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RARE η DECAYS AND THE CP SYMMETRY[*]

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Among the light mesons, the η is very well suited for tests of the Standard Model (SM). Besides its negative parity and predominantly SU(3) octet structure, the η has the quantum numbers of the vacuum, it is comparatively massive and it is long-lived since first-order strong, electromagnetic and weak decays are suppressed. Since the η meson is an eigenstate of both C and CP, these fundamental symmetries can be studied in detail. Searches for C or CP violating decays such as $\eta \rightarrow \gamma\gamma\gamma$, $\eta \rightarrow \pi\pi$, $\eta \rightarrow \pi^0 e^+ e^-$ and for effects beyond the Standard Model in $\eta \rightarrow e^+ e^-$ are challenging research topics. New experimental facilities that will come into operation in the next few years will allow detailed investigations of the η rare decays. In Uppsala, a wide-angle spectrometer, WASA, is being prepared for investigations of symmetries, searches for exotics and for precise measurements of decays which are sensitive tests of Chiral Perturbation Theory, for example the decays $\eta \rightarrow 3\pi$ and $\eta \rightarrow \pi^0\gamma\gamma$.

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1. Introduction

The present Standard Model (SM) of elementary particles and their strong, electromagnetic and weak interactions, although extremely successful in explaining vast amounts of experimental data, is unsatisfactory as a

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fundamental theory since it contains too many free parameters. Tests of basic symmetries and searches for processes which are forbidden within the SM are interesting for the revelation of a deeper theory. The symmetries of the forces under reflection of spatial coordinates, parity (P), charge conjugation (C) and time reversal (T) are of special interest in this context. They are considered to hold in electromagnetic and strong interactions while parity and charge conjugation are not conserved in weak processes. The pattern of separate P and C violations is naturally accommodated into the SM (V−A coupling).

Violation of combined C and P (CP) symmetry was discovered in the K_L weak decays more than 30 years ago [1]. The discovery prompted reconsideration of our knowledge about the symmetries. It has been found that the commonly assumed conservation of the symmetries quite often suffers from experimental justification. From a theoretical view point, conservation of the symmetries is a convenient assumption but is by no means necessary. However, it is difficult to propose a relativistic quantum field theory without CPT conservation (the three successive operations, C, P and T applied in any order). The CPT theorem predicts that a particle and its antiparticle have equal masses, lifetimes and magnetic moments and opposite electric charges. The best test of the theorem is the mass difference between the K^0 and its antiparticle which has been found recently at LEAR to be less than 10^{-18} with respect to the K^0 mass [2].

Wolfenstein divides theories of CP violation into three general groups [3]; the superweak, the milliweak and the millistrong interactions. According to the superweak theories, CP violation occurs only in the double strangeness changing transitions, $\Delta S = 2$. The milliweak theory is represented by the SM where the CP violation is accommodated into the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix through a single phase. The hypothesis that the origin of the CP violation is exclusively due to the CKM matrix will be tested extensively at $B/\bar{B}$ factories. The B system should be sensitive to CP violation since the two elements V_{ub} and V_{td} of the CKM matrix have relatively large phases.

The millistrong interactions are here regarded as parity conserving and thus represent CP violation in strong and electromagnetic interactions. This possibility was suggested by Bernstein, Feinberg and Lee [4] for the interpretation of the CP violation seen in weak decays. Wolfenstein [3], in making use of the CPT theorem, assumes that CP violation leads to T violation and hence elementary particles may have non-zero electric dipole moment. According to Wolfenstein, the neutron electric dipole moment (NDM) should be greater than the now known upper limit of 10^{-25} $e$cm if the CP violation is only of electromagnetic origin. However, electromagnetic CP violation is not ruled out. Some of the best tests of C conservation in electromagnetic interactions are the upper limits for the decays $\eta \rightarrow \pi^0 e^+ e^-$ and $\eta \rightarrow \pi^0 \mu^+ \mu^-$ where the final lepton-antilepton pair couples to one intermediate virtual photon.

In the future, CP violation will be searched for in other processes than the $K_L \rightarrow 2\pi$ decay. In this decay, contributions can come from direct CP violation in the decay amplitude or indirectly from CP violation in the quark-mixing matrix. Planned measurements at Fermilab and Brookhaven of direct CP violation in $K_L \rightarrow \pi^0 \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 e^+ e^-$ decays are important for the understanding of the origin of CP. These are very hard experiments because the expected branching ratios are of the order of 10^{-11}. For the interpretation of the $K_L \rightarrow \pi^0 e^+ e^-$ experiments it is important to understand an important background process, namely the one where the K_L makes a transition to an intermediate η meson which in turn decays to the final state. Precise information about the $\eta \rightarrow \pi^0 \gamma\gamma$ and $\eta \rightarrow \pi^0 e^+ e^-$ are very important in this context.

