FURTHER MEASUREMENTS OF PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING*

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Summary

We report on measurements of the y-dependence of the parity non-conserving asymmetries for inelastic electron scattering from deuterium. The measurements cover a range of y values from 0.15 to 0.36 and show only a small y-dependence. The results are in good agreement with the Weinberg-Salam model for $\sin^2\theta_W = 0.224 \pm 0.020$.

Evidence for the existence of parity non-conservation in inelastic scattering of electrons from deuterium and hydrogen has already been reported.[1] We have since extended our measurements over a wider kinematic range for the process

$$e(\text{polarized}) + D(\text{unpolarized}) \rightarrow e' + X \quad . \tag{1}$$

The amplitude for the reaction (1) consists of two parts, the usual electromagnetic part, of strength α/Q^2 shown in Fig. 1 as a single virtual photon exchange, and a weak neutral current piece, of strength G_F, where α is the fine structure constant, G_F is the Fermi coupling of the weak interactions, and Q^2 is the invariant four-momentum squared. We measure a parity non-conserving asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \tag{2}$$

where $\sigma_{R(L)}$ is the cross section $d^2\sigma/d\Omega dE'$ for right-handed (left-handed) incident electrons scattering from deuterium. This quantity is expected to be non-zero due to interference between the weak and electromagnetic terms and is estimated to be of the order

$$A \cong \frac{G_F Q^2}{2\pi\alpha} \approx \frac{10^{-4}Q^2}{M_p^2} \quad . \tag{3}$$

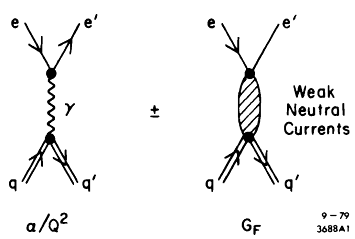

Fig. 1. The amplitude for e-hadron scattering consists of an electromagnetic piece, shown as a single virtual photon exchange, and a weak neutral current piece. The characteristic strengths are α/Q^2 and G_F respectively. Under parity, the weak term contains parts which change sign, leading to weak-electromagnetic interference effects in the cross section for scattering of polarized electrons.

It is the smallness of the expected asymmetries that makes the measurements difficult and requires special experimental techniques to control the size of statistical and systematic errors.

Within the framework of the simple quark-parton model of the nucleon, where the electrons are assumed to scatter off spin 1/2 constituents only, it can be shown that the asymmetry A has the general form

$$\frac{A}{Q^2} = a_1(x) + a_2(x)\left\{\frac{1-(1-y)^2}{1+(1-y)^2}\right\} \tag{4}$$

where $x = Q^2/2M_p(E_o - E')$ and $y = (E_o - E')/E_o$ is the fractional energy transferred from the electron to the hadrons.[2,3,4] For an isoscalar target such as deuterium, the parameters a_1 and a_2 are expected to be constants. Gauge theory models predict values for a_1 and a_2, and in the Weinberg-Salam model Eq. (4) has the form[5,6,7]

$$\frac{A}{Q^2} = \frac{-G_F}{2\sqrt{2}\pi\alpha}\cdot\frac{9}{10}\left[\left(1-\frac{20}{9}\sin^2\theta_W\right) + \left(1-4\sin^2\theta_W\right)\frac{1-(1-y)^2}{1+(1-y)^2}\right] \quad . \tag{5}$$

A measurement of the y-dependence of A permits a separation of the coefficients a_1 and a_2. These coefficients correspond to vector and axial-vector parts of the neutral current quark couplings, respectively, and separation of a_1 and a_2 contributes to the more detailed understanding of the neutral current structure. In particular, measurements of the y-dependence provides a more stringent test of the Weinberg-Salam model than can be obtained by a single measurement at one value of y. Searches for parity violation in the spectra of high Z atoms are related to only one of these parameters, a_1, so comparison with these experiments requires some knowledge of the y-dependence.

I will briefly review the experimental techniques used in our experiment and the earlier evidence we obtained for existence of parity non-conservation. The data and fits to the forms Eqs. (4) and (5) will be shown. I will conclude with remarks about the model-independent analysis and the connections our results have to the recent parity violation seen in atomic physics spectra.

