Symmetries and Symmetry Breaking

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Measurements of parity-violating longitudinal analyzing powers (normalized asymmetries) in polarized proton-proton scattering and asymmetries in polarized neutron capture on the proton provide a unique window on the interplay between the weak and strong interactions of hadrons. Several new proton-proton parity violation experiments are presently either being performed or are being prepared for execution in the near future. A new measurement of the parity-violating gamma-ray asymmetry with a ten-fold improvement over previous measurements is being developed. These experiments are intended to provide stringent constraints on the set of seven effective weak meson-nucleon coupling constants, which characterize the weak interaction between hadrons in the energy domain where meson exchange models provide a proven description of the nucleon-nucleon interaction. Time-reversal-invariance non-conservation has for the first time been unequivocally demonstrated in a direct measurement at CPLEAR. What then about tests of time-reversal-invariance non-conservation in systems other than the kaon system? There exist two classes of time-reversal-invariance breaking interactions: P-odd/T-odd and P-even/T-odd interactions. Constraints on the first ones stem from measurements of the electric dipole moment of the neutron, while constraints on the second ones stem from the same and measurements of charge symmetry breaking in neutron-proton elastic scattering and from $K$ semi-leptonic decays. The electromagnetic and neutral weak interactions probe the pointlike structure of the nucleon. In particular, a direct comparison can be made between the electromagnetic and neutral weak ground state currents of the nucleon. This allows a delineation of the contributions to these currents of the various quark flavours, e.g., strange-antistrange quark pairs, which belong exclusively to the nucleon sea. A series of precision experiments, either ongoing or being prepared, will determine the neutral weak current of the proton by measuring the parity-violating normalized asymmetry in electron-proton elastic scattering. An extension of these precision experiments to very low momentum transfer would permit stringent limits to be placed on physics beyond the standard model.

*Work supported in part by the Natural Sciences and Engineering Council of Canada.
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1. NUCLEON-NUCLEON PARITY VIOLATION

At low- and intermediate-energies, the parity violating weak $N-N$ interaction can be described in terms of a meson exchange model involving a strong interaction vertex and a weak interaction vertex (assuming one boson exchanges). The strong interaction vertex is well understood; it is represented by the conventional meson-exchange parameterization of the $N-N$ interaction. The weak interaction vertex is calculated from the Weinberg-Salam model assuming that the $W$- and $Z$-bosons are exchanged between the intermediate mesons ($\pi, \rho$, and $\omega$) and constituent quarks of the nucleon. The parity violating interaction can then be described in terms of seven weak meson-nucleon coupling constants. The six weak meson-nucleon coupling constants ($f^1_\pi$, $h^0_\rho$, $h^1_\rho$, $h^2_\rho$, $h^0_\omega$, $h^1_\omega$, with the superscripts indicating isospin changes and the subscripts the exchanged meson) have been calculated by Desplanques, Donoghue, and Holstein (DDH) [1], synthesizing the quark model and SU(6) and treating strong interaction effects in renormalization group theory. The seventh weak meson-nucleon coupling constant $h^3_\pi$ is estimated to be smaller and is usually deleted from further consideration. DDH tabulated ‘best guess values’ and ‘reasonable ranges’ for the six weak meson-nucleon coupling constants. Following the seminal paper by DDH, various other groups have calculated the weak meson-nucleon coupling constants, but the considerable ranges of uncertainty attached to these remain (see Ref. 2). The parity violating $\pi\Delta N$ vertex plays an increasingly important role in elastic and inelastic proton-proton scattering above the pion-production threshold. It is also apparent that the theoretical situation regarding $f^1_\pi$ is not settled by any means. For a recent review see also Haeberli and Holstein [3].

A complete determination of the six weak meson-nucleon coupling constants demands a minimum of six experimental, linearly independent combinations of the weak meson-nucleon coupling constants. Of to date there do not exist enough experimental constraints of the required precision. This situation can only be remedied by performing a set of judiciously chosen, precise parity violation experiments.

