Medium modification of the nucleon: the NuTeV anomaly and PVDIS

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Are nucleon properties modified by the nuclear medium?
  ✦ Of fundamental importance
  ✦ Remains an open question

Areas where medium modifications seem important:
  ✦ Quenching of $g_A$ in-medium
  ✦ Nuclear magnetic moments
  ✦ In-medium Form Factors (e.g. $^4\text{He}(e,e'p)^3\text{H}$)

Importantly nuclear structure functions
  ✦ the EMC effect

Is the NuTeV anomaly evidence for medium modification?

Can parity violating DIS provide additional information on medium modification?
The EMC Effect

- Theme
- EMC Effect
  - NuTeV anomaly
  - NJL model
  - Nucleon . . .
  - Quark Dis.
  - NJL Quark Dis.
  - Nuclear Matter
  - NM Quark Dis.
  - NuTeV anomaly
  - Vector Potential
  - EMC effect
  - PVDIS $a_1$ ratios
  - Conclusion


- Result surprised nuclear physics community
- Long distance nuclear effects not expected to influence “short distance” quark physics
- Evidence for medium modification?
- After 25 years no consensus on cause of EMC Effect
The NuTeV anomaly

- In 2001 NuTeV collaboration, using $\nu$ DIS, “measured”:

$$R_{PW} = \frac{\sigma[\nu \text{Fe} \rightarrow \nu X] - \sigma[\bar{\nu} \text{Fe} \rightarrow \bar{\nu} X]}{\sigma[\nu \text{Fe} \rightarrow \mu^- X] - \sigma[\bar{\nu} \text{Fe} \rightarrow \mu^+ X]}$$

- Isoscalar target: $R_{PW} \overset{N=Z}{\longrightarrow} \frac{1}{2} - \sin^2 \Theta_W + \delta R_{PW}$

- $\sin^2 \theta_W = 0.2277 \pm 0.0013^{(\text{stat})} \pm 0.0009^{(\text{syst})}$


- World average: $\sin^2 \theta_W = 0.2227 \pm 0.0004$

- 3 $\sigma$ discrepancy!!! $\implies$ “NuTeV anomaly”

- Huge amount of experimental & theoretical interest:
  - $\sim 370$ citations as of November 2008

- No universally accepted complete explanation

- EMC and NuTeV anomaly $\iff$ medium modification?
Nambu–Jona-Lasinio Model

- Low energy chiral effective theory of QCD

- Investigate the role of quark degrees of freedom.

- Much in common with Dyson Schwinger Equations

- Lagrangian has same symmetries as QCD:
  - Importantly chiral symmetry and DCSB,
    - Dynamically generated quark masses,
    - Non-zero chiral condensate.

- Lagrangian \((\Gamma = \text{Dirac, colour, isospin matrices})\)

\[
\mathcal{L}_{NJL} = \bar{\psi} \left( i \gamma \cdot \not{\! \! p} - m \right) \psi + G \left( \bar{\psi} \Gamma \psi \right)^2
\]
Nucleon in the NJL model

- Nucleon approximated as quark-diquark bound state.

- Use relativistic Faddeev approach:

- Diquark - bound state of two quarks:

- Solve Bethe-Salpeter equation for diquark.

- We include scalar \((0^+)\) and axial-vector diquarks \((1^+)\).
Regularization

- **Proper-time regularization**

\[
\frac{1}{X^n} = \frac{1}{(n-1)!} \int_0^\infty d\tau \tau^{n-1} e^{-\tau X} \quad \rightarrow \quad \frac{1}{(n-1)!} \int_{1/(\Lambda_{IR})^2}^{1/(\Lambda_{UV})^2} d\tau \tau^{n-1} e^{-\tau X}
\]

- $\Lambda_{IR}$ eliminates unphysical thresholds for the nucleon to decay into quarks: → simulates confinement.


- Needed for: nuclear matter saturation, $\Delta$ baryon.

Model Parameters

- **Free Parameters:**
  \[ \Lambda_{IR}, \Lambda_{UV}, M_0, G_\pi, G_s, G_\alpha, G_\omega \text{ and } G_\rho \]

- **Constraints:**
  - \[ f_\pi = 93 \text{ MeV}, \ m_\pi = 140 \text{ MeV} \ \& \ M_N = 940 \text{ MeV} \]
  - \[ \int_0^1 dx (\Delta u_v(x) - \Delta d_v(x)) = g_A = 1.267 \]
  - \[ (\rho, E_B / A) = (0.16 \text{ fm}^{-3}, -15.7 \text{ MeV}) \]
  - \[ a_4 = 32 \text{ MeV} \]
  - \[ \Lambda_{IR} = 240 \text{ MeV} \]

- **We obtain [MeV]:**
  - \[ \Lambda_{UV} = 644 \]
  - \[ M_0 = 400, \ M_s = 690, \ M_\alpha = 990, \ldots \]

- **Can now model a very large array of observables**
Three twist-2 parton distributions \((k_{\perp} = 0)\):

- Spin-Independent, Helicity, Transversity

\[
\begin{align*}
q(x) & \quad \Delta q(x) & \quad \Delta_T q(x)
\end{align*}
\]

Usually measured via DIS and SIDIS

Bjorken-\(x\) is the quark momentum fraction

All distributions have probability interpretation

- \(q(x)\): prob. to strike quark with momentum fraction \(x\)
Nucleon quark distributions