The η like the π^0 meson has a positive eigenvalue for its charge conjugation (C) operator. It follows that decays into an odd number of photons are forbidden since the photon has a negative C eigenvalue. Thus also the very rare $\eta \rightarrow \pi^0 e^+ e^-$ decay is forbidden by C if the electron-positron pair comes from a virtual intermediate photon *i.e.* $\eta \rightarrow \pi^0 \gamma^*$. Provided sufficient statistics can be obtained, it will be possible to test also CP and CPT by exploring not only the value for the branching ratio but also various differential decay distributions. The decays $\pi^0\pi^0$ or $\pi^+\pi^-$ of the η are forbidden by P and CP because of the negative eigenvalues of P for these pseudoscalar mesons.

Many other decays of the η meson are useful for tests of the SM. By means of Chiral Perturbation Theory (ChPT), decay rates such as the $\eta \rightarrow 3\pi$ rate can be shown to be sensitive to the mass difference $m_u - m_d$. The decay $\eta \rightarrow e^+ e^-$ is strongly suppressed according to conventional mechanisms and should be sensitive to non-standard physics such as a leptoquark exchange between the quark-antiquark constituents or an exotic heavy propagator between the initial η meson and the final lepton-antilepton pair.

There are many reasons to gain more precise knowledge of various rare decay modes of the η meson, and the searches for CP violation are particularly challenging. Decays of the η meson have not been precisely measured since, unlike the mesons K and π, there have been no efficient ways to produce a great number of η mesons. Experiments, where present branching ratios will be improved and limits lowered substantially, are being prepared in Brookhaven, Frascati, Grenoble and Uppsala. In Brookhaven, where experiments have recently started, the ηs are produced in π^-p charge-exchange reactions and the decay fragments are measured in the modified Crystal Ball spectrometer. In Frascati, the ηs will come from the radiative decays of ϕ

mesons produced in the DAPHNE e^+e^- collider and the decay fragments will be measured in the KLOE 4π detector. In Grenoble the ηs are produced in photoproduction experiments using photons from the European Synchrotron Radiation Facility (ESRF). In Uppsala, the ηs are produced in proton-hydrogen interactions in the CELSIUS storage ring and the decay fragments will be measured using the WASA 4π detector. The WASA detector is designed to handle a luminosity of 10^{32}–10^{33} cm^{-2}s^{-1}. The goal is to have at least 10^{10} ηs produced per year. This will make it possible to study rare η decays down to a branching ratio (BR) around 10^{-9}.

2. Properties of the η meson

The η together with the π and K belong to the lowest-mass pseudoscalar meson octet of SU(3) flavour symmetry which would be exact if the quarks d, u, s had equal masses; this symmetry is the generalization to strange particles of the isospin symmetry. The approximate SU(3) flavour symmetry is explained nowadays in the language of chiral symmetry – the symmetry of the QCD Lagrangian in the limit of zero quark masses. The left-handed and right handed currents of the theory are then separately conserved, at least in the classical limit. The chiral symmetry must be spontaneously broken because otherwise particles with positive and negative parity would have the same mass. The pseudoscalar meson octet is then identified with the octet of Goldstone bosons of the broken chiral symmetry, *i.e.*, the particles belonging to this octet would have been massless for zero quark masses.

Since the η meson is one of the Goldstone mesons, its decay modes become a good testing ground for chiral dynamics at low energy. Furthermore, the η unlike the K meson is an eigenstate of the C and CP operators enabling a variety of tests of C, CP and CPT in flavour-non-changing strong and electromagnetic interactions. All quantum numbers except for parity are equal to those of the vacuum. The basic properties of the η meson are:

> Mass m_η=547.4 MeV, life time τ=5×10^{-19} s, decay width Γ=1.2 keV. Quantum numbers zero for charge (Q), spin (J), isospin (I), baryon number (B), lepton number (L). Positive charge conjugation (C) and negative parity (P).

The physical η is a mixture of η_8 state related to the octet and the singlet η_1 part. The η wave function has a fairly uncomplicated quark structure in which the q and $\bar{q}$ have opposite spin and no relative angular momentum:

$$\eta = -\sin\theta_p\eta_1 + \cos\theta_p\eta_8 \approx 1/\sqrt{3}(u\bar{u} + d\bar{d} - s\bar{s}), \tag{1}$$

where $\eta_8 = 1/\sqrt{6}(u\bar{u} + d\bar{d} - 2s\bar{s})$ and $\eta_1 = 1/\sqrt{3}(u\bar{u} + d\bar{d} + s\bar{s})$. Using the value $\theta_p = -19.5^\circ$ ($\sin\theta_p = -1/3$) for the octet-singlet mixing angle, derived from theoretical predictions and phenomenological analyses [5], the η wave function with approximately equal probabilities of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ is obtained. Theoretically one expects also some admixture of $c\bar{c}$ but experimental hints for this have not yet been found.

