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PARITY VIOLATING ELECTRON SCATTERING AND THE STRANGENESS CONTENT OF THE NUCLEON

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A measurement of the weak form factors of the proton gives access to the contribution of the strange quarks to the vector form factors of the nucleon due to the electro-weak mixing. The parity violation of the weak interaction gives rise to a parity violating cross section asymmetry and is utilized to measure of the weak form factors of the nucleon. The different experimental approaches of the SAMPLE, HAPPEX, A4 and G0 experiments are discussed and the results summarized.

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1 Strangeness

The structure of the nucleon is often described in terms of three constituent quarks where these are understood as effective particles with a mass of several 100 MeV that arises dynamically from a sea of virtual gluons and virtual quark antiquark pairs. The contribution of the strange quarks to this sea is of special interest, since the any strangeness contribution in the nucleon can only be a pure sea quark effect, and since the mass value of the strange quarks is approximately equal to the scale of λ_{QCD} and lies between the masses of the very light u and d current quarks and the mass of the much heavier quarks like c,b and t which are neglected here. There is a detailed discussion of the present understanding of the role of strangeness within the nucleon in the literature [1,2]. One can maybe say that the strangeness contribution to the matrix elements of the nucleon is one of the best studied sea quark effects in literature.
Unfortunately, the scalar strangeness density $\bar{s}s$ does not couple directly to the electromagnetic probe, therefore the question of how much does strangeness contribute to the mass of the nucleon can not be directly answered. The analysis of the scattering amplitude in πN-scattering and the connection to the Σ_π term and the scalar density matrix element $< N|\bar{s}s|N >$ gives a contribution of the strange quark antiquark pairs to the mass of the nucleon on the order of 130 MeV [3]. New data from πN-scattering suggest even a larger value up to 50 % of the proton mass.
The observed charm production rate from deep-inelastic neutrino nucleon scattering can only be explained if there is a 2% contribution of the strange quarks to the momentum of the nucleon. In polarized deep inelastic muon and electron scattering the axial matrix

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element $< N|\bar{s}\gamma^\mu\gamma^5 s|N >$ is measured. It is equal to the contribution of the strange quarks to the spin of the Proton Σ_s. A value for Σ_s of 0.12 ± 0.1 has been extracted[4].
The dynamic response of the nucleon structure to electron scattering via the exchange of virtual photons is described in terms of the four elastic form factors: the Dirac form factor $F_1^{p,n}(Q^2)$ of proton and neutron and the Pauli form factor $F_2^{p,n}(Q^2)$ (another combination are the Sachs form factors, $G_E^{p,n} = F_1^{p,n} - \tau F_2^{p,n}$ and $G_M^{p,n} = F_1^{p,n} + F_2^{p,n}$). It has been first noted by Caplan and Manohar [5], that a flavor decomposition of the form factors into the three lightest quark flavors u,d and s can be obtained. This is obtained by combining the form factors of proton and neutron using isospin symmetry and electro-magnetic and weak neutral current form factors. If one writes the electro-magnetic ($F_{1,2}^{p,n}$) and the weak form factors ($\tilde{F}_{1,2}^{p,n}$) decomposed into the three lightest quark flavors:

$$F_{1,2}^{p,n} = Q_u\, {}^uF_{1,2}^{p,n} + Q_d\, {}^dF_{1,2}^{p,n} + Q_s\, {}^sF_{1,2}^{p,n} \tag{1}$$
$$\tilde{F}_{1,2}^{p,n} = \tilde{Q}_u\, {}^u\tilde{F}_{1,2}^{p,n} + \tilde{Q}_d\, {}^d\tilde{F}_{1,2}^{p,n} + \tilde{Q}_s\, {}^sF_{1,2}^{p,n} \tag{2}$$