- Associated with a Feynman diagram calculation

\[
[q(x), \Delta q(x), \Delta_T q(x)] \quad \rightarrow \quad X = \delta \left( x - \frac{k^+}{p^+} \right) \left[ \gamma^+, \gamma^+\gamma_5, \gamma^+\gamma^1\gamma_5 \right]
\]

- Covariant and gives correct support
- Satisfies baryon and momentum sum rules
- Satisfies positivity constraints and Soffer bound
- No “VMD” \[ \delta(1 - x) \]; No pions \[ Q_0^2 \rightarrow \tilde{Q}_0^2 \]
$u_v(x)$ and $d_v(x)$ distributions

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$Q^2_0 = 0.16 \text{ GeV}^2$

$Q^2 = 5.0 \text{ GeV}^2$

MRST (5.0 GeV$^2$)

$\Delta u_v(x)$ and $\Delta d_v(x)$ distributions

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\[ \Delta_T u_v(x) \text{ and } \Delta_T d_v(x) \text{ distributions} \]

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- \( M \sim 400 \) MeV, large relativistic corrections unexpected

- Potential problem for models based on concept of “constituent quarks”
Transversity: Reanalysis

Q^2 = 2.4 GeV^2

Anselmino et al DIS 08


Constituent quarks survive
Transversity Moments

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![Graph showing models for $\Delta_T u$ and $\Delta_T d$](image)

- **Anselmino et al DIS 08**
Asymmetric Nuclear Matter: Lagrangian

- Finite Density Lagrangian: $\sigma$, $\omega$, $\rho$ mean fields

$$\mathcal{L} = \bar{\psi} \left( i \hat{\partial} - M^* - \mathcal{V} \right) \psi + \mathcal{L}'_I$$

- $\sigma$: isoscalar-scalar – attractive
- $\omega$: isoscalar-vector – repulsive
- $\rho$: isovector-vector – attractive/repulsive

- Fundamental piece of physics is that these mean scalar and vector fields couple to the quarks in the nucleon!!

- Finite density quark propagator

$$S(k) = \frac{1}{k^2 - M^2 - i\varepsilon} \quad \rightarrow \quad S_q(k) = \frac{1}{k^2 - M^{*2} - \mathcal{V}_q - i\varepsilon}$$

- Quark vector potentials:

$$V_u = \omega_0 + \rho_0 \quad V_d = \omega_0 - \rho_0$$
Asymmetric Nuclear Matter: Effective Potential

- Hadronization → Effective potential

\[
\mathcal{E} = \mathcal{E}_V - \frac{\omega_0^2}{4 G_\omega} - \frac{\rho_0^2}{4 G_\rho} + \mathcal{E}_p + \mathcal{E}_n
\]

\[
\mathcal{E}_p(n) = 2 \int \frac{d^3 \vec{p}}{(2\pi)^3} n(k) \left[ \sqrt{M_N^2 + \vec{p}^2} + 3\omega_0 \pm \rho_0 \right]
\]

- \(\mathcal{E}_V\): Vacuum Energy
- \(\mathcal{E}_p(n)\): Energy of nucleons moving in \(\sigma, \omega, \rho\) fields

- Vector fields

\[
\frac{\partial \mathcal{E}}{\partial \omega_0} = 0 \quad \Rightarrow \quad \omega_0 = 6 G_\omega (\rho_p + \rho_n)
\]

\[
\frac{\partial \mathcal{E}}{\partial \rho_0} = 0 \quad \Rightarrow \quad \rho_0 = 2 G_\rho (\rho_p - \rho_n)
\]

- In-medium Constituent Quark Mass:

\[
\frac{\partial \mathcal{E}}{\partial M^*} = 0 \quad \Rightarrow \quad M^* \text{ at given density}
\]
Binding Energy for Nuclear Matter

- Binding Energy depends on $Z/N \leftrightarrow \rho_0$-field
- Nuclear Matter unbound for $Z/N < 0.12$. 
Mass versus Density for Nuclear Matter

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**Nuclear Matter Quark Distributions**

- **Finite Density Propagator:**

\[
S_q(k) = \frac{1}{k - M^* - \nu_q}, \quad V_u = \omega_0 + \rho_0, \quad V_d = \omega_0 - \rho_0
\]

- **Scalar field introduced via effective masses**

- **Fermi motion introduced via convolution**

\[
f_{p0}(y_A) = \frac{Z}{A} \frac{3}{4} \left( \frac{\hat{M}_N}{p_{Fp}} \right)^3 \left[ \left( \frac{p_{Fp}}{\hat{M}_N} \right)^2 - \left( \frac{E_{Fp}}{\hat{M}_N} - y_A \right)^2 \right]^2
\]

\[
f_{n0}(y_A) = \frac{N}{A} \frac{3}{4} \left( \frac{\hat{M}_N}{p_{Fn}} \right)^3 \left[ \left( \frac{p_{Fn}}{\hat{M}_N} \right)^2 - \left( \frac{E_{Fn}}{\hat{M}_N} - y_A \right)^2 \right]^2
\]