3. Decays of the η meson — overview

Due to the comparatively large mass of the η meson there are many possible decay channels. Most of them are summarized in Table I. Frequent decays are the two-photon decay with the $BR = 39\%$, the three-pion decays, $\eta \to \pi^0\pi^0\pi^0$ ($BR = 32\%$) and $\eta \to \pi^0\pi^-\pi^+$ ($BR = 23\%$). In the table, the decays are grouped according to similar decay mechanisms. Therefore the branching ratios and distributions of decay products for the decays within a group are related. For example, the decays numbered 20–27 have two photons, real or virtual, coupled to the η.

The physics is generally related to some symmetry-breaking phenomena: isospin breaking due to different quark masses or to the electromagnetic interactions and the non-abelian anomaly. All first-order strong, electromagnetic and weak decays of the η are forbidden, a fact that explains why the η is comparatively long lived.

Some of the decays in the table are forbidden by conservation laws. For example, the decay $\eta \to \mu^\pm e^\mp$ violates lepton flavor and is strictly forbidden in the SM. Decays forbidden by P or CP symmetries are two-pion and four-pion decay modes (decays 17–19). The decays with an odd number of photons (real or virtual) are forbidden by C conservation (decays 9, 14, 15, 29, 30). The decays $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$ together with the neutral pion decay $\pi^0 \to e^+e^-$ are of interest for the understanding of mechanisms behind the annihilation of the constituent quark-antiquark pairs of the meson into lepton-antilepton pairs. The rates are sensitive to exotic intermediate exchange propagators.

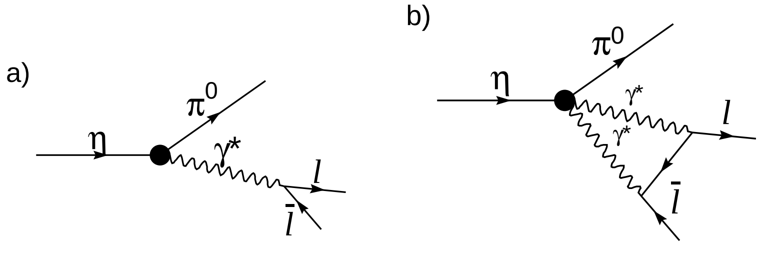

Fig. 1. C and CP forbidden (a) and allowed (b) mechanisms of the $\eta \to \pi^0 \ell\bar{\ell}$ decay.

TABLE I

Decays of the η meson. $\not C$ means violation of C

Nr	Decay	BR(exp) PDG [2]	BR(SM)	Comments
	Hadronic decay modes			
1	$\pi^0\pi^0\pi^0$	$(32.1\pm0.4)\times10^{-2}$		(m_u-m_d); ChPT
2	$\pi^+\pi^-\pi^0$	$(23.2\pm0.5)\times10^{-2}$		(m_u-m_d); ChPT
3	$\pi^+\pi^-\gamma$	$(4.78\pm0.12)\times10^{-2}$		ChPT
4	$\pi^+\pi^-e^+e^-$	$(1.3\pm1.0)\times10^{-3}$	3×10^{-4} [6]	
5	$\pi^+\pi^-\mu^+\mu^-$		2×10^{-8} [6]	
6	$\pi^+\pi^-\gamma\gamma$	$<2.1\times10^{-3}$		
7	$\pi^0\pi^0\gamma\gamma$	$<2.8\times10^{-2\,(a)}$		
8	$\pi^0\pi^0e^+e^-$		3×10^{-8} [6]	$\not C$– $\eta\pi^0\pi^0\gamma^*$
9	$\pi^0\pi^0\gamma$	$<2.8\times10^{-2\,(a)}$		$\not C$
10	$\pi^0\gamma\gamma$	$(7.1\pm1.4)\times10^{-4}$		ChPT, VMD
11	$\pi^0\mu^+\mu^-\gamma$	$< 3\times10^{-6}$		ChPT
12	$\pi^0e^+e^-\gamma$			ChPT
13	$\pi^0e^+e^-e^+e^-$			ChPT
14	$\pi^0\mu^-\mu^+$	$<5\times10^{-6}$	3×10^{-9} [7]	$\not C$– $\eta\pi^0\gamma^*$
15	$\pi^0e^+e^-$	$<4\times10^{-5}$	3×10^{-9} [7]	$\not C$– $\eta\pi^0\gamma^*$
16	$\pi^+\pi^-\pi^0\gamma$	$<6\times10^{-4}$		
17	$\pi^+\pi^-$	$<1.5\times10^{-3}$	10^{-16} [8]	$\not{CP}$
18	$\pi^0\pi^0$	$<7.7\times10^{-4\,(b)}$	10^{-16} [8]	$\not{CP}$
19	$\pi^0\pi^0\pi^0\pi^0$	$<2.8\times10^{-2\,(a)}$		$\not{CP}$
	Non hadronic decay modes			
20	$\gamma\gamma$	$(3.93\pm0.03)\times10^{-1}$		$\eta\gamma\gamma$ vertex
21	γe^+e^-	$(4.9\pm1.1)\times10^{-3}$		$\eta\gamma\gamma^*$ vertex
22	$\gamma\mu^+\mu^-$	$(3.1\pm0.4)\times10^{-4}$		$\eta\gamma\gamma^*$ vertex
23	$\mu^+\mu^-$	$(5.8\pm0.8)\times10^{-6}$		$\eta\gamma^*\gamma^*$ vertex
24	e^+e^-	$< 7.7\times10^{-5}$ [9]	5×10^{-9}	$\eta\gamma^*\gamma^*$ vertex
25	$e^+e^-e^+e^-$	–	2.4×10^{-5} [10]	$\eta\gamma^*\gamma^*$ vertex
26	$\mu^+\mu^-e^+e^-$	–	7.9×10^{-7} [10]	$\eta\gamma^*\gamma^*$ vertex
27	$\mu^+\mu^-\mu^+\mu^-$	–	2.4×10^{-9} [10]	$\eta\gamma^*\gamma^*$ vertex
28	$\gamma\gamma\gamma\gamma$	$<2.8\times10^{-2\,(a)}$		
29	$\gamma\gamma\mu^+\mu^-$			$\not C$– $\eta\gamma\gamma\gamma^*$
30	$\gamma\gamma\gamma$	$<5\times10^{-4}$ (CL=95%)	$10^{-19\pm6}$ [8]	$\not C$– $\eta\gamma\gamma\gamma$
31	$\mu^\pm e^\mp$	$<6\times10^{-6}$ [11]	0	$\not L$

