

PREX CREX Archival Paper for PRC

98% finished

114 authors 49 institutes

56 pages

Precision Neutron Skins of ^{208}Pb and ^{48}Ca from Parity-Violating Electron Scattering (The PREX Collaboration)

We have measured the parity-violating elastic electron scattering asymmetry in the PREX and CREX experiments on ^{208}Pb and ^{48}Ca respectively; these are both doubly-magic nuclei whose excited states can be discriminated from the ground state by the high resolution spectrometers in Hall A at Jefferson Lab. This asymmetry provides a precise determination of the weak charge form factor at one Q^2 and pins down the neutron radius in these two nuclei in a relatively clean and model-independent way. This is because the Z^0 boson of the weak interaction couples primarily to neutrons. The heavier lead nucleus, with a neutron excess, provides an interpretation of the neutron skin thickness in terms of properties of bulk neutron matter. For the lighter ^{48}Ca nucleus, which is also rich in neutrons, comparisons to microscopic nuclear theory calculations are sensitive to poorly constrained 3-neutron forces. The weak neutral form factors $F_W(Q^2)$ were extracted to be 0.368 ± 0.013 at $Q = 0.3977\text{fm}^{-1}$ for ^{208}Pb from PREX-2 and 0.1304 ± 0.0055 at $Q = 0.8733\text{fm}^{-1}$ for ^{48}Ca . The form factor differences $(F_{ch} - F_W)(Q^2)$ were calculated to be 0.041 ± 0.013 at $Q = 0.3977\text{fm}^{-1}$ for ^{208}Pb from PREX-2 and 0.0277 ± 0.0055 at $Q = 0.8733\text{fm}^{-1}$ for ^{48}Ca . Correcting for Coulomb distortions and using nuclear model information, we find the neutron skin thicknesses to be $R_{\text{skin}}^{208} = 0.283 \pm 0.071$ fm combining PREX-1 and PREX-2 and $R_{\text{skin}}^{48} = 0.121 \pm 0.035$ fm. This paper provides a full description of the special experimental and data analysis techniques employed for precisely measuring these small asymmetries.

25.30.Bf Elastic Electron Scattering 21.65.Ef Symmetry Energy 21.10.Gv Nucleon Distributions

PREX CREX Archival Paper for PRC

CONTENTS

I. INTRODUCTION

- A. Theoretical Motivation
- B. Weak form factor extraction
- C. Experimental Challenges

II. EXPERIMENTAL APPARATUS

- A. Experimental Overview
- B. Polarized Electron Source
 1. The PITA effect
 2. Insertable (IHWP) and Rotatable (RHWP) Half-Wave Plates
 3. Double Wien Flip Apparatus
 4. Helicity Control Electronics
 5. Setup of the Laser and Electron Beam
 6. Helicity-Correlated Laser Spot Size
- C. Control of Electron Beam Properties
 1. Beam Properties
 2. Helicity-Correlated Beam Asymmetries
 3. Intensity Asymmetry and Feedback
 4. Position Differences
 5. Adjustments to PC During the Run
 6. Electron Beam Spot Size Variation
 7. Beam Polarization Components
 8. Adiabatic Damping
 9. Beam Modulation System
 10. Synchronized Beam Raster
- D. Targets
 1. Lead Targets
 2. Calcium Targets

3. Calibration Targets Ladder

- E. Spectrometers
- F. Detectors
 1. Quartz focal plane detectors
 2. Gas Electron Multipliers
 3. Small Angle Monitors
- G. Data acquisition
 1. Integrating Mode DAQ
 2. Counting Mode DAQ
 3. Slow Controls
- H. Simulation
 1. Radiation Shielding in the Hall
 2. Site Boundary Dose
 3. Reliability of GEANT4 Simulation
- I. Polarimetry
 1. Møller Polarimeter
 2. Compton Polarimeter
 3. Mott Polarimeter

