SYMMETRIES*

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The symmetries in some interesting η meson and charge symmetry breaking processes are under observation. The relevant and crucial few body reactions are presented, with the particular attention put to determining the down-up quark mass difference. The short presentation of the state of the art of world knowledge is summarized.

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1. Introduction

Beauty and happiness are two salient features of scientific research. "It is the beauty of the theory which is the *real* reason in believing in it."(P.A.M. Dirac). Symmetry is where aesthetics and science coalesce. Indeed, Archimedian tradition preferred justification by symmetry to that by experiment and observation. We will concentrate here on two topics:
i) symmetry studies using η mesons and
ii) charge symmetry breaking.

The η meson has a rather simple quark structure with q and $\bar{q}$ having opposite spins and no orbital angular momentum. All quantum numbers are zero: spin, isospin, electric charge, strangeness, charm, baryon and lepton numbers. G-parity and charge conjugation are +1. If it were not for parity being -1, the η might be called massive vacuum. The η decay width is 1.2 ± 0.1 keV.

Charge symmetry (CS) is the invariance of the strong interaction under the interchange of the u and d quarks (a better name for CS is the *first*

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generation or light-flavor symmetry). Therefore, charge symmetry breaking (CSB) is solely due to the difference between u and d quarks, *i.e.* $Q_u = {}^2/_3 e$ and $Q_d = -{}^1/_3 e$ and $m_d - m_u = 3$ MeV [1]. Since the long-range electromagnetic interaction is not sensitive to whether matter occurs in the form of hadrons or quarks, the CSB *enables to determine the down-up quark mass difference.*

2. Rare decays of η mesons

The importance of η mesons for symmetry studies has been pointed out by Nefkens [2]. Here we discuss only few examples. The Standard model and symmetry requirements put extremely small limits on some of the rare decay modes (less than 10^{-13}) and the discovery of the branching ratios larger than this would be a signal for symmetry breaking or even for a new physics.

1) The decay $\eta \to \pi^+\pi^-$ is CP forbidden. An estimated [3] branching ratio based on the upper limit of the neutron dipole moment is 10^{-15}.
2) The origin of CP violation is still a mystery and many models have been proposed. It is imperative to find violations of CP outside of the neutral Kaon system. A promising candidate to study CP violation is $\eta \to \mu^+\mu^-$. Since the two muon states behave under CP as $(-1)^{S+1}$ and under P as $(-1)^{L+1}$, then in the $^1S_0$ state both CP and P are odd and in the $^3P_0$ state both CP and P are even. If CP is conserved, then P must also be conserved, *i.e.* CP invariance requires that the muons have no average longitudinal polarization $P = (N_R - N_L)/(N_R + N_L)$, where $N_{R(L)}$ are the numbers of negatively charged muons with positive (negative) helicity in the η decay. The extension of the Higgs models using the upper limit of the neutron electric dipole predicts [4] P to be about 1%.
3) The decay $\eta \to \mu e$ violates lepton family conservation. An estimate [5] for the branching ratio is 10^{-10}.
4) The decay of $\eta \to e^+e^-$ could be enhanced by leptoquarks [6]. Leptoquarks are color triplet particles which couple to leptons and quarks, they have spin 0 or 1, integral or nonintegral electric charge and can come as singlets, doublets or triplets.
5) The decay $\eta \to 3\pi^0$ is suppressed by CS, *i.e.* it is driven by the $d - u$ quark mass difference. Using for $m_d - m_u$ 3 MeV, one obtains for $\Gamma(\eta \to 3\pi^0)$ 0.25 keV [7].

Interest in measuring rare η decays has been stimulated by a discovery of a large production cross section of η mesons near threshold [8]. The recoil particle makes possible tagging of η . The Jacobian decreases with the energy T above the threshold, while the cross section typically increases with $\sqrt{T}$. The following reactions can serve as a basis for η factories [2]: $pp \to pp + \eta$, $pd \to {}^3\text{He} + \eta$, $p^3\text{H} \to {}^4\text{He} + \eta$ [9], $\pi^- p \to n + \eta$, $\pi^+ d \to pp + \eta$ [10] and $\pi^{-3}\text{He} \to^3 \text{H} + \eta$ [2].

The yield of η in the $p + d$ reaction just above the threshold is much larger than of ρ and ω and it is comparable to the yield of pions at their threshold. Using this reaction Saturne II can deliver $10^3 \eta$/sec. The reaction $p+{}^3\text{H}$ could yield at LAMPF up to 100 η/sec using 1 nA proton beam and a 1000 Ci target. The proposed PILAC could give 100 and 10^4 η/sec using the $\pi^+ d$[10] and $\pi^- p$ reactions, respectively.