(a) — the limit on BR $\eta\rightarrow$ *neutrals*

(b) — new unpublished VEPP 2M data, Novosibirsk

4. C and CP tests

C and CP invariances of the strong and electromagnetic interactions have not been tested extensively. As can be found in Table II, η decays are very interesting in this context and some of them are briefly discussed in the following.

TABLE II

How the conservation of discrete symmetries can be tested in η decays. The table is taken from reference [12].

Decay	Symmetry	Observable	Exp. Limit
$\pi^0\ell\bar{\ell}^{(a)}$	C	rate	$<5\times10^{-6}$
$\pi^0\ell\bar{\ell}^{(a)}$	C,CP$^{(b)}$	charge asym.	
$\pi^0\mu^+\mu^-$	T	$\mu^+ \perp$ pol.	
$\pi^0\ell\bar{\ell}^{(a)}$	CPT	decay correl.	
3γ	C	rate	$<5\times10^{-4}$
$\mu^+\mu^-$	P,CP	$\mu^+ \parallel$ pol.	
$\pi^+\pi^-$	P,CP	rate	$<1.5\times10^{-3}$
$\pi^0\pi^0$	P,CP	rate	
$4\pi^0$	P,CP	rate	
$\pi^+\pi^-\ell\bar{\ell}^{(a)}$	P,CP$^{(b)}$	decay correl.	
$\pi^+\pi^-\gamma$	P,CP	spectral shape$^{(c)}$	
$\pi^+\pi^-\pi^0$	C	charge asym.	$<3\times10^{-3}$
$\pi^+\pi^-\gamma$	C	charge asym.	$<1\times10^{-2}$
$\pi^0\pi^0\gamma$	C	rate	
$\pi^0\pi^0e^+e^-$	C	rate$^{(c)}$	

(a) – ℓ stands for μ or e.
(b) – in the limit of the one-photon intermediate state.
(c) – bremsstrahlung component.

One of the best places to study a possible C and CP violation is the decay $\eta \to \pi^0\gamma^* \to \pi^0e^+e^-$. If this decay is to be described by a single three-particle vertex, $\eta\pi^0\gamma^*$ (Fig. 1a), the decay is both C and CP violating as has been pointed out long ago [4]. The C violation is trivial and comes from the positive C eigenvalues of the two mesons, π^0 and η, and the negative C eigenvalue of the virtual photon ($\ell^+\ell^-$). To see how CP violation occurs in Fig. 1a the process can be viewed in the centre-of-mass frame of the $\eta\pi^0$ system which must have orbital angular momentum $l = 1$ in order to match the photon spin $j = 1$. Thus, the CP of the $\eta\pi^0$ system is odd ($P_{\eta\pi^0} = P_\eta \cdot$

$P_{\pi^0} \cdot (-1)^l$, $C_{\eta\pi^0} = +1$) but the CP of the photon is even. The information on this decay is also essential for the interpretation of the directly CP-violating $K_L \to \pi^0 e^+ e^-$ decay which will have a small but finite contribution from the $K_L - \eta$ mixing and the $\eta \to \pi^0 e^+ e^-$ decay. The $\eta \to \pi^0 \ell\bar{\ell}$ decays have not been observed experimentally and the presently measured limits are $BR(\eta \to \pi^0 e^+ e^-) < 4\times10^{-5}$ and $BR(\eta \to \pi^0 \mu^+ \mu^-) < 5\times10^{-6}$. The latter is one of the best test of C conservation in electromagnetic/strong interactions. The limits restrict the C non-conserving amplitude to be less than 10% of the C invariant one [12].