Figure 2 shows the elements of our experiment in a highly schematic form. Longitudinally polarized electrons were obtained by photoemission from a gallium arsenide crystal optically pumped with laser light. Based on a suggestion in 1974 by Garwin (SLAC), and Pierce and Siegmann (Zurich) that circularly polarized laser light could photoemit large currents of longitudinally polarized electrons from gallium arsenide,[8] development of an injector for the linac was undertaken in 1974, and completed in 1977. The source routinely provides full SLAC beam intensities at a polarization around 40%. Polarization is fixed for the 1.5 μsec long beam pulses at SLAC, but can be reversed between beam pulses by reversing the circular polarization of

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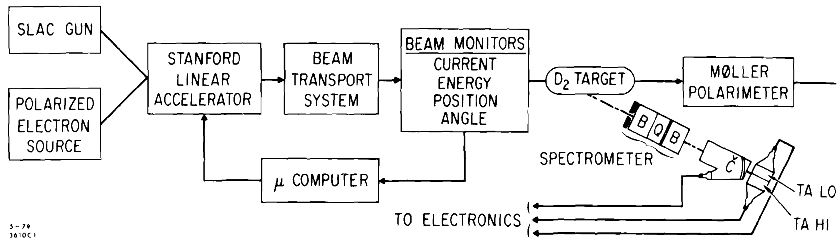

Fig. 2. Schematic layout of experiment.

the laser light. Most importantly, the polarization can be reversed with little or no influence on other beam parameters such as current, position or angle on the target, energy, or beam phase space. Thus cross section comparisons between + and - helicity can be meaningfully made. We chose to randomize the pattern of + and -'s to remove biases due to drifts in our apparatus and drifts or periodic changes in beam parameters. The accelerator operated at 120 pulses per second at energies from 16.2 GeV to 22.2 GeV. No problems with depolarization of the longitudinal spin were seen (or expected) during the acceleration.

Extensive monitoring of the important parameters (current, energy, position and angle) was performed continually during the runs, and ruled out systematic errors in A from these sources above a level of 10^{-5}. The transport system was instrumented with toroid charge monitors that measure the charge delivered in each pulse to the target, and with resonant microwave position monitors that permitted measurement of the position and angle of the beam at the target. A microwave cavity position monitor was placed in the transport system where energy was dispersed horizontally, permitting measurement of beam energy. Signals derived from the position monitors were analyzed by a microcomputer and corrections were generated to remove drifts seen in the beam parameters. These procedures significantly improved stability in the important beam parameters.

The experimental asymmetry is related to the parity violating asymmetry, defined by Eq. (2), according to

$$A_{exp} = P_e A \quad , \tag{6}$$

and our final values for A are obtained by dividing the experimental asymmetries by measured values of the beam polarization, P_e. The experiment was instrumented to monitor on a frequent basis the value of P_e, under the same beam conditions as for our data. Errors in P_e contribute directly to errors in A, and are included in our systematic errors. The technique used was elastic scattering of polarized beam electrons from polarized target electrons (Møller scattering) at high energy. Polarized target electrons were obtained by magnetically saturating a thin iron foil, oriented so that target electron spins were nearly parallel to the beam direction. The Møller measurements were made several times per day, and obtained an average polarization $P_e = (37 \pm 2)\%$. We also monitored the polarization at the source by the traditional low energy technique of Mott scattering from gold foils. For the latter measurements $P_e = (39 \pm 4)\%$. We use the more accurate high energy value.

Cross sections for electrons scattered at 4^o were measured with a magnetic spectrometer. The spectrometer momentum was varied from 11 to 16.5 GeV/c during the course of the experiment, to obtain a range of y values. Electrons passing into the acceptance of the spectrometer were counted by two counters. The first was a 3 meter long atmospheric gas Cerenkov counter, and the second a lead glass shower counter divided into low and high momentum halves, placed behind the Cerenkov counter. Anode currents from the photomultiplier tubes in each counter were integrated and digitized for each beam pulse. These counters were analyzed independently through separate electronic channels. They were not operated in coincidence. The integrated signals from the photomultipliers provided a measure of the flux of electrons through the spectrometer for each beam pulse, and when these measured fluxes were normalized by the charge delivered to the target, each beam pulse resulted in a cross section value from each counter, in arbitrary units. Precise normalization of cross section measurements is unnecessary for asymmetries defined in Eq. (2). By averaging over a sufficiently large number of beam pulses, the statistical errors were reduced below the 10^{-5} level.

