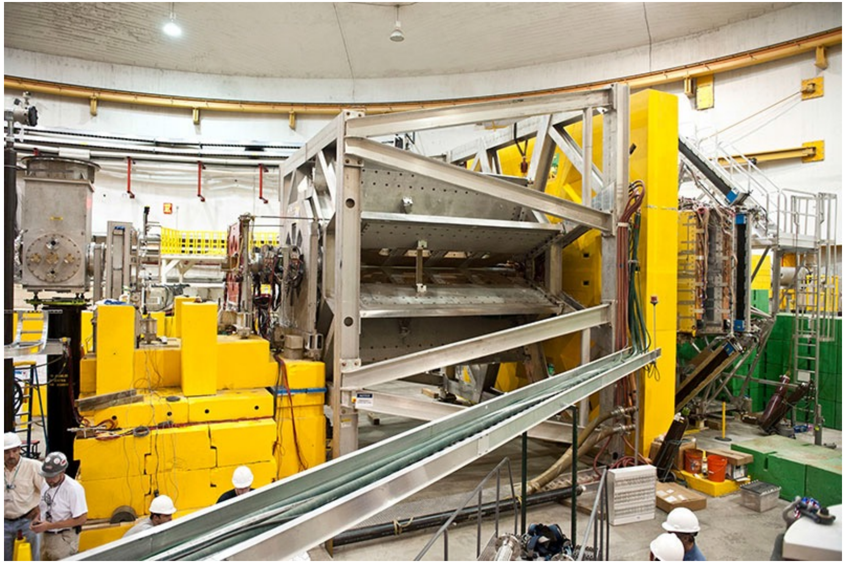
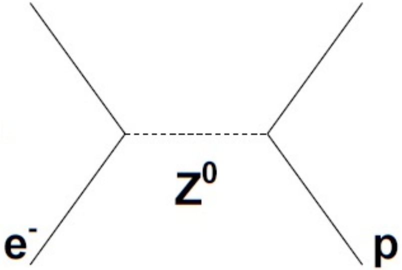
Parity-violating electron scattering and the neutron distribution in ^{27}Al



David S. Armstrong

William & Mary

for the Qweak Collaboration



APS/DNP meeting
October 11-14 2021

WILLIAM & MARY
CHARTERED 1693

Jefferson Lab

Parity Violating Electron Scattering (PVES)

Qweak experiment in Hall C at Jefferson Lab:

- Precision measurement of proton's weak charge as a Standard Model test
- Electroweak interference in parity-violating elastic electron scattering from proton
- Generic new-physics constraints with parity-violating couplings: $\Lambda/g > 3.6$ TeV

Published: Nature **557**, 207 (2018).

Additional result: PVES on aluminum target.

- Data taken to determine target-window background for weak charge measurement.

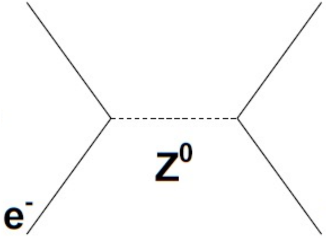
- Largest single correction to A_{PV} for weak charge measurement ($\approx 20\%$)

Elastic PVES on ^{27}Al

Context: only three previous elastic PVES measurements on complex nuclei*:

1. ^{4}He (HAPPEX) *PRL 96, 022003 (2006)*
2. ^{12}C (MIT/Bates) *PRL 65, 694 (1990)*
3. ^{208}Pb (PREX I & II) *PRL 126, 172502 (2021)*

**New result from CREx on ^{48}Ca reported by C. Palatchi yesterday!*



Weak charge of neutron >> weak charge of proton:

≈ Model-independent probe of neutron distribution of heavy nucleus: access to "neutron skin"

$$A_{\rm PV} = \frac{\sigma_+(\theta) - \sigma_-(\theta)}{\sigma_+(\theta) + \sigma_-(\theta)} \approx \frac{G_F Q^2 Q_W}{4\pi\alpha Z\sqrt{2}} \frac{F_{\rm W}(Q^2)}{F_{\rm EM}(Q^2)}$$

- Test of approach used by PREx, CREx
- Sanity check on target window correction for Q_{weak}