Precise measurements of the $p-p$ parity violating longitudinal analyzing power have been made at 13.6 MeV [$A_z = (-0.93 \pm 0.20 \pm 0.05) \times 10^{-7}$] at the University of Bonn [4] and at 45 MeV [$A_z = (-1.53 \pm 0.23) \times 10^{-7}$] at SIN (now PSI) [5]. Here $A_z$ is defined as $A_z = (\sigma^+ - \sigma^-) / (\sigma^+ + \sigma^-)$, with $\sigma^+$ and $\sigma^-$ representing the scattering cross sections for polarized incident protons of positive and negative helicity, respectively, integrated over the range of angles determined by the acceptance of the experimental apparatus in question. From the SIN measurement at 45 MeV and the $\sqrt{E}$ dependence of $A_z$ at lower energies, one can extrapolate that at 13.6 MeV $A_z = (-0.86 \pm 0.13) \times 10^{-7}$. Consequently, the two precise, low energy measurements are in excellent agreement. Both results allow determining a combination of effective $\rho$ and $\omega$ weak meson-nucleon coupling constants: $A_z = 0.153 h^0_\rho + 0.113 h^1_\rho$, with $h^1_\rho = h^0_\rho + h^1_\rho + h^2_\rho / \sqrt{6}$ and $h^0_\omega = h^0_\omega + h^1_\omega$. One should note that a measurement of $A_z$ in $p-p$ scattering is sensitive only to the short range part of the parity violating interaction (parity violating $\pi^0$ exchange would be also CP violating and is therefore suppressed by a factor of about $2 \times 10^{-3}$).

A partial wave decomposition allows $A_z$ to be written as a sum of the various transition amplitudes ($^{1}S_0 - ^3P_0$, $^{3}P_2 - ^1D_2$, $^{1}D_2 - ^3F_2$), $^{3}F_1 - ^1G_4$), etc. For incident energies below 100 MeV essentially only the first transition amplitude ($^{1}S_0 - ^3P_0$) is contributing,
but for higher energies the second parity violating transition amplitude \((^3P_2 - ^1D_2)\) is of increasing importance. The contribution of the next higher order (third) transition amplitude \((^1D_2 - ^3F_2)\) is negligibly small. The TRIUMF 221.3 MeV \(p-p\) parity violation experiment is unique in that it selected an energy where the \((^1S_0 - ^3P_0)\) transition amplitude contribution integrates to zero, taking into account the angular acceptance of the apparatus. This is a reflection of the fact that the \(^1S_0\) and \(^3P_0\) phase shifts change sign near 230 MeV. Simonius has shown that the \((^3P_2 - ^1D_2)\) transition amplitude depends only weakly on \(\omega\) exchange (to an extent depending on the strong vector meson-nucleon coupling constants). Consequently, the TRIUMF 221.3 MeV experiment presents a determination of \(h_{pp}^\rho\). In the TRIUMF experiment a 200 nA proton beam with a polarization of 0.80 is incident on a 0.40 m long LH\(_2\) target, after extraction from the optically pumped polarized ion source (OPPIS), passing a Wien filter in the injection beam line, acceleration through the cyclotron to an energy of 221.3 MeV, and multiturn extraction by a stripping foil. A combination of solenoid-dipole-solenoid-dipole magnets on the external beam line provides a longitudinally polarized beam with either positive or negative helicity or vice versa. \(A_z\) follows from the helicity dependence of the p-p total cross section as determined in precise measurements of the normalized transmission asymmetry through the 0.40 long LH\(_2\) target: 

\[
A_z = -(1/P)(T/S)(T^+ - T^-)/(T^+ + T^-),
\]

