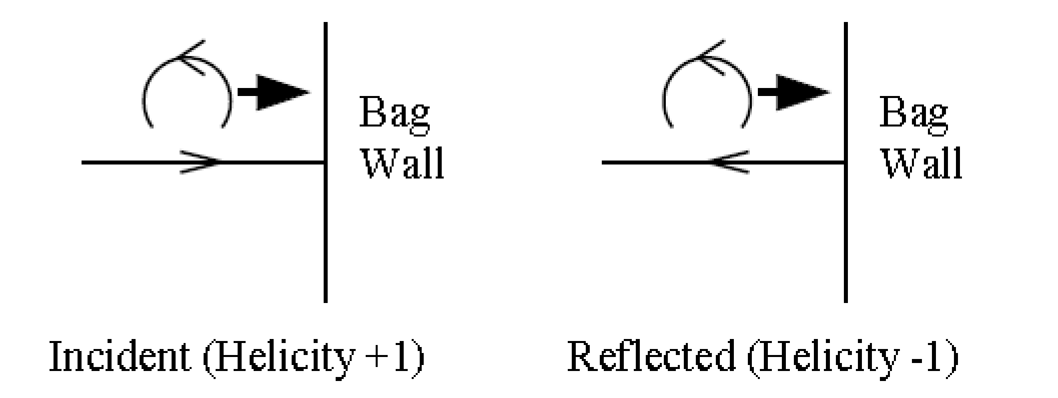
- Where a is the „eta(prime)-nucleon scattering length"

QCD, models and in medium mass shifts

- Include key aspects of QCD as input motivation
  - » Confinement
  - » Chiral symmetry
  - » Eta-etaprime mixing
- Quark-meson coupling, chiral coupled channels, NJL, linear sigma model... include different aspects of QCD input with very different predictions
  - – Etaprime mass shift predictions from zero up to about -150 MeV
  - – Sign of eta mass shift in medium ?
- Suppose we see a mass shift or bound state ☺
  - » What do we learn about QCD ?

Confinement and chiral symmetry

- Scalar confinement dynamically breaks chiral symmetry
  - E.g. In Bag model confinement the Bag wall connects left and right handed quarks
  - Quark – pion coupling and the pion cloud of the nucleon
- Pions, kaons, eta ... as Goldstone bosons



- OGE as residual vector (colour hyperfine) interaction

Eta bound-states in nuclei

- Sigma mean field couples to light quarks and not to strange quarks
  → Flavour-singlet component is important !
  The bigger the eta-eta´ mixing angle, the bigger the singlet component in the eta
  → greater the attraction
  → more binding
  → bigger eta-N scattering length
  Likewise, more mixing gives smaller singlet component in the eta'
  → reduced binding and smaller eta'N scattering length

Without QCD axial anomaly, eta' a strange state and no mass shift

QCD arguments

→ gluonic mass term is suppressed in the medium

but theory technology to calculate the size of the effect direct from QCD still some time away → look at QCD inspired models

QCD Inspired Models

- Quark Meson Coupling Model:
  - Can vary the mixing angle !
  - Use large eta and eta´ masses to treat the eta and eta´ as MIT Bags embedded in the medium with coupling between the light-quarks and the sigma mean field

  Solve for in-medium mass and binding energy

  → Extract an „effective" scattering length for the model

  → Increases with increasing singlet component in the eta !

	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

- Hints from CBELSA/TAPS for etaprime [Nanova et al, 2013]