Within the SM, the CP-conserving coupling of an $\eta\pi$ system to a two-photon intermediate state (Fig. 1b) is expected to be the dominant decay mechanism. Theoretical calculations within the VMD model and the quark-box diagram give an expected rate for the decay around 3×10^{-9} [7]. These predictions are believed to be accurate to some 20–30 per cent and the errors come mainly from assumptions on the formfactor $\eta\pi^0\gamma^*\gamma^*$. In order to improve the predictions, the $\eta \to \pi^0\gamma\gamma$ decay must be known more precisely than at present.

The decays $\eta \to \pi^0\pi^0$ and $\eta \to \pi^+\pi^-$ violate simultaneously P and CP invariance. This can be easily understood since conservation of angular momentum requires the two pions, both having odd parity, to be in a state of zero relative angular momentum. The parity of the final state is even and the parity of the η is odd so parity is violated. Since the CP for two-pion system is even it follows that also CP is violated. The decay can be induced by a P and CP violating interaction, or by a P conserving CP violating interaction through interference with the usual weak interaction [8]. The rates of the decays are incredibly small in the SM. As an example Jarlskog and Shabalin have estimated that the rate is less than 2×10^{-27} and they conclude that a search for the decay at planned eta factories would indeed be a search for unconventional mechanisms of CP violation [13]. As can be seen from Table I, the present limits of the rate of charged and neutral modes could be improved considerably.

There is a threefold motivation for studying the $\eta \to \pi^0\pi^-\pi^+$ decay. Firstly, an improved measurement of the BR will give information on the difference of the d and u quark masses. Secondly, precise measurements of the Dalitz plot provide information on the $\pi\pi$ interactions. Lastly, measurements of the asymmetries of the energy distributions of π^+ and π^- provide constraints on C violation in electromagnetic decays. The present experimental value for the asymmetry is $A = 0.09 \pm 0.17 \times 10^{-2}$ [2]. The required sensitivity in A for being comparable to the experimental limit of the electric dipole moment of the neutron is of the order of 10^{-5} [8].

The reasons for studying the $\eta \to \pi^-\pi^+\gamma$ decay are to improve the accuracy of the BR and the Dalitz plot distributions which will serve for tests of the ChPT predictions. The $\pi^+\pi^-$ asymmetry, A, helps to put limits on C violation in η decays. The presently measured asymmetry in the $\eta \to \pi^-\pi^+\gamma$ decay is $(0.9\pm0.4)\times10^{-2}$ [2].

The decay $\eta \to \gamma\gamma\gamma$ violates charge conjugation. It could be induced by a parity-violating CP-conserving interaction provided by the usual weak interaction. The estimated rate is $BR(\eta \to \gamma\gamma\gamma) \approx 3\times10^{-19\pm6}$ [8]. An alternative mechanism could be an interaction which violates C and CP. The constraint from the present limit for the electric dipole moment of the neutron gives the limit $BR(\eta \to \gamma\gamma\gamma) \leq 10^{-10}$ which should be compared with the experimental limit $BR(\eta \to \gamma\gamma\gamma) < 5\times10^{-4}$.

5. Decays into lepton-antilepton pairs

The decays $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$ are of interest when searching for non-standard physics. They cannot proceed via a single-photon intermediate state due to angular momentum conservation since the spins of an η and a photon differ by one unit. Within the framework of the Standard Model, the decays are dominated by a two-photon intermediate state as shown in Fig. 2a. This second order electromagnetic contribution is further suppressed by helicity factors m_ℓ/m_η at each $\gamma\ell^+\ell^-$ vertex. Therefore the rates are small and the decays are sensitive to hypothetical interactions that arise from physics beyond the SM. Such interactions could be mediated by a heavy intermediate propagator (Fig. 2b) or by a leptoquark carrying both quark and lepton flavors (Fig. 2c).

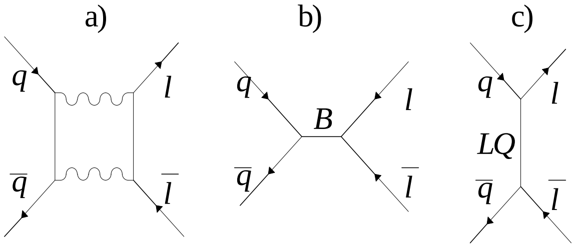

Fig. 2. Possible mechanisms for the decay of a pseudoscalar meson (π^0, η) into a lepton-antilepton pair: (a) QED, (b) heavy propagator, (c) hypothetical leptoquark.

