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Colloquia: PAVI11

Conference summary

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Summary. — A perspective on the PAVI11 conference is given.

PACS `12.15.Mm` – Neutral currents.
PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.

1. – Introduction

In this perspective on the conference, I plan to emphasize the connections (see fig. 1) that I have found between the various talks. Since it is easier for me to find connections with topics on which I have worked personally, this talk will be biased.

For example, we had a talk on the recent results from COMPASS, including amazingly precise data on g_1. The speaker commented that he wondered why this topic is relevant for a parity conference. In my opinion, given the history of the field, the connection is quite strong. Parity experiments with polarized electrons rely on a polarized electron source, and such sources were initially developed for spin-structure studies at SLAC. Indeed, the first polarized source used at an accelerator, PEGGY I [1], was used to make the first spin structure function measurement. In addition, the first parity experiment with polarized electrons used the PEGGY I source. [2] That early experiment revealed the problems that are still important when measuring small asymmetries, especially the issue that the beam parameters can be different for different helicities. As a result, the GaAs based PEGGY II source, [3] together with precision beam instrumentation, was developed for the successful Prescott experiment in 1978 that clearly saw parity violation in neutral currents [4, 5].

An Electron-Ion-Collider (EIC), a possible future large nuclear physics facility, has the potential to expand the horizon of both parity-violation and studies of spin-structure functions. One example that fuses both concepts is the measurement of the parity-violating structure functions g_4 and g_5 [6].

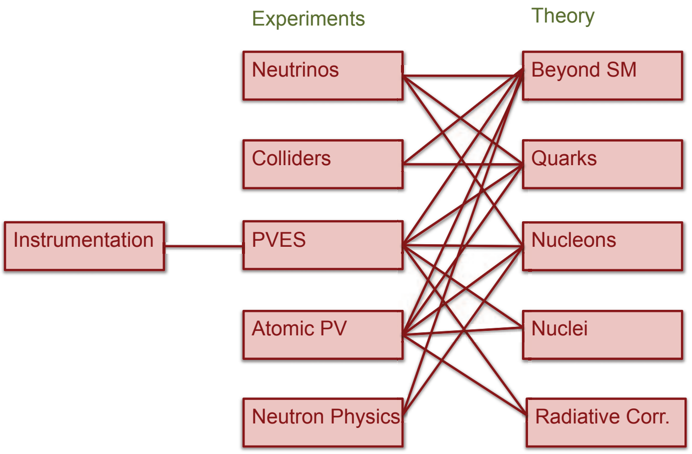

Fig. 1. – Shown are the various topics discussed at the Conference and some of their connections.

2. – Hadronic parity violation

The early experiments with parity violation were with hadrons. I note in particular the experiment that measured the proton-proton scattering asymmetry $A_L^{pp}(45\,\mathrm{MeV})$ to be -0.150 ppm with an impressive error of only 0.022 ppm [7]. I remember being in awe of the precision obtained by the authors and became determined to achieve similar sensitivity in experiments with polarized electron. That is a goal that only recently has been achieved.

Traditionally, hadron parity experiments have been described in terms of the DDH formalism, which uses mesons as a degree of freedom. With this method, for example, useful estimates of the size of parity violation effects were made. However, little progress has been made recently with this procedure.

More recently, as reported by B. Holstein [8] and M. Gericke [9], the data are being analyzed in terms of four-Fermion contact interactions. This method does not lead to better theoretical predictions, but does serve to simplify the phenomenological analysis. For the case of parity violation in *electron scattering*, the corresponding Lagrangian is quite simple:

$$(1)\qquad \mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)],$$

and there are four independent constants, C_{1u}, C_{1d}, C_{2u}, and C_{2d}, that can be measured. This is the phenomenology that has been used for analyzing parity violation in both atomic physics and polarized electron scattering.