where \(P\) is the incident beam longitudinal polarization, \(T = 1 - S\) is the average transmission through the target, and the + and - signs indicate the helicity. Very strict constraints are imposed on the incident longitudinally polarized beam in terms of intensity, transverse horizontal (x) and vertical (y) beam position and direction, beam width (\(\sigma_x\) and \(\sigma_y\)), longitudinal polarization (\(P_z\)), transverse polarization (\(P_x\) and \(P_y\)), first moments of the transverse polarization (\(<xP_y>\) and \(<yP_x>\)), and energy, together with deviations of the transmission measuring apparatus from cylindrical symmetry. Helicity correlated modulations in the beam parameters originate at OPPIS, but can be amplified by the beam transport through the injection beam line, the cyclotron accelerator, and the extraction beam line. Residual systematic errors arising from the imperfections of the incident beam and of the response of the transmission measuring apparatus, are individually not to exceed one-tenth of the expected value of \(A_z\) (or \(6 \times 10^{-9}\)). Particular troublesome are the first moments of residual transverse polarization, as well as helicity correlated changes in energy. The approach which has been followed is to further measure the sensitivity or response to residual imperfections, to monitor these imperfections during data taking, and to make corrections where necessary. Random changes in the incident beam parameters cause a dilution of the effect to be measured and therefore necessitate longer data taking times. Details about the experimental arrangements and procedures can be found in Ref. 2, while an account of the data analysis will be reported elsewhere. Fig. 1 presents the three lower energy results in a comparison with the meson exchange model theoretical predictions of Driscoll and Miller and Iqbal and Niskanen, the chiral soliton model prediction of Driscoll and Meissner, and the quark model prediction of Grach and Shmatikov. Note that the first two predictions have used the DDH weak meson-nucleon coupling constants. For the TRIUMF 221.3 MeV experiment one can derive that \(A_z = -0.0296\) \(h_{pp}^\rho\). The three lower energy measurements establish the (expected) energy behaviour and allow a delineation of \(h_{pp}^\rho\) and \(h_{\omega}^{pp}\).
Fig. 1 Theoretical predictions of Driscoll and Miller, Iqbal and Niskanen, Driscoll and Meissner, and Grach and Shmatikov compared to the low-energy $p$-$p$ parity violating longitudinal analyzing powers $A_z$.

There exist two further higher energy parity violation experiments. The first one is a $p$-$p$ parity violation measurement at 800 MeV with $A_z = (2.4 \pm 1.1) \times 10^{-7}$ at LANL. Its interpretation in terms of the effective $\rho$ and $\omega$ weak meson-nucleon coupling constants is more difficult due to the presence of a large inelasticity (pion production). The second one is a $p$-$N$ parity violation measurement at 5.13 GeV on a water target with $A_z = (26.4 \pm 6.0 \pm 3.6) \times 10^{-7}$ at ANL with the ZGS. This result is an order of magnitude larger than what is expected based upon using simple scaling arguments. New $p$-$p$ parity violation experiments are being planned at TRIUMF possibly at 450 MeV and with COSY at the Forschungszentrum Jülich near 2 GeV as a storage ring experiment.

