Quark Mass Difference and the Origin of Charge Symmetry Breaking

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ABSTRACT

Evidence for charge symmetry breaking in nuclear and particle physics is presented and it is shown that all of the observed effects can be explained by the mass and electric charge difference between d and u quarks. While hadron masses depend on the sum of the quark masses, charge symmetry breaking effects depend on the difference between d and u quark masses providing a new quark mass relation.

1. INTRODUCTION

The discovery of the neutron and the near equality of its mass to that of a proton led Heisenberg in 1932 to introduce the isospin formalism[1], but it was assumed that the binding of the atomic nuclei is entirely due to the neutron-proton (n-p) force[2], i.e. in our present language - a strong charge dependence of nuclear interaction. By 1936 studies of binding energies of hydrogen and helium isotopes, and of n-p and proton-proton (p-p) scattering brought evidence that the nuclear neutron-neutron (n-n), n-p and p-p forces in the same state are identical, after correcting for electromagnetic (e.m.) interaction effects[3]; this feature of nuclear interaction is called charge independence. The equality of n-n and p-p nuclear forces, called charge symmetry (CS), was conjectured in 1935[4]. The CS operator changes neutrons into protons and vice versa. If CS operator commutes with the Hamiltonian, then CS is a valid symmetry. Since the masses of a neutron and a proton and similarly those of charged and neutral pions are slightly different, it was realized from the beginning that the isospin invariance is broken, albeit slightly. It was believed that these differences are of e.m. origin, thus modifying the nuclear interaction both directly (Coulomb forces, magnetic interaction, etc.) and indirectly (mass splitting among charged states of nucleons and pions; e.m. effects on the coupling constants, etc.). Charge symmetry and isospin invariance were the first broken symmetries to be studied; they paved the way for the SU(3) and kindled our present fascination for non-Abelian groups.

The concept of CS obviously has to be extended to all hadrons. Hadrons are composed of quarks and the fundamental theory of the strong interaction is QCD. On the level of quark degrees of freedom, the CS operator changes d quarks into u quarks and vice versa ($P_{CS}|d\rangle = |u\rangle$, $P_{CS}|d\rangle = -|d\rangle$) and consequently for the G-parity $G|d\rangle = |\bar{u}\rangle$ and $G|u\rangle = -|\bar{d}\rangle$ ($\bar{u}$ is anti u). The quark definition of CS provides a clear understanding of CS breaking (CSB)[5]: CSB is due to the difference between d and u quarks: the mass difference $m_d - m_u$ and different electric charges. Therefore, all experimental evidences for CSB should be explained in terms of d-u differences! CSB is concerned with understanding the flavor dependence of the quark mass spectrum - one of the most important unsolved problems in physics.

2. EXPERIMENTAL EVIDENCE FOR CSB

- i) If two hadrons are related by switching a d to an u quark, the hadron with the d quark is always more massive as Table 1 [5] demonstrates. E.m. interaction cannot explain the data in Table 1 (see column e.m.). It is necessary to assume that m_d is larger than m_u . The concept of CS, which originated in nuclear physics is naturally extended to systems containing s, c and b quarks. Light nuclear and hypernuclei doublets follow the same rule: systems with d instead of u quark are heavier. For systems with more than 3 protons, the e.m. effects become dominant[6].
 - ii) A strong signature for p - ω mixing has been observed in the cross section measurement of the reaction $e^+e^- \pi^+ \pi^-$ [7]. The

experimentally determined $\langle \sigma | H | \omega \rangle$ is -2.7 ± 0.4 MeV and it cannot be explained by e.m. interaction which gives $+0.43 \pm 0.04$ MeV, i.e. it is smaller and of the opposite sign! Strong evidence for n - η - η' mixing has been obtained from studies of η , ψ and ψ' decays[8].

