First Determination of the ^{27}Al Neutron Distribution Radius from a Parity-Violating Electron Asymmetry Measurement

Qweak Collaboration

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Hall C Collaboration Meeting

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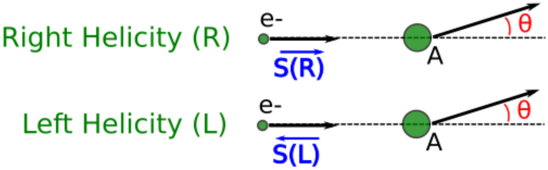
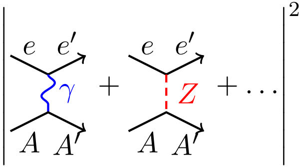
What is parity-violating electron scattering?



- Longitudinally polarized incoming electrons
- Unpolarized target
- Interference of electromagnetic and weak neutral Z exchange amplitudes.

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \quad \text{with} \quad \sigma =$$



Physics Importance

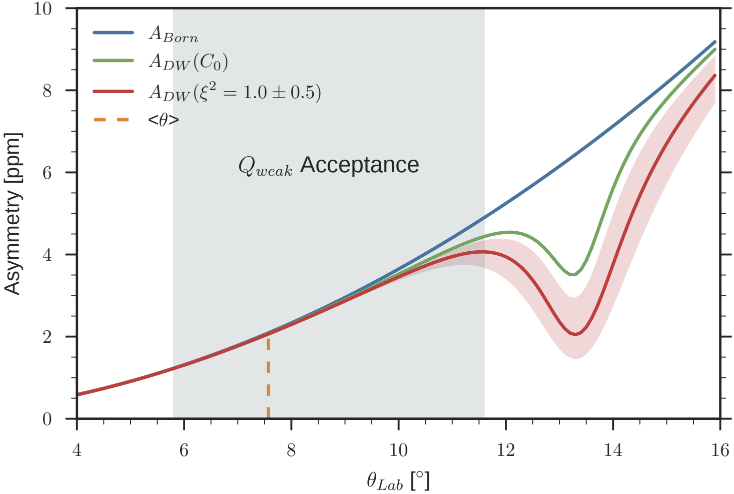
- Q_{weak} has made the first measurement of the ^{27}Al parity-violating elastic scattering(PVES) asymmetry.
- A single asymmetry measurement allows for the extraction of the weak charge density, with theoretical interpretation so can the radius of the neutron distribution (R_n). [Phys. Rev. C 63, 025501 (2001)]

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{ch}(Q^2)} \quad (\textit{for} \quad Q^2 \ll M_Z^2)$$

- Difference between R_n and R_p yields neutron skin. Expecting to find a small ^{27}Al neutron skin.

C. Horowitz's Theory Asymmetry Prediction

C. J. Horowitz Phys. Rev. C 89, 045503 (2014)



At Qweak's average acceptance expect $A_{PV} \approx 2.1$ ppm ($E_{beam} = 1.16$ GeV).

Comparing World Data

- According to Horowitz a 4% measurement of the **pure** ^{27}Al A_{PV} is sensitive to 2% changes in R_n.
- ^{27}Al's R_n (neutron distribution radius) helps benchmark theory that is important for other nuclei and astrophysics.

Predicted ^{27}Al results compared to PREx and CREx:

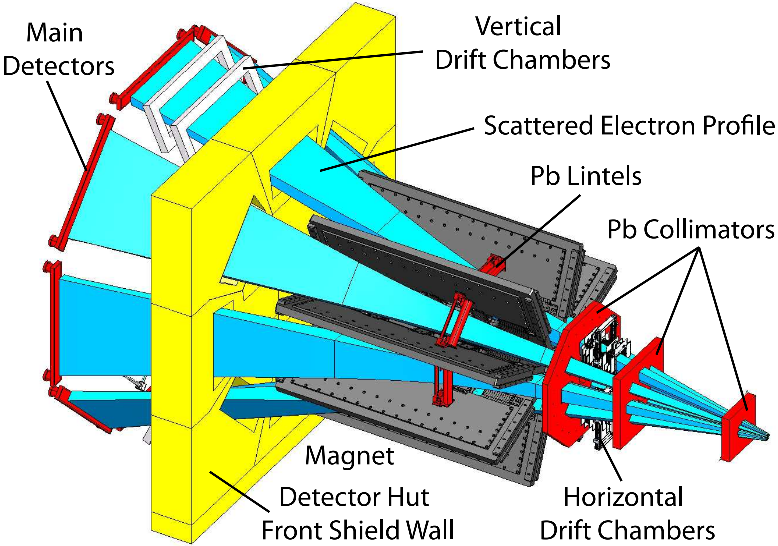
Exp.	Target	R_p[fm]	R_n[fm]	R_{ch}[fm]	$\mathbf{R_n - R_p}$[fm]	Src.
Q_{weak}	^{27}Al	2.904	2.913	3.013	**0.009**	I
PREx	^{208}Pb	5.45	$5.78^{+0.16}_{-0.18}$	5.50	$\mathbf{0.33^{+0.16}_{-0.18}}$	II
CREx	^{48}Ca	3.438	3.594	3.526	**0.156**	III

I:[Phys. Rev. C89, 045503 (2014)] II:[PRL 108, 112502 (2012)] III:CC Calculations [CREx Proposal (2013)]

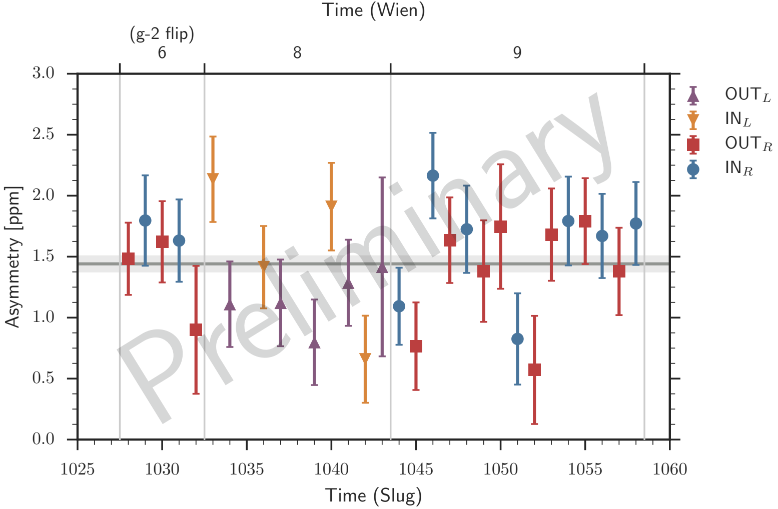
Experimental Conditions

- Ran in Hall C of Jefferson Lab.
  - ^{27}Al data taken during two periods of Q_{weak} running:
    - Run 1: February-May 2011
    - Run 2: November 2011-May 2012
- Targets: (X_0 = radiation lengths)
  - ^{27}Al alloy: 4.2 % X_0 (3.68 mm) thick
- Beam Conditions:
  - E = 1.16 GeV
  - I = 60-70 μA
  - $P_L = 88\%$
- Spectrometer Conditions:
  - $<\theta> = 7.6^\circ$, $5.8^\circ \leq \theta \leq 11.6^\circ$
  - $<Q^2> \approx 0.024$ GeV^2
  - ≈ 150 MeV energy acceptance

Experimental Apparatus



Uncorrected Data



$$\partial A/A = 4.7\ \%\ \text{(stat. only)}$$

Extraction of A_{PV}

$$\mathbf{A_{PV}} = R_{tot}\frac{\frac{A_{msr}}{P} - \sum_i f_i A_i}{1 - \sum_i f_i}$$

- Largest uncertainties come from background asymmetries that dilute the elastic aluminum asymmetry.
  - Examples: Quasi-elastic, Inelastic ($N \rightarrow \Delta$), Alloy Elements (Zn, Mg, ...), Discrete excitations, ...