III. ANALYSIS

- A. Event Selection and Run Conditions
- B. Calculation of Raw Asymmetries
- C. Pedestals and Linearity
- D. Beam Asymmetries
 1. Beam Corrections
 2. Multivariate Regression
 3. Beam Modulation Analysis
 4. Beam Modulation Monitoring
 5. Combined Modulation and Regression Analysis: Method of Lagrange Multipliers
 6. Beam Asymmetry Correction Results
 7. Additional Cross Checks
 8. Systematic Uncertainty
- E. Backgrounds
 1. Isotope Contamination

2. Diamond foil Background
3. Inelastic Backgrounds
4. Rescattering Backgrounds
5. Spectrometer Magnet Poletip rescattering

F. Acceptance Function $\epsilon(\theta)$

1. Counting mode data analysis
2. Optics Model - reconstructions

G. A_T Measurement

1. A_T Correction for CREX
2. A_T Correction for PREX-2

H. Beam Polarization

1. Møller Polarization Results
2. Compton Polarization Results
3. Mott Polarization Results

I. Blinding factor

J. Summary of Measurements

IV. RESULTS

- A. Extraction of Form Factor Differences

V. INTERPRETATION

- A. Weak Radius
- B. Neutron Radius
- C. Comparisons to Models
- D. Implications for the Nuclear Equation of State

VI. Conclusions

References

VII. Appendix I - models

PREX CREX Archival Paper for PRC

About 25 people wrote the paper.

Editorial Board

- David Armstrong William & Mary
- Cameron Clarke Jefferson Lab
- Chandan Ghosh Jefferson Lab
- Ciprian Gal Jefferson Lab
- Krishna Kumar Univ. Massachusetts
- Robert Michaels Jefferson Lab
- Sanghwa Park Jefferson Lab
- Kent Paschke Univ. Virginia
- Paul Souder Syracuse University

What is ?

⁴⁸Ca CREX

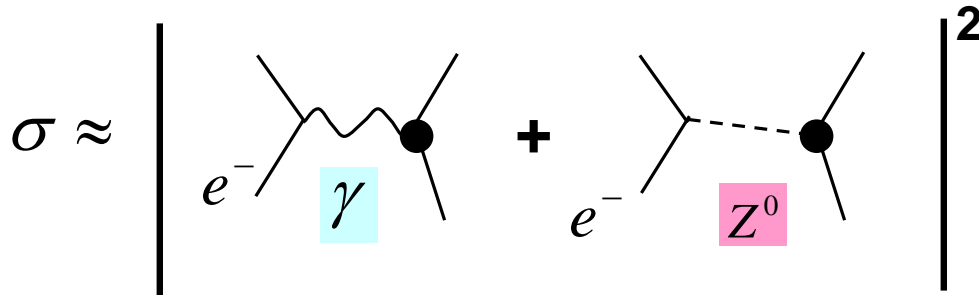
and

²⁰⁸Pb PREX

<http://hallaweb.jlab.org/parity/prex>

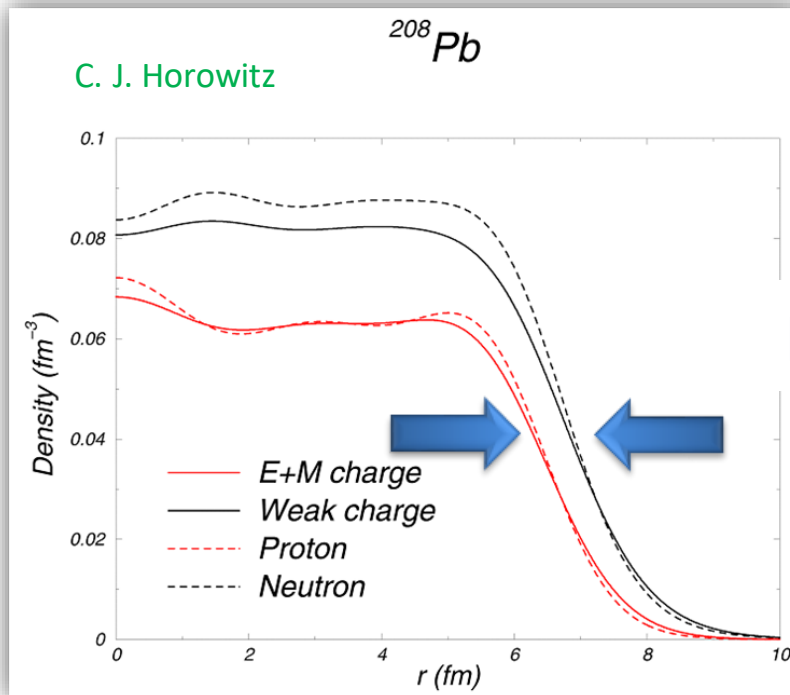
PRL 129, 042501 (2022)