The key to the success of these measurements lies in the control of systematic effects in the beam. It is very difficult if not impossible to measure <u>all</u> important sources of systematic error. Rather than attempt to do so, we rely on consistency checks and null measurements to show that our measurements are free of large systematic errors. The best example of this is shown in Fig. 3. Here we demonstrate that experimental asymmetries exhibit the modulation expected for the g-2 precession of the electron spin in the beam transport system. Owing to the anomolous magnetic moment of the electron, and to the 24½ degree bend in the transport system, the electron spin will precess ahead of the electron direction by an amount

$$\begin{aligned} \theta_{prec} &= \gamma \frac{g-2}{2} \theta_{bend} \\ &= \frac{E_o \pi}{3.237 \text{ (GeV)}} \text{ radians} \end{aligned} \tag{7}$$

The majority of our data were taken at 19.4 GeV, ($\theta_{prec} = 6\pi$), where positive electron helicity at the source gave positive helicity at the target. But at 16.2 GeV and 22.2 GeV, this was not so. Experimental asymmetries are measured relative to the <u>source</u> polarization, and should be modulated by the additional g-2 precession according to

$$\frac{A_{exp}}{Q^2} = P_e \frac{A}{Q^2} \cos\left(\frac{E_o \pi}{3.237}\right) \quad . \tag{8}$$

Figure 3 shows the asymmetries that were measured separately in the two counters at four energies, and a fit of the form given by Eq. (8). The point at 17.8 GeV corresponds to the spin transverse to the scattering plane, where physics asymmetries are expected to vanish. This is one of our null points, and it limits the contribution we may get from unexpected systematic effects. No systematic effects we know of can mimic the g-2

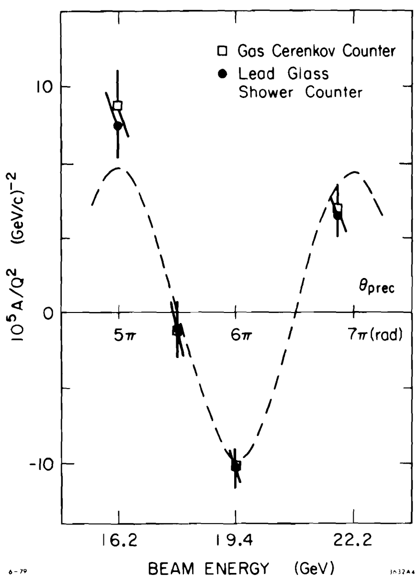

Fig. 3. Experimental asymmetries, divided by P_eQ^2 are compared for two counters (Cerenkov counter and lead glass shower counter) at four beam energies and to a fit representing the expected modulation due to g-2 precession of the electron spin in the beam transport system. The data points at 17.8 GeV constitute one of several null measurements satisfied by our data, and limit the sizes of systematic errors that may be in the data.

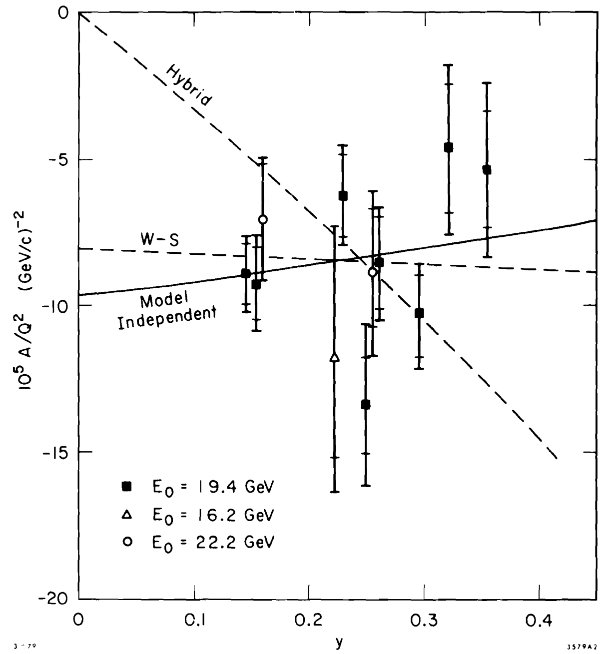

Fig. 4. Asymmetries measured at these incident energies are plotted against $y = (E_0 - E')/E_0$. The total error bar gives the combined statistical and systematic error. The inner error shows the statistical part only. The data are compared to two SU(2) × U(1) models, the minimal Weinberg-Salam model and the hybrid model. The W-S model is a satisfactory fit, but the hybrid model fails. A two-parameter model-independent fit (see Eq. (4)), based only on simple quark-parton model assumptions, is also shown. The Weinberg-Salam fit falls within the 1-σ errors for the model-independent fit.