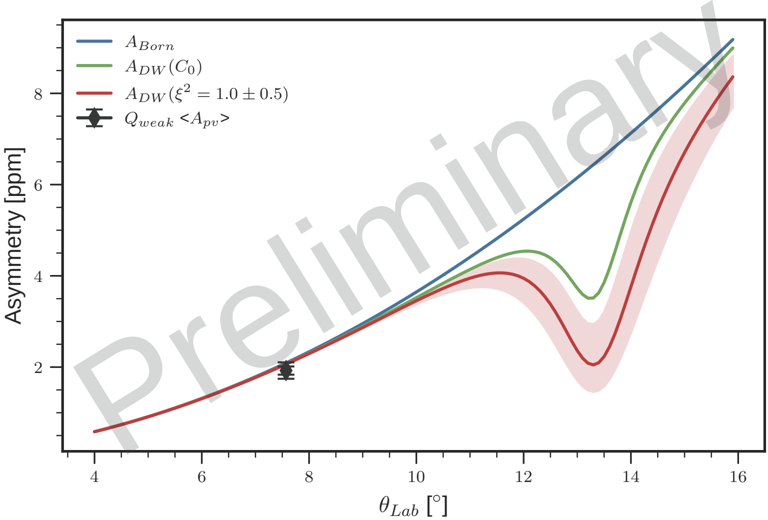
$$A_{msr} = A_{raw} + A_{BCM} + A_{beam} + A_{BB} + A_L + A_T + A_{bias}$$

- Measurement based corrections or false asymmetries typically on the order of a few ppb or 10s of ppb.

$$R_{tot} = R_{det}R_{rc}R_{acc}R_{Q^2}$$

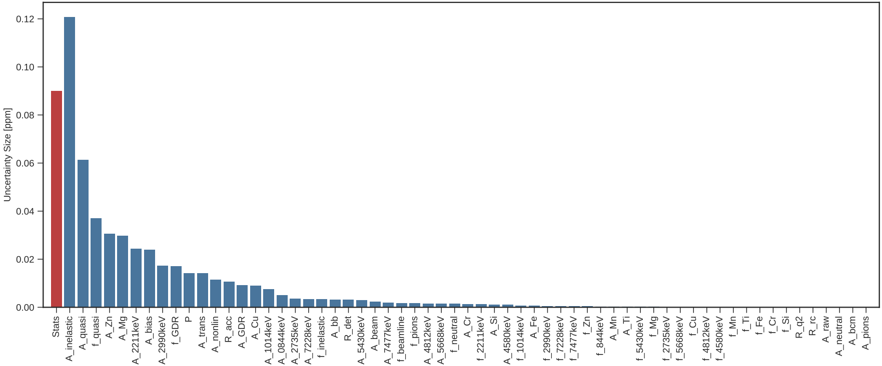
- Background corrected asymmetry requires additional small, few percent level, corrections for detector acceptance, radiative energy loss, and detector light collection bias.

Preliminary Result



$$A_{PV} = 1.924 \pm 0.180(\text{tot.})\ \text{ppm}\ [0.090(\text{stat.}) \pm 0.156(\text{sys.})] \quad \partial A/A = 9.4(\text{tot.})\ \%$$