Photoproduction of η and η' will be studied using the CEBAF bremsstrahlung tagger (providing good photon energy resolution of 0.3% and a large flux 10^7/sec)and the large acceptance spectrometer. The measurement of the cross section will provide information on the mesons themselves and on the $S_{11}(1535)$ and $P_{11}(1710)$ nucleon resonances. η decays from nucleon resonances selectively probe those with isospin $^1/_2$, helping to unravel overlapping resonances [11].

3. Charge symmetry breaking

Extensive reviews [1] summarize evidences for CSB:

1) Mass difference of multiplet members and the solution of the long standing sign-of-the-mass-splitting riddle;
2) Meson mixing. The reaction $e^+e^- \to \pi^+\pi^-$ shows a large interference in the region of ω mass displaying strong $\omega - \rho$ mixing [12]. The comparison of CS reactions $\pi^- p \to \pi^+\pi^- n$ and $\pi^+ n \to \pi^-\pi^+ p$ (from $\pi^+ d \to \pi^+\pi^- pp_s$ and using $\pi^- d \to \pi^+\pi^- nn_s$ as a test for deuteron corrections) at 3, 4 and 6 GeV/c [13] also measures $\rho - \omega$ mixing. Decays $\eta \to 3\pi^0$ and $\psi' \to \psi_+\pi^0$ and $\psi' \to \psi_+\eta$ are accounted in terms of $\pi^0\eta\eta'$ mixing [1];
3) Difference between neutron-neutron (nn) and proton-proton (pp) ${}^1S_0$ scattering lengths: a_{nn} and a_{pp} [14];
4) Difference between the polarizations in $n - \vec{p}$ and $\vec{n} - p$ elastic scattering at 188 and 477 MeV [15]. The difference at 477 MeV is dominated by a term proportional to $m_n - m_p$ (one-pion-exchange potential), while the difference at 188 MeV is due mainly to the $\omega - \rho$ mixing [16]. Measurement designed to have an uncertainty in the difference between polarizations of 0.0005 is in progress at 350 MeV [17];
5) Okamoto–Nolen–Schiffer anomaly [1, 18]: in mirror nuclei the binding energies of a neutron-rich nuclei are about 5-10% larger than those of their respective isodoublets, after electromagnetic effects have been taken into account.

All evidences for CSB can be explained in terms of $d - u$ quark mass difference. Though it seems that the CSB is explained, there is a need for further studies. This paper summarizes open problems and progress currently achieved.

3.1. Is $\rho - \omega$ mixing the dominant mechanism of CSB?

A common assumption in generating the CSB potential is that the $\omega - \rho$ mixing amplitude is constant and equal to the observed value at the omega pole. This assumption has been [19] investigated in a very simple model and it was found that, when one allows for the off-shell variation of the mixing amplitude, the contribution to CSB would be severely suppressed. This requires further studies.

Quark masses can depend on nuclear density [20]. The $\omega - \rho$ interference can provide a sensitive probe of $d - u$ dependence on density through the study of the $pd \rightarrow {}^3\mathrm{He}\omega$ reaction, where different densities can be achieved by varying the incident energy and the momentum transfer [2].

3.2. Do we know the neutron-neutron scattering length?

There are more than 30 extracted values of a_{nn} from processes yielding 3 or 4 particles in the final state: *e.g.* $\mathrm{D}(n,p)2n$, $\mathrm{T}(n,d)2n$, $\mathrm{D}(d,pp)2n$, $\mathrm{D}(\pi^-,\gamma)2n$. The most recent value of a_{nn} from the reaction $\mathrm{D}(\pi^-,\gamma)2n$ disagrees by four standard deviation from the world average of the 3 and 4 hadron final state experiments: $a_{nn} = -16.7 \pm 0.3$ fm. It has been suggested [14] that the reason for this discrepancy is the three nucleon force (3NF) which acts in the final state of the reaction $\mathrm{D}(n,p)2n$, while it is absent in the reaction $\mathrm{D}(\pi^-,\gamma)2n$. Though this bold conjecture reconciled all extracted a_{nn} values from the reaction $\mathrm{D}(n,p)2n$ with those from the reaction $\mathrm{D}(\pi^-,\gamma)2n$, and the resulting a_{nn} value led to CSB fully consistent with all other CSB effects in nuclear physics, it is necessary to reemphasize its speculative character and shortcomings:

1) Reconciliation has been achieved using a simple 3NF and it was confirmed by a three body model [21] using a simple nucleon-nucleon (NN) force and the Tucson–Melborne 3NF. Even if a rigorous three body calculation with the Tucson–Melborne 3NF confirms [22] our conjecture [14], we still have to admit that our knowledge of the 3NF is meager [23].
2) The value of a_{nn} extracted from reactions involving more than three nucleons have been rejected in Ref. [14]. However, the reactions ${}^9\mathrm{Be}(n,2n){}^8\mathrm{Be}$ and ${}^9\mathrm{Be}(p,pn){}^8\mathrm{Be}$ gave [24] $a_{nn} = -16.5 \pm 1.0$ fm in conjuction with $a_{np} = -23.8 \pm 1.2$ fm.