- **\( N \neq Z \): Fermi motion breaks nucleon isospin symmetry**

  - that is: \( u_p \neq d_n \) and \( u_n \neq d_p \)
Recall: 
\[ S_q = \frac{1}{k - M^* - V_q}, \quad V_u = \omega_0 + \rho_0, \quad V_d = \omega_0 - \rho_0 \]

Vector field introduced via scale transformation
\[ q(x) = \frac{P^+}{P^+ - V^+} q_0 \left( \frac{P^+}{P^+ - V^+} x - \frac{V^+}{P^+ - V^+} \right) \]

For asymmetric nuclear matter
\[ q_A(x_A) = \frac{M_N}{\hat{M}_N} q_{A0} \left( \frac{M_N}{\hat{M}_N} x_A - \frac{V_q}{\hat{M}_N} \right) \]

\[ N \neq Z: \text{ Vector field breaks nucleon isospin symmetry} \]

that is: \[ u_p \neq d_n \text{ and } u_n \neq d_p \]
Results: Nuclear Matter $Z/N = 1$

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\[ r_{pn} = 1 \]

Proton Quark Distributions

$u_p(x)$

$d_p(x)$

free

scalar

+ Fermi

+ vector

\[ x \quad 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \]

\[ x \quad 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \]

Proton Quark Distributions
Results: Nuclear Matter $Z/N = 1$

- Vector field plays critical role: non-local operator
- We have: $u_p(x) = d_n(x)$ and $d_p(x) = u_n(x)$
Results: Nuclear Matter $Z/N = 0.6$

- We have: $u_p(x) \neq d_n(x)$ and $d_p(x) \neq u_n(x)$
- “Nucleon isospin symmetry violation” $\leftrightarrow \rho^0$ field.
Nucleon Isospin Symmetry Breaking

- Nucleon isospin symmetry broken by nuclear effects – $\rho_0$-field
- Medium induced charge asymmetry
- This effect will provide correction to NuTeV anomaly
The NuTeV anomaly

- Recall
  \[ R_{PW} = \frac{\left(\frac{1}{6} - \frac{4}{9} \sin^2 \Theta_W\right) \langle x u^-_A \rangle + \left(\frac{1}{6} - \frac{2}{9} \sin^2 \Theta_W\right) \langle x d^-_A \rangle}{\langle x d^-_A \rangle - \frac{1}{3} \langle x u^-_A \rangle} \]

- Redo NuTeV experiment theoretically

- Use our "Fe" medium modified \( q_A(x) \):
  \[ (\delta N = 5.74\%) \]

- Evaluate \( R_{PW} \) using S.M. value for \( \Theta_W \)

- Apply "standard" non-isoscalarity correction to \( R_{PW} \)

\[ R_{PW} = 0.2741 \quad \text{compare NuTeV: } R_{PW} = 0.2723 \pm \ldots \]

- Convert to effective \( \sin^2 \Theta_W \equiv \frac{1}{2} - R_{PW} \)

\[ \sin^2 \Theta_W = 0.2259 \]
\[ \sin^2 \Theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst}) \quad (\text{NuTeV}) \]
The NuTeV anomaly cont’d

- Nucleon isospin violation is small
- Define effective $\Theta_W$:
  $$\sin^2 \Theta_W \equiv \frac{1}{2} - R_{PW}$$

<table>
<thead>
<tr>
<th></th>
<th>Free</th>
<th>Fermi</th>
<th>Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle xu_{\bar{A}} \rangle$</td>
<td>0.4889</td>
<td>0.4885</td>
<td>0.4855</td>
</tr>
<tr>
<td>$\langle xd_{\bar{A}} \rangle$</td>
<td>0.5111</td>
<td>0.5115</td>
<td>0.5145</td>
</tr>
<tr>
<td>$\langle x\tilde{u}_{\bar{A}} \rangle$</td>
<td>0.5000</td>
<td>0.4996</td>
<td>0.4966</td>
</tr>
<tr>
<td>$\langle x\tilde{d}_{\bar{A}} \rangle$</td>
<td>0.5000</td>
<td>0.5004</td>
<td>0.5034</td>
</tr>
<tr>
<td>$\sin^2 \Theta_W$</td>
<td>0.2227</td>
<td>0.2231</td>
<td>0.2259</td>
</tr>
</tbody>
</table>
Convert to effective $\sin^2 \Theta_W \equiv \frac{1}{2} - R_{PW}$

\[
\sin^2 \Theta_W = 0.2259 \\
\sin^2 \Theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst}) \quad (\text{NuTeV})
\]

Non-isoscalarity $\rho_0$ correction can explain $\sim 64\%$ of anomaly

\[ CSV_{\delta m} + \rho_0 = 0.0017 + 0.2259 \implies \text{No NuTeV anomaly} \]

NuTeV $R_{PW}$ result consistent with S.M.

Instead “anomaly” evident for medium modification

Equally interesting:

- e.g. EMC effect $\sim 830$ citations as of Nov 2008

Vector Potential & Model Independence

- Recall: \[ q_A(x_A) = \frac{M_N}{M_N} q_{A0} \left( \frac{M_N}{M_N} x_A - \frac{V_q}{M_N} \right) \]

- \( N \neq Z \implies u\)- and \( d\)-quarks feel different \( V_q \)

- \( N > Z \implies V_u < V_d \), \( \langle x u^- \rangle < \langle x d^- \rangle \)

- Therefore: \( \langle x u^-_A \rangle < \langle x u^-_0 \rangle, \langle x d^-_A \rangle > \langle x d^-_0 \rangle \)

- Vector fields maintain momentum sum rule!!