Uncertainty Chart



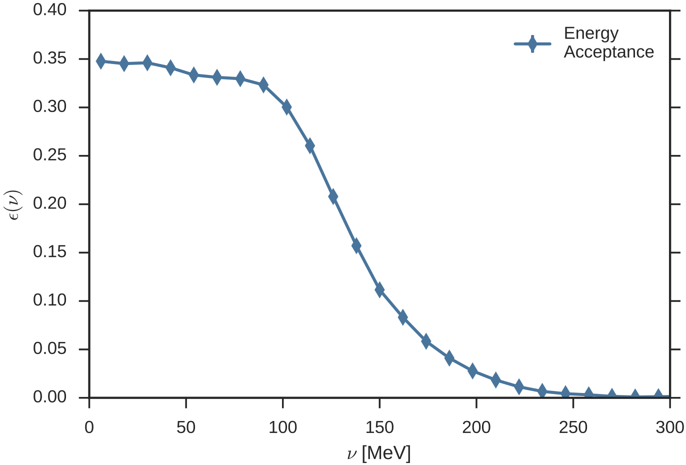
- Only $A_{inelastic}$ is larger than the statistical (red) uncertainty.

Uncertainty Table

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

Energy Acceptance



Large energy acceptance for non-elastic scattering processes that dilute the asymmetry measurement.

Dominant Systematic Corrections

- The quasi-elastic and inelastic ($N \to \Delta$) background asymmetry corrections are the dominant uncertainties in A_{PV}.

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 to data by P. Bosted and V. Mamyan (arXiv:1203.2262v2).

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 his student Zidu.
  - 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 the asymmetry.

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

  - Possible theoretical calculation?

Aluminum Alloy Elements

Elemental Composition

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

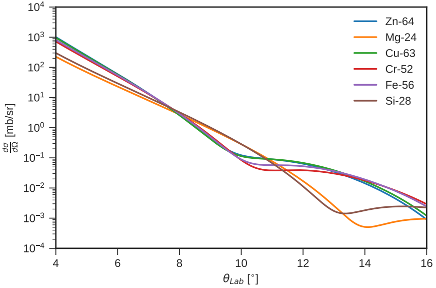
(Units: [w%])

- Considering only elastic scattering from alloy elements.
- Horowitz's student Zidu has calculated the cross-sections and asymmetries using their distorted wave model(for Zn, Mg, Cu, Cr, Fe, Si).
- Consider only common isotopes of Zn, Mg, Cu, Cr, Fe, and Si.
- Mn and Ti uses a Born approx. cross-section model, with Fourier-Bessel form factor fit.

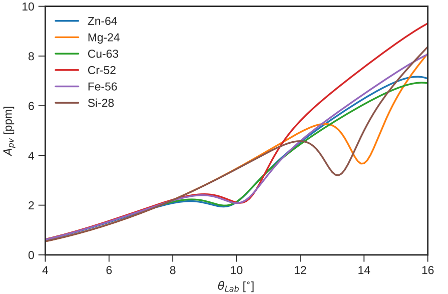
- Modifies the luminosity calculation.

Aluminum Alloy Elements

Rates/Yields Cont.:



Asymmetry:



- Mn and Ti are using the Born approximation asymmetry:

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}(Q_p + \frac{N}{Z}Q_n) \approx 2 \text{ ppm}$$

Model Uncertainties:

- Cross Section - 10% Zn-Si, 50% Mn and Ti
- Asymmetry - 50%

Extraction of R_n

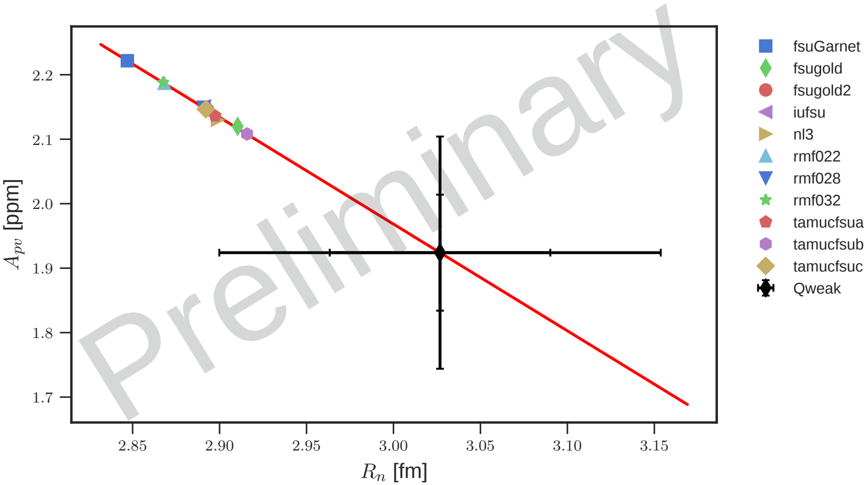
- Chuck, Farrukh, and Zidu calculated the correlation between R_n and A_{pv}. Using "ten distinct relativistic mean-field interactions". At a $Q^2 = 0.0235$ or $\approx 7.6°$, assuming E $=$ 1.160 GeV.