PRL 126, 172502 (2021)



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} \times Q^2 \sim 10^{-6}$$

Electroweak Asymmetry in Elastic Electron-Nucleus Scattering



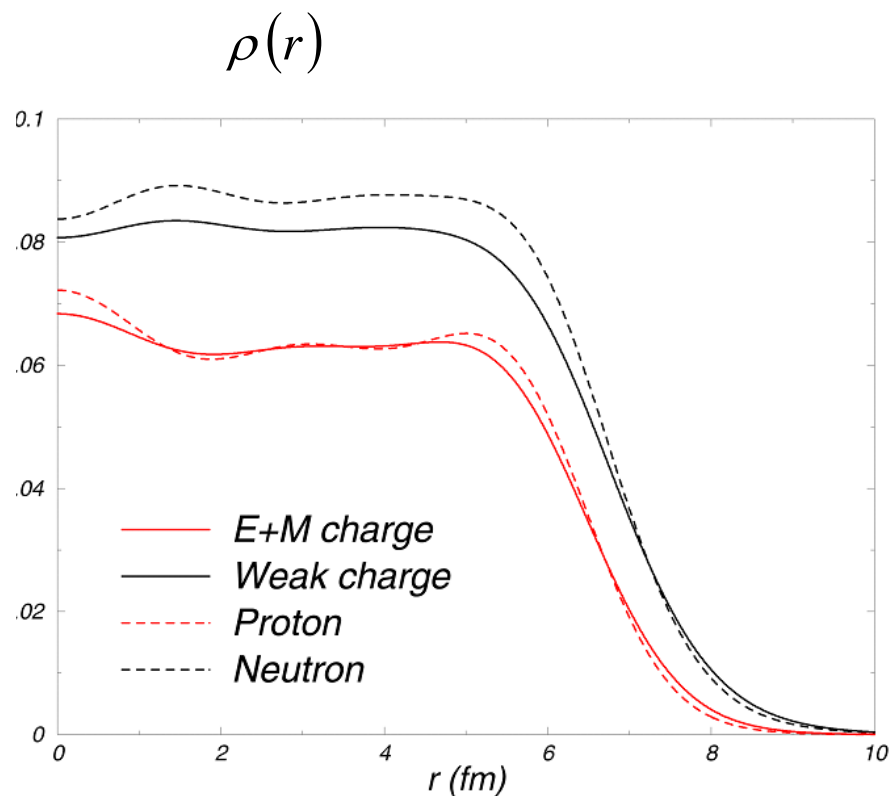
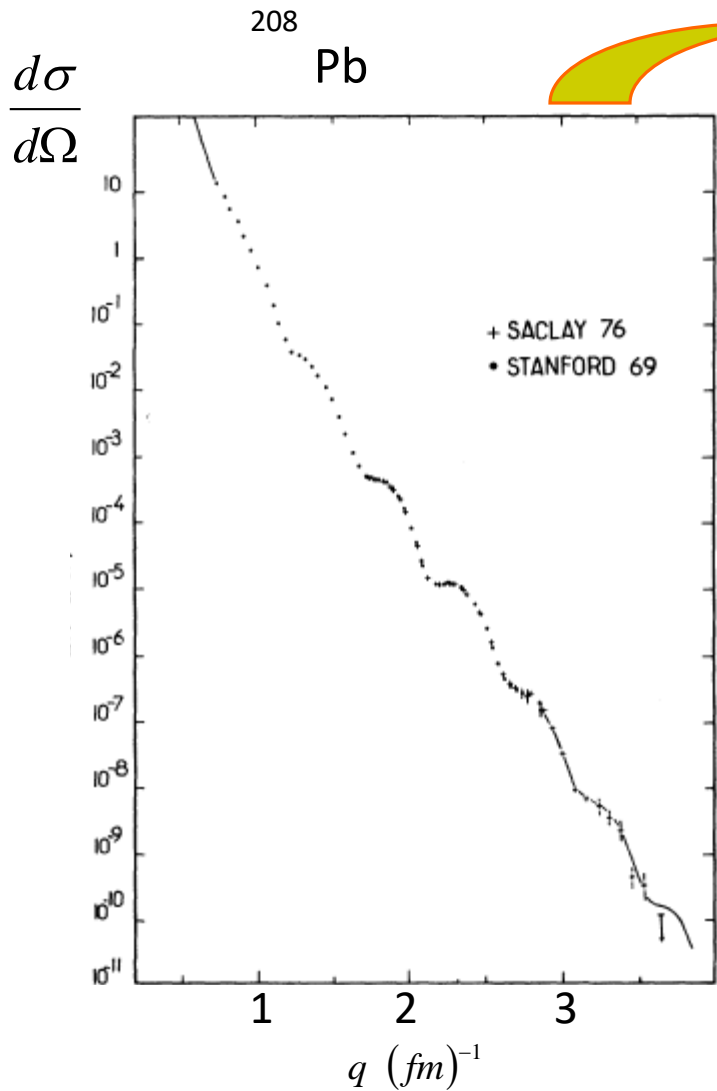
Neutron Skin