For parity violation in hadron interactions, the situation is more complicated. First s-wave amplitudes are assumed to dominate the interaction but the parity violation is dominated by p-waves. Then a number of four-Fermion interactions such as

$$\tilde{\mathcal{O}}_1 = \frac{\tilde{t}_1}{\Lambda_\chi^3}\bar{\psi}_N \mathbf{1} i\sigma_{\mu\nu}q^\nu\psi_N\bar{\psi}_N\tau_3\gamma^\mu\gamma_5\psi_N$$

may be defined. They are not all independent, but a careful analysis shows that there is a complete set of five independent coupling constants that may be denoted by λ^{pp}, λ^{pn}, λ^{nn}, λ_t, and ρ_t. For example, $A_L^{pp}(45\,\mathrm{MeV}) = -0.82\lambda_s^{pp}M_N$ and the circular polarization from $np \to d\gamma$ is $P_\gamma = (0.63\lambda_t - 0.16\lambda_s^{np})M_N$. The plan is to determine all five coupling constants from low-energy experiments involving nuclei with $A < 4$ so that issues with nuclear physics can be isolated from the weak interaction physics.

Once the couplings are established, the effects in more complex nuclei can be predicted. One open question in the field is the puzzling result of the large anapole moment of Cs. S. Cahn described how it might be possible to measure the anapole moment of many more nuclei across the periodic table [10]. Such measurements might establish an informative pattern of nuclear enhancements.

It is amusing that the particle physics community, which during the past 40 years or so has avoided using heavy nuclei as targets as much as possible, is now embracing heavy nuclei, including double-beta decay experiments and dark matter searches. An interesting connection made by Tony Thomas [11] is that the strange scalar matrix element is very important for dark matter searches since the coupling of the dark sector may be dominated by the Higgs, and the Higgs couples most strongly to the heaviest available quark. Thus strange quarks in the nucleon may dominate the interaction. The vector matrix elements of strange quarks are a major topic for this series of conferences and will be discussed below. Modern neutrino experiments use nuclear targets at moderately low beam energies.

Understanding heavy nuclei is also important for understanding the properties of neutron stars. In particular, the density dependence of the symmetry energy is one of the most important unknown quantities relevant for understanding the density, cooling, and crust of neutron stars. These properties are also correlated to the skin thickness of a heavy nucleus such as Pb [12]. Recently PREx has reported the first measurement of the parity-violating asymmetry in Pb and has confirmed that the neutron skin is nonzero [13]. In a future measurement the collaboration expects to obtain sufficient precision to distinguish among the many models that are used today to interpret data on neutron stars. Moreover, additional nuclei, such as ^{40}Ca or Sn, may be possible.

3. – CP and P violation in atoms

CP violation has been an important topic in physics since it was discovered in K decays in the 60's. With the discovery of heavy quarks, the frontier moved to the CKM matrix and measurements of B decays. The CKM matrix explains CP violation in both B and K decays.

Today there are two important new areas where CP violation not due to the CKM matrix might be observed. The first is neutrino oscillations, which is especially interesting in light of the recent hint that θ_{13} is nonzero. Experiments in progress should convincingly settle the θ_{13} issue in the next few years. K. Scholberg gave an excellent review of the field [14].

The other active area in CP violation is electric dipole moments (EDM)'s, which are also parity violating. The search for EDMs is motivated by, among other theories, supersymmetry. An extensive program studying the EDMs of the neutron, electron, etc. is underway [15,16]. We also heard a new result for an improved limit on $D(n)$ in neutron decay.

Atomic parity violation has always been a topic central to the PAVI series of conferences. M. Bouchiat gave an excellent review of the important goals for the field [17].

The basic thrust is that both theory and experiment need to be improved; improvements in one without the other is of little use. One new development on the experimental side is that radioactive, super-high Z nuclei including Ra^+ ions [18] and Fr atoms [19] are becoming feasible to study. The advantage of Ra^+ or Fr is that the theory is as "easy" as that of Cs but the predicted asymmetries are much larger. We also heard from M. Safronova [20] about significant improvements in the theory. We are making significant progress in the field along a broad front.

