Measurement of the neutron charge radius through the study of the nucleon excitation

A proposal for Jlab PAC49

A. Camsonne, M. Jones, M. Paolone, N. Sparveris

H. Atac, A. Atencio, B. Duran, S. Jia, R. Li, M. Nycz, N. Sparveris (spokesperson)
Temple University, Philadelphia, PA 19122, USA

Argonne National Laboratory, Lemont, IL 60439, USA

A. Camsonne (spokesperson), J.-P. Chen, S. Covrig Dusa, M. Diefenthaler, D. Higinbotham

M. K. Jones (spokesperson), D. Meekins, B. Sawatzky, G. Smith, A. Tadepalli, S. Wood
Temple Jefferson National Accelerator Facility, Newport News, VA, USA

M. Paolone (spokesperson), M. Sievert
New Mexico State University, Las Cruces, NM, USA

M. Katramatou, G. Petratos
Kent State University, Kent, OH 44240, USA

W. Lin, R. Gilman, O. Yeung
Rutgers University, Piscataway, NJ 08855, USA

A. Christopher, T. Gautam, M. Kohl, J. Nazeer, T. Patel, M. Rathnayake, M. Suresh
Hampton University, Hampton, Virginia 23668, USA

M. Mihovilović, S. Širca
University of Ljubljana, Slovenia Jožef Stefan Institute, 1000 Ljubljana, Slovenia

N. Kalantarians
Virginia Union University, VA 23220, USA

P. Markowitz
Florida International University, FL USA

E. Brash
Christopher Newport University, VA 23606, USA

A. Puckett
University of Connecticut, CT 06269, USA

D. Androi
University of Zagreb, Zagreb, Croatia

M. Elaasar
Southern University at New Orleans, LA 70126, USA

A. Mkrtchyan, H. Mkrtchyan, V. Tadevosyan
A.I. Alikhanyan National Science Laboratory, Yerevan Physics Institute, Armenia

G. Niculescu, I. Niculescu
James Madison University, VA 22807, USA

D. Byer, H. Gao, B. Karki, V. Khachatryan, G. Matousek, E. Nieuwenhuizen

A. Smith, B. Yu, Z. Zhao, J. Zhou
Duke University and Triangle Universities Nuclear Laboratory, NC 27708, USA
Primary Physics Goals

- **Proton N-Δ Transition Form Factors (TFFs):**
  - JLab has invested significantly to the physics program of the N-Δ TFFs, with multiple experiments (in Halls A, B, and C).
  - TFFs have been measured up to $Q^2=6$ GeV$^2$
    Here we aim to push the limits of the low $Q^2$, where the mesonic cloud dynamics is predicted to be dominant and rapidly changing
  - Test bed for ChEFT and LQCD calculations
  - Can constrain systematics from 1/Nc and BChPT calculations

- **Neutron charge radius:**
  - One of the system’s most basic properties.
  - Measured with only one (rather indirect) method.
  - World data exhibit tensions. Underestimated systematics.
  - Cross checking with a different method, whenever nature allows a path for it, is a scientific obligation.
The dominant transition from proton to delta involves a dipole (M1) transition (spherical S-wave proton WF -> spherical S-wave Delta WF)
There also exists a quadrupole (E2 or C2) transition from proton to delta. (non-spherical proton WF -> non-spherical Delta WF)
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The quadrupole to dipole ratio (E2/M1 or C2/M1) is non-zero... Why?

EMR       CMR
There also exists a quadrupole (E2 or C2) transition from proton to delta. (non-spherical proton WF -> non-spherical Delta WF)

The quadrupole to dipole ratio (E2/M1 or C2/M1) is non-zero... Why?

Non-central (tensor) interactions between valence quarks and relativistic corrections can account for some of the spherical deviation, but not all...
There also exists a quadrupole (E2 or C2) transition from proton to delta.
(non-spherical proton WF -> non-spherical Delta WF)

Proton (938 MeV)  γ*, E2, C2  Delta (1232 MeV)

The quadrupole to dipole ratio (E2/M1 or C2/M1) is non-zero... Why?

The dynamics of a meson cloud are important to describe the structure of the nucleon:
The nucleon structure directly relates to the nucleon radius.
How does the N-Δ transition provide information on the neutron?

- The neutron has a non-zero charge radius:
  - Measurements of the neutron scattering length show a net negative charge radius for a neutral object: how? \( \langle r_n^2 \rangle_{\text{PDG}} = -0.1161 \pm 0.0022 \)
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  - One interpretation includes a spin-1 dd diquark configuration:
    - Not adequate to describe the magnitude of the charge radius from measurement!

\[
\langle r_n^2 \rangle \sim -0.06
\]

Charge Distribution using measured \( b_{\text{ne}} \)
How does the N-Δ transition provide information on the neutron?