- Isoscalarity: \( \langle x u^- - x d^-_0 \rangle = 0, \langle x u^-_A - x d^-_A \rangle < 0 \)

- Recall \( \delta R_{PW}^\rho \simeq \left( 1 - \frac{7}{3} \sin^2 \Theta_W \right) \frac{\langle x u^-_A - x d^-_A \rangle}{\langle x u^-_A + x d^-_A \rangle} \)

- Therefore \( \delta R_{PW}^\rho \) is negative – after isoscalarity

- \( \rho_0 \) vector field reduces anomaly – Model Independent!!
We claim $\rho_0$-field explains NuTeV, but is this nucleon isospin violation consistent with other observables?

Important to check effect of $\rho_0$-field on EMC effect

Definition of EMC ratio

$$R^i = \frac{F_{2A}^i}{F_{2A}^{\text{naive}}} = \frac{F_{2A}^i}{ZF_{2p}^i + N F_{2n}^i} \quad i \in \gamma, \gamma Z, \dotsc$$

Ratios equal unity in no Fermi motion and no-medium modification limit

Can PVDIS provide evidence for the $\rho_0$-field mechanism
**EMC Effect: Asymmetric Nuclear Matter**

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\[ \rho = \rho_p + \rho_n = 0.16 \text{ fm}^{-3} \]

\[ R^\gamma = \frac{F_{2A}}{F_{2A}^{\text{naive}}} \sim \frac{4}{4} \frac{u_A(x)+d_A(x)}{u_0(x)+d_0(x)}, \quad u(x) = \frac{Z}{A} u_p(x) + \frac{N}{A} u_n(x) \ldots \]

- If $\frac{Z}{N} > 1 : u(x) > d(x)$, $V_u$ increases, $V_d$ decreases
- If $\frac{Z}{N} < 1 : u(x) < d(x)$, $V_u$ decreases, $V_d$ increases

- Decreasing EMC effect for $\frac{Z}{N} > 1$
- EMC effect increases for $0.6 < \frac{Z}{N} < 1$

  - At fixed density EMC effect depends on $\frac{Z}{N}$
\( F_2^\gamma \) and \( F_2^{\gamma Z} \) EMC ratios

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\[
R_1^\gamma \sim \frac{4u_A(x)+d_A(x)}{4u_0(x)+d_0(x)} \quad \& \quad R^{\gamma Z}_1 \sim \frac{1.16u_A(x)+d_A(x)}{1.16u_0(x)+d_0(x)}
\]

- For isoscalar target \( R^\gamma = R^{\gamma Z} \) – provided \( u_A = d_A \)
$F_2^\gamma$ and $F_2^{\gamma Z}$ EMC ratios

- $R^\gamma \sim \frac{4 u_A(x) + d_A(x)}{4 u_0(x) + d_0(x)}$ & $R^{\gamma Z} \sim \frac{1.16 u_A(x) + d_A(x)}{1.16 u_0(x) + d_0(x)}$

- $\frac{Z}{N} < 1 : u_A(x) < d_A(x)$, $V_u$ decreases, $V_d$ increases

Iron ($r_{pn} = 26/30$)

$Q^2 = 5.0$ GeV$^2$
\[ F_2^\gamma \text{ and } F_2^\gamma Z \text{ EMC ratios} \]

\[ Q^2 = 5.0 \text{ GeV}^2 \]

\[ R^\gamma \sim \frac{4u_A(x)+d_A(x)}{4u_0(x)+d_0(x)} \quad \& \quad R^\gamma Z \sim \frac{1.16u_A(x)+d_A(x)}{1.16u_0(x)+d_0(x)} \]

\[ \frac{Z}{N} < 1: u_A(x) < d_A(x), \ V_u \text{ decreases}, \ V_d \text{ increases} \]

\[ \rho_0\text{-field} \implies R^\gamma Z > R^\gamma \quad \text{Model Independent} \]
PVDIS $a_1$ ratios

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- No exactly sure how to interpret these results
- After non-isoscalarity correction medium effects large
- Medium effects largely disappear if $\rho_0 = 0$
- Effect seems to reflect underlying nucleon isospin symmetry breaking

\[
a_1A = \frac{2 \sum e_q C_{1q} q_A^+(x)}{\sum e_q^2 q_A^+(x)} \approx 2.11 \frac{1.16 u_A(x) + d_A(x)}{4 u_A(x) + d_A(x)}
\]
Conclusion

- **NuTeV** $\sin^2 \Theta_W$ result one of the most important results in recent nuclear/particle physics
- Interpretation of **NuTeV** result requires detailed understanding of nuclear, hadronic and particle physics effects
- We claim nucleon isospin violation induced by $\rho_0$-field can explain 64% of **NuTeV** anomaly
- Therefore CSV $\delta m + \rho_0$ explains $\sim 100\%$ of anomaly
- Instead **NuTeV** anomaly is interpreted as evident for modification of quark wavefunctions by the nuclear medium
- The same mechanism – binding of quarks to mean scalar and vector fields – explains the EMC effect
- Predict $\gamma Z$-EMC effect smaller that $\gamma$-EMC effect
- If true – very important result for nuclear physics
Why is Transversity Interesting?