modulation of our asymmetries, and we take the results of Fig. 3 to be clear evidence of parity violation in electron scattering.

The results of Fig. 3 were obtained in the Spring of 1978, and further data were obtained in November and December. Only minor changes were introduced for the latter data. The most significant change was to the optics configuration in the spectrometer. The quadrupole strength was increased to provide a momentum focus at the location of the lead glass shower counter. This resulted in a somewhat reduced momentum acceptance, but provided a sharp separation in momentum acceptances for the two halves of the lead glass counter. These two halves were always analyzed in separate electronic channels (along with the sum signal in a third channel). For what follows we have taken only the lead-glass counter data, resulting in better definition of the y value. The earlier data from the Spring 1978 runs has also been re-analyzed in the separate halves of the shower counter, and we include the older data for our final analysis. Although the older data have the y-acceptances less sharply defined, we observe no significant differences where they overlap with the recent fall results, and treat them on an equal footing with the more recent data.

Figure 4 and Table I show the combined results from all our runs taken mostly at 19.4 GeV for secondary energies E' = 11 to 14.5 GeV. The earlier data taken at 16.2, 19.4 and 22.2 GeV are also included. We plot asymmetries divided by Q^2 at the mean y values obtained for each setting. Each point is shown with double error bars. The inner errors are statistical errors only. The outer error bars have systematic and statistical errors combined. An additional ±5% overall uncertainty in scale, due to the error on P_e, is not shown.

Figure 4 also shows 3 fits to the data. The first is the Weinberg-Salam model, taken with the simple quark-parton model of the nucleon, and has the form shown in Eq. (5). It depends on a single parameter $\sin^2\theta_W$, which has a fit value

$$\sin^2\theta_W = 0.224 \pm 0.020 \quad . \qquad (9)$$

The chi-squared value for the fit is 1.04 per degree of freedom (10 d. of f.), assuming the combined errors correspond to gaussian standard deviations. A second SU(2) × U(1) model, which assumes the right-handed electron has a heavy neutral partner, $\begin{pmatrix} E^0 \\ e^- \end{pmatrix}_R$ is also shown. In the "hybrid" model the asymmetry must go to 0 at y = 0 due to the vanishing of the electron axial-vector part of the neutral current coupling. The data rule this model out. A third fit to the data is shown for the "Model Independent" form defined by Eq. (4). "Model Independent" refers to the absence of gauge theory assumptions, although quark-parton model ideas are still required. This fit yields the two parameters

$$a_1 = (-9.7 \pm 2.6) \times 10^{-5} \ (\mathrm{GeV/c})^{-2}$$

and (10)

$$a_2 = (4.9 \pm 8.1) \times 10^{-5} \ (\mathrm{GeV/c})^{-2} \quad .$$

Table I

Asymmetries and kinematic parameters. This table includes earlier data presented in Ref. 1. An additional ±5% error in scale, due to uncertainty in P_e, is not included. $x \equiv Q^2/2M(E_o - E')$ and $y \equiv (E_o - E')/E_o$.