iii) A new analysis of 1S_0 n - n effective range parameters: a_{nn} and r_{nn} , extracted from the reactions $D(n,2n)p$ and $D(n,\gamma)^2n$ and the reduction of the uncertainty in the e.m. correction to the p - p scattering length, a_{pp} , give results in Table 2 [5,9] which show clear CSB.

iv) Low energy nucleon(N)-deuteron(d) scattering sensitively depends on 3P_J phase shifts. Exact $3N$ calculations are now done with accuracies of better than 1% [10]. Using n - p , p - p , p - d and n - d data it is possible to obtain 3P_J phases to an accuracy of about 0.2 degree. Table 3 [10,11] shows 3P_0 nuclear phase shifts. Charge independence and CS are broken. It is worth mentioning that while a large difference between n - p and n - n (p - p) scattering lengths of 5.7 ± 0.3 fm is fully explained in terms of different masses of charged and neutral pions in one, two, three and four pion exchanges and of the photon-pion exchange contribution, the pion mass difference in the one pion exchange contribution gives for the 3P_0 state an effect opposite to the one listed in Table 3. However, caution is necessary: a) The results in Table 3 are based only on the vector analyzing power data. Tensor analyzing power and polarization transfer coefficient data will provide much more accurate determination of all 3P_J phase shifts. b) It

is necessary to investigate the effect of the pion-photon exchange contribution in the 3P_J waves.

v) The reaction involving two spin 1/2 particles, when only Lorentz invariance is imposed, is characterized by 16 independent amplitudes leading to 256 observables. Parity conservation and time reversal invariance reduce 16 to 6 independent amplitudes, and hence 256 to 36 independent observables. Charge symmetry reduces 6 to 5 independent amplitudes and hence to 25 independent observables. This means that there are 11 independent tests of CS [12]. These tests should be done at various energies and angles, since mechanisms for CSB vary with angle and energy. Measurements at TRIUMF at 477 MeV [13] and at IUCF at 183 MeV [14] are examples of such tests involving only one polarized particle and clearly demonstrate a CSB caused by non-e.m. forces in the n - p system.

vi) The studies of pion-deuteron elastic scattering[15] and of $n^- d \rightarrow nn$ vs $n^+ d \rightarrow pp$ processes [16] show CSB in the P_{33} wave.

vii) New measurements of the ^3He and ^3H e.m. form factors [17] allowed an improved determination of the e.m. contribution to their binding energies resulting in a difference of $(71 \pm 19 \pm 5)$ keV (the first error is due to experimental uncertainties and the second estimates model dependence) demonstrating that the n - n interaction is more attractive than the p - p one[18].

viii) Similarly, differences between binding energies of heavier mirror nuclei, $A=13-41$ cannot be explained by e.m.

effects and n-p mass differences (Nolen-Schiffer anomaly [19]): the discrepancies are 0.1-0.4 MeV and considerably larger than the uncertainties) leading to the conclusion that the n-n force is more attractive.

ix) Elastic electron scattering provides proton radii for ${}^3\text{H}$ and ${}^3\text{He}$. Recent n^+ scattering from ${}^3\text{H}$ and ${}^3\text{He}$ in the region of the Δ resonance [20] enabled the determination of the differences:

$$r_p({}^3\text{He}) - r_p({}^3\text{H}) = 0.035 \pm 0.007 \text{ fm and } r_n({}^3\text{H}) - r_p({}^3\text{He}) = -0.030 \pm 0.008 \text{ fm, thus showing a CSB effect [21].}$$

x) Study of ${}^4\text{H}$ and ${}^4\text{He}$ hypernuclei shows pronounced CSB. The differences between Λ separation energies for the ground (0+) and the first excited state (1+) after removing e.m. effects are 0.39±0.06 MeV and 0.27±0.06 MeV, respectively [22]. The CSB effect is about 5 times larger than the corresponding difference for the nuclear A=3 system. The Λ -p interaction is more attractive than the Λ -n one. A large CSB effect in Λ -N interaction is due to the fact that the two-pion exchange (OPE is isospin forbidden) involves π^+ and π^- , their masses differ only 10 MeV and the Λ - Σ mass difference is 80 MeV, while the N- Δ mass difference is 300 MeV.