Other $N$-$N$ parity violation measurements have dealt with the circular polarization $P_\gamma$ of the $\gamma$-rays in $n$-$p$ capture and with the asymmetry $A_\gamma$ in $n$-$p$ capture with polarized cold neutrons, as well as the inverse reaction, deuteron photodisintegration with circularly polarized $\gamma$-rays. However, these experiments were not of enough statistical precision to have an impact on the determination of $f_{1\pi}$. A new measurement of $A_\gamma$ is being prepared at LANSCE, aiming at a ten-fold improvement in accuracy (to a precision of $\pm 0.5 \times 10^{-8}$, which will determine $f_{1\pi}$ to $\pm 0.4 \times 10^{-7}$). In the experiment, neutrons from the pulsed spallation source are moderated by a LH$_2$ moderator, and their energy determined by time-of-flight. The cold neutrons are polarized by transmission through polarized $^3$He gas; the neutron spin direction can be subsequently reversed by a rf resonance flipper. The neutrons are then guided to a liquid para-hydrogen target which is surrounded by an array of $\gamma$-ray detectors. Similarly, a new measurement of the asymmetry in photodisintegration of the deuteron with circularly polarized photons, obtained when a 8 MeV polarized electron beam from the CEBAF injector is incident on a gold Bremsstrahlung target, is being developed at Jefferson Laboratory. It is planned to measure $f_{1\pi}$ to an accuracy better than 30% of the current theoretical 'best value' of $f_{1\pi}$. The latter two experiments are designed to resolve the experimental discrepancy between the value of $f_{1\pi}$ as deduced from measurements of the circularly polarized 1.081 MeV $\gamma$-rays from the well known parity-mixed doublet in $^{18}$F and as deduced from the measurements of the anapole moment...
of $^{133}$Cs. A plot of the constraints on the isoscalar and isovector weak meson-nucleon coupling constants, obtained from the more precise low-energy parity violation data, is shown in Fig. 2.

2. PARITY-EVEN/TIME-REVERSAL-ODD INTERACTION

Time-reversal-invariance non-conservation has for the first time been unequivocally demonstrated in a direct measurement in the CPLEAR experiment. The experiment measured the difference in the transition probabilities $P(K^0 \to K^0)$ and $P(K^0 \to \bar{K}^0)$. Assuming CPT conservation but allowing for a possible breaking of the $\Delta S = \Delta Q$ rule, the result obtained for $A_T = [(R(K^0 \to K^0) - R(K^0 \to \bar{K}^0))/[R(K^0 \to K^0) + R(K^0 \to \bar{K}^0)] = [6.6 \pm 1.3(\text{stat.}) \pm 1.0(\text{syst.})] \times 10^{-3}$ is in good agreement with the measure of CP violation in neutral kaon decay. A more recently reported result is a large asymmetry in the distribution of $K_L \to \pi^+\pi^-e^+e^-$ events in the CP-odd/T-odd angle $\phi$ between the decay planes of the $\pi^+\pi^-$ and $e^+e^-$ pairs in the $K_L$ center of mass system. The overall asymmetry found was $[13.6 \pm 2.5(\text{stat.}) \pm 1.2(\text{syst.})]\%$. This raises the question about time-reversal-invariance non-conservation in systems other than the kaon system.

Tests of time-reversal-invariance can be distinguished as belonging to two classes: the first one deals with P-odd/T-odd interactions, while the second one deals with P-even/T-odd interactions (assuming CPT conservation this implies C-conjugation non-conservation). But it is to be noted that constraints on these two classes of interactions are not independent since the effects due to P-odd/T-odd interactions may also be produced by P-even/T-odd interactions in conjunction with Standard Model parity violating radiative corrections. The latter can occur at the $10^{-7}$ level and may present a limit on the constraint of a P-even/T-odd interaction derived from experiment. Limits on a P-odd/T-odd interaction follow from measurements of the electric dipole moment (edm)
of the neutron (which currently stands at $< 6 \times 10^{-26}$ e.cm [95% C.L.]). This provides a limit on a P-odd/T-odd pion-nucleon coupling constant which is less than $10^{-4}$ times the weak interaction strength. Measurements of $^{129}$Xe and $^{199}$Hg edm’s ($< 8 \times 10^{-28}$ e.cm [95% C.L.]) give similar constraints. [see Ref. 20]

