FROM PARITY VIOLATION TO HADRON STRUCTURE AND MORE . . .

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New developments in physics associated with parity-violating interactions are discussed in this PAVI 2002 workshop summary.

1. Introduction

The parity-violating property of the weak interaction allows us to observe its effects in many situations where it would otherwise be practically impossible. This property in turn affords many opportunities to study the weak interaction itself, and, perhaps surprisingly, to study hadronic structure as well. For those of us in the field it is easy to forget that significant advances are being made - the experiments and the calculations look quite different than they did 5 - 10 years ago; the PAVI 2002 workshop provides a timely snapshot of our recent history and present activities. This talk is divided into three sections – advances in technology, in understanding of the physics and the open questions for the next meeting.

How do the measurements and calculations described below change the way we think about physics – the gold standard test for any endeavor in our field? Although the answer is perhaps more obvious for the investigations of the weak interaction, in my view, the advances in hadronic structure are of equal importance. There are lots of ways to express our ignorance of the manifestations of QCD in hadronic structure; suffice to say that we have a pretty poor picture of how more than 99% of visible mass in the universe is put together.

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2. Technology

Unlike most electron scattering experiments, parity-violation measurements are very tightly coupled to beam properties. The quality of the polarized beam and measurements of its properties are crucial.

There has been tremendous recent progress in the overall figure of merit for these experiments

$$\frac{\Delta A}{A} = \frac{1}{f.o.m.} = \frac{1}{A_{phys}P_e N},$$ (1)

where N is the number of measured particles, because of the advent of high polarization (P_e) electron sources. Whereas experiments were previously limited to polarizations of less than 50% for bulk GaAs, new strained crystals in use at Mainz,[1] SLAC[2] and JLab[3] have provided high currents with polarizations in excess of 80%. These crystal materials continue to be improved, now involving multilayer structures, yielding larger and more uniform strains with quantum efficiencies of order 1%. By activating only the central region of the crystal with Cs, emission from the crystal edges (which can hit the vacuum chamber) is greatly reduced and the crystal lifetime is consequently increased.[4] Not surprisingly, the lasers being used for these sources also continue to improve, both in terms of power and stability.

These strained crystals necessarily have an analyzing power for linearly polarized light (caused by the strain) and because the circular polarization of the incident laser light is not perfect, care must be taken to reduce the effects of the residual linearly polarized component. This is particularly difficult at SLAC where the laser beam diameter is large (14 mm) and the associated large diameter Pockels cell generates only 99.2% circular polarization. Nevertheless, the helicity-correlated position differences have been reduced to the few tens of nm. The intensity asymmetries are now quite routinely corrected to the ppm level, most often using a scheme originated at Bates where a second Pockels cell (the first being used to produce the circular polarization of the light) is used as a variable shutter to adjust the laser intensity in a helicity-correlated manner. More sophisticated analysis techniques are now being used to better understand the transport of the various components of the polarized light in an effort to further reduce these effects.

The uncertainty in beam polarization continues to be one of, or the largest, systematic uncertainty in these experiments. As the precision of the actual parity-violating asymmetry determinations improves, beam polarimetry must keep up. Combinations of conventional Mott and Möller

measurements[5], measurements using Compton backscattering[6] and developments of new analyzers[7] are supporting the new experiments. My sense, however, is that improvements in these measurements will have to be pursued even more aggressively in the future.

With the success of early measurements of parity-violating electron scattering have come more ambitious experiments with more sophisticated technology. In order to measure[8] Q_{weak} at JLab a roughly 2 kW liquid hydrogen target is required (with very stringent limits on boiling). In order to help determine accurately the neutron radius in lead,[9] a new JLab experiment will use a diamond backed lead target to deal with the heating from intense beam required. Detectors have also become more sophisticated. The G0 experiment[10] at JLab will, for the first time, utilize a "mixed" detector in a parity-violation measurement with the addition of Cerenkov detectors to supplement the scintillation detectors in the backward angle phase for the purpose of pion rejection. The detectors for the E158 experiment[11] at SLAC have the unusual requirement that they must be radiation hard because of the enormous Möller rate. Both G0 and PVA4[12] at Mainz are, for the first time in such experiments, counting individual particles and therefore using large numbers of detectors with the associated (standard for other experiments) difficulties of maintenance of thresholds, gains, etc. G0 also has sophisticated custom electronics to produce histograms in hardware to allow total count rates of order 100 MHz. PVA4 uses advanced trigger electronics to reject physics backgrounds (inelastic electrons) at very high real rates ($\sim$ 100 kHz per channel, $\sim$ 100 MHz overall).

