Strange Form Factors of the Nucleon

Sebastian Baunack

27th Students' Workshop on Electromagnetic Interactions,
Bosen (Saar), September 3, 2010
Outline

- Strangeness in the nucleon
- Strange form factors
- PV experiments
- Measurement / Results
- Outlook
Nucleon structure


Only little of the spin of the proton is carried by the valence quarks (*spin crisis*)

=> Significant spin might be carried by strange quarks


Strange quarks might have a significant contribution to the vector matrix elements of the nucleon

=> Measurement of weak neutral current amplitude in elastic lepton-nucleon scattering
Strangeness in the nucleon

Contribution of strange quarks to the nucleon properties:

- Deep inelastic neutrino scattering
  Momentum: ~ 3%

- Mass (πN-Sigma term): 0 - 30%

- Spin: between 0 and -10%

- Vector current: Electromagnetic form factors
History


STRANGER THAN FICTION:
THE STRANGENESS RADIUS AND
MAGNETIC MOMENT OF THE NUCLEON

R. L. Jaffe

ABSTRACT

The nucleon matrix elements of the operators \( r_s^2 \equiv s^+(\bar{x})\bar{x}^2 s(\bar{x}) \) and
\( \bar{\mu}_s \equiv \frac{1}{2} \bar{x} \times \bar{s} \gamma_s \) are estimated using dispersion theory fits to the nucleon isoscalar form factor, together with a standard treatment of \( \phi - \omega \) mixing and some mild assumptions on the asymptotic behavior (at large-\( q^2 \)) of nucleon form factors. The results indicate a significant strange quark content in the nucleon.
History

Participants of the Workshop on Parity Violation in Electron Scattering at Caltech, February 1990.
Theory: Models

- Vector meson dominance (VDM)
- Kaon loops
- Skyrme model
- Chiral quark model
- Dispersion relations
- ...
- Lattice
Model predictions

Graph showing model predictions for $r^2$ vs $\mu_s$ [n.m.]. The graph compares different models:
- VMD (Jaffe)
- VMD (Hammer et al.)
- Skyrme (Park et al.)
- $\chi$QSM (Silva et al.)
- Lattice (Lewis et al.)
- Lattice (Leinweber et al.)
Strangeness contribution to the nucleon form factors

Flavour Decomposition of form factors:

\[
G_{E,M}^p = \frac{2}{3} G_{E,M}^{p,u} - \frac{1}{3} G_{E,M}^{p,d} - \frac{1}{3} G_{E,M}^{p,s}
\]

\[
G_{E,M}^n = \frac{2}{3} G_{E,M}^{n,u} - \frac{1}{3} G_{E,M}^{n,d} - \frac{1}{3} G_{E,M}^{n,s}
\]

4 equations, 12 unknown quantities...
Charge Symmetry

Proton and neutron form an isospin doublet with $T=1/2$ and $T_3=+1/2$ (p) and $T_3=-1/2$ (n)

\[ G^{p,u}_{E,M} = G^{n,d}_{E,M} \]
\[ G^{p,d}_{E,M} = G^{n,u}_{E,M} \]
\[ G^{p,s}_{E,M} = G^{n,s}_{E,M} \]
Strangeness in the Nucleon

Charge symmetry:

\[ G^p_{E,M} = \frac{2}{3} G^u_{E,M} - \frac{1}{3} G^d_{E,M} - \frac{1}{3} G^s_{E,M} \]

\[ G^n_{E,M} = \frac{2}{3} G^d_{E,M} - \frac{1}{3} G^u_{E,M} - \frac{1}{3} G^s_{E,M} \]

4 equations, 6 unknown quantities…
Weak interaction

Exchange of photon and $Z^0$

Universality of quark distribution

\[ G_{E,M}^p, Z = \left( \frac{1}{4} - \frac{2}{3} \sin^2 \Theta_W \right) G_{E,M}^u - \left( \frac{1}{4} - \frac{1}{3} \sin^2 \Theta_W \right) G_{E,M}^d - \left( \frac{1}{4} - \frac{1}{3} \sin^2 \Theta_W \right) G_{E,M}^s \]

Two more equations => Problem in principle solved
Parity violating electron scattering

- Polarised electron beam
- Unpolarised target

\[ \sigma \propto |M^{EM} + M^{NC}|^2 \approx 1 + 10^{-6} + 10^{-12} \]

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M^{NC}|}{|M^{EM}|} \sim \frac{Q^2}{(M_Z)^2} \approx 10^{-6} \]