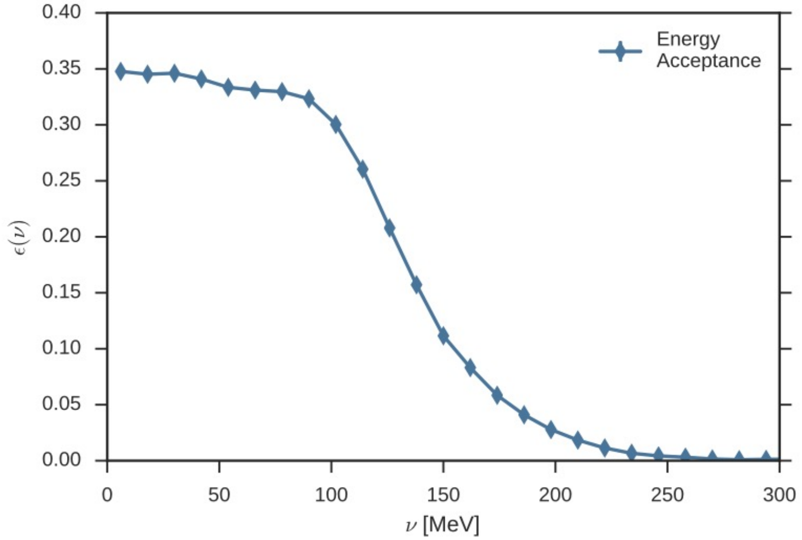
Challenges

Two Primary Challenges in ^{27}Al elastic analysis:

1. Target not made of pure aluminum: alloy instead.

2. Spectrometer not designed with narrow energy acceptance to separate elastic state from excited states in nuclei.

- 150 MeV wide acceptance
- Non-elastic scattering processes dilute the asymmetry measurement
- Corrections required for:
  - Nuclear excited states
  - Inelastic ($N \rightarrow \Delta$)
  - GDR
  - Quasielastic



Experimental Conditions

Target: ^{27}Al alloy 4.2% X_0 (3.7 mm thick)

Beam Conditions:

E_e = 1.16 GeV

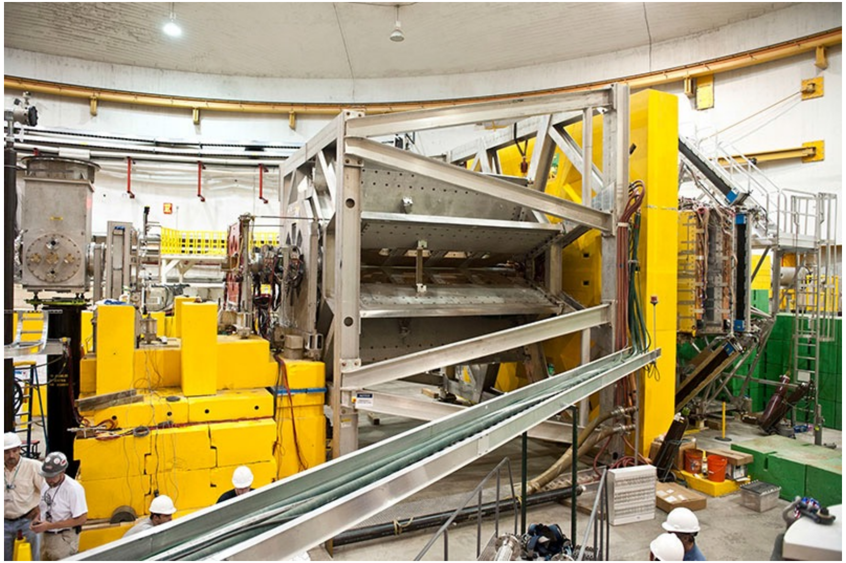
I = 65 μA

Polarization = 88.8 ± 0.6 %

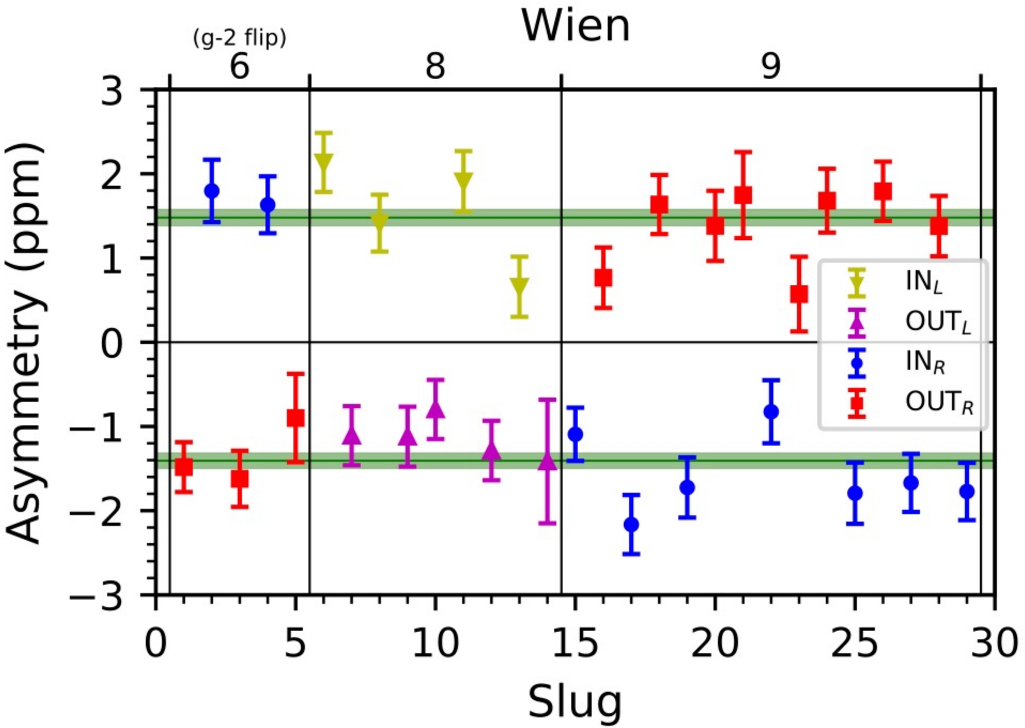
Spectrometer:

$\langle\theta\rangle = 7.6°$ $5.8° \leq \theta \leq 11.6°$

$\langle Q^2\rangle$ = 0.0236 GeV^2



^{27}Al - asymmetries



- Asymmetry is well-behaved under three kinds of slow helicity reversal.
- Corrections for helicity-correlated beam properties at the few ppb scale: (0.4 ± 1.4) ppb

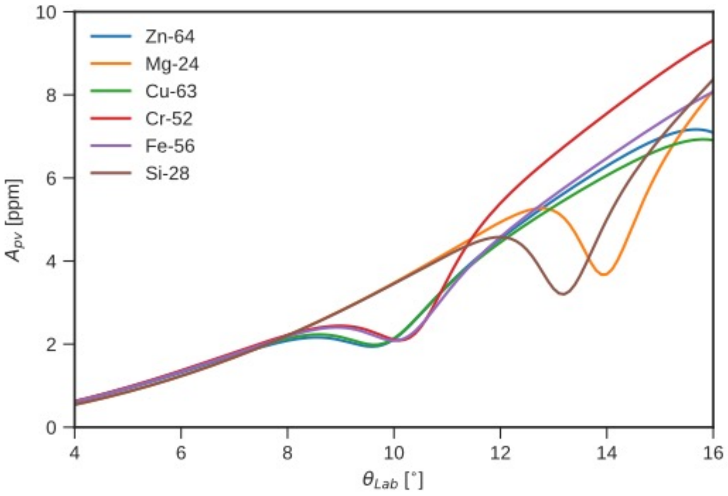
^{27}Al – alloy corrections

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:

- Considered most abundant isotopes of Zn, Mg, Cu, Cr, Fe, and Si
- Dilution and asymmetry calculations using distorted-wave cross sections from Horowitz & Lin for Zn, Mg, Cu, Cr, Fe, Si.



