What is so Special About Eta-Meson Physics?

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Abstract. The η is a remarkable particle as regards its production, interaction, and its various suppressed, rare and forbidden decay modes. Eta production is always large; near threshold it is dominated by 3 special S-wave resonances. The ηN and $\eta \Lambda$ scattering lengths are attractive and large; this has generated speculations about the possible existence of a new type of nuclear matter, bound or quasi bound eta-mesic nuclei and eta-mesic hypernuclei. η is an isospin singlet, η production is therefore an isospin selective reaction which is particularly helpful in baryon spectroscopy. $\pi^0 - \eta$ mixing causes intrinsic (non Coulombic) violation of charge symmetry, which allows for new measurements of the mass difference between the up and down quarks at different four-momentum transfers. The η is a Goldstone boson; this provides opportunities for unique probes of chiral perturbation theory. Finally, the η is an eigenstate of the charge-conjugation and CP operators; this makes possible a variety of tests of C and CP invariance of flavor-non-changing strong/electromagnetic interactions.

1 Introduction

The eta-meson is associated with a wide variety of interesting nuclear and particle physics. Firstly, η production by π, K^-, γ, p and d near threshold is surprisingly large, it is associated with three unusual S-wave resonances. The ηN S-wave scattering length $a_{\eta N}$, is attractive and large, unlike $a_{\pi N}$ which is repulsive and small. Secondly, η production is an important isospin selector e.g. $\pi^- p \rightarrow n \eta$ selects the pure $I = \frac{1}{2}$ states while the common pion scattering reaction involves a mixture of N^* and Δ^* states. Thirdly, the η which has G-parity +1 mixes with the π^0 -meson which has G-parity -1. This $\pi^0 - \eta$ mixing induces potentially large charge-symmetry breaking. It provides a good way to measure the mass difference of the up and down quarks under different kinematical conditions. Fourthly, the η is a Goldstone boson so the not-so-rare η decays provide unique tests of chiral perturbation theory. Finally, the η is an eigenstate of the charge-conjugation operator, C, and of CP. This is special, it is a rarity in nature and it makes possible unique tests of C, CP and even CPT invariance in flavor-non-changing interactions in rare η decays.

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2 Properties of the η

The η has the following vital statistics. Its rest mass is $547.4 \text{ MeV}/c^2$ which is 58% of the proton's mass. The quantum numbers of the η are zero, this includes the spin, isospin, electric charge, strangeness and other quark-flavor numbers, lepton number and baryon number. The η half life is $5 \times 10^{-19} \text{ sec}$, which corresponds to a width of 1.2 keV. Charge conjugation and G-parity are +1. Thus the η has all the appearances of being massive vacuum, the only exception is that parity and CP are -1. The short η half life precludes making an η beam that travels a practical distance. Instead, precise η decay measurements can be made using tagged etas that are produced in a reaction such as $\pi^- p \rightarrow \eta n$ and $pd \rightarrow \eta {}^3\text{He}$.

The simplest allowed η decay mode is $\eta \rightarrow 2\gamma$. It is a second order electromagnetic transition, this explains the observed η half life. This process is actually forbidden in the limit of massless quarks, but takes place by the grace of the Wess-Zumino term. The strong decay $\eta \rightarrow 2\pi$ is forbidden by P and CP invariance while $\eta \rightarrow 3\pi$ is not allowed by charge symmetry conservation. The decay $\eta \rightarrow 3\pi$ occurs as a result of the quark-mass term in the QCD Lagrangian and thus provides a way for determining the up-down quark mass difference.

3 Eta-Meson Production

The η is produced prolifically in high energy reactions [1]. In heavy ion collisions it is the second most abundantly produced particle, after the pion, as much as 10%.

The large η threshold production is intimately connected with the existence of three special S-wave resonances, listed in Table 1. These resonances have a Q-value near zero and they decay predominantly under η emission, which is contrary to expectations based on the available phase space, favoring π emission. It is not difficult to speculate [2] on the possible existence of a similar type S-wave Ξ^* (1870) resonance that belongs to the same SU(3) octet as the Σ^* (1750). Truly spectacular would be an S-wave Ω^* (2220) resonance with a major η decay branch because it would have to be classified as a member of a decuplet.

