Measurements of Transverse Spin Asymmetries in eC and eAl Elastic Scattering in the Qweak Experiment.

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for the Qweak Collaboration

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Several Electroweak Charges are Suppressed

Parity-violating electron scattering couplings

- Weak vector quark coupling: $C_{1q} = 2g_A^e g_V^q$ ($\gamma^\mu\gamma^5$ on e vertex)
- Weak axial quark coupling: $C_{2q} = 2g_V^e g_A^q$ ($\gamma^\mu\gamma^5$ on q vertex)

Particle	Electric charge	Weak vector charge ($\sin^2\theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$
e	-1	$Q_W^e = -2g_A^e g_V^e = -1 + 4\sin^2\theta_W \approx 0$

Weak vector charges of the proton and electron approximately zero

Accidental suppression of the weak vector charges in Standard Model makes them relatively more sensitive to new physics

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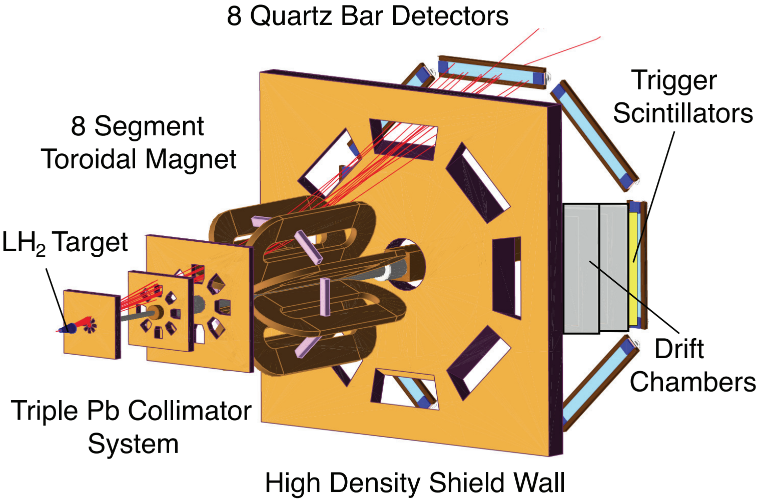
Weak vector charge of the neutron is large

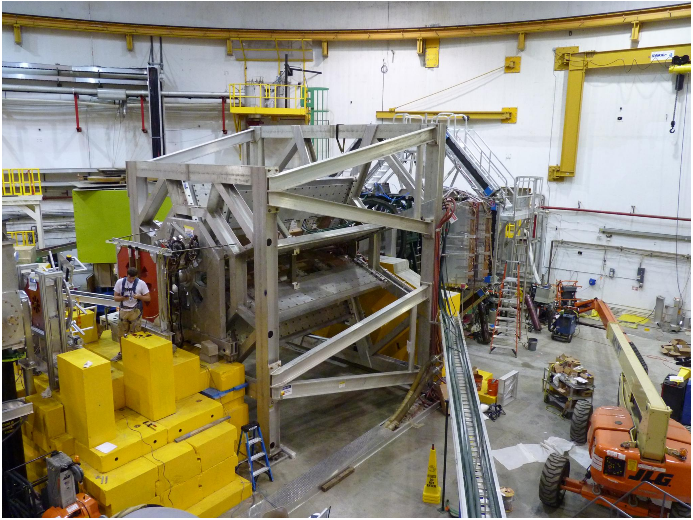
Dominance of neutron over proton weak charge means that parity-violating scattering is sensitive to neutron distributions

Determination of the Weak Charge of the Proton



[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton



[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton

Background treatment in integrating experiments

- Measured asymmetry A_{msr} corrected for all background contributions
  - with their own parity-violating asymmetry A_i (ppm-level)
  - and their dilution in the measured asymmetry f_i (%-level)

$$A_{PV} = R_{total} \frac{\frac{A_{msr}}{P} - \sum f_i A_i}{1 - \sum f_i}$$

Example of a background: Aluminum target walls

- Dominant correction to the asymmetry: background from scattering of the thin aluminum entrance and exit windows of the hydrogen target
  - Dilution $f_1 \approx 2.5\%$: directly measured with empty target, slightly different for run1 and run2
  - Effective Al alloy asymmetry $A_1 = 1515 \pm 77\,\text{ppb}$: directly measured with thick "dummy" target of identical alloy as hydrogen target windows