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  - Including the two-body exchange currents (valence + pion cloud) can describe the measurements. [Buchmann, Phys. Rev. Lett. 93, 212301 (2004) ]

\[ \langle r_n^2 \rangle \sim -0.11 \] using measured \( b_n \)
How does the $N$-$\Delta$ transition provide information on the neutron?

- The neutron has a non-zero charge radius:
  - Measurements of the neutron scattering length show a net negative charge radius for a neutral object: how? $\langle r_n^2 \rangle_{\text{PDG}} = -0.1161 \pm 0.0022$
  - One interpretation includes a spin-1 dd diquark configuration:
    - Not adequate to describe the magnitude of the charge radius from measurement!
  - Including the two-body exchange currents (valence + pion cloud) can describe the measurements. [Buchmann, Phys. Rev. Lett. 93, 212301 (2004)]
    - This same procedure can simultaneously describe the magnitude of the $N$-$\Delta$ TFFs!

$\langle r_n^2 \rangle \sim -0.11$ using measured $b_{\text{ne}}$
How does the N-Δ transition provide information on the neutron?

Through quadrupole N-Δ transition measurements, we can learn about neutron charge radius!

- The connection "relies only on the spin-flavor structure of the wave functions and operators involved, i.e., only on general algebraic properties of the quark model and not on specific assumptions, such as values for quark masses, coupling constants, etc." (Buchmann 2010)
- Derived initially through the framework of a non-relativistic constituent quark model, but also re-derived via a general SU(6) symmetry-breaking analysis and 1/Nc operator expansion!
N-Δ transition as a pathway to nucleon structure

Theoretical calculation of the mesonic cloud contribution to CMR

\[ \text{CMR} = \frac{C_2}{M_1} \]

Quark-core

π-cloud

\[ \text{SL (full vs bare)} \]

\[ \text{C2} \]

\[ \text{M1} \]

LFRQM
Aznauryan & Burkert
PRC92,035211 (2015)

Signature of pion cloud

Dominant role of mesonic d.o.f. at large distance scale:
Mesonic cloud ~ 50% of the quadrupole amplitude magnitude & 1/3 of the magnetic dipole strength
N-Δ transition as a pathway to nucleon structure

Low $Q^2$ region is poorly measured and can provide precision leverage for determining mesonic cloud contributions.

Can also help constrain uncertainties within a theoretical framework that combines Chiral Perturbation Theory with the 1/Nc expansion [Phys.Rev.D 101 (2020) 5, 054026]

In this region, one can study the interplay of the two dynamical scales in the baryon form factors.
Our current understanding of the neutron charge radius

The value of \(< r_n^2 >\) is based on one method of extraction → measurement of \(b_{ne}\) using Pb, Bi, ...(very indirect method)

- Some details on the PDG compiled neutron radius:
  - Most recent measurements over 2 decades old.
  - Some world data is omitted.
  - Input data shows significant tension
  - Simply averaging data with significant discrepancies can be misleading.

The world data results essentially come from two research groups: Gartching-Argonne and Dubna
With a 5\(\sigma\) tension between them!!!

Our current understanding of the neutron charge radius

The value of $< r_n^2 >$ is based on one method of extraction → measurement of $b_{ne}$ using Pb, Bi, ...(very indirect method)

The same methodology is used in each group's radius extraction: a measurement of $b_{ne}$

A $5\sigma$ discrepancy most likely implies an underestimation of systematic uncertainty associated with the methodology

\[ < r_n^2 > = 3 (m_e a_0 / m_n) b_{ne} \]
An alternative method to measure the neutron charge radius

If one can measure with precision $G_E^n(Q^2 \to 0)$, one can determine the neutron charge radius.

Doing such would provide an alternative path to the charge radius, and provide an important cross-check to the existing measurements. (And could reveal surprises!)

\[
\langle r_n^2 \rangle = -6 \left. \frac{dG_E^n(Q^2)}{dQ^2} \right|_{Q^2 \to 0}
\]
An alternative method to measure the neutron charge radius

Historical $G_E^n$ measurements:
- No truly "free" neutron target
- Polarized $^2$H, $^3$He targets & polarized electron beam
- Quasi-elastic electron scattering
- Double polarization observables

A fit is needed for $Q^2 \to 0$
- Relies on precision of measurements
- ... and on how close measurements are to $Q^2 = 0$
A path to extend our low $Q^2$ reach for $G^n_E$

Large-$N_c$ Relations (Pascalutsa & Vanderhaeghen)

\[ \frac{E^2}{M_1} (Q^2) = \left( \frac{M_N}{M_\Delta} \right)^{3/2} \frac{M_\Delta^2 - M_N^2}{2Q^2} \frac{G^n_E (Q^2)}{F^n_p (Q^2) - F^n_n (Q^2)} \]

\[ \frac{C^2}{M_1} (Q^2) = \left( \frac{M_N}{M_\Delta} \right)^{3/2} \frac{Q_+ Q_-}{2Q^2} \frac{G^n_E (Q^2)}{F^n_p (Q^2) - F^n_n (Q^2)} \]