- Moments $\implies$ tensor charge
- Non-relativistic limit: $\Delta_T q(x) = \Delta q(x)$
  - $\Delta_T q(x)$ measure of relativistic effects
- Helicity conservation $\implies$ no mixing bet. $\Delta_T q$ & $\Delta_T g$
- $\Delta_T g(x) = 0$ unless $J \geq 1$.
- $\implies$ Valence quark dominated
- Important: Transverse Spin Sum

$$\int dx \Delta_T q(x) = \langle \bar{\psi}_q \gamma^+ \gamma^1 \gamma^5 \psi_q \rangle \neq \langle \psi^+_+ \gamma^0 \gamma^1 \gamma^5 \psi_+ \rangle = \Sigma_{Tq}$$

- Transversity moment $\neq$ spin of quark in $\perp$ direction.
**PVDIS $a_1$ ratios**

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**Graphs**

- Carbon
- Iron
- Lead

$Q^2 = 5.0 \text{ GeV}^2$
**PVDIS $\alpha_1$ ratios**

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**Gap Equation & Mass Generation**

- **Gap Equation:**

\[ \begin{align*}
\text{Gap Equation:} \\
\text{Self-consistent solution} \quad \text{-- gives Quark Propagator} \\
\text{Mass is generated via interaction with vacuum}
\end{align*} \]

\[ \frac{1}{p - m + i\varepsilon} \rightarrow \frac{1}{p - M + i\varepsilon} \]

\[ m_q = 0 \text{ MeV} \quad m_q = 5 \text{ MeV} \quad m_q = 50 \text{ MeV} \]
Gap Equation & Mass Generation

- **Gap Equation:**

\[ \Delta \rightarrow \Delta + \Delta \]

- **Self-consistent solution** – gives Quark Propagator

\[ \frac{1}{\not{p} - m + i\varepsilon} \rightarrow \frac{1}{\not{p} - M + i\varepsilon} \]

- **Mass is generated via interaction with vacuum**

---

**Plot:**

- Application of different masses: \( m_q = 0 \text{ MeV}, m_q = 5 \text{ MeV}, m_q = 50 \text{ MeV} \)

- Graph showing the dynamical quark mass evolution with a ratio \( G/G_{\text{crit}} \) and momentum \( p \) in [GeV].

- Rapid acquisition of mass is shown as an effect of a gluon cloud for different masses: \( m = 0 \text{ (Chiral limit)}, m = 30 \text{ MeV}, m = 70 \text{ MeV} \).
### Parameter Values

<table>
<thead>
<tr>
<th>$r_{pn}$</th>
<th>$M$</th>
<th>$M_N$</th>
<th>$\bar{M}_N$</th>
<th>$\hat{M}_N$</th>
<th>$\omega_0$</th>
<th>$\rho_0$</th>
<th>$V_u$</th>
<th>$V_d$</th>
<th>$p_{Fp}$</th>
<th>$p_{Fn}$</th>
<th>$\varepsilon_p$</th>
<th>$\varepsilon_n$</th>
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<tbody>
<tr>
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<td>331</td>
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**Table 1:** Values of the masses, mean vector fields, fermi momentum and fermi energy for and various values of $r_{pn}$, at a fixed density of $\rho_0 = 0.16 \text{ fm}^{-3}$. Note, this density is the saturation density for $r_{pn} = 1$. 
In 2002 NuTeV collaboration measured

\[ R_{PW} = \frac{\sigma (\nu \text{ Fe} \rightarrow \nu X) - \sigma (\bar{\nu} \text{ Fe} \rightarrow \bar{\nu} X)}{\sigma (\nu \text{ Fe} \rightarrow \mu^- X) - \sigma (\bar{\nu} \text{ Fe} \rightarrow \mu^+ X)} = \frac{\sigma_{NC}}{\sigma_{CC}} \]

In isoscalar limit:

\[ R_{PW}^{N=Z} \to \frac{1}{2} - \sin^2 \Theta_W \]

After “standard” isoscalarity correction, NuTeV found

\[ R_{PW} = 0.2723 \implies \sin^2 \Theta_W = 0.2277, \text{ (S. M. } \sin^2 \Theta_W = 0.2227) \]


However important isoscalarity correction missing

For \( Z \neq N \), isovector-vector field, \( \rho^0 \neq 0 \)

\[ u_p(x) \neq d_n(x) \text{ and } d_p(x) \neq u_n(x) \text{ in-medium} \]
Assumptions:

- Heavy quark momentum fractions equal zero
- Isospin (charge) symmetry preserved
  \[ u_A^- = d_A^- \implies u_p(x) = d_n(x), \quad d_p(x) = u_n(x) \]
- No higher twist effects

Corrections at LO for \( N = Z \):

\[
\Delta R_{PW} \propto \left[ \frac{1}{2} \left( \langle x \delta u_V \rangle - \langle x \delta d_V \rangle \right) + \langle x (c - \bar{c}) \rangle - \langle x (s - \bar{s}) \rangle \right]
\]

\[
\delta q_V(x) = u^P_V(x) - d^V_n(x), \quad \langle q(x) \rangle \equiv \int_0^1 dx \ q(x).
\]
**Sum Rules**