The value of the ηN scattering length, $a_{\eta N}$, has been the subject of several recent analyses [3-6] and a new AGS experiment [7]. The various evaluations are not yet in complete agreement but it is safe to say that $a_{\eta N} > 0.6 \text{ fm}$. This large value has raised the prospect of a new type of nuclear matter, an eta-mesic nucleus [8]. This is a nuclear system in which the η also provides strong binding between the nucleons. One could consider it a novel nuclear state with an excitation energy of $\sim 540 \text{ MeV}$. The width is subject to debate. The original prediction by Liu and Haider [8] was a narrow width of about 9 MeV. We expect that the pionic decay of the $S_{11}(1535)$, which accounts for about 1/3 to 1/2 of the decay rate, remains an open channel for a bound eta-mesic nucleus resulting in a width of 50-100 MeV. A direct search for a narrow bound eta-mesic nucleus via a narrow proton peak in the reaction $\pi^+ + {}^{16}\text{O} \rightarrow p + {}^{15}_\eta\text{O}$

Table 1. Three isobars with a well established large η decay branch and one proposed new such isobar. Sp= spectral notation, Q is the energy release, e.g., $Q = m(S_{11}) - m_n - m_\eta$, R is the ratio of branching fractions to η and π (or K) decay modes. + The pole position is around 1487 MeV which implies that $Q \sim 2$ MeV.

symbol	I, J^P	Sp	mass (MeV)	width (MeV)	η decay (%)	Q (MeV)	R
$N^*(1535)$	$\frac{1}{2}, \frac{1}{2}^-$	S_{11}	$\approx 1535^+$	≈ 150	45-55	$\sim 50^+$	$\eta N/\pi N \sim 1$
$\Lambda^*(1670)$	$0, \frac{1}{2}^-$	S_{01}	1670 ± 5	≈ 35	15-35	7 ± 5	$\eta \Lambda/\bar{K} N \sim 1$
$\Sigma^*(1750)$	$1, \frac{1}{2}^-$	S_{21}	≈ 1760	≈ 90	15-55	20 ± 20	$\eta \Sigma/\pi \Sigma > 2$
$\Xi^*(1870)$	$\frac{1}{2}, \frac{1}{2}^-$	S_{11}	?			?	

was unsuccessful [9] at an incident pion momentum of 800 MeV/c. It has been pointed out [4] that this momentum is too high as the ηN scattering will have turned from attractive near threshold to repulsive.

The original value of the ηN scattering length, $a_{\eta N} = 0.27$, used in ref. [8] was based on a poor choice of input data. It required an eta-mesic nucleus to have a mass number larger than $A \approx 10$. The currently favored value, $a_{\eta N} > 0.6$ fm, makes both $\eta^3 He$ and $\eta^4 He$ possible candidates for a quasi-bound or even a bound eta-mesic nucleus. Indicative is a large η -nucleus scattering length which has been obtained in recent calculations [5, 10, 11]. Besides having a large and attractive η -nucleus scattering length, an eta-mesic nucleus will manifest itself in production processes such as $pd \rightarrow \eta^3 He$ near threshold by a characteristic momentum dependence of the invariant production amplitude as discussed by Wilkin [5]. A recent measurement [12] appears to bear this out.

Since the expected width of 50-100 MeV of eta-mesic nuclei will make direct detection in a two-body production reaction very challenging it is of interest to search for other η -mesic systems. Recently we have considered the possible existence of an eta-mesic hypernucleus [4], this was prompted by the outcome of a determination of the $\eta \Lambda$ scattering length finding a large value, $a_{\eta \Lambda} \sim 0.6$ fm. Since the width of the relevant resonance, the $\Lambda^*(1670)$, is much narrower than the $N^*(1535)$, see Table 1, the η -mesic hypernucleus would have a width of only 10 MeV. An eta-mesic hypernucleus would more likely be a bound state than an eta-mesic nucleus since the Q-value of the $\Lambda^*(1670)$ is closer to zero than that of the $N^*(1535)$. This suggests a direct 2-body reaction search such as [4]