Measurements on Al Alloy Allow for Physics Results Too

Parity-Violating Asymmetry $A_{PV}(^{27}\text{Al})$

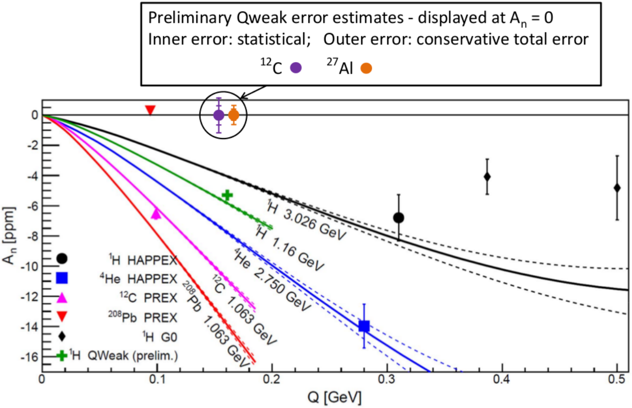
- Extraction of neutron distribution radius R_n in aluminum
  - Precision of 4% on A_{PV} of pure ^{27}Al translates to 2% on R_n
  - $R_n(^{27}\text{Al})$ helps benchmark theory important for nuclear astrophysics
- Part of larger program with CREX/PREX-II running in Summer 2019

Parity-Conserving Transverse Asymmetries $B_n(^{27}\text{Al})$, $B_n(\text{C})$

- Surprisingly small Pb transverse asymmetry in PREX[1]
- Qweak has several data sets which speak to this observable:
  - Elastic scattering on hydrogen: already presented
  - Elastic scattering on aluminum, carbon: new results
- Aluminum adds new data between carbon (where data agrees with A/Z scaling) and lead (where there is disagreement)

[1] *Abrahamyan et al., PRL 109, 192501 (2012)*

Potential to Elucidate the Behavior Between Carbon and Lead

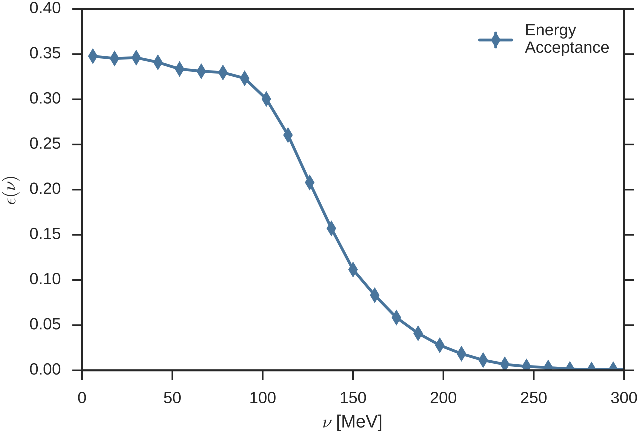


- $B_n \propto AQ/Z$: Gorchtein, Horowitz, Phys. Rev. C77, 044606 (2008)
- HAPPEX, PREX: Abrahamyan *et al.*, PRL 109, 192501 (2012)

Two Primary Challenges in these Ancillary Results

- Spectrometer not designed with narrow energy acceptance to separate elastic state from excited states in nuclei
- Target not made of pure aluminum but alloy instead (carbon is cleaner)

Spectrometer Energy Acceptance Approximately 150 MeV



- Non-elastic scattering processes dilute the asymmetry measurement
- Corrections required for nuclear excited states, GDR, …

Correction for 20% ppm-level Non-Elastic Asymmetries

f_i: Background Fraction

$$f_i = \frac{y_i}{\sum_i y_i}$$

where y_i is the detector signal yield

- Using Geant4 Monte Carlo simulation to determine y_i
- Cross-section parameterization in simulation from empirical fit[1]

Process	$f[\%]$	$\partial f[\%]$	$\partial f/f[\%]$
Quasi	12.75	1.14	8.91
Inelastic	7.38	0.70	9.50