3. Physics

It is the parity-violating nature of the weak interaction that enables us to actually see it in experiments where electromagnetic or strong interactions dominate. In the experiments considered at this meeting, the small contribution of the weak interaction is extracted by "beating" it against the dominant electromagnetic interaction, i.e. by taking advantage of the quantum mechanical interference. In one type of experiment, the neutral weak current so extracted is compared with the corresponding electromagnetic current to learn about hadron structure. In the other, the structure of the target is assumed to be known and the couplings and structure of the interaction itself are investigated. Let us look first at the hadronic structure physics.

The strange quark contribution to hadronic structure has been the fo-

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cus of electron-scattering parity-violation experiments for some time. The neutral weak current of the nucleon is critical in this connection, because the flavor singlet current (the difference between the electromagnetic and neutral weak currents) does not couple to the photon as the total charge of the u, d and s quarks is zero. Cahn and Gilman[13] were the first to recognize that the weak interaction could be useful in separating contributions from the quark flavors although they chose to neglect the contribution of the strange quarks (by assuming charge symmetry for the proton and neutron, they predicted the neutral weak form factors and hence the elastic scattering asymmetry for a given weak interaction model – the subject of investigation at the time). The development of experiments to investigate the strange quark vector currents derived from several sources in the late 1980's. The measurement of the polarized deep-inelastic scattering structure function $g_1(x)$ by the EMC collaboration[14] led to the suggestion[15] that the discrepancy in the measured Ellis-Jaffe sum rule[16] was due to the contribution of strange quarks, in this case, to the axial vector matrix element $\langle \bar{s}\gamma_\mu\gamma_5 s \rangle$. At about the same time, Steve Polluck was re-examining the elastic e-p scattering asymmetry in his thesis[17] (he has also been a strong advocate of the parity-violation experiment to measure the neutron radius in lead). Perhaps the key development was the connection drawn by Kaplan and Manohar[18] between the axial-vector strange quark matrix elements in deep-inelastic scattering and elastic neutrino scattering[22] and the suggestion that the analogous vector current matrix element should be investigated. Thereafter the idea was picked up by McKeown,[19] Napolitano[20] and myself.[21]

Understanding the role of strange quarks in the structure of "light quark" hadrons is likely to be difficult – as was pointed out by a number of speakers at the conference. They are neither light nor heavy; in fact their mass of ~ 100 MeV is roughly comparable to the QCD scale ($\Lambda_{QCD} \sim 200$ MeV). There are a number of indications, however, that their role could be an important one in the structure of light quark hadrons as well as in such diverse areas as color superconducting quark matter[23] and the nature of the chiral phase transition in hot nuclear matter[24].

Despite the difficulties, several different approaches to modeling light hadron structure including strange quarks were presented[a]. In the model of Riska and collaborators[26], constituent quarks interact via the exchange of Goldstone bosons. Whereas this model avoids the large couplings asso-

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[a]See also the recent review by Beck and Holstein[25]

ciated with interactions of Goldstone bosons with the nucleon, the meson-quark couplings must be inferred. Further, at present, only the lowest order interactions have been included.

It has been noted that a widely quoted result from chiral perturbation theory, namely the model-independent slope of G_M^s at $Q^2 = 0$[27] is, in fact, model dependent because some 1-loop order diagrams are canceled at higher order.[28] This problem was signaled by the realization that at the calculated order, the slope should simply be that of the isoscalar magnetic moment (which it is not). As a guide, using a form factor with a cutoff, suggests that the actual slope might be only 1/4 - 1/3 as large as originally predicted.

Dispersion calculations provide perhaps the surest way to use available experimental information together with well-defined theoretical techniques to calculate strange quark form factors.[29] In principle, they combine the simpler "pole" and "loop" calculations performed previously. One of the interesting aspects of these calculations is that they give the same sign for G_E^s and G_M^s (< 0) resulting in a potential conflict with the measured HAPPEX point (showing that $G_E^s + 0.39 G_M^s$ is near zero). It is therefore possible that such calculations should include higher lying meson resonances (though the requisite data are sparse at best).

Over the past couple of years, it has been realized that generalizing the standard forward Compton scattering diagram used to describe electron scattering to the off-forward case leads to a set of structure functions (Generalized Parton Distributions - GPD's) that link deep-inelastic and elastic physics.[30] For example, with the assumption of the dominance of the simple hand-bag diagram, the Dirac form factor F_1^s can be calculated as a weighted integral of the difference between $s(x)$ and $\bar{s}(x)$ measured in deep-inelastic neutrino scattering. The weighting itself depends on determining the parameters of Regge trajectories. This interesting approach suggests that if F_1^s turns out to be significant ($s(x)$ and $\bar{s}(x)$ are nearly indistinguishable), higher lying meson resonances may be responsible.