$$K^- + {}^{12}C \rightarrow n + {}_{\eta\Lambda}^{11}B, \quad (1)$$

as well as a careful threshold measurement of η production to measure the invariant amplitude e.g. in $K^- + {}^{12}C \rightarrow \eta + {}_{\Lambda}^{12}B$. Also of interest is

$$K^- + {}^3He \rightarrow \eta + {}_{\Lambda}^3H. \quad (2)$$

Elsewhere [1] we have discussed the hints for exotica found in a large η production in $pd \rightarrow \eta^3 He$ especially at 180° and also in $\pi^- {}^3He \rightarrow \eta^3 H$. We want to

emphasize the large difference in the threshold production of π^0 and η in the $pd \rightarrow {}^3\text{He}X$ reaction. Both π^0 and η are Goldstone bosons and one might expect some similarities in their threshold-production characteristics. Experiment has found the opposite. The dependance of $\sigma_t(pd \rightarrow \pi^0 {}^3\text{He})$ is $\sigma_t \sim p_\pi$ just as expected for an S-wave production of a pseudoscalar meson and predicted long time ago by Gell-Mann and Watson [13]. The angular distribution has a near-exponential decrease with increasing four-momentum transfer, suggestive of a $(d-{}^3\text{He})$ transition-form-factor dominated process; the forward-backward asymmetry in the angular distribution is a factor of 5 when $p_{\pi^0} = 14$ MeV/c or $\lambda_{\pi^0} \simeq 8$ fm; this makes the strict dependence of σ_t on p_{π^0} even more remarkable. The behavior of $\sigma_t(pd \rightarrow \eta {}^3\text{He})$ is very different, increasing initially much stronger with p_η than an S-wave reaction, becoming nearly constant a few MeV above threshold. The angular distribution, however, is completely isotropic up to the maximum energy measured, 11 MeV above threshold, where $p_\eta = 75$ MeV/c and $\lambda_\eta = 2.7$ fm.

4 Baryon Spectroscopy with Eta-mesons

The η is an isospin singlet and therefore two-body η production reactions are isospin selective. For example $K^-p \rightarrow \eta\Lambda$ concerns only the pure $I = 0$ states and $K^-p \rightarrow \eta\Sigma$ only pure $I = 1$. The well known elastic scattering reaction $K^-p \rightarrow K^-p$ is a mixture of $I = 0$ and 1 states requiring an additional experiment of the difficult charge exchange reaction. η production has not been measured in much detail because of experimental limitations. The proposed move of the famous SLAC Crystal Ball [14] to a π^- and K^- beam at the AGS would improve the situation dramatically. The Crystal Ball is a multiphoton spectrometer with good energy and angular resolution and 94% solid angle coverage. It would be particularly useful in the search for heavy S- and P-wave N^* resonances which have been predicted to exist by various models especially the successful Isgur-Karl quark model [15].

Another unique aspect of η -baryon spectroscopy derives from the fact that low energy etas are a potential signature of the $N^*(1535)$, $\Lambda^*(1670)$ or $\Sigma^*(1750)$ resonances. This allows the identification of certain sequential decays of massive baryons. Consider the reaction $N^* \rightarrow \pi^0\eta N$, this is really the decay of the N^* under π^0 emission to the $N^*(1535)$. Such an identification has never been made; the existing studies of sequential decays are based on two-pion emission and in general are far from definitive.

5 $\pi^0 - \eta$ Mixing and Charge Symmetry Breaking

Free quarks do not exist according to QCD and thus it is not possible to measure directly the mass of a quark. However, the mass difference between the up and down quarks can be readily obtained from suitable measurements of charge symmetry breaking [16]. A clean way is from a measurement of $\pi^0 - \eta$ mixing. This works as follows. There is only one term in the QCD Hamiltonian density

original prediction by Liu and Haider [8] was a narrow width of about 9 MeV. We expect that the pionic decay of the $S_{11}(1535)$, which accounts for about 1/3 to 1/2 of the decay rate, remains an open channel for a bound eta-mesic nucleus resulting in a width of 50-100 MeV. A direct search for a narrow bound

which depends explicitly on the quark mass namely,

$$H_m = m_d d \bar{d} + m_u u \bar{u} + \dots \quad (3)$$

The matrix element between the π^0 and η meson states is therefore

$$\langle \pi^0 | H_m | \eta \rangle = \frac{1}{2} \sqrt{2} \langle u \bar{u} - d \bar{d} | m_d d \bar{d} + m_u u \bar{u} | u \bar{u} + d \bar{d} - s \bar{s} \rangle \frac{1}{3} \sqrt{3} = \frac{1}{3} \sqrt{6} (m_u - m_d). \quad (4)$$