A_i: Background Asymmetry

- Quasi-elastic:
  - Theoretical support from C. Horowitz and Z. Lin
  - Initial calculation agrees well with "free nucleon" estimate

$$A_{QE} = -0.34 \pm 0.34\,\text{ppm}$$

- Inelastic:
  - Have statistics dominated ($\partial A/A = 71\ \%$) measurement of this asymmetry

$$A_{IN} = 1.61 \pm 1.15\,\text{ppm}$$

[1] *P. Bosted, V. Mamyan, arXiv:1203.2262v2*

Aluminum Alloy Has About 10% Higher-Z Contaminants

Aluminum alloy elements [w%]

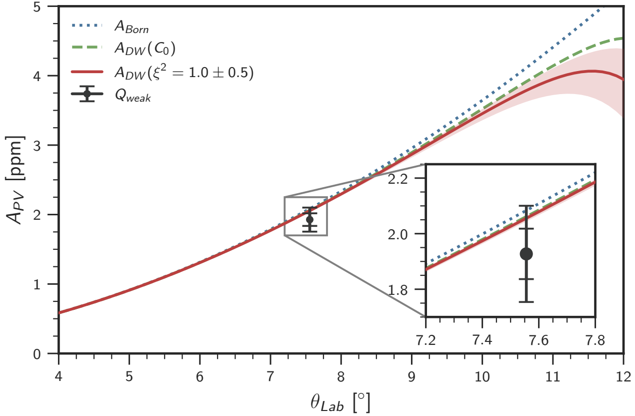
Element	Run 1	Run 2
Al	89.53	89.23
Zn	5.90	5.87
Mg	2.60	2.63
Cu	1.50	1.81
Cr	0.19	0.19
Fe	0.14	0.11
Si	0.08	0.09
Mn	0.04	0.04
Ti	0.02	0.03

Correction method

- Only most common isotopes of Zn, Mg, Cu, Cr, Fe, and Si
- Only elastic scattering from contaminants
- Modified luminosity calculation
  - Zn, Mg, Cu, Cr, Fe, Si: cross sections and asymmetries using distorted wave model[1]
  - Mn, Ti: Born approximation cross section model with Fourier-Bessel form factor fits

[1] *C. Horowitz, Z. Lin, private communication*

Measured Parity-Violating Asymmetry Agrees With Theory

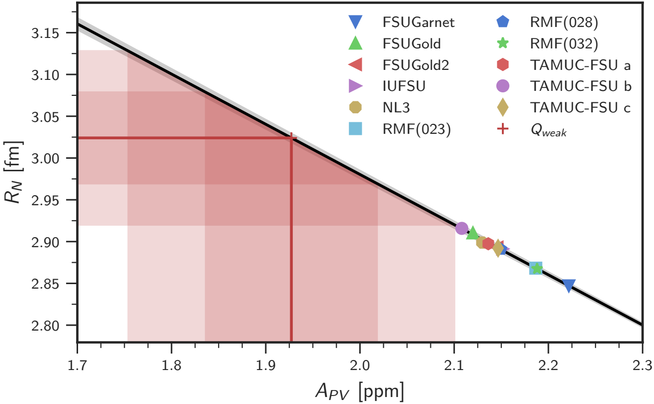


Distorted wave calculation[1] prediction of 2.1 ppm at 1.16 GeV

$A_{PV} = 1.927 \pm 0.173(\text{tot.})\,[0.091(\text{stat.}) \pm 0.148(\text{sys.})]\,\text{ppm} \quad \Delta A/A \approx 9\%(\text{tot.})$

[1] *C. J. Horowitz Phys. Rev. C 89, 045503 (2014)*

Determined Neutron Distribution Radius Agrees with Proton's



Extraction of R_n based on collection of nuclear models

- $R_n = 3.024 \pm 0.104\,\text{fm}$ and $R_n - R_p = 0.092 \pm 0.104\,\text{fm}$
- Neutron 'skin' consistent with expected range 0.004–0.024 fm

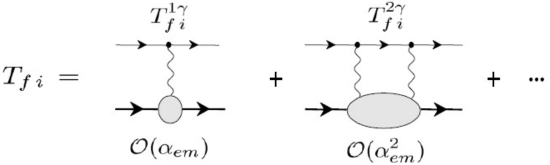
Beam Normal Asymmetry is the Size of Azimuthal Variation