Therefore, additional measurements of a_{nn} are needed:

3.2.1. Direct measurement of the $n-n$ cross section

It is now possible to perform a direct $n-n$ scattering experiment [25]. Los Alamos National Laboratory has a unique facility for this kind of measurement by virtue of underground nuclear explosions. The experiment is designed to collide two finely collimated beams of neutrons generated by hydrogen devices and to detect the scattered neutrons at the edge of the kinematic scattering cone. The angle of approach determines the $n-n$ center of mass energy. A small angle of approach (3.82°) between the colliding neutron beams provides a low $n-n$ energy (4 to 35 keV), and also high signal to background ratio (about 3600), since the n-n scattered neutrons are thrown sharply forward, whereas the background processes are isotropic. In order to achieve the accuracy of 3% for the a_{nn} in the proposed experiment [26] it is intended to measure the $n-n$ cross section at 58 energies from 20 to 40 keV. The "laboratory" was constructed inside a cylindrical tank: 2.4 m dia ×36 m long. The lines of sight were so rigid that distortion of the axis is less than 0.3 mm along the entire experiment after loading the tank with 6.4 $\times 10^5$ kg of iron, copper, lead and tungsten. The vacuum was better than 10^{-7} torr. The "laboratory" was tested with high reliability: a fault tree analysis using experimental failure rate data of the system components indicated an acceptable probability of success. The colliding neutron beams experiment can be designed to measure $n-n$ cross sections at keV energies and also at higher energies (incident angle of 25° gives $E_{nn} = 1.3$ MeV) which provides information on P wave force.

3.2.2. Pion induced deuteron breakup

There are only two high accuracy measurements of the reaction $D(\pi^-,\gamma)2n$, both performed by the same group [27]. It is imperative to do additional measurements with comparable accuracy. A new measurement planned at LAMPF [28] aims to determine a_{nn} to an accuracy of about ± 0.3 fm.

3.2.3. The reaction $D(n,p)2n$ at 200 to 460 MeV

It has been argued [14] that at high energies the NN final state interaction in the $D(p,pn)p$ breakup is not influenced by the 3NF and that the impulse approximation gives a correct a_{np}. A recent measurement of $D(p,p')pn$ at 198.5 MeV at TRIUMF gives $a_{np} = -24.7 \pm 0.4$ fm [29].

3.2.4. CSB test in pion induced η production on Deuterium

The large mass difference between π and η suppresses their mixing effects at low energies. It is proposed [10] to use the AGS pion beam of sufficient energy that span the opening of the channel, *i.e.* 570-750 MeV/c, to investigate $\pi-\eta$ mixing in the following processes: $D(\pi^+,pp)\pi^0$, $D(\pi^-,nn)\pi^0$,

$D(\pi^+, pp)\eta$ and $D(\pi^-, nn)\eta$. Measurements are planned to investigate nn vs pp and $n\eta$ vs $p\eta$ final state interaction regions. The quark mass difference leads to different ηN coupling constants [30]: CSB QCD effects are -1.1% for $n\eta$ and $+1.1\%$ for $p\eta$, while QED effects are $+0.07\%$ for $p\eta$ coupling constants. These coupling constants have never been measured. Using $m_d - m_u = 3.4$ MeV and $E_c = -2$ MeV, the mass splitting of the $S_{11}(1535)$ doublet is estimated to be 1.8 MeV.

The reaction $D(\pi,\eta NN)$ is treated in a relativistic lowest order model. Dominant contributions are S_{11}, P_{11} and D_{13} partial waves with a strong branching ratio to η channel. The simplest version uses only a resonant description, it is on-shell and it ignores NN and Nη final state interactions (FSI). Since measurement will be done at $\Theta_N = \Theta_\eta$ and at $\Theta_N = \Theta_N$ the FSI effects are crucial. The complete model will include FSI, off-shell and a realistic description of πN system. In comparing the reactions $D(\pi^+$,pp) and $D(\pi^-$,nn) one has to consider Coulomb effects in the initial (energy shifts) and final states as well as the n-p mass difference.