Is it possible to forget the models and just wait for the lattice calculations to provide the answers? The answer for me is clearly no. The reason for starting this experimental program in the first place was to help develop the picture of how the quarks (in this case the sea quarks) and gluons are organized in the nucleon. Simply calculating the form factors on the lattice and comparing with data is, in my view, not physics. Physics requires a reasonably compact and efficient description of natural phenomena. In this case I expect we will be able to identify the appropriate quasi-particles to

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describe hadron structure and be able to describe the interactions of these quasi-particles in some effective theory.

In any case, despite strong progress in lattice calculations, there is still quite a long way to go.[31] Two prominent steps have recently been taken. Dynamical quarks can now be included in calculations albeit with a significant cost in computation time ($\sim$ x10). It does not appear to date as if there are any quantities where this contribution is dominant, but the calculations are at an early stage. The problem of getting down to physical quark masses (a few MeV for the light quarks) has been largely circumvented by taking advantage of known mass dependences in chiral perturbation theory to extrapolate the lattice results to the appropriate mass. Teraflop computers are now on the way; a few 10's of teraflops are probably necessary to calculate strange quark form factors. However, getting all the way to including s quarks in an exact calculation is still problematic in principle. The methods used to include dynamical quarks rely on having an even number of flavors. It is not clear how the large mass difference between the strange and charmed quarks can be handled, although there is time to work on this problem while the computers and algorithms catch up on dynamical light quarks.

A couple of talks at this workshop addressed the weak interactions of hadrons as measured in parity-violation experiments.[32] Measurement of the weak pi-nucleon coupling constant, called variously $h_{\pi NN}$ and f_π in the literature, by looking at parity-violating pion photoproduction near threshold was proposed.[33] Much of our understanding of these phenomena is coded in the Desplanques-Donoghue-Holstein (DDH) parameterization of the leading order coupling constants. At present, the determination of $h_{\pi NN}$ and the other parameters from measurements in nuclei, from pp scattering and from atomic parity-violation (via the anapole moment) are in some disarray. I know of at least one alternative to measuring this particular coupling – via the $np \to d\gamma$ capture in the development stages at Los Alamos. The experiment discussed at this meeting is an important but difficult one which will challenge a next generation of electron or real photon parity-violation experiments.

The techniques that make use of the weak interaction to look at hadronic structure physics are clearly also applicable, in the proper context, to studying the weak interaction itself. Three such situations were discussed at this meeting – all with daunting requirements for precision. Having said this, what is remarkable is that one of the measurements, the weak mixing in the cesium atom, has been completed at a level which provides powerful

constraints on TeV scale physics (making measurements of weak electric dipole matrix elements at the tiny scale 10^{-18} e-cm).[34] In fact, the 0.3% experimental accuracy for the weak charge of the cesium nucleus has outstripped the atomic calculations necessary to relate the observable to the underlying theory. Work continues to improve these calculations. At this meeting we heard a very promising report on the Möller scattering parity-violation experiment (SLAC E158).[11] In this case the physics asymmetry is a bit more than 10^{-7} and the goal for the overall uncertainty is about 10^{-8}. Remarkably, with a lot of hard work on controlling systematic uncertainties associated with the beam, as well as on backgrounds, this experiment is poised for its main data-taking phase. Lastly, the approved Jefferson Lab experiment, Qweak, will measure the proton weak charge in parity-violating electron-proton scattering at very low momentum transfer ($Q^2 = 0.03$ GeV^2).[8] Again, with a desired statistical precision of 10^{-8}, this will be a difficult measurement. The aim is to run this experiment in 2005.

These experiments are particularly sensitive to certain types of new physics.[8] Heavier Z' gauge bosons are more visible at low energies than they are at the ordinary Z pole where the most precise electroweak studies have been done. There are two schemes for mixing families, R-parity violating supersymmetry and its cousin – leptoquarks – wherein quarks are transformed into leptons and vice versa, which could make significant contributions to these observables. One of the nice features of this set of measurements is that these new physics effects have complementary impacts. For example, R-parity violating SUSY has a larger impact in Qweak than E158 and vice versa for leptoquarks. This discussion brings to mind a recent speech by the US Presidential Science Advisor and former Brookhaven director John Marburger in which he challenged us to imagine doing physics at the frontier after the last large accelerator is built. His speculation is that a significant part of our work will involve precision measurements of which these experiments may be precursors.