Beam normal single spin asymmetries B_n

- Measurement of $A_T(\phi)$ with transversely polarized beam (H or V)
- Parity-conserving T-odd transverse asymmetry of order ppm

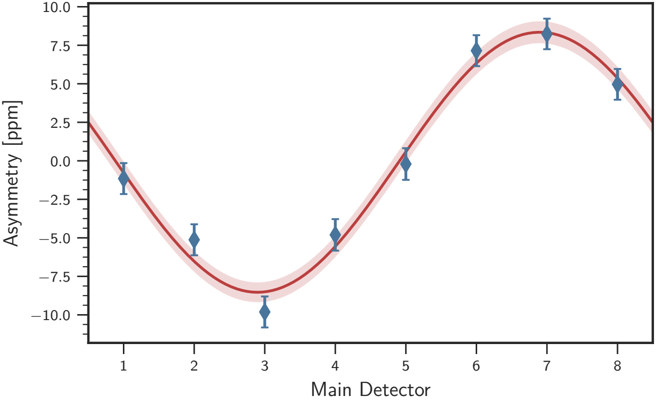
$$A_T(\phi) = \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)} = B_n S \sin(\phi - \phi_S) = B_n(P_V \cos\phi + P_H \sin\phi)$$

$$B_n = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = \frac{2\Im(T^{1\gamma *} \cdot Abs T^{2\gamma})}{|T^{1\gamma}|^2} \propto \frac{A \cdot Q}{Z} \approx \mathcal{O}(\alpha \frac{m}{E}) \approx \text{ppm}$$



Beam Normal Asymmetry is the Size of Azimuthal Variation

Aluminum azimuthal asymmetry (uncorrected for backgrounds)



Beam Normal Asymmetry on C is Consistent with PREX-I

$B_n(\mathrm{C}) = -11.1 \pm 2.1\,\mathrm{ppm}$ in elastic scattering off C

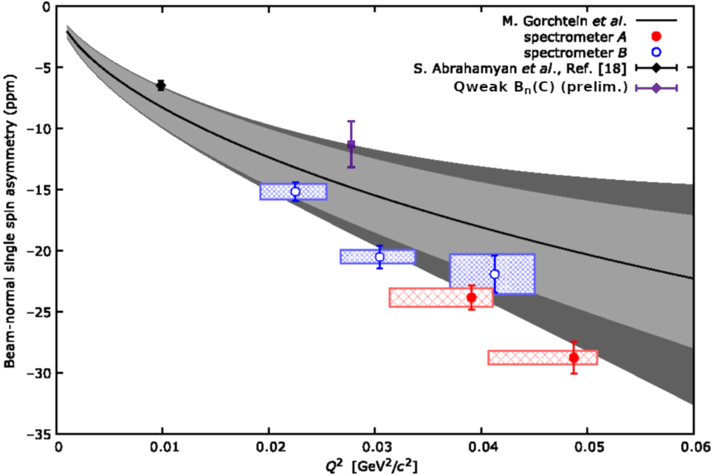
- Target consists of 99% ^{12}C, no significant contaminations
- Correction for contribution from quasi-elastic scattering, but no attempts at separation of nuclear excited states and GDR
- $B_n(\mathrm{C})$ is a quantity that applies not to a purely elastic state

J^P	E [MeV]	weight [%]
0^+	0	71.6 ± 7.9
2^+	4.44	3.5 ± 0.3
0^+	7.65	10.3 ± 2.1
3^-	9.64	11.6 ± 1.4
GDR	(24)	1.9 ± 0.4

- Scaling PREX-I to $E_b = 1.165\,\mathrm{GeV}$ and $Q^2 = 0.0270 \pm 0.0079\,\mathrm{GeV}^2$ leads to expected $B_n(\mathrm{C}) = -10.8 \pm 0.3\,\mathrm{ppm}$ (ground state)

Beam Normal Asymmetry on C is Consistent with Mainz

Consistent with both PREX-I[1] and 2018 Mainz[2] measurements



[1] Abrahamyan et al., PRL 109, 192501 (2012)

[2] A. Esser, Phys. Rev. Lett. 121, 022503 (2018)