E_o (GeV)	Q^2 $(\mathrm{GeV/c})^2$	x	y	$10^5\ A/Q^2$ Asymmetry $(\mathrm{GeV/c})^{-2}$		Total Error $(\mathrm{GeV/c})^{-2}$	Statistical Error Only $(\mathrm{GeV/c})^{-2}$
16.2	0.92	0.14	0.22	-11.8	±	4.5	± 3.4
19.4	1.53	0.28	0.15	- 8.9	±	1.3	± 1.1
19.4	1.52	0.26	0.16	- 9.2	±	1.7	± 1.2
19.4	1.33	0.16	0.23	- 6.3	±	1.7	± 1.4
19.4	1.28	0.14	0.25	-13.4	±	2.8	± 1.6
19.4	1.25	0.13	0.26	- 8.6	±	2.0	± 1.6
19.4	1.16	0.11	0.29	-10.4	±	1.8	± 1.4
19.4	1.07	0.09	0.32	- 4.6	±	2.9	± 2.2
19.4	0.93	0.07	0.36	- 5.3	±	3.0	± 2.0
22.2	1.96	0.28	0.17	- 7.0	±	2.1	± 1.9
22.2	1.66	0.15	0.26	- 8.9	±	2.8	± 2.2

I will return to discuss the significance of these parameters in a moment, but first let me say a few words about errors.

We determine the best value for $\sin^2\theta_W$ by fitting the data to the form of Eq. (5). The error on $\sin^2\theta_W$ consists of the statistical part (0.012) and a systematic part (0.008). The systematic error comes from several sources; beam monitoring and background subtractions contribute point-to-point systematic errors, and uncertainty in P_e contributes an overall scale uncertainty in A. Beyond these experimental errors, there may be uncertainties in the "theory" as represented in Eq. (5). The simple quark-parton model assumes scattering from valence quarks only. If we add a 10% $q\bar{q}$ sea contribution, the coefficients in Eq. (5) are modified slightly, and the best value for $\sin^2\theta_W$ is nearly identical 0.226. The effects of $q\bar{q}$ sea terms are negligible. However effects outside the framework of the simple quark-parton model can be larger. This question has been studied by several authors.[2,9,10] The y-dependence is modified by finite non-zero $R = \sigma_L/\sigma_T$ values, the a_2 term of Eq. (5) is modified by non-scaling effects at low Q^2 (as observed in neutrino data), and the a_1 part of Eq. (5) can be modified by coherent scattering effects. Based on the modification to Eq. (5) suggested by these authors, we obtain best values of $\sin^2\theta_W$ from 0.210 to 0.230 for our data. From these numbers we estimate that the error due to parton model uncertainties is ±0.010. We have not included this term in our experimental error, but conclude that the error on the "theory" may be as large as our experimental error.

I would now like to make a few brief remarks about progress in the model independent analysis of neutral current reactions and the connections our work has to parity violation in bismuth and thallium atoms. We have taken note of the remarkable success of the Weinberg-Salam model of weak and electromagnetic interactions, but in the spirit of objective experimental investigation one can ignore all gauge theory ideas and look at the model independent approach. This approach has been emphasized by a number of authors[2-4,9-16] particularly with regard to neutrino neutral current interactions, but has now been extended to include the parity violation results in electron-hadron interactions.

The neutral current interaction has both a vector part and an axial-vector part. Where ordinary hadronic matter is involved (as is the case in e D or e-nuclei interactions) each of these parts can be decomposed into isovector and isoscalar pieces. That is, there are four phenomenological couplings, the vector-isovector term, the vector-isoscalar term, the axial-vector-isovector term, and the axial-vector-isoscalar term. In the notation of Hung and Sakurai,[12,14,15] these terms are denoted $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$, and $\tilde{\delta}$ respectively. In the simple quark parton model the heavier quarks (s,c,b,...) are neglected. In terms of these phenomenological couplings, the asymmetry, Eq. (2), becomes

$$\frac{A}{Q^2} = \frac{G_F}{2\sqrt{2}\pi\alpha} \cdot \frac{9}{10}\left[(\tilde{\alpha} + \tilde{\gamma}/3) + (\tilde{\beta} + \tilde{\delta}/3)\ \frac{1-(1-y)^2}{1+(1-y)^2}\right]. \quad (11)$$