- **Baryon Number and Momentum**

\[ \int dx \, q_v(x) = N_q, \quad \int dx \, x [u(x) + d(x) + \ldots] = 1 \]

- **Spin Sum: spin carried by quarks**

\[ \int dx \, [\Delta u(x) + \Delta d(x) + \ldots] = \Sigma_q \]

- **Nucleon axial & tensor charges**

\[ g_A = \Delta u - \Delta d, \quad g_T = \Delta_T u_v - \Delta_T d_v, \]

- **Satisfy positivity constraints and Soffer bound**

\[ \Delta q(x), \Delta_T q(x) \leq q(x), \quad q(x) + \Delta q(x) \geq 2 |\Delta_T q(x)| \]
$q_A^{JH}(x_A) = \sum_{\kappa,m} \int dy_A \int dx \, \delta(x_A - y_A x) \, f_{\kappa,m}^{(JH)}(y_A) \, q_\kappa(x)$

$q^{(JK)}(x) \equiv \sum_H (-1)^{J-H} \sqrt{2K + 1} \left( \begin{array}{ccc} J & J & K \\ H & -H & 0 \end{array} \right) q^{JH}(x)$
Shell Model: Nucleon distribution functions

- Relativistic single particle shell model
- Nucleon distribution functions

\[ f_{\kappa m}(y_A) = \frac{\sqrt{2} M_N}{A} \int \frac{d^3 p}{(2\pi)^3} \delta(p^3 + \varepsilon_\kappa - M_N y_A) \bar{\Psi}_{\kappa m}(\vec{p}) \gamma^+ \Psi_{\kappa m}(\vec{p}), \]

- Central Potential Dirac eigenfunctions

\[ \Psi_{\kappa m}(\vec{p}) = (-i)^\ell \begin{bmatrix} F_\kappa(p) \Omega_{\kappa m}(\theta, \phi) \\ -G_\kappa(p) \Omega_{-\kappa m}(\theta, \phi) \end{bmatrix}, \]

- Dirac Equation

\[ \left[ -i \vec{\alpha} \cdot \vec{\nabla} + \beta [M(r) - V_s(r)] + V_v(r) \right] \psi_\kappa(r) = \varepsilon_\kappa \psi_\kappa(r) \]

- Assume Wood-Saxon scalar and vector potentials.
Nucleon distributions: $^{28}\text{Si}$

- Theme
- EMC Effect
- NuTeV anomaly
- NJL model
- Nucleon . . .
- Quark Dis.
- NJL Quark Dis.
- Nuclear Matter
- NM Quark Dis.
- NuTeV anomaly
- Vector Potential
- EMC effect
- PVDIS $a_1$ ratios
- Conclusion
Quark distributions in $^{27}$Al

- Theme
- EMC Effect
- NuTeV anomaly
- NJL model
- Nucleon . . .
- Quark Dis.
- NJL Quark Dis.
- Nuclear Matter
- NM Quark Dis.
- NuTeV anomaly
- Vector Potential
- EMC effect
- PVDIS $\alpha_1$ ratios
- Conclusion
Multipole distributions in $^{27}$Al

- Theme
- EMC Effect
- NuTeV anomaly
- NJL model
- Nucleon...
- Quark Dis.
- NJL Quark Dis.
- Nuclear Matter
- NM Quark Dis.
- NuTeV anomaly
- Vector Potential
- EMC effect
- PVDIS $a_1$ ratios
- Conclusion

- Higher multipole quark distributions encapsulate difference from system of nucleons at rest
Probability for find bare quark: \[ Z_q = 1 + \frac{\partial \Sigma_q}{\partial \psi} \]

Pion cloud → anomalous m.m for constituent quarks.

\[
F_{1q}(Q^2) = Z_q \left( \frac{1}{6} F_\omega + \frac{1}{2} \tau_3 F_\rho \right) + (F_\omega - \tau_3 F_\rho) F_{1q}^{(q)} + \tau_3 F_\rho F_{1q}^{(\pi)}
\]

\[
F_{2q}(Q^2) = (F_\omega - \tau_3 F_\rho) F_{2q}^{(q)} + \tau_3 F_\rho F_{2q}^{(\pi)}
\]

Self-consistent pion cloud

However no pion exchange between quarks

Better to add pion at nucleon level
Future Directions

- Important to perform calculation for nuclei
- Need model for nucleus in terms of quark d.o.f.
- Completed naive relativistic “single-particle” shell model
  - Used Wood-Saxon scalar and vector potentials
  - Local density approximation for each nucleon orbital
  - Use NJL model to translate into fields felt by quarks
  - Calculate medium modified quark distributions
  - Good description of EMC effect in $N \sim Z$ nuclei
- Working on self-consistent model with $\sigma$, $\omega$, $\rho$ and Coulomb fields
- Interplay between Coulomb and $\rho$-field potentially important for correct $A$-dependence of EMC effect
EMC ratio $^7\text{Li}$

- Theme
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- Conclusion

\[ Q^2 = 5 \text{ GeV}^2 \]
EMC ratio $^7\text{Li}$, $^{11}\text{B}$, $^{15}\text{N}$ and $^{27}\text{Al}$

- Theme
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Nuclear Matter

- Theme
- EMC Effect
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$Q^2 = 10.0 \text{ GeV}^2$