$$R_n - R_p = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

Reminder: Electromagnetic Scattering determines

$$\rho(r)$$

(charge distribution)



Weak Interaction: Sees the Neutrons

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

Measured Asymmetry

Correct for Coulomb Distortions

Weak Density at one Q^2

Small Corrections for
 G_E^N G_E^S MEC
 surface thickness

APPLICATIONS

T.W. Donnelly, J. Dubach, and Ingo Sick,
 Nuc. Phys. A 503 (1989) 589.

C.J. Horowitz, S.J. Pollock, P.A.
 Souder, R. Michaels, Phys. Rev. C63,
 025501 (2001)

Nuclear Theory
 (Symmetry Energy)

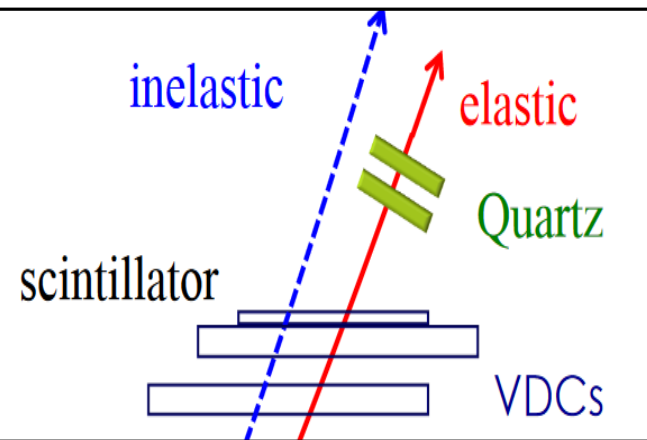
Atomic Parity Violation

Heavy Ions

Neutron Stars

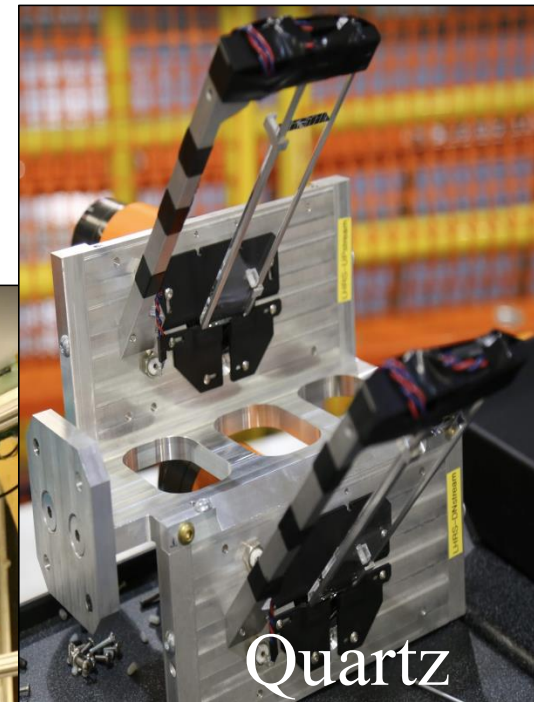
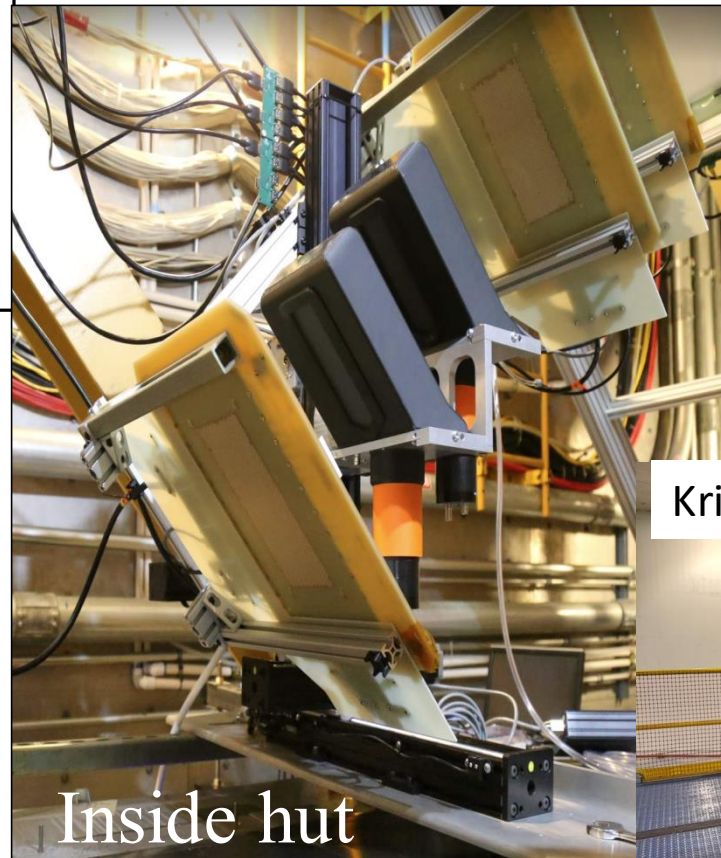
Skin
 $R_N - R_P$

Detectors at the HRS Focus



“HRS” = high resolution spectrometers

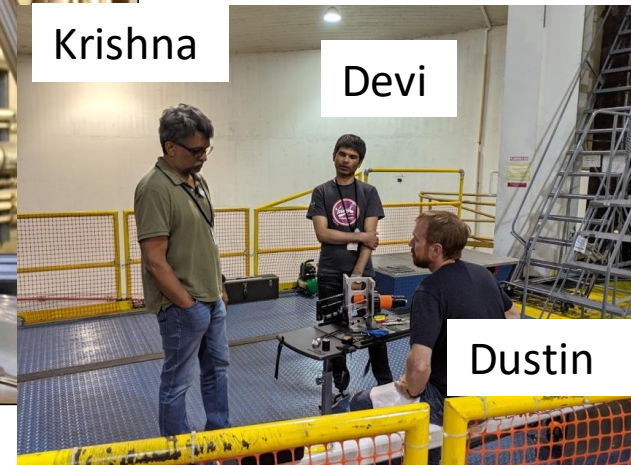
Quartz detectors are placed in the detector hut. They were used for both PREX and CREX.