4. – Advances in theory

The study of parity violation in polarized electron scattering has been an attractive field because of the simplicity of the theoretical interpretation. However, with the recent improvements in the precision either achieved of proposed, uncertainties due to the exchange of more than one boson, such as $\gamma - Z$ box diagrams, have become an important issue. Accordingly, we had a number of talks on the subject [21,12]. The issue is particularly critical for the Q_{weak} experiment. One result of the discussion at PAVI11 is that the theoretical predictions can be improved if we can obtain a larger data set of asymmetry data in inelastic scattering over a wide kinematic range. Data taken to make radiative corrections for the PVDIS experiment at JLab [22] may be helpful for this program. Also, the G0 collaboration presented new results for the $N \rightarrow \Delta$ transition [23].

Another probe of multi-boson exchange physics is the Beam-Normal asymmetry observed in a number of experiments. Data are available for both the nucleon and a few nuclei, including ^{4}He, ^{12}C, and ^{208}Pb. New results for the neutron were given by Mainz. The theory gives qualitative agreement with the data with the exception of new results presented here for Pb [13]. The OLYMPUS experiment promises to provide excellent data for measuring the effects of two-photon exchange from the difference between e^+ and e^- cross sections.

5. – PV in electron scattering

The main motivation for the parity experiments using the scattering of polarized electrons during the past decade or so has been on the measurements of strange form factors of the nucleon. There have been four major groups, including SAMPLE at MIT-Bates, HAPPEX and G0 at JLab, and A4 at Mainz. The experiments have used a variety of targets, H, D, and ^{4}He as well as a large range of scattering angles. With the results presented at this conference by HAPPEX III and A4 [24], this program is now almost complete. For some values of Q^2, all of the form factors have been separated. There are two conclusions from this body of work

1) All the different experiments are in agreement.

2) There is no evidence for non-zero strange form factors.

The first point encourages us to undertake even more challenging experiments.

A number of such ambitious experiments are being planned or are underway. A summary of the field, both past and future, is given in fig. 2. There has been a tremendous improvement in both the absolute error in the small asymmetries and also in the fractional error in the asymmetries. Future experiments promise to push the envelope much further. The Mainz P2 experiment will set the standard for small asymmetries and the PV-DIS experiment will set the standard for the smallest fractional error in an asymmetry.

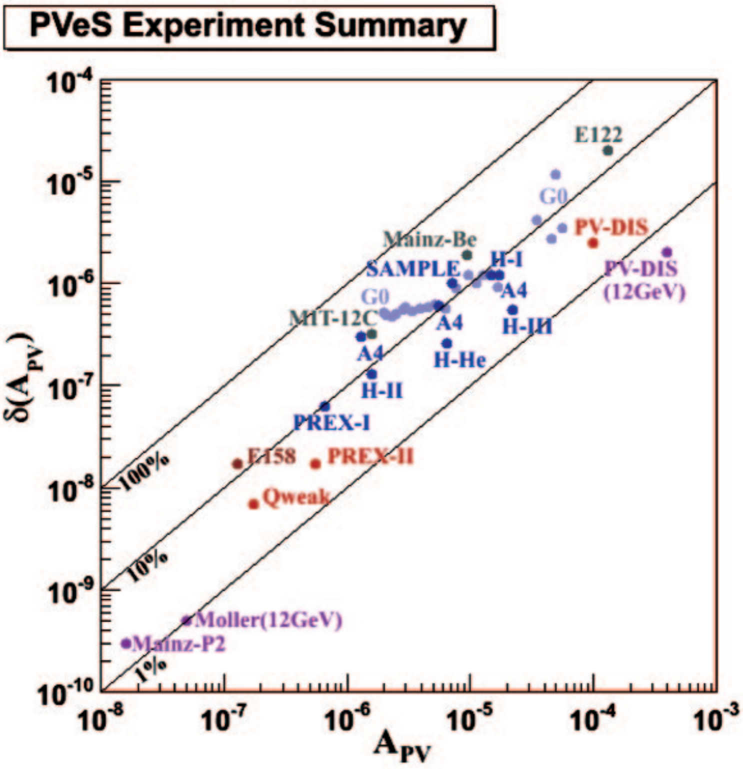

Fig. 2. – Sensitivity of experiments measuring parity violation in polarized electron scattering. Vertical axis: proposed sensitivity. Horizontal axis: expected asymmetry. The diagonal lines correspond to constant fractional errors.