3. THE ORIGIN OF CSB

In the quark models the value of $m_d - m_u$ that yields the mass difference between hadrons in agreement with the experiment also reproduces the experimental result for the ρ - ω mixing [23]. The

experimental value $M_n - M_p = 1.29 \text{ MeV}$ is obtained if one uses as input in a quark model the value $m_d - m_u = 2.8 \text{ MeV}$ (individual contributions are: mass+kinetic energy for d and u quarks is 2.11 MeV, the difference in gluon exchange energy is -0.244 MeV and the e.m. is -0.573 MeV [5]). Using again $m_d - m_u = 2.8 \text{ MeV}$ and harmonic oscillator wavefunctions leads to a ρ - ω mixing matrix element of -3.17 MeV, in agreement with the experimental value of 3.1 MeV (the value of 2.8 MeV is model dependent. However, the main point is that the same value of $m_d - m_u$ explains both mass difference and ρ - ω mixing.).

The ρ - ω mixing is the main cause of the difference between n-n and p-p interaction (additional contributions are the π - η - η' mixing, pion-photon exchanges), which is a medium range force not very sensitive to the short range uncertainties. This force leads to a difference between n-n and p-p effective range parameters [18]: $\Delta_{\text{calc}} = 1.5 \pm 0.4 \text{ fm}$ and $\Delta_{\text{calc}} = 0.02 \pm 0.02 \text{ fm}$. A similar CSB force gives the n-n ${}^3\text{P}_0$ phase shift, which is about 0.2-0.8 degrees smaller than the p-p one, again in agreement with our Table 3.

The CSB in elastic n-p scattering at 477 MeV is dominated by the one pion exchange term proportional to $M_n - M_p$, while at 183 MeV it is dominated by the ρ - ω mixing (both are due to $m_d - m_u$!).

The CSB force that explains n-n and p-p low energy phase shifts, predicts for the A=3 binding energy difference a value of 68 keV [18] (in excellent agreement with the experimental value) and it explains about 85% of the Nolen-Schiffer anomaly [5,25].

We conclude that a theoretically derived CSB meson exchange force, determined by quark mass difference, constrained by $e^-e^+ \rightarrow \pi^+\pi^-$, accounts for the N-N scattering data and the binding energy differences between mirror nuclei. While hadron masses depend on the sum of quark masses, CSB depends on the difference between d and u quark masses, providing a new quark mass relation.

Table 1. Quark composition and doublet mass splitting[6]

Particle	Quarks	Mass(MeV)	e.m.(MeV)	Particle	Quarks	Mass(MeV)
K^0	ds	497.7		B^0	db	5280
K^+	us	493.7	-1.1	B^+	ub	5278
n	dud	939.6		3H	d4(ud)	2808.94
p	udd	938.3	-0.5	3He	u4(ud)	2808.42
Σ^-	dds	1197.3		4H_A	ds5(ud)	3922.53
Σ^0	uds	1192.5	+1.5	4He_A	us5(ud)	3921.66

Table 2. Nucleon-nucleon effective range parameters

	n-n	n-n(nuclear)	p-p	p-p(nuclear)
a(fm)	-18.5±0.3	-18.8±0.3	-7.8063±0.0026	-17.3±0.4
r(fm)	2.75±0.11	2.75±0.11	2.794±0.0014	2.85±0.04

Table 3. Nuclear phase shifts for 3P_0 (in degrees)(10,11]

Energy (MeV)	n-p	p-p	n-n
5.0	1.99	1.59	1.36
12.0	5.36	4.27	3.64
25.0	9.80	7.8	6.65
50.0	12.81	10.28	8.79

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