The left side of Eq. (1) and Eq. (2) represents the eight experimentally accessible electro-magnetic and weak form factors of the nucleon and on the right side are the 12 unknown flavor contributions. The Q-factors are the electro-magnetic and weak charges of the appropriate quark flavor, i.e the electric and the weak charge of quark flavor u,d and s. Isospin symmetry allows to eliminate one half of the unknown quark flavor contributions by replacing the u-quark contributions in the proton by the d-quark contribution in the neutron (${}^uF_{1,2}^p = {}^d F_{1,2}^n \rightarrow {}^u F_{1,2}$, ${}^sF_{1,2}^p = {}^s F_{1,2}^n \rightarrow {}^s F_{1,2}$) and vice versa and to use one strangeness contribution for both proton and neutron. In addition the universality of the standard model requires, that the quark distributions are an intrinsic property of the nucleon and do not depend on the probe. This allows to use the same flavor form factor contributions in Eq. 1 and Eq. 2 (${}^{u,d,s}F_{1,2} = {}^{u,d,s}\tilde{F}_{1,2}$). Therefore the number of unknown flavor contributions on the right side of Eq. 1 and Eq. 2 is now reduced down to 6 unknown flavor contributions ${}^{u,d,s}F_{1,2}$, which can be determined, provided the electro-magnetic and weak neutral form factors are measured by experiment.
The weak neutral form factors enter into the amplitude M for elastic scattering of electrons off protons which is described at lowest order (one boson exchange) by the sum of the amplitudes m_γ and m_{Z_0}. The cross section is given by the square of the amplitude MM^* and consists of three terms: the pure γ-exchange ($m_\gamma m_\gamma^*$), the γ-Z_0 interference term ($m_\gamma m_{Z_0}^*$) and the pure Z_0-exchange ($m_{Z_0} m_{Z_0}^*$). At the proton vertex the elastic electro-magnetic and weak form factors enter and can therefore be measured in electron scattering. In elastic electron proton scattering at four momentum transfer in range of 0.1 Gev$^2 < Q^2 < 1$ GeV^2 the γ-Z_0 interference term is about 5 orders of magnitude smaller than the pure γ exchange. The direct measurement of the weak contribution to the cross section is therefore at present beyond experimental reach. But the parity violating coupling of the Z_0 gives a unique possibility to separate the pure γ exchange from the interference term. In a measurement of the parity violating asymmetry in elastic scattering of longitudinally polarized electrons on unpolarized protons the pure γ exchange ($m_\gamma m_\gamma^*$) vanishes and one measures directly the interference term. Therefore one has direct access to the weak form factors of the nucleon, since the electro-magnetic form factors are known from other experiments. As we have seen above, the determination of the weak form factors is equivalent to a determination of the strangeness contribution to the vector form factors of the nucleon. The experimen-

tal quantity which is measured is the difference in the cross section in the scattering of left handed or right handed electrons on unpolarized protons divided by the sum of the two cross sections. This is a parity violating asymmetry which can be calculated in the framework of the standard model.

$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \tag{3}$$

$$= -[\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}] \tag{4}$$

$$\times \frac{\varepsilon G_E^p \tilde{G}^p{}_E + \tau G_M^p \tilde{G}_M^p - (1-4sin^2\theta_W)\varepsilon' G_M^p \tilde{G}_A}{\varepsilon {G_E^p}^2 + \tau {G_M^p}^2}$$

$$= -[\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}] \times \{ \tag{5}$$

$$(1-4sin^2\theta_W) - \frac{\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\varepsilon {G_E^p}^2 + \tau {G_M^p}^2} - \tag{6}$$

$$\frac{\varepsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\varepsilon {G_E^p}^2 + \tau {G_M^p}^2} - \tag{7}$$

$$\frac{(1-4sin^2\theta_W)\varepsilon' G_M^p \tilde{G}_A}{\varepsilon {G_E^p}^2 + \tau {G_M^p}^2}\} \tag{8}$$

Here $\tau = \frac{Q^2}{4M_p^2}$ and $\varepsilon = (1+2(1+\tau)tan^2(\frac{\theta}{2}))^{-1}$ and $\varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}$ Using the flavor decomposition of Eq. 1, the asymmetry in Eq. 4 can be written like Eq. 5 as the sum of three terms (6), (7) and (8). (6) contains fundamental constants and the electro-magnetic form factors only. (6) is often referred to as A_0. (7) contains the unknown strangeness contribution to the vector form factors of the nucleon. (8) contains the weak axial form factor G_A which is known only at $Q^2 = 0GeV^2$ from neutron beta decay. In forward scattering (8) is strongly suppressed due to the kinematical factors. The sensitivity on the axial term is on the order of 1-2% for HAPPEX and A4 kinematics. In the case of backward scattering the sensitivity to the axial form factor is of the same order as the sensitivity to the magnetic form factor, the determination of term (8) requires an additional measurement of the parity violating asymmetry A^{PV} on deuterium. Any significant difference between the measured parity violating asymmetry A and A_0 is in forward scattering a direct measure of the strangeness contribution to the vector form factors of the nucleon.

2 Experiments

In parity violation electron scattering one finds two experimental difficulties and the existing experiments use different techniques to overcome these as summarized in table 1.

First difficulty is the size of the asymmetry without strangeness contribution A_0 which is used as an estimate of the expected measured asymmetry. For the existing and planned experiments it is on the order of $A_0 \approx 10^{-6}$. A significant determination of the strangeness contribution requires a measurement at a very high rate of elastic scattered electrons in order to determine the asymmetry in reasonable experimental time with an accuracy of a few percent.

Table 1. The different experimental approaches to separate inelastic from elastic scattering processes at the very high scattered particle flux have been optimized to meet the specific kinematical requirements of each of the experiments.

