Fundamental Nature and Relevance of Charge Symmetry Breaking

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Charge symmetry breaking (CSB) in the strong interaction occurs because of the difference between the masses of the up and down quarks and is therefore an important feature of the Standard Model. This small mass difference has important consequences for many reactions of fundamental importance. Using effective field theories allows many experimental and theoretical nuclear physicists to follow this influence of confined quarks in hadronic and nuclear systems and make much recent progress.

The isospin quantum number $\mathbf{T}$ was introduced so that the nucleon with isospin 1/2 has two states, in analogy to the spin quantum number. As long as only the strong interaction is present, the isospin vector $\mathbf{T}$ can point in any direction and the strong Hamiltonian obeys $[H_S, \mathbf{T}] = 0$. To satisfy this equation is to satisfy isospin invariance.

The effects of the light quark mass difference and electromagnetism do not commute with the isospin operator. The isospin rotation by 180° about the y axis is the special transformation that defines the charge symmetry operator $P_{\rm cs}$: $P_{\rm cs} = e^{i\pi T_2}$, and charge symmetry holds provided $[H_S, P_{\rm cs}] = 0$. If charge symmetry is broken then isospin invariance and charge independence are broken, but the converse is not true. In particular, $P_{\rm cs}|u\rangle = -|d\rangle$ and $P_{\rm cs}|d\rangle = |u\rangle$. The term "charge symmetry" should not be confused or interchanged with the term "charge conjugation," which involves replacing a particle by its antiparticle.

If charge symmetry were exact, the proton and the neutron would have the same mass. CSB causes the neutron to be about 0.1% heavier than the proton. The electrostatic repulsion between quarks should make the proton heavier. But the mass difference between the quarks wins over their electrostatic repulsion by a factor of about two, making it the dominant cause of CSB. The neutron-proton mass difference has important consequences for the structure of the universe because it means that a neutron can decay into a proton (plus an electron and an anti-neutrino) in radioactive beta decay. When protons and neutrons combined to form elements in the first few minutes after the Big Bang, the resulting elemental abundances depended on the neutron-proton mass difference and the lifetime of the neutron. All the neutrons that survived were bound inside nuclei, which left many protons free. The interactions between these protons are the main source of energy in stars like the Sun.

The mass difference between the up and down quarks is the *only* strong interaction effect that breaks charge symmetry [1] and isospin invariance. Electromagnetic effects also violate charge symmetry, so that these effects and those of the quark mass difference are responsible for all charge-dependent effects and all violations of isospin. However, to focus on the light quark mass difference it is necessary to concentrate on CSB.

The quark mass difference is manifest in low energy nuclear structure physics. It accounts for the well-known Nolen-Schiffer anomaly, and is an important part of modern attempts to understand the spectra of mirror nuclei and isobaric analog states; see the reviews [1].

CSB is of high current interest because of recent experimental progress [2, 3] in measuring CSB in the production of neutral pions in neutron-proton and deuteron-deuteron collisions. The current importance of such studies is increased by new theoretical insight – an appropriate use of a convergent effective field theory (EFT) can be equivalent to using QCD. Indeed, the last decade has seen a paradigm shift in trying to understand CSB from within a meson-exchange framework to within an effective field theory framework. In the EFT scheme, the degrees of freedom are nucleons and pions with interactions of forms constrained by the approximate chiral symmetry of QCD. Precise calculations of strong interaction effects are possible, provided expansions in terms of small momenta converge. The use of different experiments combined with a carefully constructed theory of the electromagnetic effects should allow the isolation of the quark mass difference effect.

We demonstrate the importance of CSB by discussing its impact on three subjects of high current interest: extraction of strangeness form factors, using neutrino interactions to determine the weak mixing angle, and $g-2$ of the muon.