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

QMC predictions

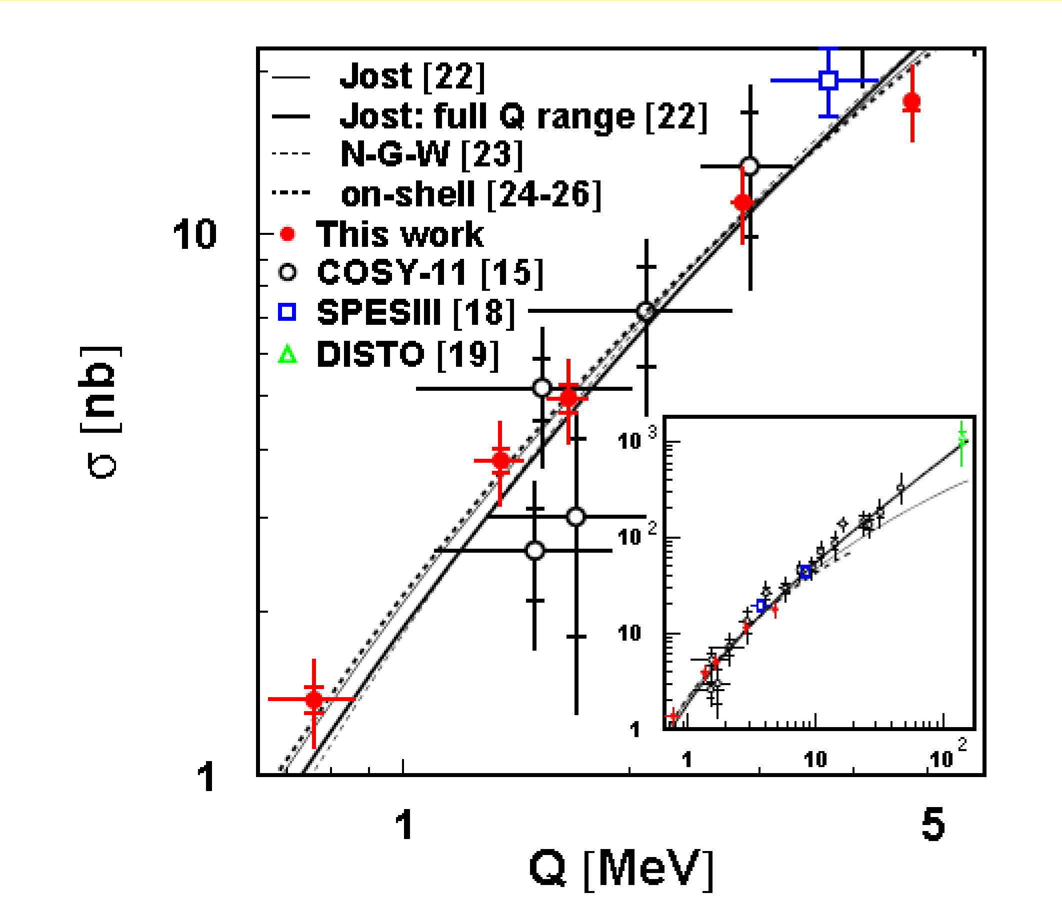
- In symmetric nuclear matter at ρ_0
  - Effective proton mass about 755 MeV
  - N*(1535)

    3 quark state (1s)2(1p) in Quark model and lattice calculations

    or

    K-Sigma quasi-bound state from Chiral coupled channels in octet approx.
  - In data and in both QMC and chiral coupled channels models, negligible shift in excitation energy in nuclei
  - Effective kaon mass about 430 MeV at ρ_0 , K^- effective mass about 350 MeV