The four electromagnetic processes (see Fig. 3) $\eta\to\gamma\gamma$, $\eta\to \ell\bar{\ell}\gamma$, $\eta\to \ell\bar{\ell}$, and $\eta\to \ell\bar{\ell}\ell'\bar{\ell}'$ are related by the same $\eta\gamma\gamma$ vertex function $F(q_1^2, q_2^2, m_\eta^2)$. Here q_1, q_2 are the four-momenta of the two photons. $F(0, 0, m_\eta^2)$ is fixed by the rate of the decay $\eta\to\gamma\gamma$. $F(q_1^2, 0, m_\eta^2)$ is called the transition form factor of the η. It has been measured fairly well in the single Dalitz decay,

$\eta \to \gamma\mu^+\mu^-$ [14] and found to be in reasonable agreement with predictions from the vector meson dominance (VMD) model.

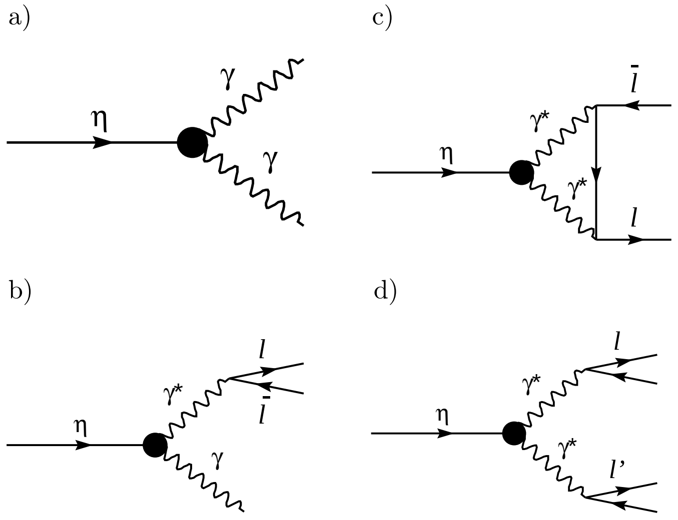

Fig. 3. Four different electromagnetic η decays having an eta-photon-photon vertex function. Here ℓ or ℓ' denote a lepton (μ or e) and $\bar{\ell}$ or $\bar{\ell}'$ the antilepton.

The amplitude A_c for the decay $\eta \to \ell\bar{\ell}$ (in Fig. 3c) is related to the amplitude, A_a, of decay $\eta \to \gamma\gamma$ (Fig. 3a) through unitarity:

$$Im(A_c) \propto (A_a) \times A(\gamma\gamma \to \ell\bar{\ell}) \tag{2}$$

which is exactly calculable and yields a lower bound (unitarity limit) for the branching ratio. $Re(A_c)$ contains the model dependence of $F(q_1^2, q_2^2, m_\eta^2)$ and is generally expected to be somewhat smaller than $Im(A_c)$. The unitarity bounds calculated from Eq. 2 are given in Table 5 where also the decay $\pi^0 \to e^+e^-$ is included.

The electromagnetic contribution (Fig. 3) to the $\eta \to e^+e^-$ decay rate has been estimated [15,16] to be $(5\pm1)\times10^{-9}$ using ChPT and the experimental $BR(\eta \to \mu^+\mu^-)$, the Saturne data [17] based on 100 events. The estimate of the $\eta \to e^+e^-$ decay rate can be constrained further by the formfactors for single and double Dalitz decays. Measurements of these decays are also interesting in their own right. For example in the double Dalitz decays, the application of the VMD model to processes with two virtual photons could be tested.

TABLE III

SM-model predictions for decays of the pseudoscalar mesons π^0 and η into lepton-antilepton pairs.

Decay	BR(exp)	Unitarity	BR(th) [15]
$\eta \to \mu^+\mu^-$	$(5.8\pm0.8)\times10^{-6}$	4.3×10^{-6}	–
$\pi^0 \to e^+e^-$	$(7.5\pm2.0)\times10^{-8}$	4.8×10^{-8}	$(7\pm2)\times10^{-8}$
$\eta \to e^+e^-$	$<7.7\times10^{-5}$	1.7×10^{-9}	$(5\pm1)\times10^{-9}$

The $\eta \to e^+e^-$ decay rate is a sensitive probe of any new interaction outside the SM since the decay rate is three orders of magnitude lower than that of the $\eta \to \mu^+\mu^-$ decay. In a recent measurement by the CLEO collaboration at the Cornell electron storage ring, the upper limit for this decay has been reduced from 2×10^{-4} [11] to 7.7×10^{-5} [9].