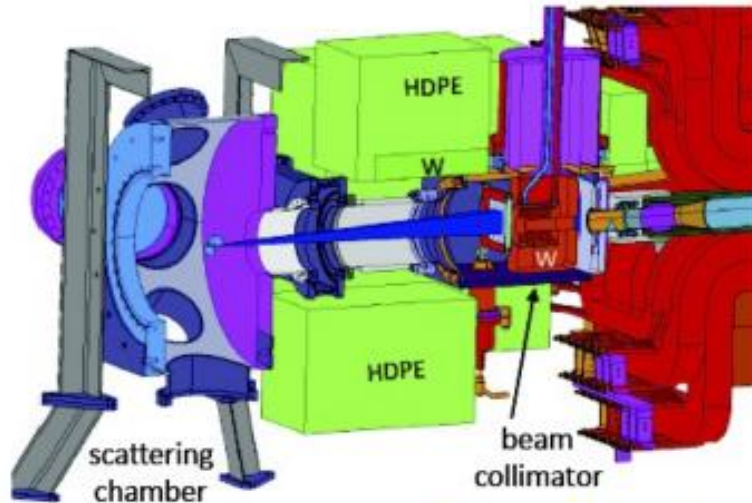
Krishna

Devi

Dustin



Newly published details about the shielding and the Geant 4 model for HRS optics



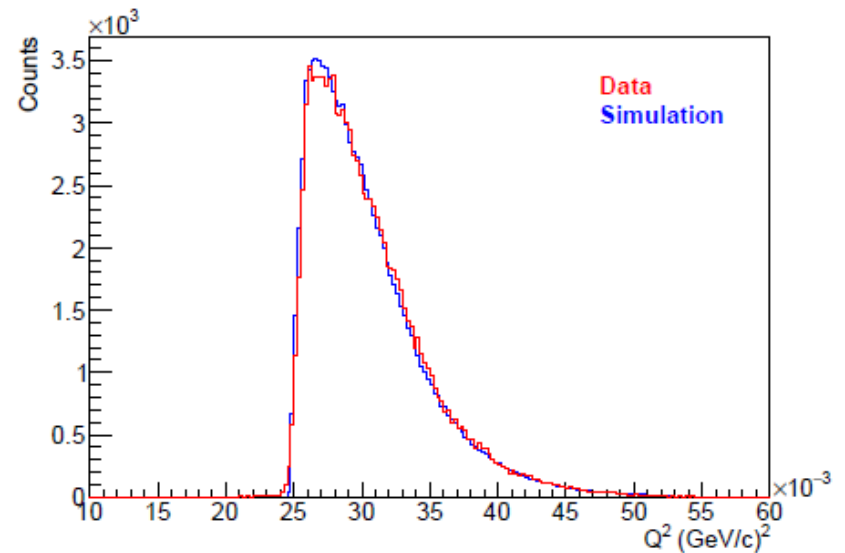
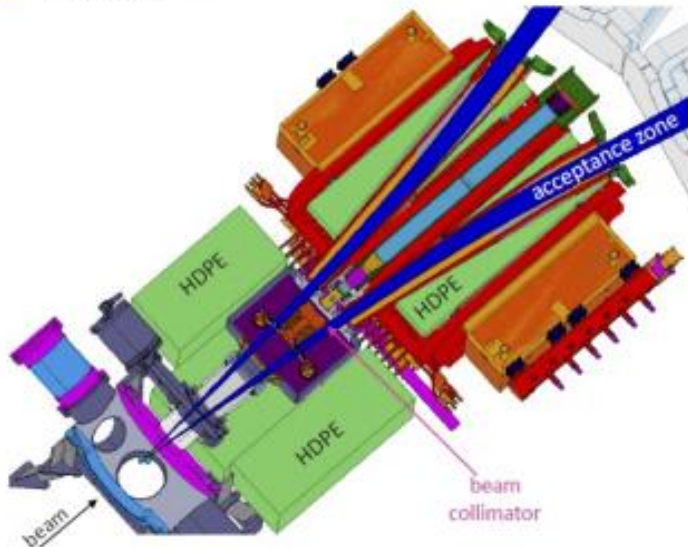
Kent Paschke (leader)
Rakitha Beminiwattha, Cameron Clarke,
Ciprian Gal, Tyler Kutz, Juliette Mammei,
Seamus Riordan, Allison Zec, Weibin Zhang.