A possible way to study this mixing is via the decay of the $S_{11}(1535)$ resonance because of its large branching ratio to the η channel. This decay has two contributions, one direct decay, $S_{11} \rightarrow N + \eta$, described by the amplitude A_η , and one indirect one via the π^0 which then turns into an η as a result of $\pi^0 - \eta$ mixing, this is represented by the amplitude $A_{\pi^0 \rightarrow \eta}$. As a result the decay amplitudes for the charged and neutral states are

$$\begin{aligned} A(S_{11}^+ \rightarrow p\eta) &= A_\eta + A_{\pi^0 \rightarrow \eta}, \\ A(S_{11}^0 \rightarrow n\eta) &= A_\eta - A_{\pi^0 \rightarrow \eta}, \end{aligned} \quad (5)$$

the + and - signs come from the Clebsch-Gordan coefficients that are associated with the isospin ($1/2 \rightarrow 1/2, 1$) transition.

Experimentally this can be measured using the ratio

$$R_\eta = \frac{d\sigma(\pi^+ d \rightarrow pp\eta)}{d\sigma(\pi^- d \rightarrow nn\eta)} \simeq \left| \frac{A_\eta + A_{\pi^0 \rightarrow \eta}}{A_\eta - A_{\pi^0 \rightarrow \eta}} \right|^2 \quad (6)$$

in the region of the S_{11} resonance from $p_\pi = 610$ to 850 MeV/c. Charge symmetry requires this ratio to be 1.0. The experiment [17] has recently been performed at the AGS. Near $p_\pi = 750$ MeV/c the on-line results show R_η to be around 0.9 indicating a dramatic violation of charge symmetry due to $\pi^0 - \eta$ mixing.

Recently, it has been argued that the $\rho - \omega$ mixing matrix element which is quite similar to the one for $\pi^0 - \eta$ mixing and which is extracted from the on-mass-shell mesons, should change significantly off-shell [18,19]. The off-shell behavior affects the contribution of meson mixing to charge symmetry breaking in low energy nuclear physics. The off-shell behavior is hard to measure so we suggest instead to investigate charge symmetry breaking for different values of the four-momentum transfer. This may be done by measuring R_η at different regions of the (ηNN) Dalitz plot.

6 Chiral Symmetry

The challenging region for applying QCD is at low energies where perturbation theory is not applicable. This covers all of nuclear physics, threshold meson production, the strong decays of mesons and baryons, and so forth. One of the promising approaches to a variety of low energy strong interaction processes is based on chiral symmetry which is a property of massless QCD. The main

idea is the following. Massless quarks come in two varieties, righthanded ones when the momentum and spin vectors are parallel and lefthanded ones with antiparallel alignment. The QCD Lagrangian has no helicity-flip term hence the handedness of the massless quarks is unaffected by strong interactions. This implies that there must be a new symmetry, which stems from the fact that the Lagrangian is invariant under the interchange of all left and right handed quarks, and is called chiral symmetry.