Beam Normal Asymmetry on Al is More Complicated

Quasi-elastic scattering

- Free nucleon approximation and some heuristics related to isoscalar/isovector impact on sign of asymmetry
- More detailed quasi-elastic implementation per Horowitz, Phys. Rev. C 47, 826 (1992), which Z. Lin has adapted to ^{27}Al

Contaminants in Al alloy

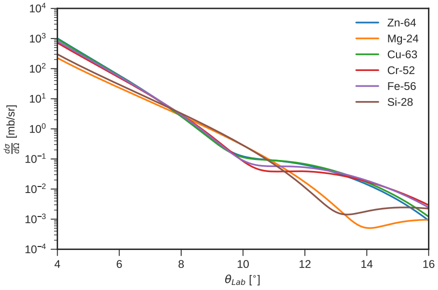
- Similar approach as C. Horowitz, Phys. Rev. C89, 045503 (2014)
- Implementation into Q_{Weak} Monte Carlo to determine contributions

Nuclear excited states

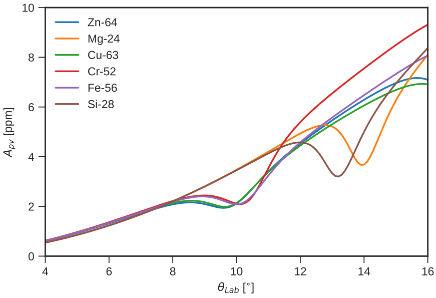
- Fitted nuclear excited state form factors using MIT Bates data
  - R.S. Hicks, A. Hotta, J.B. Flanz, H. deVries, Phys. Rev. C21, 2177 (1980)
  - P.J Ryan, R.S. Hicks, A. Hotta, J. Dubach, G.A. Peterson, D.V. Webb, Phys. Rev. C27, 2515 (1983)

Accounting for the Aluminum Alloy Contaminants

Rates/Yields Contributions:



Asymmetry:

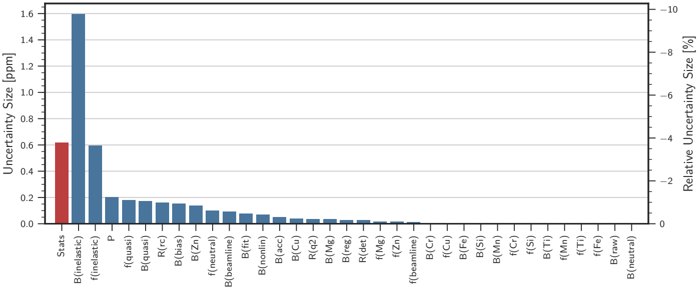


- For Mn and Ti: using the Born approximation asymmetry: $A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}(Q_p + \frac{N}{Z}Q_n) \approx 2\text{ppm}$
  - Cross section uncertainty: 10% Zn-Si, 50% Mn and Ti
  - Asymmetry uncertainty: 50%

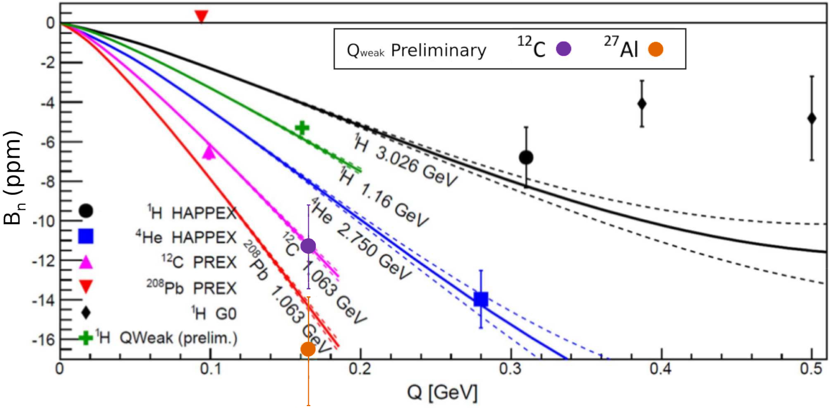
Beam Normal Asymmetry on Al is More Complicated

$B_n(^{27}Al) = -16.3 \pm 2.7\,(\text{tot.})$ ppm in elastic scattering off ^{27}Al