Experimental limits on a P-even/T-odd interaction are much less stringent. Following the conventional approach of describing the $N-N$ interaction in terms of meson exchanges, it can be shown that only charged rho-meson exchange and $a_1$-meson exchange can lead to a P-even/T-odd interaction. [21] The better constraints stem first from measurements of the edm of the neutron and second from measurements of charge symmetry breaking (CSB) in $n-p$ elastic scattering. Haxton, Hoering, and Ramsay-Musolf [20] have deduced constraints on a P-even/T-odd interaction from nucleon, nuclear, and atomic edm’s with the better constraint coming from the measurement of the edm of the neutron. In terms of a ratio to the strong rho-meson nucleon coupling constant, they deduced for the P-even/T-odd rho-meson nucleon coupling: $|\frac{\rho}{f_{DDH}}| < 0.53 \times 10^{-3} \times \frac{|f_{\pi}^{\text{meas.}}|}{|f_{\pi}^{\text{theo.}}|}$. But as indicated above there exists great uncertainty about the value of $f_{\pi}^{\text{theo.}}$; the ratio of the theoretical to experimental value of $f_{\pi}^{\text{theo.}}$ may be as large as 15! [10] However, constraints derived from one-loop contributions to the edm of the neutron exceed the two-loop limits by more than an order of magnitude and are much more stringent. [22] It is to be noted that a translation in terms of coupling strengths in the hadronic sector still needs to be made.

It is very difficult to accommodate a P-even/T-odd interaction in the Standard Model. It requires C-conjugation non-conservation, which cannot be introduced at the first generation quark level. It can neither be introduced into the gluon self-interaction. Consequently, one needs to consider C-conjugation non-conservation between quarks of different generations and/or between interacting fields. [23]

Charge symmetry breaking in $n-p$ elastic scattering manifests itself as a non-zero difference of the neutron ($A_n$) and proton ($A_p$) analyzing powers, $\Delta A = A_n - A_p = 2 \times [\text{Re}(b f) + \text{Im}(c h)]/\sigma_0$. Here the complex amplitude $f$ is charge symmetry breaking, while the complex amplitude $h$ is both charge symmetry breaking and time-reversal-invariance non-conserving. The complex amplitudes $b$ and $c$ belong to the usual five $n-p$ scattering amplitudes and $\sigma_0$ is the unpolarized differential cross section. The three precision experiments performed (at TRIUMF at 477 MeV [24] and at 347 MeV [25], and at IUCF at 183 MeV [26]) have unambiguously shown that charge symmetry is broken and that the results for $\Delta A$ at the zero-crossing of the average analyzing are very well reproduced by meson exchange model calculations. (see Fig. 3) A P-even/T-odd interaction introduces a term in the scattering amplitude which is simultaneously charge symmetry breaking (the complex amplitude $h$ in the above expression). Thus, Simonius [27] deduced an upper limit on a P-even/T-odd interaction from a comparison of the three experimental results with the theoretical predictions. The upper limit so derived is $|\frac{\rho}{f_{DDH}}| < 6.6 \times 10^{-3}$ [95% C.L.]. This result is therefore comparable to the upper limit deduced from the edm of the neutron, taking the current experimental value of $f_{\pi}^{\text{theo.}}$ extracted from $^{18}$F, and is considerably lower than the limits inferred from direct tests of a P-even/T-odd interaction. Even though it is inconceivable in the Standard Model to account for a P-even/T-odd interaction, there is a need to clarify the experimental situation by providing a better experimental result.
Fig. 3 Experimental results of $\Delta A$ at the zero-crossing at incident neutron energies of 183, 347, 477 MeV compared with theoretical predictions of Iqbal and Niskanen, and Holzenkamp, Holinde, and Thomas. The inner error bars present the statistical uncertainties; the outer error bars have the systematic uncertainties included (added in quadrature). For details see Ref. 25.