Consider a certain system of particles that has a Lagrangian which is invariant under some symmetry. Furthermore, this system has a continuum family of ground-state solutions which are related to each other by the symmetry but which individually are not invariant under the symmetry. This is misleadingly called a spontaneously broken symmetry. This rather subtle property is prominent in certain gauge theories of massless quanta. Such a spontaneously broken symmetry implies the existence of a new **massless** field particle [20]. This is Goldstone's theorem and conceptually has a simple origin. Define the ground state to have $E = 0$ then there must be other states with $E = 0$ and their corresponding particles must have zero mass! The general theorem states that whenever a continuous global symmetry is spontaneously broken the particle spectrum must have a massless, spin-zero boson called a Goldstone boson [21]. There are 3 quarks implying the existence of $3 \times 3 - 1 = 8$ Goldstone bosons which are the π , K and η . To take into account that the physical quarks are not massless, Weinberg [22] has introduced an expansion of the Lagrangian in powers of the pion mass and momentum. The algebra that governs this is called chiral perturbation theory, it has been developed by Gasser and Leutwyler [23]. Chiral perturbation theory has already given important relations that govern pion-pion scattering, threshold production of the Goldstone bosons, the decay of many systems under emission of a soft pion and a large variety of meson decays. A particularly interesting example is the decay $\eta \rightarrow \pi^0 \gamma \gamma$ which allows probing the p^6 order term, because the lower order terms are forbidden or much suppressed by various symmetries.

7 Testing Charge Conjugation and CP Invariance

Matter is distinct from antimatter in most instances. For example, proton and antiproton have opposite electric charge. Since they have also opposite baryon number, they may annihilate each other. The neutron has its spin and magnetic dipole moment vectors antiparallel, while those of the antineutron are parallel. There is a small number of mesons which are their own antiparticles, they must be neutral and flavorless such as a π^0 and η . Their quark structure is $q\bar{q}$. These special mesons can be used to investigate if matter and antimatter interact identically which is difficult to test otherwise. We anticipate, as a consequence of the CPT theorem, that particles and antiparticles have identical lifetimes and rest masses but that does not imply that they have identical interactions, this is well known for the case of neutrino and antineutrino interactions.

C-invariance of the strong interactions has not been tested extensively [24].

Table 2. Testing C, CP, T and CPT in rare η decays.

Decay	Symmetry	Observable	Exp.Limit
$\eta \rightarrow \pi^0 \ell^+ \ell^-^{(a)}$	C	rate	$< 5 \times 10^{-6}$
$\eta \rightarrow \pi^0 \ell^+ \ell^-^{(a)}$	C, CP ^(b)	charge asym.	
$\eta \rightarrow \pi^0 \mu^+ \mu^-$	T	μ^+ trans.pol.	
$\eta \rightarrow \pi^0 \ell^+ \ell^-^{(a)}$	CPT	decay correl.	
$\eta \rightarrow 3\gamma$	C	rate	$< 5 \times 10^{-4}$
$\eta \rightarrow \mu^+ \mu^-$	P,CP	μ^+ long.pol.	
$\eta \rightarrow \pi^+ \pi^-$	P,CP	rate	$< 1.5 \times 10^{-3}$
$\eta \rightarrow \pi^0 \pi^0$	P,CP	rate	
$\eta \rightarrow 4\pi^0$	P,CP	rate	
$\pi \rightarrow \pi^+ \pi^- \ell^+ \ell^-^{(a)}$	P,CP ^(b)	decay correl.	
$\eta \rightarrow \pi^+ \pi^- \gamma$	P,CP	spectral shape ^(c)	
$\eta \rightarrow \pi^+ \pi^- \pi^0$	C	charge asym.	$< 3 \times 10^{-3}$
$\eta \rightarrow \pi^+ \pi^- \gamma$	C	charge asym.	$< 1 \times 10^{-2}$
$\eta \rightarrow \pi^0 \pi^0 \gamma$	C	rate	
(a) ℓ stands for μ or e			
(b) in the limit of the one photon intermediate state			
(c) bremsstrahlung component			

The best limit is $A_{\ell} < 0.1A_C$ where A_{ℓ} is the C-violating and A_C is the C-conserving strong amplitude. The review of Particle Properties lists the absence of the decay mode $\eta \rightarrow \pi^0 \mu^+ \mu^-$ as our best test of C-invariance. This decay is a second order electromagnetic transition and its decay rate must be less than that for $\eta \rightarrow \pi^0 \gamma \gamma$ modified by the $\gamma \gamma \rightarrow \mu^+ \mu^-$ transition factor. Even if C were maximally violated we expect that $BR(\eta \rightarrow \pi^0 \mu^+ \mu^-) \lesssim 3 \times 10^{-5}$. In view of the fact that the experimental upper limit, see Table 1 first line, for this is $< 5 \times 10^{-6}$, the estimate $A_{\ell} < 0.1A_C$ is a very generous one.