4. Open Questions

There are a number of "technology" issues that are apparent in our current state of the art. Although progress has been made, successful completion of the first analysis (probably E158) where the systematic uncertainties are in the few ppb range will be a milestone. This will likely require continued work on control of helicity-correlated beam properties associated particularly with strained crystals as discussed at this meeting. Similarly, success-

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ful completion of an analysis associated with more sophisticated detectors
(e.g. PVA4), where some of the systematic considerations are different,
will also be a milestone. There have frequently been questions about how
accurately the strange quark contributions to the form factors should be
determined – I would say that the level of a few % of the overall form
factor, as expected in the G0 experiment, is sufficient to significantly ad-
vance the picture of their role in hadron structure. At present there do
not seem to be particular values commonly emerging from theory, except
perhaps for the clustering of a number of results for μ_s around -0.3 – preci-
sion of a few % is clearly enough to evaluate this prediction. Finally, there
is the old problem of charge symmetry in the proton-neutron system. We
really need to know whether the probability of finding a u quark at radius
r in the proton is the same as finding a d quark at the same radius in the
neutron. Gerry Miller has done a calculation[35] that indicates the effects
in the strange quark experiments will be very small – directly applicable
experimental input is scarce or non-existent.

In terms of physics, I would like to address four topics. First, there has
been progress in modeling strange quark effects, notably in the dispersion
theory approaches and in continuing exploration of new connections such
as generalized parton distributions. However, as the experiments push for-
ward, it is important to try to picture what happens to these effects as
the momentum transfer increases toward 1 GeV^2. Although a number of
technical problems have been solved in lattice calculations, it seems we are
still quite some distance from reliable strange quark matrix elements.

Second, I think the axial current observed in the SAMPLE experiment
is interesting to follow up. Although we have had several calculations from
Mike Ramsey-Musolf and collaborators, I believe there is room for others
to contribute here. First of all, perhaps it would be useful to focus on the
observable axial current difference between neutrino and electron scattering
as the definition of what to calculate (or approximate) in order to relieve
confusions about definitions. It might be beneficial to follow the lead of
Claude Bouchiat whose picture of nucleons with longitudinal (relative to
momentum) components of spin, arising from weak interactions between
nucleons, underlies the anapole moment effects calculated for nuclei and
observed in the atomic cesium experiment.[34,36] I expect we will find in the
end that questions of definition will recede and that this observable will tell
us about weak interactions among the quarks in the nucleon.

Third, and on a closely related note, continuing to press on calculations
of (and perhaps some related measurements relevant to) all the radiative,

or perhaps one should say higher-order corrections, will be critical to continuing to make progress across this broad field. Related effects enter in a number of other important measurements – neutron β decay and muon $g - 2$, for example, and we are learning (again) about their critical role to interpretation of the experiments. Of course, even in fundamental measurements, it is again effects associated with hadrons or quark loops that are the toughest to address.

Lastly, perhaps the most common question we hear about the strange quark effects is "what if you see zero?" On the surface this may seem like a defeat, but I believe such a result is, if anything, more directly informative than measuring some particular values. I think it is important to discuss the physics of this possibility more vigorously and I particularly like the framework suggested by von Harrach in our discussions at this meeting. To start, even though s quarks may contribute to the nucleon mass and spin (where quarks and antiquarks contribute with the same sign), they may be relatively invisible in the (charge conjugation even) observables like the charge and magnetization distributions. The issue, then, is whether the s quarks and anti-quarks that are there either a) are significantly separated or b) are in a relative spin singlet (such that their magnetic moments are parallel). The first possible cause of a zero or near zero result is that the s and $\bar{s}$ simply do not live long enough to interact with the medium and become significantly separated. This may be in contrast to the explanation for the excess of $\bar{d}$ quarks over $\bar{u}$ quarks in the proton (Gottfried sum and direct Drell-Yan data). In this case, there are as many fervent defenders of the pion cloud explanation (where the pairs do interact and separate into some quasi-nucleon and pion packages) as there are of some effect related to the Pauli principle (where simply fewer $u\bar{u}$ pairs are formed). The recent observations of the HERMES collaboration that the spin carried by anti-quarks is very small at high energies suggests that in this case the quarks are produced in relative spin-singlet states (gluon spin carried by relative orbital angular momentum between the q and the $\bar{q}$), likely a simple result of helicity conservation. Therefore, in the second case, it may be that the soft physics is sufficiently different that the pairs are created in spin triplet states leading to a zero contribution to the magnetization. These questions, I think, remain among the most interesting in nucleon structure physics.

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Acknowledgments

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