The Structure of the Neutron and the BoNuS experiment

Gabriel Niculescu
James Madison University
Baryons 2016
Motivation

**Probing the longitudinal structure of the nucleon (in 7 easy steps!):**

- Take a nucleon. Move it real fast along z. Def. l.c. mom.: \( P_+ = P_0 + P_z \) (\( \gg M \))
- Hit a "parton" (q, g, ...) inside with a lepton of your choice…
- Measure its l.c. momentum: \( p_+ = p_0 + p_z \) (\( m \approx 0 \))
- Def. the Momentum Fraction: \( \xi = p_+ / P_+ \)
- In DIS: \( x \approx (q_z - n) / M \approx x_{Bj} = Q^2 / 2Mn \) (in the target rest frame)

**Probability:**

\[
F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x)
\]

- Because of spin-1/2: 2nd sf \( F_2(x) \)
  
\( ^\ast )\) Advantage: Boost-independent

---

Gabriel Niculescu – Baryons 2016, FSU
\[
\frac{d\sigma}{d\Omega dE} = \sigma_{\text{Mott}} \left( \frac{F_2(x)}{\nu} + 2\tan^2 \frac{\theta_e}{2} \frac{F_1(x)}{M} \right); \quad F_2(x, Q^2) = x \sum_{f=\text{up, down, ...}} z_f^2 \left( q_f(x, Q^2) + \bar{q}_f(x, Q^2) \right)
\]

**Motivation**

\[F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x)\]

So sf give access to PDFs!

\(q_f(x \to 1)\) for both nucleons is a crucial test of valence quark models

- Isospin, SU(6) breaking, pQCD,…
- Precise PDFs at large \(x\) needed as input for LHC, neutrino experiments, etc.
  - Large \(x\), medium \(Q^2\) evolves to medium \(x\), large \(Q^2\)
  - Also: NUCLEAR structure functions
- Moments can be directly compared with OPE (twist expansion), Lattice QCD and Sum Rules
  - All higher moments are weighted towards large \(x\)
- Quark-Hadron Duality

\[M_n^{\text{CN}}(Q^2) = \int_0^\infty dx x^{n-2} F_2(x, Q^2) = \sum_{\tau=2k}^{\infty} E_{\tau\tau}(\mu, Q^2) O_{\tau\tau}(\mu) \left( \frac{\mu^2}{Q^2} \right)^{1/2(\tau-2)} + \text{TM corr.}\]
Behavior of PDFs still unknown for \( x \to 1 \)

- \( SU(6) \): \( \frac{d}{u} = \frac{1}{2} \), \( \Delta \frac{u}{u} = \frac{2}{3} \), \( \Delta \frac{d}{d} = -\frac{1}{3} \) for all \( x \)
- Relativistic Quark model: \( \Delta u \), \( \Delta d \) reduced
- Hyperfine effect (1-gluon-exchange): Spectator spin 1 suppressed, \( \frac{d}{u} \to 0 \), \( \Delta \frac{u}{u} \to 1 \), \( \Delta \frac{d}{d} \to -\frac{1}{3} \)
- Helicity conservation (pQCD): Spectator spin \( S_z \neq 0 \) suppressed, \( \frac{d}{u} \to 1/5 \), \( \Delta \frac{u}{u} \to 1 \), \( \Delta \frac{d}{d} \to 1 \)
- Orbital angular momentum: can explain slower convergence to \( \Delta \frac{d}{d} = 1 \)

Plenty of data on proton \( \to \) mostly constraints on \( u \) and \( \Delta u \)

Knowledge on \( d \) limited by lack of free neutron target (nuclear binding effects in \( d \), \( ^3\)He)

Large \( x \) requires very high luminosity and resolution; binding effects become dominant uncertainty for the neutron
Motivation  BoNuS  Results  Outlook

d/u (x → 1) ...