COSY 11



$$|M_{pp\to pp\eta'}|^2 \approx |M_0|^2 \cdot |M_{FSI}|^2$$

$$M_{FSI} = M_{pp}(k_1) \times M_{p_1\eta'}(k_2) \times M_{p_2\eta'}(k_3)$$

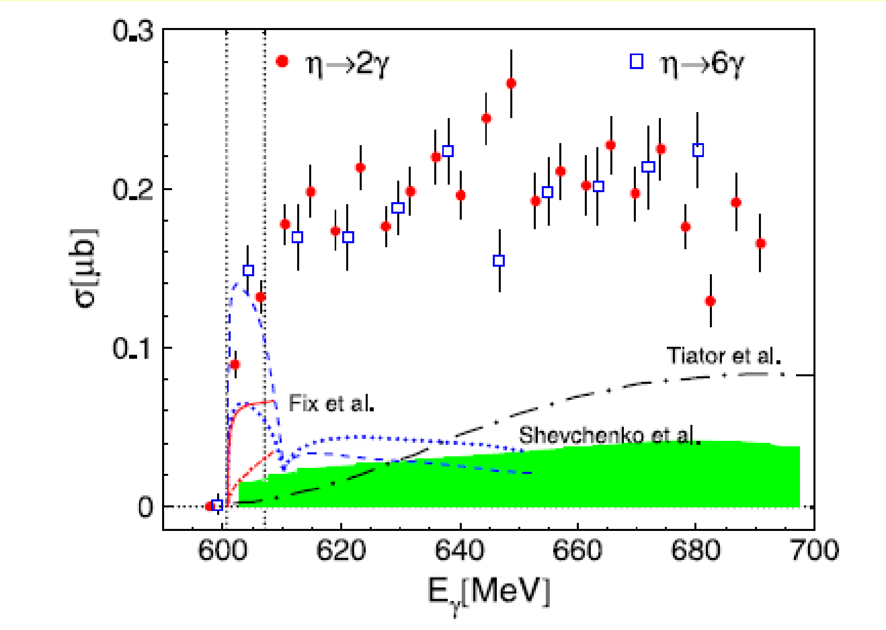
$$\mathrm{Re}(a_{p\eta'}) = 0 \pm 0.43_{stat} \text{ fm}$$

$$\mathrm{Im}(a_{p\eta'}) = 0.37 \,{}^{+0.02_{stat}}_{-0.11_{stat}}\,{}^{+0.38_{sys}}_{-0.05_{sys}} \text{ fm}$$

- E. Czerwinski et al (2014),
  COSY 11 Collaboration, Phys. Rev. Lett. 113 (2014) 062004

Eta bound states in Helium (?)

- Require large meson-nucleon scattering length
  - Real part bigger than 0.9fm for Helium [Friedman,Gal,Mares]
- Clean observation requires real part of optical potential much bigger than the imaginary part
- Some hints for reduced eta mass in medium from sharp rise in cross section at threshold for eta photoproduction from Helium-3 and for eta production in pd collisions



Outlook and Conclusions

- Eta and etaprime physics probes the role of long range gluonic dynamics
- Etas and etaprimes in nuclei:
  - Aspects of Confinement, chiral symmetry and their interplay, range of masses for pseudoscalars to be treated as Goldstone states in the models
  - Binding energies and scattering lengths sensitive to the flavour-singlet component in the eta and eta´
  - Without QCD anomaly, no effect in the eta´ in QMC
  - QMC model:
    - » Factor of 2 increase in the eta-nucleon scattering length and binding energy in nuclei with eta-etaprime mixing cf. Theory prediction with a pure octet eta
    - » Good agreement with CBELSA/TAPS for the eta´
    - » Eta bound state search goes on ... ☺
    - » No sharp bound state in helium 4. (? less sharp state ?)

What about in Helium 3 with 2014 data ?

Theoretical development

ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT®

PHYSICS LETTERS B

Physics Letters B 634 (2006) 368–373

www.elsevier.com/locate/physletb

η bound states in nuclei: a probe of flavour-singlet dynamics

Steven D. Bass [a,*], Anthony W. Thomas [b]

[a] *Institute for Theoretical Physics, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria*

[b] *Jefferson Laboratory, 12000 Jefferson Avenue, Newport News, VA 23606, USA*

Received 2 July 2005; received in revised form 9 January 2006; accepted 31 January 2006

Available online 9 February 2006

Editor: J.-P. Blaizot

For extra reading

Vol. 45 (2014) *ACTA PHYSICA POLONICA B* No 3

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

STEVEN D. BASS

Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences
Boltzmanngasse 3, 1090 Vienna, Austria

ANTHONY W. THOMAS

CSSM and ARC Centre of Excellence for Particle Physics at the Terascale
School of Chemistry and Physics, University of Adelaide
Adelaide SA 5005, Australia

(Received January 7, 2014)