A better experimental constraint may be provided by an improved upper limit on the electric dipole moment of the neutron. Indeed a new measurement with a sensitivity of $4 \times 10^{-28}$ e.cm has been proposed at LANSCE. This would constitute a more than two orders of magnitude improvement over the present upper limit. Performing an improved $n$-$p$ elastic scattering CSB experiment also appears to be an attractive possibility. One can calculate with a great deal of accuracy the contributions to CSB due to one-photon exchange and due to the $n$-$p$ mass difference affecting one-pion and rho-meson exchange. Furthermore, one can select an energy where the $\rho^0 - \omega$ meson mixing contribution changes sign at the same angle where the average analyzing power changes sign and therefore does not contribute to $\Delta A$. This occurs at an incident neutron energy of 320 MeV and is caused by the particular interplay of the $n$-$p$ phase shifts and the form of the spin/isospin operator connected with the $\rho^0 - \omega$ mixing term. Also the one-photon exchange term at 320 MeV changes sign at about the same angle as the average of the analyzing powers. The contribution due to two-pion exchange with an intermediate $\Delta$ is expected to be less than one tenth of the overall $\Delta A$, essentially determining an upper limit on the theoretical uncertainty. (see Fig. 4) It has been shown that simultaneous $\gamma - \pi$ exchanges can only contribute to $\Delta A$ through second order processes and can therefore be neglected. At 320 MeV the effects of inelasticity (pion production) are negligibly small. It appears therefore well within reach to reduce the theoretical uncertainty in the comparison of theory with experiment. Both the statistical and systematic errors, obtained in the 347 MeV TRIUMF experiment, can be considerably improved upon (by a factor three to four). With the developments of optically pumped polarized ion sources which have taken place in the intervening years it will be possible to obtain up to 50 $\mu A$ of 342 MeV 80% polarized proton beam on the neutron production target (a factor of 50 increase in neutron beam
Fig. 4 Angular distributions of the different contributions to $\Delta A$ at an incident neutron energy of 320 MeV. (Ref. 29) Note that the $\rho^0 - \omega$ mixing contribution passes through zero at the same angle as the average of $A_n$ and $A_p$ (vertical bars). The figure on the right gives the total $\Delta A$ angular distribution.

3. ELECTRON-PROTON PARITY VIOLATION

The structure of the nucleon at low energies in terms of the quark and gluon degrees of freedom is not well understood. Of particular interest are the two proton ground state matrix elements which are sensitive to point-like “strange” quarks and hence to the quark-antiquark sea in the proton. The two matrix elements of interest are the elastic scattering vector weak neutral current ‘charge’ and ‘magnetic’ form factors, $G^Z_E$ and $G^Z_M$, respectively. These form factors can be deduced from parity violating electron-proton elastic scattering measurements. Assuming charge symmetry, i.e., the proton and neutron differ only by the interchange of the “up” and “down” quarks, one can determine the “up”, “down”, and ”strange” quark contributions to the ‘charge’ and ‘magnetic’ form factors of the nucleon. These contributions would result from taking the appropriate linear combinations of the weak neutral form factors and their electromagnetic counterparts.

Determinations of both the ‘charge’ and ‘magnetic’ “strange” quark form factors, $G^Z_E$ and $G^Z_M$, would constitute the first direct information on the quark sea in low energy observables. Electron-proton parity violation experiments are to determine these contributions to the proton form factors at the few percent level. High energy experiments suggest that the “strange” quarks carry about half as much momentum as the “up” and “down” quarks in the sea. The matrix elements, $G^Z_E$ and $G^Z_M$, are also of relevance to discussions of the Ellis-Jaffe sum rule and the $\pi - N$ sigma term; there is uncertainty in both of these about the “strange” quark contributions. The quantity to be measured is...
the longitudinal analyzing power $A_z$, which is defined completely analogous to the $p-p$ one. Making pairs of measurements at forward and backward angles will allow the separation of $G_E^z$ and $G_M^z$. Predicted analyzing powers are in the $10^{-6}$ to $10^{-5}$ range.