- Large-$N_c$ relations:
  - Carry about 15% theoretical uncertainty.
  - Two relations (CMR and EMR) can be used to cross-check validity.
A path to extend our low $Q^2$ reach for $G^n_E$

A. J. Buchmann

\[
\frac{G^n_E(Q^2)}{G^n_M(Q^2)} = \frac{Q}{|q|} \frac{2Q}{M_N} \frac{1}{n_b(Q^2)} \frac{C2}{M1} (Q^2)
\]

- **Buchmann SU(6) form:**
  - Ratios are related due to the underlying spin-flavor symmetry and its breaking by spin-dependent two- and three-quark currents
  - Theoretical correction ($n_b$) is $\sim 10\%$ (i.e. it reduces the $G^n_E/G^n_M$ ratio by $n_b \sim 1.1$) mainly due to third order SU(6) breaking terms (three-quark currents) omitted in the relation between $G^n_M$ and $G^{\Delta \rightarrow \Delta}_M$
A path to extend our low $Q^2$ reach for $G_E^n$
A path to extend our low $Q^2$ reach for $G_E^n$
Experimental Setup

- Standard Hall-C equipment
- 1300 MeV electron beam
- Detect proton and electron in coincidence
- Reconstruct pion from missing mass.

Simulation of missing mass (pion)
**Measurement Settings**

- Cover a $Q^2$ range of 0.015 to 0.055 (GeV/c)$^2$
- 28 arm configurations
- Coverage for 9 $Q^2$ bins.
- 7.8 days production
- 1.7 days other (dummy, calibration, etc.)

### Table: Measurement Settings

<table>
<thead>
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<th>Setting</th>
<th>SHMS $\theta$ (deg)</th>
<th>SHMS P (MeV/c)</th>
<th>HMS $\theta$ (deg)</th>
<th>HMS P (MeV/c)</th>
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![Graph](image)
Projected CMR and EMR measurements

High precision in very low $Q^2$ region that is sparsely populated
- Region where pion-cloud effects are expected to be prominent

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</table>
Projected CMR and EMR measurements

- **CMR = 4.5%**
- **CMR = 0%**
- Statistical: 1%
- Systematic: < 4%

- High precision in very low $Q^2$ region that is sparsely populated
- Region where pion-cloud effects are expected to be prominent
\langle r_n^2 \rangle \text{ extraction through direct } G_n^E \text{ fitting}

\begin{align*}
\langle r_n^2 \rangle &= -6 \frac{dG_n^E(Q^2)}{dQ^2} \bigg|_{Q^2 \to 0} \\
\end{align*}

Extract radius through fit of slope as \( Q^2 \to 0 \)

Projected precision: \( \sim 3.7\% \) !!!
\[ \langle r_{n,p}^2 \rangle \text{ extraction and flavor decomposition} \]

\[ G_n^E \]

Determine \( G_n^E \) from N-\( \Delta \) TFFs

\[ \langle b_{u(d)}^2 \rangle = \frac{-4}{F_1^{u(d)}(0)} \frac{dF_1^{u(d)}(Q^2)}{dQ^2} \bigg|_{Q^2 \to 0} \]

Decompose quark FFs

\[ F_1 = \frac{G_E + \tau G_M}{1 + \tau} \]
\[ F_1^u = 2F_1^n + F_1^p \]
\[ F_1^d = 2F_1^n + F_1^p \]

Determine transverse flavor radii

\[ \langle r_{n,p}^2 \rangle = 2\langle b_{u}^2 \rangle - \frac{1}{2}\langle b_{d}^2 \rangle + \frac{3}{2}\frac{\kappa_N}{M_N^2} \]
\[ \langle r_{n}^2 \rangle = \langle b_{d}^2 \rangle - \langle b_{u}^2 \rangle + \frac{3}{2}\frac{\kappa_N}{M_N^2} \]

Recover nucleon radii
Summary

- Proposed: A precise measurement (~3.7%) of the neutron charge radius.
  - A very basic system property; sensitive to the internal structure & dynamics of the nucleon
  - Traditional method of extraction shows discrepancies which indicates unaccounted / underestimated systematics
    - PDG world data average value is elusive
    - Cross check with a different method ensures the honesty of the measurement and is a scientific obligation, whenever possible.
- Measurement of the N-Δ TFFs in a mostly unmeasured region where the mesonic cloud dynamics is predicted to be dominant and rapidly changing
  - Offers a test-bed for ChEFT and LQCD calculations
  - Can constrain systematics from 1/Nc and BChPT calculations
- Resolve the long-standing neutron-electron scattering length discrepancies
  - Important in setting constraints for the existence of new forces in nature
- Direct extraction of the u- and d-quark distributions TMSR
- Request:
  - 9.5 days
  - Beam energy: 1.3 GeV (flexible within +/- 0.1 GeV)
  - Hall C standard setup

Thank you!