Q$_{weak}$ acceptance $\langle\theta\rangle = 7.6°$ $5.8° \leq \theta \leq 11.6°$

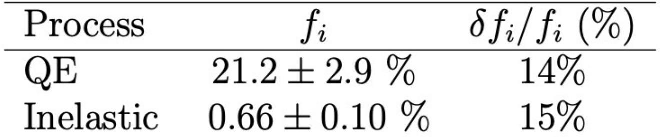
^{27}Al – non-elastic backgrounds

Quasielastic and inelastic ($N \rightarrow \Delta$) backgrounds *(low-lying nuclear levels & GDR smaller)*

Background fraction: f_i

- Use GEANT 4 simulation with cross-section parameterization from empirical fits to data

(Phys. Rev. C 104 (2021)014606 (Qweak); E. Christy)



Process	f_i	$\delta f_i / f_i$ (%)
QE	21.2 ± 2.9 %	14%
Inelastic	0.66 ± 0.10 %	15%

Our largest systematic uncertainty: f_{QE}

Asymmetry: A_i

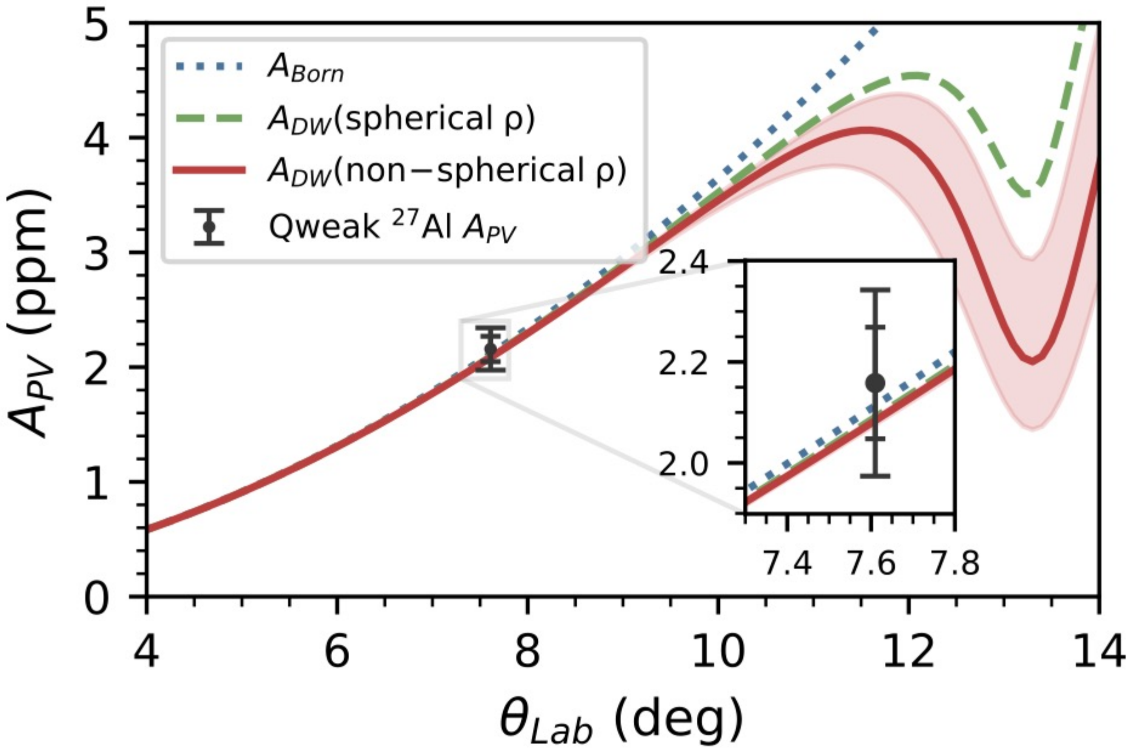
- Quasielastic: relativistic Fermi Gas model (Horowitz & Piekarewicz, Phys. Rev. C 47 (1993)2924)

$$A_{QE} = -0.34 \pm 0.17 \text{ ppm}$$

- Inelastic: made a low-statistics measurement: $A_{inel} = -0.56 \pm 5.8$ ppm

PVES on ^{27}Al - result

Theory for $A_{elastic}$ using DWBA *C. J. Horowitz Phys. Rev. C 89, 045503 (2014)*



$A_{elastic}$ = 2.16 ± 0.19 ppm

[± 0.11*(stat.)* ± 0.15 *(sys.)* ppm]

Dominant systematics:

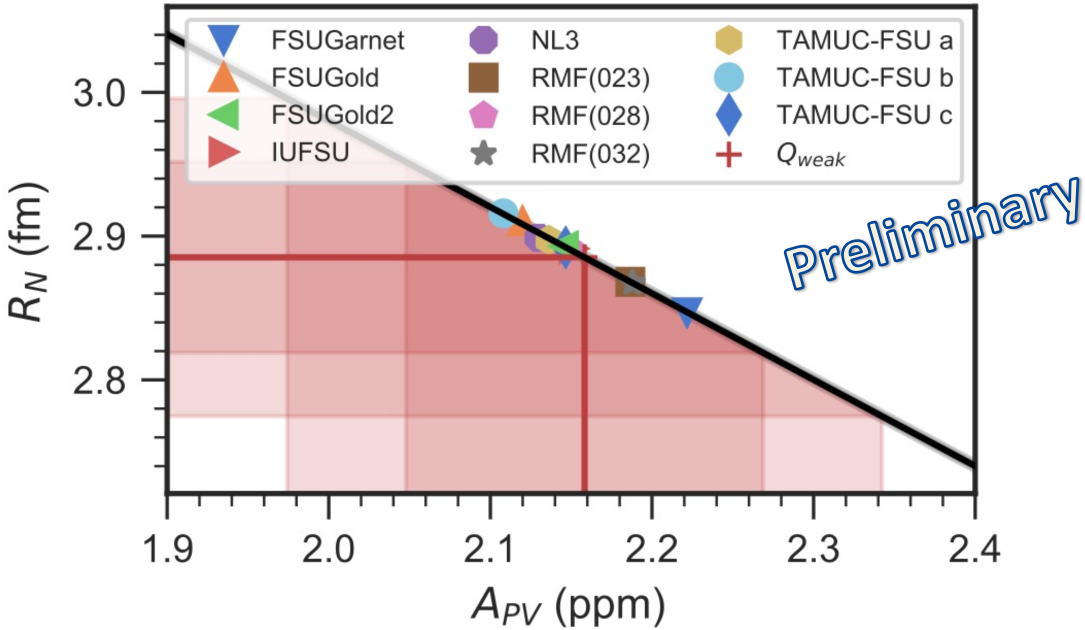
f_{QE}	5.0%
A_{QE}	2.4%
A_{inel}	2.6%
A_{nucl}	2.1%
A_{alloy}	1.6%

Total systematic: 6.8%
Statistics: 5.1%

Q$_{weak}$ acceptance $\langle\theta\rangle = 7.6^\circ$ $5.8^\circ \leq \theta \leq 11.6^\circ$

PhD Thesis - Kurtis Bartlett W&M 2018

PVES on ^{27}Al - result



$A_{elastic}$ = 2.16 ± 0.19 ppm

$R_n = (2.88 \pm 0.11)$ fm

(preliminary)

Neutron skin thickness:

$R_n - R_p = -0.04 \pm 0.11$ fm

(preliminary)

Extraction of neutron distribution radius: RMF calculations
C. Horowitz, F. Fattoyev & Z. Lin

RMF models tuned to reproduce nucleon binding energies, charge radii, and strengths of the isoscalar & isovector giant resonances in various nuclei

Summary

PVES on ^{27}Al: Only 4th elastic parity-violation result on complex nucleus*

$A_{elastic} = 2.16 \pm 0.19$ ppm

Neutron distribution radius in ^{27}Al: $R_n = (2.89 \pm 0.11)$ fm *(preliminary)*