- Alloy is a mixture with up to 10% other elements
- Attempts to treat quasi-elastic nuclear excited states and GDR more appropriately
- $B_n(^{27}Al) = -16.3 \pm 0.62\,(\text{stat.}) \pm 1.78\,(\text{syst.}) \pm 1.91\,(\text{exc.})$ ppm
- $B_n(^{27}\text{Al})$ interpretable as referring to an elastic state

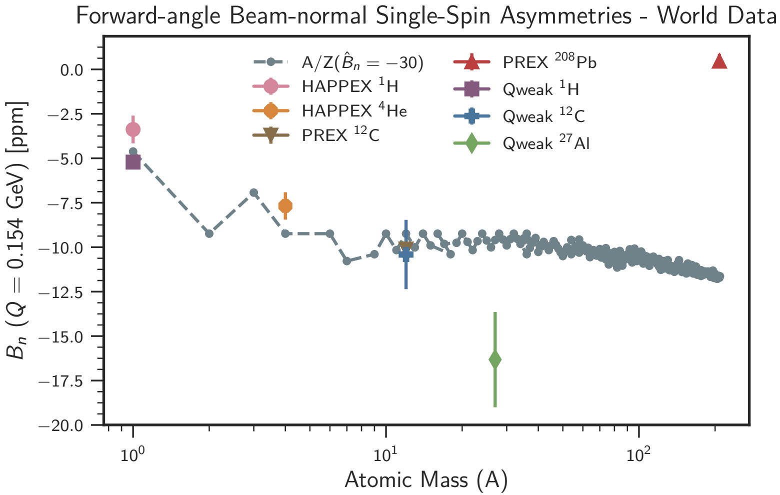


Beam Normal Asymmetry World Data vs. Momentum Transfer



Qweak data points PRELIMINARY

Beam Normal Asymmetry World Data vs. Atomic Mass



Qweak data points PRELIMINARY

Beam Normal Asymmetry Qweak Data for C and Al

Updated theory calculations by M. Gorchtein

- Calculated for Q_{Weak} kinematics
  - ^{12}C: $Q^2 = 0.0257\,\text{GeV}^2,\ E_{beam} = 1.16\,\text{GeV},\ \theta_{lab} = 8.1^\circ$
  - ^{27}Al: $Q^2 = 0.0236\,\text{GeV}^2,\ E_{beam} = 1.16\,\text{GeV},\ \theta_{lab} = 7.6^\circ$
- Applicability for ^{27}Al with spin $5/2$

  Since B_n is insensitive to the target spin, I do not think that the fact that ^{27}Al has a high spin changes much. What matters is the total photo-absorption cross section that scales roughly as number of nucleons, at least in this energy range.

  This means the nuclear excited state background processes in ^{12}C are less of a concern.

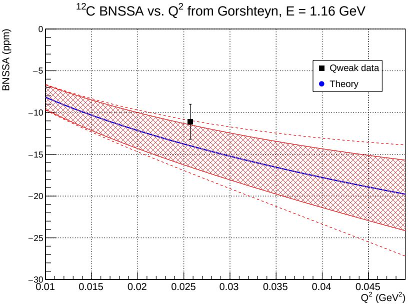
Beam Normal Asymmetry Qweak Data for C and Al

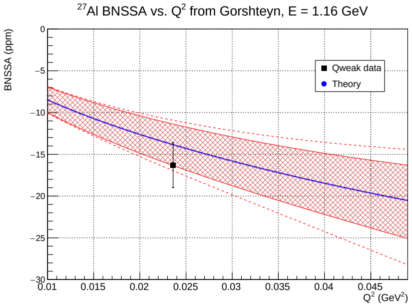
Updated theory calculations by M. Gorchtein

- Theoretical uncertainty contributions: dominant log-enhanced Compton slope and constant term, added in quadrature
  - Constant term: 100% uncertainty assigned
  - Compton slope parameter: 10% (full) and 20% (dashed) uncertainties assigned

It is calculated following our paper where we found that for H and ^{4}He, for which the data exist, the Compton form factor is roughly the charge form factor of the target times exp$(-4Q^2)$. Then, taking for the charge FF $= \exp(-R^2Q^2/6)$, *with R the charge radius, I obtain the Compton slope as* $(R^2/6) + 4$.