$$A_{pv} = -1.6555 R_n + 6.9347$$

- Extract R_n by inverting equation then use our A_{pv} as input.
- Relative Uncertainty on R_n extracted with **ln** derivative.

$$\frac{\partial R_n}{R_n} = \frac{\partial A_{pv}}{A_{pv}} \div \frac{\partial \ln A_{pv}}{\partial \ln R_n} \quad \text{where} \quad \frac{\partial \ln A_{pv}}{\partial \ln R_n} = 2.23252$$

$$R_n = 3.027 \pm 0.127 \text{ [fm]} \quad \frac{\partial R_n}{R_n} = 4.2 \text{ [\%]}$$



Note models very sensitive to kinematics (Q^2). Need final kinematics before this plot can be truly interpreted.

Skin Thickness $(R_n - R_p)$

- Using a value of $R_p = 2.932$ fm from the set of relativistic mean field models.

$$\begin{aligned} R_n - R_p &= (3.027 \pm 0.127) - (2.932) \\ &= 0.095 \pm 0.127 \text{ [fm]} \end{aligned}$$

- Consistent with zero, which physically makes sense. Aluminum (Z $=$ 13, N $=$ 14) doesn't have a tremendous neutron excess.
- $A_{inelastic}$ contribution to A_{pv} is the reason for the large uncertainty in R_n and thus the skin thickness.
- Chuck's models predict a range of skin thicknesses: 0.004 fm – 0.024 fm.

Summary & Outlook

- Preliminary extraction of the elastic aluminum parity-violating asymmetry complete.
- Missing a few small, percent level, corrections to the asymmetry. Will be completed soon.
- Final Q^2 needs to be determined before an updated calculation of the correlation between A_{pv} and R_n can be completed.
- $A_{inelastic}$ correction is the dominant uncertainty in analysis, a theoretical measurement could bring this down.
- Future publication in the works.

Special Thanks

For the ongoing theoretical help from:

- Indiana University:
    - Charles Horowitz
    - Farrukh Fattoyev
    - Zidu Lin

The Qweak Collaboration

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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Additional Slides

Farrukh's Comments

"*... we have used a set of ten distinct relativistic mean-field interactions, whose parameters are finely tuned to produce a set of nuclear structure observables, such as binding energies and charge radii, as well as isoscalar and isovector giant resonances in select nuclei. These models also support neutron stars of two solar masses. The striking difference in these models is in their predictions for the neutron skin thickness in Pb-208 that ranges from 0.16 fm all the way up to 0.33 fm, the latter being the central value measured by the PREX collaboration. This difference should broadly define our uncertain knowledge of the nature of nuclear isovector interaction. Note the corresponding neutron skin thickness in Al-27 is from 0.004 fm to 0.024 fm.*"

Farrukh's Comments Cont.

"*In addition, we have also used a different approach, where we followed a simple procedure that enables one to fine tune the density dependence of the symmetry energy to get various neutron skin thicknesses while keeping exactly same parameters for the isoscalar sector of the interaction. We refer to these set of parametrizations as an FSUGold2 family because they were originated from the FSUGold2 interaction. Similarly, neutron skin thicknesses in Pb-208 are in the range of 0.15 fm to 0.29 fm.*"