Neutron skin thickness: $R_n - R_p = -0.04 \pm 0.11$ fm *(preliminary)*

Consistent with zero: *makes intuitive sense: (Z=13, N=14)*

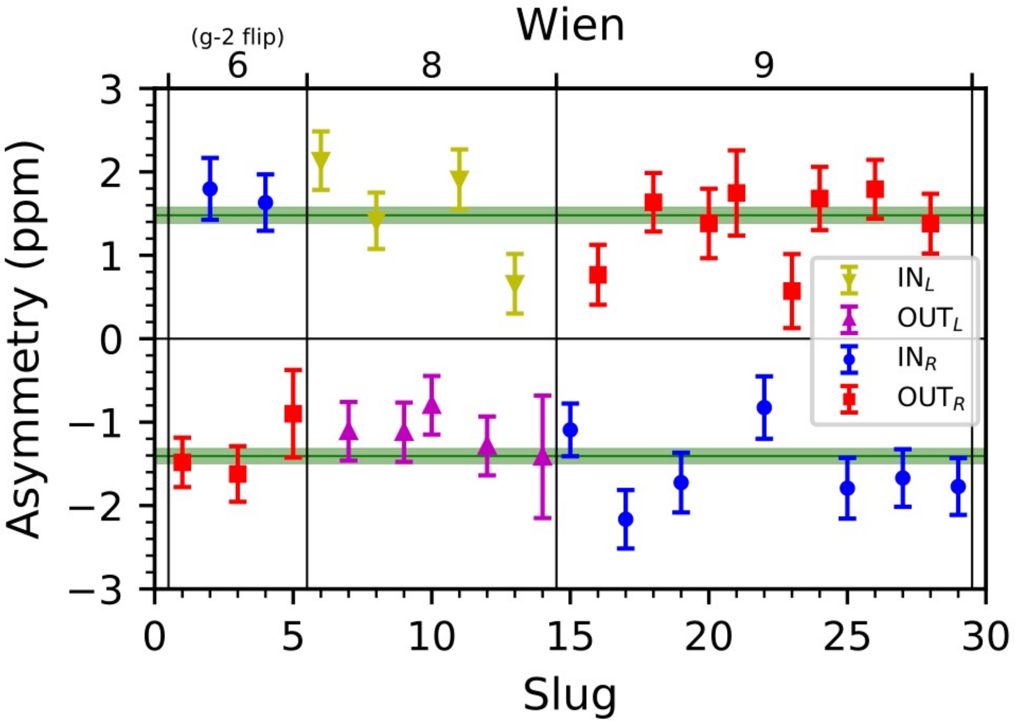
Tests use of PVES to determine R_n

Thanks to all my Qweak collaborators
& our theory colleagues

*CREx result presented yesterday by C. Palatchi will be the 5th

Backup Slides

^{27}Al - asymmetries



Average	Asymmetry(ppm)	$\chi^2/d.o.f.$	χ^2 Prob.
NEG	-1.407 ± 0.093	1.26	0.225
POS	1.480 ± 0.099	1.62	0.073
NULL	0.036 ± 0.068	–	–
$A_{\rm raw}$	1.441 ± 0.068	1.39	0.082

- Asymmetry is well-behaved under three kinds of slow helicity reversal.
- Corrections for helicity-correlated beam properties at the few ppb scale: (0.4 ± 1.4) ppb

^{27}Al – nuclear excited states

Low-lying levels:

- Use form factor data from Glasgow(1970s) and MIT/Bates (1980s) in our kinematic range.

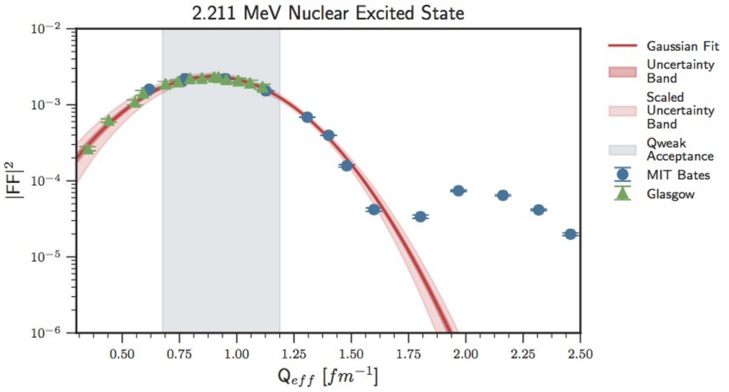
- Fit FF data to Gaussians, input to GEANT 4