Direct measurement not possible

=> Asymmetry measurement
Extraction of form factors

Parity violating asymmetry (proton target):

\[
A^{PV} = A_V + A_A + A_S
\]

\[
A_V = -\frac{G_F Q^2}{4 \pi \alpha \sqrt{2}} \left( (1 - 4 \sin^2 \Theta_w) - \frac{\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right)
\]

\[
A_A = -\frac{G_F Q^2}{4 \pi \alpha \sqrt{2}} \left( -\frac{(1 - 4 \sin^2 \Theta_w) \sqrt{1 - \varepsilon^2} \sqrt{\tau(1 + \tau) G_M^p}}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} G_A^p \right)
\]

\[
A_S = -\frac{G_F Q^2}{4 \pi \alpha \sqrt{2}} \left( -\frac{\varepsilon G_E^s G_M^s + \tau G_M^s G_M^s}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right)
\]

Standard model calculation

Axial form factor

Strange form factors
Measurement of strange form factors

Three quantities to measure: $G_E^s$, $G_M^s$, $G_A$

For a specific momentum transfer $Q^2$: At least three measurements

**Scattering experiment**

<table>
<thead>
<tr>
<th>Scattering experiment</th>
<th>Sensitive to</th>
</tr>
</thead>
<tbody>
<tr>
<td>e + p (elastic), forward angles:</td>
<td>$G_E^s$ and $G_M^s$</td>
</tr>
<tr>
<td>e + p (elastic), backward angles:</td>
<td>$G_M^s$ and $G_A$</td>
</tr>
<tr>
<td>e + $^4$He (elastic), forward angles:</td>
<td>$G_E^s$</td>
</tr>
<tr>
<td>e + d (quasi-elastic), backward angles:</td>
<td>$G_M^s$ and $G_A$</td>
</tr>
</tbody>
</table>

Strangeness contribution

Large electroweak corrections?
Nuclear anapole moment
Parity violation experiments
## PV experiments

<table>
<thead>
<tr>
<th></th>
<th>e+p forward</th>
<th>e+p backward</th>
<th>e+(^4)He forward</th>
<th>e+d backward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
<td>0.10 (GeV/c)(^2)</td>
<td></td>
<td></td>
<td>0.04 (GeV/c)(^2) 0.1 (GeV/c)(^2)</td>
</tr>
<tr>
<td>Happex</td>
<td>0.10 (GeV/c)(^2) 0.48 (GeV/c)(^2) 0.62 (GeV/c)(^2)</td>
<td>0.10 (GeV/c)(^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>0.11 (GeV/c)(^2) 0.23 (GeV/c)(^2) 0.62 (GeV/c)(^2) 0.11 (GeV/c)(^2)</td>
<td>0.23 (GeV/c)(^2) 0.11 (GeV/c)(^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G(^0)</td>
<td>(0.12... 1.0) (GeV/c)(^2) 0.23 (GeV/c)(^2) 0.62 (GeV/c)(^2)</td>
<td>0.23 (GeV/c)(^2) 0.62 (GeV/c)(^2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental requirements

• Statistics:

\[ A^{PV} \approx 10^{-6} \quad \Delta A^{PV} = \frac{1}{P \sqrt{N}} \]

\[ N \approx 10^{12} - 10^{14} \]

Large cross section and/or large acceptance, high luminosity, high polarisation

• Systematics:
  - Separation of elastic and inelastic events
  - Control of helicity correlated beam properties
SAMPLE, MIT-Bates

- Backward angle, $Q^2=0.1 \text{ (GeV/c)}^2$
- Large acceptance (1.5 sr) air cherenkov detector
- Beam energy (200 MeV) near pion threshold
- Background measurements with shutters closed
- Hydrogen and Deuterium target
• Small forward angles, $Q^2=0.48$ (GeV/c)$^2$ and 0.1 (GeV/c)$^2$
• Small acceptance (5 msr) high resolution spectrometer
• Hydrogen and Helium target
A4, MAMI

- Calorimeter with 1022 PbF$_2$ crystals
- Hydrogen and deuterium target
- Calorimetric separation of elastic from inelastic events
- Large solid angle: 0.6 sr
- Momentum transfers between 0.1 GeV$^2$ and 0.6 GeV$^2$
- Forward and backward angles
G⁰, Jefferson Lab

- Forward and backward angles
- Large acceptance (0.9 sr) spectrometer
- Time of flight measurement
- Momentum transfers between 0.12 (GeV/c)² and 1.00 (GeV/c)²
- Hydrogen and Deuterium target
PV experiments: Results
Using Zhu et al. for $G_A^e(T=1)$:

$G_M^s = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$

$A^{PV} = (-5.61 \pm 0.67 \pm 0.88)$ ppm

$G_A(T=1) = -0.53 \pm 0.57 \pm 0.50$
HAPPEX I - Results

• Experimental result:
  \[ A^\text{PV} = (-15.05 \pm 0.98 \pm 0.56) \text{ ppm} \]

• Linear combination of \( G_E^s \) and \( G_M^s \):
  \[ G_E^s + 0.39 \ G_M^s = 0.025 \pm 0.020 \pm 0.014 \]

- \( Q^2 = 0.48 \ (\text{GeV/c})^2 \)
- \( E = 3.3 \ \text{GeV}, \ \theta = 12.3^\circ \)
Q^2 = 0.23 (GeV/c)^2
A_{PV} = (-5.44 \pm 0.54_{\text{stat}} \pm 0.26_{\text{syst}}) \text{ ppm}
G_E^s + 0.23 \ G_M^s = 0.039 \pm 0.036

Q^2 = 0.11 (GeV/c)^2
A_{PV} = (-1.36 \pm 0.29_{\text{stat}} \pm 0.13_{\text{syst}}) \text{ ppm}
G_E^s + 0.11 \ G_M^s = 0.071 \pm 0.036
G^0, Jefferson Lab

- Forward angle: Several Q^2
- Target: p
Parity experiments


• HAPPEx II
• A4 backward angle
• $G^0$ backward angle
MAMI: Beam current asymmetry
MAMI: Position stability

L xymo27x fluc rms

Run number
A4: Luminosity stability
A4 Detector rearrangement

Detector

145°

35°

e-

p-Target

Detector

Plane Steel Plate

Hydraulic Oil Plunger
Additional scintillator system
Readout and trigger electronics

**Analog unit**
- Data generation
  - SUM
  - Integrator & FADC
- Trigger-erzeugung
  - CFD
  - Local Max.
  - OR
  - Trigger
- Pile up logic
  - PS
- Neighbour modules

**Digital unit**
- Data storage
  - FIFO
  - FPGA
- Electron tagger
  - prog. Delay
  - CFD

**Electron tagger**
- Scintillator

**Readout and trigger electronics**

- PbF$_2$
- $S_0$
- $S_1$
- $S_2$
A4 backward angle energy spectrum, hydrogen

Coincidence spectrum from experiment

Background estimated from measured noncoincidence spectrum

$\pi^0$ decay photons (photo-production) from MC

$\pi^0$ decay photons (electro-production) from MC

$\pi^0$ decay photons (aluminium), measured
A4 backward results ($H_2$)

\[ A_{PV} = (-17.23 \pm 0.84_{\text{stat}} \pm 0.89_{\text{syst}} ) \text{ ppm} \]

\[ A_0 = (-15.87 \pm 1.22 ) \text{ ppm} \]

About 1100 h of data
A4: Strange FF at $Q^2=0.23$ GeV$^2$

$G_E^s = 0.050 \pm 0.042 \ (\pm 0.038_{\text{exp}} \pm 0.019_{\text{FF}})$

$G_M^s = -0.14 \pm 0.16 \ (\pm 0.11_{\text{exp}} \pm 0.11_{\text{FF}})$

S. Baunack et al.,
Phys Rev. Lett. 102, 15803 (2009)
Happex: Strange FF at $Q^2=0.1$ GeV$^2$

- Data from SAMPLE, Happex, G0 and A4

Solid ellipse: uses theoretical constraints for $G_A$

Dashed ellipse: no theory constrains for $G_A$

\[
\% \text{ contrib} = \frac{G_{E,M}^s}{G_{E,M}^p} \times \left(-\frac{1}{3}\right) \times 100
\]


Thanks to K. Pashke and R. Young
G0: FF at 0.1 GeV$^2$ and 0.6 GeV$^2$

D. Androic et al.,
A4@1.5 GeV: Motivation
A4@1.5 GeV

Energy spectra: Measurement
A4@1.5 GeV

Energy spectra: MC Study

- Elastically scattered electrons
- Inelastically scattered electrons
- Decay Photons

counts

$E$ [MeV]
A4 @ 1.5 GeV: Asymmetries

Sampleplot for Rings 2-6 (Elastic peak)

Fit results:
GVZ out: $A = (-23.37 \pm 0.94)$ ppm
GVZ in: $A = (+22.29 \pm 1.01)$ ppm