In connection with the $\eta \to e^+e^-$ decay, it is of interest to mention the surplus of high-Q^2 events, found recently at HERA, in *ep* deep inelastic scattering which may indicate a discovery of physics beyond the Standard Model. A leptoquark with mass around 200 GeV has been discussed as one possible source of the effect. Calculations by Wyler [18] show that the $\eta \to e^+e^-$ decay is sensitive to a certain type of leptoquark heavier than 200 GeV for branching ratios below 10^{-6}.

6. The Uppsala CELSIUS ring and the WASA facility

The CELSIUS cooler storage ring at the The Svedberg Laboratory in Uppsala (Fig. 4) provides cooled proton beams up to 0.55 GeV (uncooled to 1.36 GeV) as well as other light and heavy ion beams [19]. The ions are injected from the Gustaf Werner synchrocyclotron/cyclotron hybrid accelerator. The ring is used for experiments in nuclear and particle physics, and thin internal targets interact with the circulating stored beam.

Stripping injection has been found to give the greatest number of particles stored in the ring. A beam of 100 MeV H_2^+-ions converts to protons in a carbon foil which is seen by the injected particles at their entry inside the bending magnet of the ring. Up to 10^{11} protons have been stored, using this technique.

The electrons of the cooler have a maximum energy of 300 keV and cool protons up to an energy of 550 MeV. The energy resolution of the beam when the cooling is applied is typically 10^{-4}. For proton energies above 550 MeV, the experiments are done without cooling. The cooling can then be applied after the particles have been injected but prior to their acceleration.

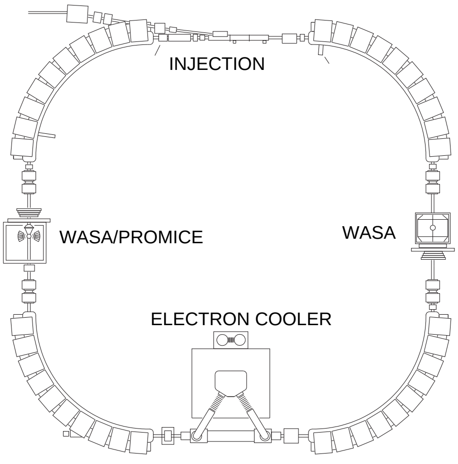

Fig. 4. The CELSIUS ring.

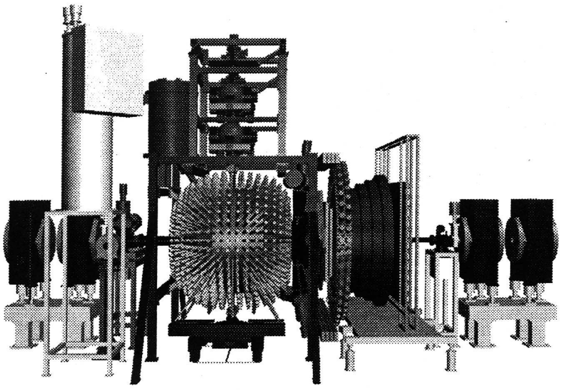

Fig. 5. The WASA wide-angle detector setup including the pellet-target system.

The rare-decay experiments will require a high-quality proton beam, a hydrogen pellet target system and a detector setup (Fig. 5) that accepts particles emitted over the full solid angle (WASA = Wide Angle Shower Apparatus). The momentum vectors of scattered beam and recoiling target particles, measured in the forward detector (FD), give the missing mass and momentum of a produced meson, and the momentum vectors of the particles emitted at large angles, give additional constraints and information on the various decay modes.

The pellet-target system [20, 21] was installed in 1995 at the CELSIUS ring and it fulfills all the major requirements needed for high-luminosity experiments with a close to 4π detector configuration. The pellets have a diameter around 30 μm, a speed of 60 m/s and the production rate is 70 kHz. At an effective target thickness of 5×10^{15} atoms/cm^2, corresponding to 30 μm pellets, and with 10^{10} protons in the ring, the luminosity is of the order 10^{32}cm^{-2}s^{-1}. The cross section for η production by 1.36 GeV protons is 5 μb, giving a production rate of 30 million ηs per day at 75% duty cycle. The CELSIUS ring with the pellet-target will thus serve as an efficient η factory.

The central detector (CD) covers a solid angle of almost 4π steradians and includes a CsI(Na) calorimeter (SEC) outside of a superconducting solenoid (SCS). The SCS is extremely thin-walled (0.18 radiation lengths) and gives a maximum central magnetic field strength of 1.3 Tesla. It was designed in a collaboration between KEK in Tsukuba and Uppsala University [22]. The main technology was developed at KEK for space-borne experiments, and the solenoid was fabricated by Japanese industry. The solenoid is now being prepared for installation into the WASA setup. The SEC has 1020 crystals of CsI(Na) scintillators. All parts of the calorimeter — crystals, light-guides, PM housings, HV sources and mechanical support — are ready. The elements are now being prepared for the assembly. Adjacent to the interior of the solenoid is a plastic scintillator barrel (PSB) consisting of 144 individual scintillators aligned axially. They surround 1738 straw tubes making up the mini drift chamber (MDC). The CD will allow efficient measurements of both charged particles and photons.