Assuming charge independence
(= invariance under $180^\circ$ rotations in isospin space):

\[
\frac{F_{2n}}{F_{2p}} \approx \frac{1 + 4d/u}{4 + d/u} \Rightarrow
\]

\[
d \approx \frac{4 F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}
\]

\[
F_{2n}/F_{2p} = F_{2d}/F_{2p} - 1 ???
\]

Neutron data limited by “Nuclear Binding Uncertainties”

Gabriel Niculescu – Baryons 2016, FSU
**Motivation**

**To access d/u...**

- Use both charged and neutral lepton probes. Possible processes: W/Z production, PV DIS, charge exchange...
  - The cleanest, most direct approach.
  - No charge symm. assumptions
  - Limitation in stat. precision
- Use different targets, i.e. p & n
  - Free neutrons decay.
  - Impossible to make a dense target.
- Alternatives: use weakly bound nuclei (d) and/or Mirror nuclei (3He, 3H)

**Nuclear Model uncertainties:** (Fermi motion, off-shell effects (binding), structure modifications (EMC effect), extra pions/Deltas, coherent effects, 6-quark bags...)

---

**BoNuS Results**

**Outlook**

- Magnetic bottle: $10^3 - 10^4$ n/cm² [TU München]
- Typical proton target: $4 \cdot 10^{23}$ p/cm² [10 cm LH] $10^{14}$ p/cm² [HERMES]

---

*Gabriel Niculescu – Baryons 2016, FSU*
For example...

→ using off-shell model, will get *larger* neutron  
   *cf. light-cone* model

→ but will get *smaller* neutron *cf. no nuclear effects*  
   or *density* model

Even Fermi motion corrections become large at large $x$. 
Alternative: Spectator Tagging

\[ d(e,e'p_s)X \]

\[ p_n = (M_D - E_S, -\vec{p}_S); \quad \alpha_n = 2 - \alpha_S \]

\[ M^*^2 = p_{n\mu}^\mu p_{n\mu}^\mu \]

**Motivation**

**BoNuS**

**Results**

**Outlook**

\[ x = \frac{Q^2}{2p_n^\mu q_\mu} \approx \frac{Q^2}{2M\nu(2-\alpha_S)} \]

\[ W^*^2 = (p_n + q)^2 = M^*^2 + 2((M_D - E_S)\nu - \vec{p}_n \cdot \vec{q}) - Q^2 \]

\[ \approx M^*^2 + 2M\nu(2-\alpha_S) - Q^2 \]
Motivation BoNuS Results Outlook

Spectator Tagging Limitations


Finite coverage of WF

Final State Interactions

BoNuS Results

EIC

“BoNuS”

“Deeps”

Binding Effects

$R_n \equiv F_2^{(\text{eff})}(W^2, Q^2, p^2)/F_2^n(W^2, Q^2)$
Motivation

BoNuS

Results

Outlook

Spectator Tagging. Enter: BoNuS

BoNuS

Gas

Electron

Multiplier

Helium/DME at 80/20 ratio

Thin Al-Mylar Window

Thin Al-Mylar Cathode

3 GEMs

Readout pad and electronic

Drift Region

7 atm $D_2$ gas

Thin-wall High Pressure Gas Target

Møller el.

e$^-$ to CLAS

CLAS

backwards
**BoNuS RTPC**

Gas

Electron Multiplier

**Motivation**

**BoNuS Results**

**Outlook**

---

**BoNuS RTPC**

7 atm $D_2$ gas

Møller el. $e^-$ (to CLAS)

dE/dx from charge along track (particle ID)

---

**Helium/DME at 80/20 ratio**

- Thin Al Mylar Window
- Thin Al Mylar Cathode
- Gain Stage
- OEM (Gas Electron Multiplier)
- Readout Electric (pads)
- Readout Connections

---

Did it work?

Motivation

BoNuS Results

Outlook

F2

F2n

F2p

FSI: Cosyn et al.