$\rho = 0.16 \text{ fm}^{-3}$

Is there medium modification

- Theme
- EMC Effect
- NuTeV anomaly
- NJL model
- Nucleon . . .
- Quark Dis.
- NJL Quark Dis.
- Nuclear Matter
- NM Quark Dis.
- NuTeV anomaly
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- EMC effect
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- Conclusion

![Graph showing EMC Ratios for $^{27}\text{Al}$](image)

Experiment: $^{27}\text{Al}$

- Unpolarized EMC effect
- Polarized EMC effect

$Q^2 = 5 \text{ GeV}^2$
Is there medium modification

- Theme
- EMC Effect
- NuTeV anomaly
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$Q^2 = 5 \text{ GeV}^2$

**27Al**

![Graph showing EMC Ratios](image)

- Unpolarized EMC effect
- Polarized EMC effect

**Experiment:** $^{27}\text{Al}$

Mathematical equations and data points are shown on the graph.
The NuTeV anomaly

- In 2001 NuTeV collaboration, using $\nu$ DIS, measured:
  - $\sin^2 \theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$

- World average (not including NuTeV):
  - $\sin^2 \theta_W = 0.2227 \pm 0.0004$

- 3 $\sigma$ discrepancy!!! $\Rightarrow$ “NuTeV anomaly”

- Fermilab press conference 7th Nov 2001:
  - “3 $\sigma$ discrepancy $\Rightarrow$ 99.75% probability $\nu$ are not like other particles . . . only 1 in 400 chance that our measurement is consistent with prediction” – MacFarland

- Huge amount of experimental & theoretical interest:
  - $\sim$370 citations as of November 2008

- No universally accepted complete explanation
New Physics Explanations

- Explain anomaly – but leave other quantities unchanged
- Detailed discussion beyond S.M. see:
  S. Davidson, S. Forte, P. Gambino, N. Rius and A. Strumia, JHEP 0202, 037 (2002)
- MSSM: corrections have wrong sign and are too small
- Heavy $Z'$ boson – unmixed with $Z$
  Maybe: but muon $g - 2$ places tight constraints
- Leptoquarks – carry both lepton and baryon number
  Can explain anomaly, but with fine tuning
- Unparticles – seem to be able to explain most things
- Probably wise to first consider S.M. explanations
Paschos-Wolfensteinn Ratio

- Paschos-Wolfensteinn ratio given by

\[ R_{PW} = \frac{\sigma [\nu A(N, Z) \rightarrow \nu X] - \sigma [\bar{\nu} A(N, Z) \rightarrow \bar{\nu} X]}{\sigma [\nu A(N, Z) \rightarrow \mu^- X] - \sigma [\bar{\nu} A(N, Z) \rightarrow \mu^+ X]} \]

- Expressing \( R_{PW} \) in terms of quark distributions:

\[ R_{PW} = \frac{\left( \frac{1}{6} - \frac{4}{9} \sin^2 \Theta_W \right) \langle x u^-_A + x c^-_A \rangle + \left( \frac{1}{6} - \frac{2}{9} \sin^2 \Theta_W \right) \langle x d^-_A + x s^-_A \rangle}{\langle x d^-_A + x s^-_A \rangle - \frac{1}{3} \langle x u^-_A + x c^-_A \rangle} \]

- Valence quarks only: \( q^- = q - \bar{q}, \quad \langle q \rangle \equiv \int dx \, q(x) \)

- Recall: \( q_A(x) \) is probability to find quark of flavour \( q \) with momentum fraction \( x \) of target \( A \)

- Sum rules:

\[ \langle u^-_A \rangle = 2Z + N, \quad \langle d^-_A \rangle = Z + 2N, \quad \langle s^-_A \rangle = \langle c^-_A \rangle = 0 \]
\[ \langle x \left( u_A + \bar{u}_A + d_A + \bar{d}_A + \ldots \right) \rangle = 1 \]
Recall

\[ R_{PW} = \left( \frac{1}{6} - \frac{4}{9} \sin^2 \Theta_W \right) \left( x u_A^+ + x c_A^- \right) + \left( \frac{1}{6} - \frac{2}{9} \sin^2 \Theta_W \right) \left( x d_A^- + x s_A^- \right) \]

\[ \frac{\left( x d_A^- + x s_A^- \right)}{\left( x u_A^+ + x c_A^- \right)} \]

For isoscalar target (i.e. \( N = Z \)) \( R_{PW} \) becomes

\[ R_{PW}^{N=Z} \xrightarrow{N=Z} \frac{1}{2} - \sin^2 \Theta_W + \delta R_{PW}^A + \delta R_{PW}^{QCD} + \delta R_{PW}^{EW} \]

Assumptions:
- (1) Heavy quark momentum fractions equal zero
- (2) Isospin (charge) symmetry preserved

\[ u_A^- = d_A^- \Rightarrow u_p = d_n, \; d_p = u_n \]

(1) Likely false — \( \langle x s_A^- \rangle \gtrsim 0 \)

(2) Very likely false — quark mass and nuclear effects
In 2001 NuTeV collaboration, using $\nu$ DIS, measured:

\[ R^\nu = \frac{\sigma[\nu \text{Fe} \to \nu X]}{\sigma[\nu \text{Fe} \to \mu^- X]}, \quad R^\bar{\nu} = \frac{\sigma[\bar{\nu} \text{Fe} \to \bar{\nu} X]}{\sigma[\bar{\nu} \text{Fe} \to \mu^+ X]} \]