For measuring charged particles emitted at angles from 4 to 18 degrees, the WASA/PROMICE forward detector (FD) will be used [23]. Forward-going particles are measured for scattering angles between 4° and 22° with essentially full coverage of their azimuthal angles. The FD consists of a tracking detector, 16 drift chamber planes of straw type (totally 1952 straws), followed by a three-layer scintillator hodoscope and a four-layer calorimeter made of 11 cm thick scintillators. A scintillator hodoscope is placed at the end of the FD to register penetrating particles. In total the FD has 208 plastic scintillator elements.

The main priority of the WASA research program is to study in great detail various rare decays of the two lightest of the pseudoscalar neutral mesons, the π^0 and the η. The detector setup is optimized for measuring decays leading to photons and e^+e^- pairs in the final state. The present

TABLE IV

Feasibility of the measurement of some very rare η decays using the WASA facility.

Decay	BR(exp)	BR(SM)	$BR(\text{lim})^{(a)}$	$BR(\text{WASA})^{(b)}$
$\pi^0 e^+ e^-$	$<4\times10^{-5}$	$3{\cdot}10^{-8}$		10^{-9}
$\pi^0 \mu^- \mu^+$	$<5\times10^{-6}$	$3{\cdot}10^{-8}$		10^{-7}
$e^+ e^-$	$<2\times10^{-4}$	$5{\cdot}10^{-9}$		10^{-9}
$\pi^0 \pi^0$	$<7.7\times10^{-4}$	10^{-16}	10^{-15}	10^{-5}
$\gamma\gamma\gamma$	$<5\times10^{-4}$	$10^{-19\pm6}$	10^{-10}	$<10^{-6}$
$\pi^+ \pi^-$	$<1.5\times10^{-3}$	10^{-16}	10^{-15}	10^{-5}
$\mu^\pm e^\mp$	$<6\times10^{-6}$	0	10^{-9}	$<10^{-8}$

(a) — phenomenological limits from other experiments (eg NDM).

(b) — sensitivity according to present status of the simulations

knowledge about the feasibility of measurements of some of the very rare η decays is summarized in Table IV. Using WASA we expect for example to measure the decays $\eta \rightarrow \pi^0 e^+ e^-$ and $\eta \rightarrow e^+ e^-$ at a level predicted by the SM. The most important known background contributions have been studied with the GEANT code. During the course of the WASA experiment we shall also measure *background* processes that many themselves be of physics interest. Prompt $e^+ e^-$ pair production in proton-proton interactions and single and double Dalitz decays of the η constitute the physics background in the $\eta \rightarrow e^+ e^-$ decay. What concerns the $\eta \rightarrow e^+ e^-$ process, the background from single Dalitz decays is found to be around 5×10^{-10} which is the current sensitivity of the simulations. Background from $\pi^+ \pi^-$ production in proton-proton interactions, where the pions are misidentified as electrons, is below that level. Conversion of photons from $\eta \rightarrow \gamma\gamma$ decay in the material of the WASA detector setup is found to contribute at a level of about 3×10^{-9}. Work is still in progress to reduce this latter background further.

For the $\eta \rightarrow \pi^0 e^+ e^-$ process, the simulations so far have not revealed any background above a level of about 10^{-9}. More work is needed — for example on how to separate photons and how to reconstruct secondary vertices. Other very rare decays of interest where we expect to improve the present limits are the decays $\eta \rightarrow \pi\pi$ and $\eta \rightarrow \gamma\gamma\gamma$.

The not-so-rare η decays could provide information about the SM parameters. For example, from the ratio of $\eta \rightarrow \pi^0 \pi^- \pi^+$ to $\eta \rightarrow \pi^0 \pi^0 \pi^0$ decay rates, the quarks mass difference $m_u - m_d$ could be extracted. Several other decays will tests ChPT or fix some of its parameters. In this context, the $\eta \rightarrow \pi^0 \gamma\gamma$ decay is of interest since it is sensitive to the sixth order term of the chiral Lagrangian.

We look forward to a very exciting physics programme at the turn of the century. On the occasion of the Mazurian Lakes School it is appropriate to mention that the WASA project was started jointly by Swedish and Polish Scientists directed, on the Polish side, by the late Professor Iwo Przemysław Zieliński, Institute for Nuclear Studies, Professor Zdzisław Wilchelmi, Warsaw University and Professor Zdzisław Pawłowski, Warsaw Technical University. We are grateful to our colleagues in the WASA and PROMICE collaborations for their support and to C. Jarlskog and B.M.K. Nefkens for useful comments on the manuscript.

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