The results of the model-independent fit, Eq. (10), then determine the linear combinations

$$\tilde{\alpha} + \tilde{\gamma}/3 = -0.60 \pm 0.16$$

$$\tilde{\beta} + \tilde{\delta}/3 = 0.31 \pm 0.51 \quad ,$$

but this is insufficient information to complete the determination of the four fundamental parameters. To make the separations we must turn to other processes which can measure different combinations of these four parameters. Comparison between ep and eD asymmetries in principle could provide new information, but differences are expected to be so small that the measurements in practice would be extremely difficult to make meaningfully. Elastic scattering off protons, deuterons and higher Z nuclei at medium energies looks more promising, and experiments now being planned may ultimately provide us new information. At present we are limited to atomic physics parity non-conservation in bismuth and thallium,[17-20] where the weak charge can be expressed in the nearly orthogonal combinations

$$Q_W \text{ (bismuth)} = 43\tilde{\alpha} - 627\tilde{\gamma}$$

$$Q_W \text{ (thallium)} = 42\tilde{\alpha} - 612\tilde{\gamma}$$

and the parity violation results in atoms, plus our latest results, can determine the parameters $\tilde{\alpha}$, $\tilde{\gamma}$. However, two other terms, $\tilde{\beta}$ and $\tilde{\delta}$, are not present for atomic physics parity violation, and these remain unseparated.

The recent work of Hung and Sakurai[14] make an important step in the determination of these parameters. They point out that the world's data on neutral currents show consistency with factorization of these phenomenological couplings into a product of leptonic and hadronic (i.e., quark) parts. The experimental evidence is not conclusive, but just suggestive. Assuming factorization to be valid, Hung and Sakurai proceed to complete the separation of all the phenomenological neutral current coupling parameters. Although not completely free of assumptions, their analysis provides for the first time a complete separation of the parity violating neutral current parameters, a result that is new since the Tokyo conference. I believe the real message from their analysis is the need to improve all neutral current data, and the importance of testing the factorization relations.

Why should we care about factorization and the experimental determination of these parameters? These parameters can be indirectly related to the questions of the Higgs structure of gauge theories and to the question of how many Z^o's exist. The single Z^o hypothesis of the minimal SU(2) × U(1) model implies factorization of the neutral current couplings (but the converse is not necessarily true). Careful measurements, and much improved experimental errors will permit more precise testing of these gauge theory predictions. In particular we will be looking for deviations from the Weinberg-Salam model as an indication of more complicated Higgs structure or a larger vector boson complement than the present theory contains. Until the day comes when we directly produce the Z^o in the laboratory, low energy experiments are the only tools we have, and it is important to pursue these difficult measurements if we are to further our understanding of the fundamental questions.

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Q. (Cald, University of Guelph, Canada) Would you like to comment on the connection to atomic physics?

A. Yes, I will say a few words about that. In the context of the Weinberg-Salam model, there is one free parameter, $\sin^2\theta_W$, which relates experiments. The optical rotation in bismuth reported by Novosibirsk and the circular dichroism measurements in thallium reported by Berkeley are in agreement with $\sin^2\theta_W = .25$, within their errors. One must relax the assumptions of the Weinberg-Salam model to study the experimental determination of the neutral current couplings. I think the spirit of the model independent analysis of neutral currents in best for that, and I refer you to the work of Hung and Sakurai for more precise definition of terms. Parity violation in e-hadron interactions can be described in terms of four free coupling parameters $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$, and $\tilde{\delta}$ in their terminology. The SLAC eD data can be broken into two parts, a_1 and a_2 corresponding to hadronic vector and hadronic axial-vector parts, respectively. The a_1 term consists of a sum of the fundamental couplings $\tilde{\alpha}$ and $\tilde{\gamma}$, while the a_2 term gets contributions from $\tilde{\beta}$ and $\tilde{\delta}$ couplings. Atomic bismuth parity violation, and similarly for thallium, are sensitive only to the $\tilde{\gamma}$ coupling. SLAC eD data alone cannot be used to extract these fundamental couplings, but taken with atomic physics parity violation results, could permit separation of the parameters. Unfortunately, the experimental situation in atomic physics remains somewhat clouded. At Berkeley they are presently taking data on thallium and in the near future you should hear more results. I think they are doing a very careful job. In Seattle and Oxford, they have continued to study bismuth but I think their results are still low compared to Weinberg-Salam predictions. They are now studying possible sources of systematic errors. Novosibirsk recently reported new results, still consistent with Weinberg-Salam predictions, but with refined errors. The SLAC eD data, in the context of the model independent analysis, can be made compatible with any of these experiments simply by adjusting the values of these coupling parameters. It is only the gauge theory that may be giving us some kind of indication as to who among these is going to be correct or not. The experimental discrepancies in atomic physics parity violation need to be resolved.