Monte-Carlo to obtain:

\[ R_{PW} = \frac{\sigma^{\nu \text{Fe}}_{NC} - \sigma^{\bar{\nu} \text{Fe}}_{NC}}{\sigma^{\nu \text{Fe}}_{CC} - \sigma^{\bar{\nu} \text{Fe}}_{CC}} \]

LO radiative corrections applied; NLO small

Fe target has 5.74% neutron excess: $\delta N \equiv \frac{1}{A}(A - 2Z)$

- Need non-isoscalarity correction
- Applied assuming protons/neutrons are free
- Therefore no medium effects (c.f. EMC effect)

Using $R_{PW}^{N=Z} \rightarrow \frac{1}{2} - \sin^2 \Theta_W$ NuTeV obtain:

\[ \sin^2 \theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst}) \]
Standard Model Corrections

- Need to account for $\Delta R_{PW} = 0.0050$

- (1) Heavy quark effects
  - Non-perturbative strange quark distributions
  - NNLO perturbative $\langle x s_A^- \rangle$
  - $\langle x c_A^- \rangle \approx 0$ or very small

- (2) Isospin violation effects
  - Charge symmetry violation effects from $m_u \neq m_d$
  - Charge symmetry violation from nuclear effects
  - High twist effects
  - QED splitting – changes quark distribution evol.

- Corrections at LO

$$\Delta R_{PW} \propto \frac{1}{\langle x u_A^- + x d_A^- \rangle} \left[ \langle x u_A^- - x d_A^- \rangle + \langle x c_A^- \rangle - \langle x s_A^- \rangle \right]$$
Strange Quark Contribution to PW Ratio

Strange quark correction to PW ratio is:

$$\Delta R_{PW}^s \simeq - \left(1 - \frac{7}{3} \sin^2 \Theta_W\right) \frac{\langle x s_A \rangle}{\langle x u_A + x d_A \rangle}$$

- Baryon number \(\Rightarrow \int_0^1 dx [s(x) - \bar{s}(x)] = 0\)
- However momentum fractions are not constrained
- Example of non-perturbative mechanism

\[K = q\bar{s}, \quad \Lambda, \Sigma = qqs, \quad \text{where} \quad m_K < M_{\Lambda,\Sigma}\]

Therefore \(\Rightarrow \int_0^1 dx x [s(x) - \bar{s}(x)] > 0\)

Strange quarks should reduce NuTeV anomaly
Strange Quark Contribution: Experiment

- Theme
- EMC Effect
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  - $-0.001 < \langle x \, s^- \rangle < 0.004 \rightarrow \langle x \, s^- \rangle = 0.0017$

- NuTeV find: $\langle x \, s^- \rangle = 0.00176 \pm 0.00043$

- Conclusion: $\langle x \, s^- \rangle$ may account for 0–25% of anomaly

- Theory: $\langle x \, s^- \rangle$ accounts for 10-20% of anomaly


**Charge Symmetry Violation in Free Nucleon**

- CSV results from: $\delta m = m_d - m_u \sim 4\text{MeV}$
- Nucleon charge (isospin) symmetry broken:
  - $\Leftrightarrow u_p \neq d_n \& d_p \neq u_n$
- PW ratio CSV correction:
  \[ \Delta R_{PW}^{CSV} \simeq \left(1 - \frac{7}{3} \sin^2 \Theta_W \right) \frac{\langle x u_A - x d_A \rangle}{\langle x u_A + x d_A \rangle} \]
- What do we expect? Consider deuteron:
  - $m_u < m_d \implies \langle x u_A \rangle < \langle x d_A \rangle$
- Expect negative $\Delta R_{PW}^{CSV} \implies$ CSV reduces anomaly
Proton-neutron CSV has been studied

Theory and parametrizations in excellent agreement


\[
\langle x u_p^- \rangle < \langle x d_n^- \rangle \quad \& \quad \langle x u_n^- \rangle < \langle x d_p^- \rangle
\]

Nucleus sum of free protons & neutrons:

\[
\Rightarrow \Delta R_{PW}^{CSV} \propto \langle x \delta u_V - x \delta d_V \rangle \sim -(0.0014 - 0.0017)
\]

CSV reduces anomaly by about \(\sim 30\%\)
Nuclear Effects

- **NuTeV non-isoscalarity** ($N \neq Z$) correction is large: 0.0080
- Many nuclear corrections may be missing in NuTeV non-isoscalarity correction
- Potentially very important – compare EMC effect
- Important effects include: Fermi motion, nuclear binding, nuclear shadowing
- Detailed discussion see:
- Fermi motion and nuclear shadowing seem to cancel
- Conclusion: “Traditional” nuclear effects unlikely to explain anomaly
Current Status

- A lot of experimental and theoretical work has been done
- Corrections to $R_{PW}$ are small → experimentally challenging, large relative errors
- Best guess is that strange quarks and CSV from quark mass differences can explain $\sim$20–60% of anomaly
- Traditional nuclear corrections seem small
- What about modification of quark wavefunctions by the nuclear medium?
- EMC effect provides strong evidence these effects must exist
- Can medium modification of the nucleon explain the NuTeV anomaly?