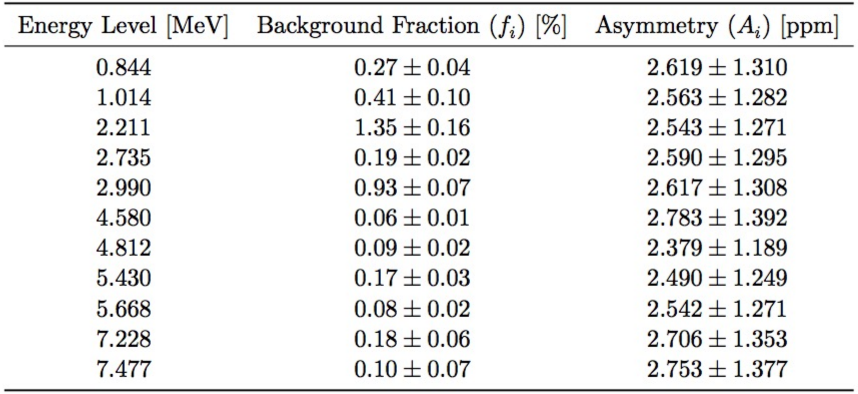
- All are dominantly isoscalar transitions, so

$$A_{Born} = A^{eA}_{PV} = A_0 Q_W = A_0[ZQ^p_W + NQ^n_W]$$

-

- Assume conservative 50% uncertainty on asymmetries due to isospin mixing.





Energy Level [MeV]	Background Fraction (f_i) [%]	Asymmetry (A_i) [ppm]
0.844	0.27 ± 0.04	2.619 ± 1.310
1.014	0.41 ± 0.10	2.563 ± 1.282
2.211	1.35 ± 0.16	2.543 ± 1.271
2.735	0.19 ± 0.02	2.590 ± 1.295
2.990	0.93 ± 0.07	2.617 ± 1.308
4.580	0.06 ± 0.01	2.783 ± 1.392
4.812	0.09 ± 0.02	2.379 ± 1.189
5.430	0.17 ± 0.03	2.490 ± 1.249
5.668	0.08 ± 0.02	2.542 ± 1.271
7.228	0.18 ± 0.06	2.706 ± 1.353
7.477	0.10 ± 0.07	2.753 ± 1.377

PhD Thesis - Kurtis Bartlett W&M 2018

^{27}Al – systematics

Quantity	Value	$\Delta A_{\mathrm{PV}}/A_{\mathrm{PV}}$ (%)
A_{msr}:	1.436 ± 0.014 ppm	1.0
P:	0.8880 ± 0.0055	0.7
R_{tot}:	0.9855 ± 0.0087	0.9
f_{QE}:	21.2 ± 2.9 %	5.0
A_{QE}:	-0.34 ± 0.17 ppm	2.4
f_{inel}:	0.665 ± 0.099 %	0.2
A_{inel}:	-0.58 ± 5.83 ppm	2.6
f_{pions}:	0.06 ± 0.06 %	0.1
A_{pions}:	0 ± 20 ppm	0.8
f_{neutral}:	0 ± 0.45 %	0.1
A_{neutral}:	1.7 ± 0.2 ppm	0.0
f_{beamline}:	0.69 ± 0.06 %	0.1
f_{alloy}:	5.41 ± 0.34 %	0.1
A_{alloy}:	1.90 ± 0.58 ppm	1.6
f_{GDR}:	0.045 ± 0.023 %	0.1
A_{GDR}:	-2.22 ± 1.11 ppm	0.0
f_{nucl}:	3.83 ± 0.23 %	0.1
A_{nucl}:	2.58 ± 0.61 ppm	2.1
Total Systematic		6.8 %

^{27}Al – Proton Distribution Radius *(preliminary)*

$$R_p^2 = R_{ch}^2 - <r_p^2> - \frac{N}{Z}<r_n^2> - \frac{3}{4m_N^2} - <r_{so}^2>$$

$R_{ch} = 3.035 \pm 0.002$ fm	At. Dat. Nucl. Dat. Tab. 87, 185 (2004)
$r_p = 0.8751 \pm 0.0061$ fm	PDG 2017
$r_n^2 = -0.1161 \pm 0.022$ fm^2	PDG 2020
$r_{so}^2 = -0.017$ fm^2	Ong, Berengut & Flambaum PRC 82, 014320 (2010)

$$R_p^2 = (2.295 \pm 0.018 \text{ fm})^2$$

If we use newer values for r_p (PDG 2020) and R_{ch} (Heylen et al., PRC 103, 014318 (2021) would increase R_p by about 1% (≈ 0.02 fm), compared to our precision on R_n of 0.11 fm.