The discovery that valence quarks carry only a small fraction of the nucleon spin [4] and the resulting searches for strangeness in the nucleon, brought attention to understanding the role of nucleonic CSB. In principle any form factor of the nucleon receives three independent contributions from u, d and s quarks (neglecting the far smaller contributions of b, c, and t quarks). If charge symmetry holds, the u, d contributions to neutron form factors are equal to the d, u contributions to proton form factors. The number of independent contributions is thereby reduced to two so that measurements of the parity violating left-right asymmetry in electron-proton scattering can in principle determine form factors whose origin can lie only in the strange and anti-strange quarks of the nucleon [5–7]. The small corrections caused by CSB can be estimated using quark models[8] or EFT, and may be detectable in future measurements.

The NuTeV group [9] measured charged and neutral current weak reactions for deep inelastic scattering of neutrinos and anti-neutrinos by iron targets. Ratios of cross sections can be used to determine the weak mixing angle, provided the target is isoscalar, the nuclear strangeness content can be ignored, charge symmetry holds, and certain nuclear effects can be neglected. Then the Paschos-Wolfenstein (PW) relation holds for the Standard Model: $\left(\langle\sigma_{NC}\rangle^{\nu} - \langle\sigma_{NC}\rangle^{\bar{\nu}}\right)/\left(\langle\sigma_{CC}\rangle^{\nu} - \langle\sigma_{CC}\rangle^{\bar{\nu}}\right) = \frac{1}{2} - \sin^2\theta_W$, where $\langle\sigma_{NC}\rangle^{\nu,\bar{\nu}}$ and $\langle\sigma_{CC}\rangle^{\nu,\bar{\nu}}$ are the neutrino and anti-neutrino neutral-current and charged-current inclusive total cross sections, averaged over the proton and neutron. NuTeV's value for $\sin^2\theta_W$ is three standard deviations larger than the Standard Model prediction. However CSB causes a change in the PW relation [10]. This essentially model-independent correction removes much of the discrepancy [11].

The anomalous magnetic moment of the muon $a_\mu \equiv (g-2)/2$ is experimentally known to an amazing relative precision of 0.5 parts in a million [12]. The measured result is either 0.9 or 2.4 standard deviations higher than predicted by standard model theory [13], obtained using two different methods to obtain the hadronic vacuum polarization term [14]. The lowest-order hadronic vacuum polarization contribution can be evaluated in terms of the experimentally measured cross section for $e^+e^- \to$ hadrons using a dispersion integral representation, but τ decay of very high accuracy can also be used to obtain hadronic input that is directly related to the isovector photon vacuum polarization currents if isospin invariance and unitarity hold. The corrections arising from the light quark mass difference and unknown isospin violating decays are significant at the required level of accuracy; but even with these corrections, the e^+e^- and τ data are incompatible [14]. The hadronic τ decay data leads to the smaller difference with theory. A key point in relating the τ and e^+e^- data involves accounting accurately for the CSB effects of $\rho^0 - \omega$ mixing.

Charge symmetry breaking in the strong interaction occurs because of the difference between the mass of the up and down quarks. CSB is an intrinsically quark effect, and the use of EFT allows us to follow the influence of confined quarks on phenomena in hadrons and nuclei. The last ten years have seen very significant developements in the understanding of CSB. The use of an EFT for QCD has led to a reasonable fundamental understanding of the strong NN interaction at all but the shortest of ranges. EFT has also allowed a similar fundamental understanding of the different classes of charge independence breaking and CSB interactions

An especially significant prediction of EFT is that CSB is very important in the interactions between neutral pions and nucleons, as represented by a particular seagull term. This observation led to the suggestion that experiments measuring the CSB production of a neutral pion would shed essential light on this important prediction. The challenge was taken up with the ultimately successful measurements of CSB in the forward-backward asymmetry of the $np \to d\pi^0$ reaction and in the non-zero cross section for the $dd \to \alpha\pi^0$ reaction. Interesting first steps in understanding the sizes of the recently observed CSB effects have been made. In particular, power counting techniques have been developed recently for the generally difficult task of understanding strong pion production in few nucleon collisons.

A significant body of experimentalists and theorists are working on many aspects of CSB. We know how to study the influence of the light-quark mass difference in nuclear physics and this skill can be marshaled to tackle a significant variety of important topics in fundamental physics.

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