Experiment	Separation Elastic↔Inelastic	Detecting at High Rate
SAMPLE	low energy,	integrating,
[6,7]	no π-production	air Cerenkov
HAPPEX I,II,He	magnetic spectrometer	integrating,
[9,10,11,12,13]		in focal plane
A4	crystal calorimeter(E)	counting,
[14,15]		histogramming E
G0	time of flight (T)	counting,
[17]		histogramming T

Second, in the applied Q^2 range of the existing and planned experiments, one has inelastic channels like nonresonant π-electroproduction or excitations of nucleon resonances like the Δ. These inelastic channels have to be separated very well from the elastic scattering, since they have their own parity violating asymmetries which are a priori unknown.
The SAMPLE collaboration has measured [6,7] at the MIT-Bates accelerator under backward scattering angles between 130 and 170 using a large solid angle air Cerenkov detector. The beam energy of 200 MeV ensures, that inelastic scattering from π-electroproduction is negligible. The Cerenkov light produced by elastic scattered electrons is focused into a photomultiplier tube and the current of the photomultiplier tube is integrated and digitized. The systematic change of beam parameters with helicity are naturally more difficult to control at the pulsed machine, but on the other hand the lack of any spectrometry or calorimetry makes the experimental setup simpler. The combination of the SAMPLE results from hydrogen and deuterium yield a value for the strangeness magnetic form factor contribution:

$$G_M^s(Q^2 = 0.1GeV^2) = 0.14 \pm 0.29 \pm 0.31 \tag{9}$$

The HAPPEX collaboration employs a magnetic spectrometer, separating the inelastic scattering channels from the elastic scattering by usage of the dispersion in a magnetic field. The elastic scattering events are transported to a certain region in the focal plane of the spectrometer, where the integrating Cherenkov detector is located. The measured asymmetry is[9,10]

$$A_p = (-14.60 \pm 0.94 \pm 0.54)\,\mathrm{ppm} \tag{10}$$

The value of the strangeness contribution to the asymmetry has been normalized to the proton magnetic form factor and is:

$$\frac{G_E^s + 0.392 G_M^s}{G_M^p/\mu^p} = 0.091 \pm 0.054 \pm 0.039 \tag{11}$$

The HAPPEX collaboration is planning on two further measurements: A measurement at a lower Q^2 of $0.1GeV^2$[11]. The second proposal[12] is a measurement with elastic

scattering from ^{4}He where all magnetic and axial contributions cancel giving a very clean measurement of G_E^s. First pilot measurements on the hydrogen and deuterium take place with a fraction of the final statistics in the summer of 2004. First results are expected in the fall of 2004. The final statistics will be reached in 2005.
The A4 collaboration[14] has performed a measurement of the parity violating asymmetry in the scattering of longitudinally polarized 854.3 MeV electrons on unpolarized protons using counting techniques. This is the first time, that a parity violating asymmetry in electron scattering has been measured by counting individual, scattered particles. The scattered electrons are registered in a Cherenkov calorimeter consisting of 1022 PbF_2 crystals. The crystals are cut so that an elastic scattered electron deposits its energy in a cluster of 9 crystals. The calorimeter has a full ϕ-coverage and is therefore symmetric around the beam axis. A scattering angle of $30° < \theta < 40°$ is covered resulting in a total solid angle of 0.63 srd. Each crystal has a dedicated electronics module, where the analogue sum of the cluster of 9 crystals is done. In addition a sophisticated trigger and pile-up veto circuit requires the connection of each circuit with the 24 neighbors. In the first set of measurements at the beam Energy of 854.3 MeV, there have only been 511 PbF_2-modules installed. The combined result on the asymmetry from all data sets at 854.3 MeV is [15]:

$$A_{exp} = (-5.44 \pm 0.54 \pm 0.26)ppm \tag{12}$$

The first error is the pure statistical error coming form the counting statistics of the scattered particles. The second error is the combined systematical uncertainty from the regression analysis and the uncertainty in the polarization. The contribution from the strange quarks to the vector form factors at $Q^2 = 0.230$ GeV^2 can be extracted as:

$$G_E^s + 0.225 G_M^s = 0.039 \pm 0.034 \tag{13}$$

The A4 collaboration has taken more data at a Q^2 of 0.1 GeV^2 with the full detector setup consisting of 1022 PbF_2 crystals and electronics modules. Results are expected in the fall of 2004. The further program of the A4-collaboration involves the installation and commissioning of a laser backscatter Compton polarimeter and a transmission Compton polarimeter, which will reduce the uncertainty in the polarization down to possibly 2-3% from now 7 %. The present planning foresees, that the whole detector will be reverted, so that the scattering angle will be changed to backward scattering between 140 and 150. We plan measurements at $Q^2 = 0.23\,GeV^2$ and $Q^2 = 0.47\,GeV^2$ at this backward angle. In combination with the SAMPLE and HAPPEX measurements it will then be possible to make a full flavor separation at the three Q^2 values in order to reveal the contribution of the strangeness to the vector form factors of the proton.
The G0 collaboration [17] is using the a toroidal magnetic field of a superconductive Magnet in combination with a measurement of the time of flight of the scattered particles in order to discriminate elastic scattering from the inelastic channels. A first round of forward angle measurements has been done covering a Q^2 range between 0.1 GeV^2 and 1.0 GeV^2. The analysis is in progress and results are expected for the fall of 2004.

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