Various electron-proton parity violation experiments have been performed or are being prepared for the near future. The SAMPLE experiment at the MIT-Bates Linear Accelerator detected backward scattered electrons in large air Čerenkov detectors in 200 MeV elastic e-p and quasielastic e-d scattering. The Čerenkov detectors subtended the laboratory angular range from $130^\circ$ to $170^\circ$, corresponding to a four momentum transfer $Q^2$ of about 0.1 (GeV/c)$^2$. The value obtained in e-p scattering of $A_z = (-4.92 \pm 0.61 \pm 0.73) \times 10^{-6}$ results in $G_M^z = -0.45G_A^Z + 0.20 \pm 0.17$(stat.) $\pm 0.21$(syst.). [31]

Taking theoretical estimates for the axial form factor $G_A^Z$ leads to a substantially positive $G_M^z$, however the preliminary value obtained in e-d scattering does not corroborate the estimated value for $G_M^Z$ and consequently the isoscalar and isovector axial radiative corrections, $R_A^0$ and $R_A^1$, used in obtaining the estimate for $G_A^Z$ may be in error. Note that the isovector radiative correction has a connection to hadronic parity violation. The HAPPEX experiment at Jefferson Laboratory detected forward scattered electrons in the two Hall-A HRS spectrometers placed left and right of the incident beam at $12.5^\circ$, corresponding to a $Q^2$ of 0.47 (GeV/c)$^2$ in 3.335 GeV elastic e-p scattering. The latter of the two data taking runs used strained GaAs crystals to give an electron beam with about 70% polarization. The experiment measured the combination $G_E^z + 0.39G_M^z$. The result from the first data taking run is $A_z = (-14.5 \pm 2.0 \pm 1.1) \times 10^{-6}$, which gives $G_E^z + 0.39G_M^z = 0.023 \pm 0.034$(stat.) $\pm 0.022$(syst.) $\pm 0.026G_E^z$. [32] Taking current information on $G_E^z$ this is essentially a null-result. A new round of experiments to measure $G_E^z$ at Jefferson Laboratory will remove the remaining uncertainty. The preliminary result of the second data taking run is $A_z = (-14.6 \pm 1.1 \pm 0.6) \times 10^{-6}$ in excellent agreement with the result of the first data taking run.

The A4 experiment at MAMI will detect forward scattered electrons in 855 MeV parity violating elastic e-p scattering at 35° in a cylindrical calorimeter made of 1022 PbF$_2$ crystals. The experiment will determine a linear combination of $G_E^s + 0.22G_M^s$ at a $Q^2$ value of 0.23 (GeV/c)$^2$. [33] The $G^0$ experiment at Jefferson Laboratory is the most comprehensive effort to date to measure both $G_E^s$ and $G_M^s$ over the range of $Q^2$ 0.1 – 1.0 (GeV/c)$^2$. [34] Forward and backward angle parity violating elastic e-p and quasielastic e-d will be measured. In the forward mode of operation, protons scattered in a polar angular range of $\pm 10^\circ$ around 70° will be detected in eightfold symmetry around the incident beam axis. In the backward mode of operation electrons scattered around 108° will be detected. Parity violating quasielastic e-d scattering is again required to determine the axial form factor $G_A^Z$ contribution. A custom designed superconducting toroidal spectrometer with eightfold symmetry is being constructed. The scattered particles are detected in segmented scintillator arrays in the focal plane of the spectrometer. Commissioning running is scheduled for late 2001. The errors anticipated to be obtained for $G_E^z$ and $G_M^z$ are shown in Fig. 5.
Fig. 5 Anticipated errors on $G_E^p$ and $G_M^s$ as function of $Q^2$ from the $G^0$ experiment. Note that the proton electric and magnetic form factors are divided by a factor 10. The SAMPLE experiment result $G_M^s = 0.61 \pm 0.17 \pm 0.21$ n.m. at $Q^2 = 0.1$ (GeV/c)$^2$ is also shown.

4. SUMMARY

Fundamental symmetries are tested with unheard precision leading to insight in the underlying structure and interactions. Subtle effects are observed in which the hadronic weak interaction plays a prominent role.

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