Combined: $A = (-22.87 \pm 0.69)$ ppm

$\chi^2 / \text{NDF} = 6.50 / 8 = 0.81$
A4 @ 1.5 GeV: Asymmetries

Asymmetries histogram Rings 2-6

Asym
Entries: 123456
Mean: 78.9 ppm
RMS: 9.8 ppm

Asym Out: (23.7 ± 0.9) ppm
Asym In: (22.2 ± 1.0) ppm
Asym RMS: (22.8 ± 0.8) ppm

Asymmetry (ppm)
A4 @ 1.5 GeV: Regression analysis

Regression coefficients:
\[ a1 = (1.070509 \pm 0.158046) \]
\[ a2 = (-10.178678 \pm 4.573303) \text{ ppm/mum} \]
\[ a3 = (12.384095 \pm 4.658200) \text{ ppm/mum} \]
\[ a4 = (80.068685 \pm 25.125262) \text{ ppm/murad} \]
\[ a5 = (-32.416799 \pm 14.182381) \text{ ppm/murad} \]
\[ a6 = (-20.166810 \pm 14.740871) \text{ ppb/eV} \]

<table>
<thead>
<tr>
<th>Sample</th>
<th>Runs</th>
<th>Counts</th>
<th>Pola</th>
<th>GVZ</th>
<th>Asymmetry (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>639</td>
<td>1.7280e+11</td>
<td>0.82</td>
<td>gysz in</td>
<td>+22.78 +/- 2.93</td>
</tr>
<tr>
<td>4</td>
<td>554</td>
<td>1.5934e+11</td>
<td>0.82</td>
<td>gysz out</td>
<td>-20.05 +/- 3.05</td>
</tr>
<tr>
<td>5</td>
<td>662</td>
<td>2.0746e+11</td>
<td>0.82</td>
<td>gysz in</td>
<td>+21.87 +/- 2.67</td>
</tr>
<tr>
<td>6</td>
<td>675</td>
<td>2.1030e+11</td>
<td>0.90</td>
<td>gysz out</td>
<td>-18.69 +/- 2.41</td>
</tr>
<tr>
<td>7</td>
<td>725</td>
<td>2.5024e+11</td>
<td>0.81</td>
<td>gysz in</td>
<td>+19.01 +/- 2.46</td>
</tr>
<tr>
<td>8</td>
<td>733</td>
<td>1.6070e+11</td>
<td>0.87</td>
<td>gysz in</td>
<td>+23.39 +/- 2.88</td>
</tr>
<tr>
<td>9</td>
<td>948</td>
<td>2.3230e+11</td>
<td>0.84</td>
<td>gysz out</td>
<td>-22.10 +/- 2.46</td>
</tr>
<tr>
<td>10</td>
<td>684</td>
<td>1.9655e+11</td>
<td>0.87</td>
<td>gysz in</td>
<td>+19.62 +/- 2.59</td>
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<tr>
<td>11</td>
<td>1403</td>
<td>4.6566e+11</td>
<td>0.88</td>
<td>gysz out</td>
<td>-23.34 +/- 1.67</td>
</tr>
</tbody>
</table>
Strange Form Factors: Existing data

- At least two measurements with the same $Q^2$
Extrapolation to $Q^2=0$

Aim: Get the strange quark contributions to the static properties of the proton
=> $Q^2$-dependence of the strange form factors?

- Strange electric FF: First order Taylor expansion

$$G_E^s(q^2) = \frac{1}{6} r_s^2 q^2$$

- Strange magnetic FF: Ansatz from HB\(\chi\)PT


$$G_M^s(q^2) = \mu_s + \frac{\pi m_N M_K}{(4\pi F_F)^2} \frac{2}{3} \left( 5D^2 - 6FD + 9F^2 \right) f(q^2)$$

$$f(q^2) = -\frac{1}{2} + \frac{4 - q^2/M_K^2}{4\sqrt{-q^2/M_K^2}} \arctan \left( \frac{\sqrt{-q^2}}{2M_K} \right)$$
Extrapolation to $Q^2=0$

- Use only the results with the two lowest $Q^2$ available
- $Q^2=0.1$ GeV$^2$: Results from Happex, SAMPLE and A4
- $Q^2=0.23$ GeV$^2$: Results from A4
Strange quark contribution: Static properties
Summary and Outlook

- Strange quark contributions to the nucleon form factors: PV asymmetry in elastic electron scattering

- Models: Difficult (non-pertubative QCD), wide range of predictions

- Experiments: Vast improvements over the last decade

- Strange quark contributions are smaller than initially predicted, constrains are given by the experiments

- Outlook: New results from Happex and A4 in 2010/2011 at $Q^2=0.6$ GeV$^2$
  A4: Deuterium result by end of 2010
  New precise measurement at $Q^2=0.1$ GeV$^2$ at backward angles?