One key to this progress is improvements in experimental technique. For example, the properties of the polarized electron sources are far superior to what was available in the days of PEGGY I or even PEGGY II. The intensity is limited by the accelerator, not the source. Under helicity reversal, the beam properties are virtually unchanged. The helicity can be flipped rapidly; rates over 1 kHz are planned [25].

Powerful cryotargets are also critical. They must be long, as long as 2 m for the MOLLER experiment, handle beam currents up to 150 μA, and avoid density fluctuations that otherwise would degrade the statistics of the experiments. The Q_{weak} target [26] is particularly impressive in this regard.

With the advent of experiments with small fractional errors, beam polarimetry has become increasingly critical. There are now many precise Compton polarimeters in various laboratories that can attain precision at the 1% level [27]. For some proposed experiments, precision in polarimetry below 0.5% is required. A high-precision Møller polarimeter based on atomic hydrogen has the potential to achieve this level of precision [28].

With the exception of the HAPPEX experiments and PREx, most parity experiments with polarized electrons use custom spectrometers. There have been major developments in spectrometers for future parity experiments. Q_{weak} and Moller are using toroidal spectrometers with high acceptance. PV-DIS and P2 plan to use solenoidal spectrometers. For many of the new experiments, integrating the signal is the method of choice. The one exception is PV-DIS, which will use counting techniques as pioneered by A4 and G0.

6. – Standard model tests

Testing the Standard Model is the focus for most of the future parity experiments. The idea for many of these experiments is that they will be complimentary to data from the LHC [29]. We heard about the first data from that facility, which has yet to find evidence for either extra Z's, SUSY, or the Higgs particle. However, major improvements in the sensitivity of the experiments is expected soon.

The most precise low-energy number for $\sin^2\theta_W$ will come form the proposed MOLLER experiment at JLab [30]. It should help resolve the discrepancy from the precise values obtained at SLAC and LEP. If the Higgs is the only new physics found at the LHC, the measurement of $\sin^2\theta_W$ will be crucial to demonstrate that the Higgs is indeed at the predicted mass.

It is possible that new particles will be discovered that could alter the Standard Model predictions for the parity-violating couplings of leptons to quarks defined above in eq. (1). The combination of APV and Q_{weak} [31] will set precise limits on the C_1's. The PVDIS experiments [32] including SoLID will provide information of comparable sensitivity on one combination of the C_2's.

There are important theoretical issues that need to be discussed to support these precise standard model tests. Radiative corrections are important for the MOLLER experiment [33] and issues of parton distribution functions (PDF's) and higher twist arise in PVDIS [34]. Indeed, the SoLID experiment will also provide unique information on higher twist effects due to quark-quark correlations and charge symmetry violation (CSV).

Two important tests of the Standard Model, APV for Cs [35] and the NuTeV experiment [36], originally published that their results were inconsistent with the Standard Model. However, theorists found additional corrections, including CSV in the parton distribution functions for NuTeV. Often today both experiments are plotted to be in perfect agreement with theory. What do we make of this? First, this means that these experiments are important. If they were not, nobody would bother to change them. Second, it means that better data are needed. We expect that the new APV data and the data on CSV from SoLID will help rectify the situation.

7. – Summary and outlook

The field of the study of parity violation is well developed but still growing. Many important results were presented at PAVI11, and the stage is set for even more impressive accomplishments in the future. We anticipate that PAVI14 will have many exciting new results.

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