EMC Ratio

Duality

Gabriel Niculescu – Baryons 2016, FSU
**BoNuS: Truncated Moments**

Motivation

BoNuS Results

Outlook

![Graph showing truncated moments](image-url)
Motivation

BoNuS: FSI

Results

Outlook

**BoNuS: FSI**

**FSI: Cosyn et al.**

\[
R = \text{ratio of tagged SF in } d(e,e'p) \text{ to “free” n SF, vs. momentum and angle (relative to } q \text{ vector) of spectator } p_s
\]

**Beam = 4 GeV, } q^* = 1.66 \text{GeV}^***
...in the not so distant future...

BoNuS12: E12-06-113

- One of the “Flagship” 12 GeV-era experiments!
- Data taking of 35 days on D₂ and 5 days on H₂ with
  \[ L = 2 \cdot 10^{34} \text{ cm}^2 \text{ sec}^{-1} \]
- Planned BoNuS detector DAQ and trigger upgrade
- DIS region with
  - \[ Q^2 > 1 \text{ GeV}^2/\text{c}^2 \]
  - \[ W *> 2 \text{ GeV} \]
  - \[ p_s > 70 \text{ MeV/ c} \]
  - \[ 10^\circ < \theta_{pq} < 170^\circ \]
- Extend to higher momenta using central detector alone

Gabriel Niculescu – Baryons 2016, FSU
Motivation     BoNuS     Results     Outlook

Plans for “12” GeV

BoNuS12 E12-06-113

- Replaces SiVtx and micro-megas barrel trackers
- Trigger rate about 2 KHz
- 18,000 “pads” read out at 5MHz over 10 µs
  1-2 mm radial spacing, 4 cm in z, 2 degrees in
  phi => Fully reconstructed track in 3D,
  suppression of < 5 MHz background through
  timing and vertex cuts
- Readout electronics: “DREAM” chip (Saclay)

- Full GEANT-4 MC based on
  CLAS12 GEMC
- < 4% p resolution
- < 2mm vertex resolution

Gabriel Niculescu – Baryons 2016
**Expected Results**

**Dark Symbols:** $W^* > 2$ GeV ($x^*$ up to 0.8, bin centered $x^* = 0.76$)

**Open Symbols:** “Relaxed cut” $W^* > 1.8$ GeV ($x^*$ up to 0.83)

*Gabriel Niculescu – Baryons 2016, FSU*
The future: JLab at 11 GeV

Projected 12 GeV d/u Extractions

- CJ12 - PDF + nucl uncert.
- BigBite $^3$H/$^3$He DIS
- CLAS12 BoNuS
- CLAS12 BoNuS, relaxed cuts
- SoLID PVDIS

Gabriel Niculescu – Baryons 2016, FSU
The more distant future: EIC

Structure function of conditional DIS \( e + D \rightarrow e' + p + X \)

Recoil LC fraction \( \alpha_R = 0.98 - 1.02 \)
\( 1.02 - 1.06 \)
\( 1.06 - 1.10 \)

MEIC simulation
Int. luminosity \( 10^6 \text{ nb}^{-1} \)
CM energy \( s_{eN} = 1000 \text{ GeV}^2 \)
\( x = 0.04 - 0.06, \quad Q^2 = 30 - 40 \text{ GeV}^2 \)

Kinematic limit

\( M_N^2 - t \) from recoil momentum [GeV^2]

\( F_{2D} \times (M_N^2 - t)^2 / (\text{residue})^2 \)

\( \gamma \) quads

Forward angle trackers
Roman pots

Central detector with endcaps

\( \gamma \) quads

Small-angle hadron detection

IP
Far forward hadron detection

\( n_z \)

Low-\( Q^2 \) electron detection

50 mrad beam (crab) crossing angle

Large-aperture electron quads

\( p \)
Motivation  BoNuS  Results  Outlook

Quo Vadis?

**Coincident spectator proton data is here!**
- FSI important in fwd, perp. kinematics.
- “simple spectator” picture works well at low mom, bwd angles.
- Modifications of internal n structure (mom. dependent) still an open question.
- First results on “free” neutron: SF, moments, duality, binding effects in d.
- Data mining on existing 6 GeV data sets ongoing.

**Lots more exciting experiments beginning with energy upgraded JLab!**
- $F_{2n}$ out to $x = 0.8$
- Detailed test of momentum-dependence of EMC effect

**Need to develop advanced models to minimize & correct for:**
- in-medium effects and FSI.

**ULTIMATE GOAL: EIC - smoothly map out $p_{\text{spect.}}$ from 0 to 1 GeV/c.**