Beam Normal Asymmetry Qweak Data for C and Al





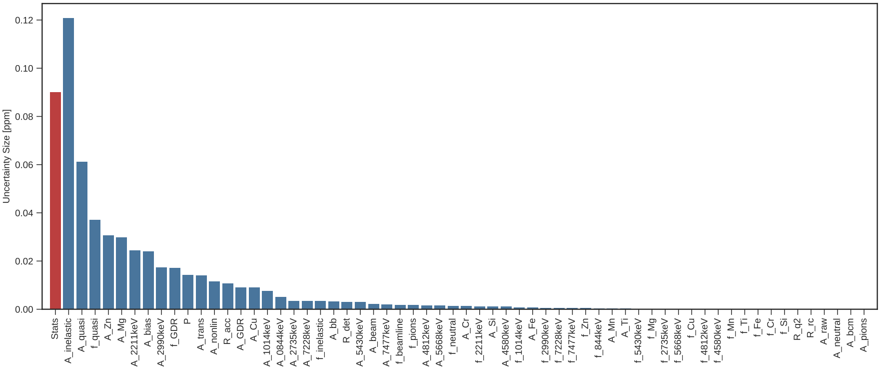
Qweak data points PRELIMINARY

Summary

- $A_{PV}(^{27}\text{Al})$ agrees with theoretical calculations
- $B_n(\text{C})$ (including mixture of pure elastic and excitations) agrees with PREX-I and Mainz measurements and $A \cdot Q/Z$ scaling
- $B_n(^{27}\text{Al})$ adds the first measurement between carbon and lead

Systematics Dominated by Inelastic Asymmetry Uncertainty

Statistical and Systematic Uncertainties

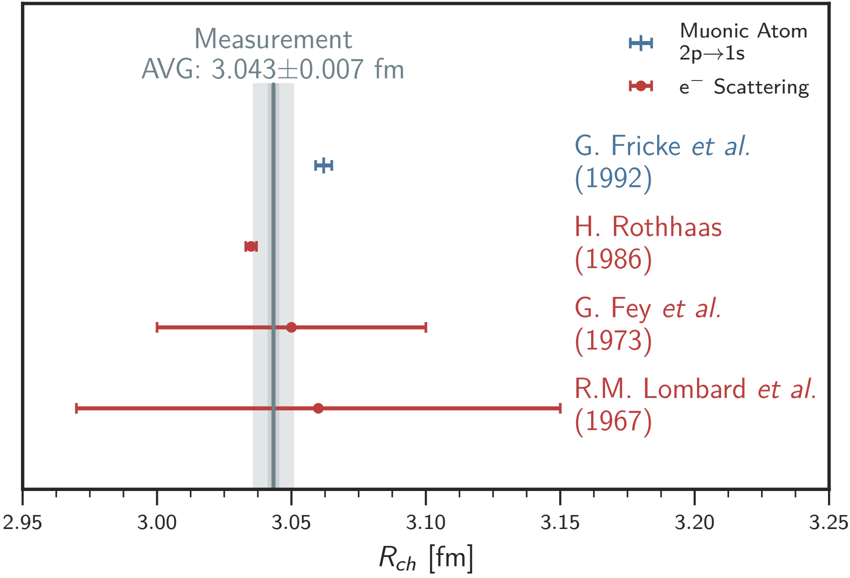


- Only $A_{inelastic}$ is larger than the statistical (red) uncertainty.

Systematics Dominated by Inelastic Asymmetry Uncertainty

Top five largest uncertainty contributions

Quantity	Error [ppm]
Statistics	0.090
A_{IN}: Inelastic Asym.	0.121
A_{QE}: Quasi-elastic Asym.	0.061
f_{QE}: Quasi-elastic Fraction	0.037
A_{Zn}: Zinc Asym.	0.031
A_{Mg}: Magnesium Asym.	0.030
$\vdots$	$\vdots$
Combined (quadrature)	0.180



Measurement
AVG: 3.043±0.007 fm
Muonic Atom
2p→1s
e⁻ Scattering
G. Fricke et al.
(1992)
H. Rothhaas
(1986)
G. Fey et al.
(1973)
R.M. Lombard et al.
(1967)
2.95
3.00
3.05
3.10
3.15
3.20
3.25
R_ch [fm]