The η meson, whose quark composition is $|\eta\rangle = \frac{1}{\sqrt{3}}|u\bar{u} + d\bar{d} - s\bar{s}\rangle$, is an eigenstate of the C-operator. Since $\eta \rightarrow 2\gamma$ is allowed the decay $\eta \rightarrow 3\gamma$ is forbidden if C is to be conserved. There are other interesting 3-body η decays involving one or more pions that are possible for testing C-invariance, they are listed in Table 2.

The preponderance of matter over antimatter in the universe is known as the cosmological matter problem. It is not explained by the small CP violation known from K^0 -decay and requires another, much stronger, source of CP

Table 3. Other interesting rare η decays.

Decay Mode	New Physics	Needed Sensitivity
$\eta \rightarrow e^+ e^-$	leptoquark	$BR \sim 10^{-9}$
$\eta \rightarrow \mu e$	lepton fam. viol.	$BR \sim 10^{-10}$
$\eta \rightarrow \pi \ell \nu$	2nd class current	$BR \sim 10^{-11}$
$\eta \rightarrow K e \nu$	ΔS weak int.	$BR \sim 10^{-13}$
$\eta \rightarrow \pi \pi \nu \bar{\nu}$	neutral weak current	$BR \sim 10^{-10}$
$\eta \rightarrow \ell^+ \ell^- \gamma$	form factor	$BR \sim 10^{-4}$
$\eta \rightarrow \pi^0 \gamma \gamma$	chiral perturb.th.	10% in spectr.
$\eta \rightarrow \pi^+ \pi^- \gamma$	chiral perturb. th.	5% in shape
$\eta \rightarrow 3\pi^0$	chiral perturb. th.	1% in shape

violation. It may come as a surprise to many nuclear/particle physicists, that there is no direct test of CP outside the neutral K-meson system [25]. Since the η is also an eigenstate of the CP operator, η decays make possible new tests of CP invariance [24-25]

Consider $\eta \rightarrow \pi^0 \pi^0$, this is forbidden by CP-invariance analogous to $K_L \rightarrow \pi^0 \pi^0$. However, it is also forbidden by parity which is known to hold in strong interaction to the level of about 10^{-6} . The major η decays are electro-strong interactions; note that at the level of 10^{-7} η decay becomes a weak interaction which violates parity thereby making $\eta \rightarrow 2\pi^0$ an honest test of CP invariance in a flavor-non-changing transition. There are practical limitations to making a sensitive search for this decay mode because of serious background from $2\pi^0$ production that inevitably accompanies all η production. We suggest therefore to search for $\eta \rightarrow 4\pi^0$ instead. It is another test of P and CP and the decay rate compared to $\eta \rightarrow 2\pi^0$ is suppressed by 3 orders of magnitude due to phase space. Thus, $\eta \rightarrow 4\pi^0$ should be searched for at the level 10^{-10} to have a true test of CP-invariance. This is a clean decay, practically without background. Some other tests of CP invariance that are possible in η decay are listed in Table 2.

η decay can be used to test other invariances as well, e.g. lepton-family conservation in $\eta \rightarrow \mu e$. Such tests have been discussed elsewhere [25]. The most interesting one are listed in Table 3.

8 Conclusions

The η is a fascinating particle. It is produced abundantly near threshold which involves three special S-wave resonances with a Q-value close to zero. The ηN scattering length is attractive and large. This has given rise to speculations

about the possible existence of a new type of nuclear matter, the eta-mesic nucleus or even an eta-mesic hypernucleus. $\pi^0 - \eta$ mixing is a rich source of violations of charge symmetry that is largely unexplored. A new charge symmetry breaking of 10% has been observed recently in η production by pions on deuterium.

The η is a Goldstone boson, it allows new and unique investigations of the p^6 term of chiral perturbation theory in measurements of the rate and spectrum of the decay $\eta \rightarrow \pi^0 \gamma \gamma$ which has a $BR \sim 10^{-4}$.

Finally, the eta-meson being an eigenstate of the C and CP operator, offers a variety of tests of these basic symmetries in the unexplored flavor-non-changing electro-strong interaction.

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