3.2.5. 3NF effects in the reaction $D(n, nn)p$

It is expected [21] that 3NF effects are pronounced in FSI, collinear and star configurations of the reaction $D(n, np)n$. Measurements are in progress at TUNL [31]. The reaction $D(p, pp)n$ has been recently studied at 10.3 [32], 13 [33], 22.7 [34, 35] and 67 MeV [36]. There are discrepancies between some data and the rigorous three body theory particularly in the $n - p$ FSI region. Since FSI is extremely sensitive to a_{np}, we investigate — in a Watson–Migdal model — a change in a_{np} required to fit the data. In the region $\theta\ (d^*) = 80° - 130°$ the effective a_{np} decreases from -23 fm ($\theta(d^*) = 80°$) to -15 fm with a statistical error of 0.3 fm. It remains to be seen whether the rigorous calculation with 3NF can explain this behavior.

4. $\pi - N$ coupling constants

The $\pi - N$ coupling constants have recently attracted much attention. The new VPI value [37] for the charged coupling constant f_c^2 is 0.0735 ± 0.0015. Their treatment of e.m. corrections and inconsistency of their amplitudes with dispersion relations has been criticized but the latest VPI results are improved in these respects. The NN analysis [38] gives: $f_p^2 = 0.0746 \pm 0.0006$, $f_n^2 = 0.075 \pm 0.002$ and $f_c^2 = 0.0748 \pm 0.0003$ along with $f_c^2 = 0.0751 \pm 0.0017$ from $N\bar{N}$ scattering. The results are independent from π vertex form factor. Therefore, there is no experimental evidence for charge dependence and the value $f^2 = 0.076 \pm 0.002$ for the coupling constant is suggested [39].

5. Pion-nucleon and nucleon-nucleon interaction

The unique determination of the complete set of $\pi - N$ amplitudes requires at least 8 independent measurements. A recent measurement [40] of the spin rotation parameters A and R for π^+p and π^-p elastic scattering at pion beam momenta of 427, 471, 547, 625 and 657 MeV/c provides together with previous cross section and analyzing power measurements such a complete set [41]. A phase shift analysis will provide a test for charge independence and more importantly, it will clarify whether the P_{11} Roper resonance has two poles. Is the second pole a physical distinct state or is it a shadow pole? Theoretical calculations also differ in their predictions for the P_{11} resonance. Two of the QCD inspired models predict [42] the existence of a ground state q^3g hybrid with mass around 1400 MeV in the vicinity of the $3qP_{11}$ resonance with $M = 1440$ MeV. During last years $\pi - N$ scattering has been studied also at PSI, TRIUMF, LNPI, ITEP and KEK. In the mass region up to 2.5 GeV 35 $\pi - N$ resonances are found, but different phase shift analyses [43] in some cases strongly disagree. New measurements in the 1–2 GeV region are planned [44].

Inspite of a significant progress in $N - N$ studies there are still open problems, *e.g.* ^3P_J and ϵ_1 phases and off-energy-shell interaction. The $\pi - \rho$ contribution plays a crucial role in describing P and D waves [45]. The possible CSB in the ^3P_J waves is still open [46]. Indeed, the study [47] of $p-p$ scattering at 25 MeV, which provides a model independent determination of $^1S_0$, ^3P_J and ϵ_2 phases favours the Nijmegen and Paris potentials and rules out the CSB potential constructed to fit the $n-p$, $p-p$, $n-d$ and $p-d$ analyzing power data. Similarly, though the Bonn A potential with deuteron D state probability P_d of only 4.4% explains $p-d$ polarization transfer $K_y{}^{y'}$, $K_x{}^{z'}$ and $K_x{}^{x'}$ data at 22.7 MeV [48] equally good fits are obtained with Nijmegen and AV14 potentials, which have $P_d = 5.4\%$ and 6.1%, respectively. This is due to the fact that the Nijmegen and AV14 potentials $^1P_1$ parameter appreciably differs from that of Paris and Bonn. Therefore, a good fit by the Nijmegen potential is probably just an artifact of a possible deficiency in $^1P_1$ parameter. The large value for ϵ_1 extracted from the $n-p$ spin correlation parameter A_{zz} at 68 MeV [49] is incorrect and these data can be explained by Bonn and Paris potentials [50] with lower ϵ_1. The preliminary results [51] of the transverse spin dependent differences in the total $n-p$ cross section favour Bonn A potential. The Bonn A potential has also a weaker off shell tensor force (smaller P_d) and it almost fully explains the nuclear structure data [45]. However, preferrence for a weaker off shell tensor force is clouded by the lack of our understanding of the role of the 3NF in nuclear systems.

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