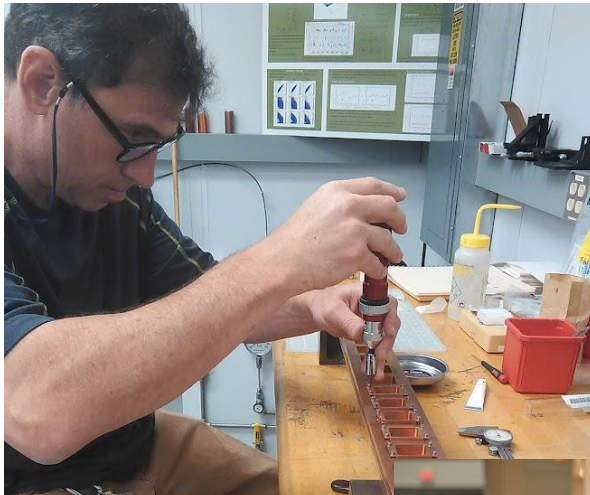
Kent



Ciprian



Newly published details about the ^{48}Ca and ^{208}Pb targets



Dave



Silviu

Thanks to the target group
(*Dave Meekins et. al.*) and
Silviu Covrig Dusa. (early
career award)

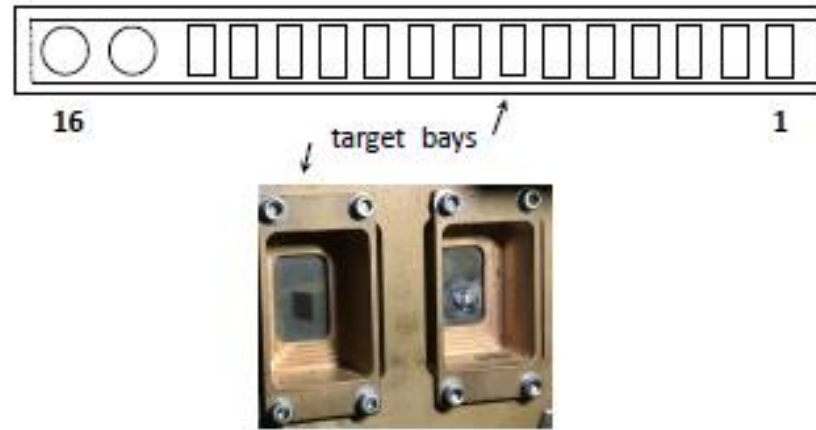


TABLE I. Listing of the production targets (see Fig. 14). Shown are the material, the thickness of the material, the type of backing, if any, and the total thickness of the two foils in the backing. “Natural Pb” means naturally-occurring 99.9% chemically pure lead. The thicknesses are nominal.

Position	Material	Thickness mg/cm ²	Backing	Tot. Back. mg/cm ²
1	Natural Pb	556	Graphite	176
2	Natural Pb	556	Diamond	180
3	^{208}Pb	630	Graphite	176
4	Graphite	445	None	N/A
5 – 13	^{208}Pb	630	Diamond	180
14	Carbon Hole	N/A	N/A	N/A
15 (1 st)	^{48}Ca	1016	None	N/A
15 (2 nd)	^{48}Ca	992	None	N/A
16	^{40}Ca	1004	None	N/A

Newly published detailed theory of the beam corrections

$$A_{\text{raw}} = A_{\text{det}} - A_{\text{Q}} + \alpha \Delta_{\mathbf{E}} + \sum \beta_i \Delta \mathbf{x}_i$$

Regression

$$\chi^2 = \sum \left(A_{\text{raw}} - \sum_i \beta_i \Delta M_i \right)^2, \quad \frac{\partial \chi^2}{\partial \beta_i} = 0$$

Dithering

$$\frac{\partial \hat{D}}{\partial C_\mu} = \sum_{i=1}^{N_{\text{BPM}}} \beta_i \frac{\partial M_i}{\partial C_\mu}, \quad \beta_i = \frac{\partial \hat{D}}{\partial M_i},$$

for $\mu = 1, 2, \dots, N_{\text{coil}}$, and can be solved if

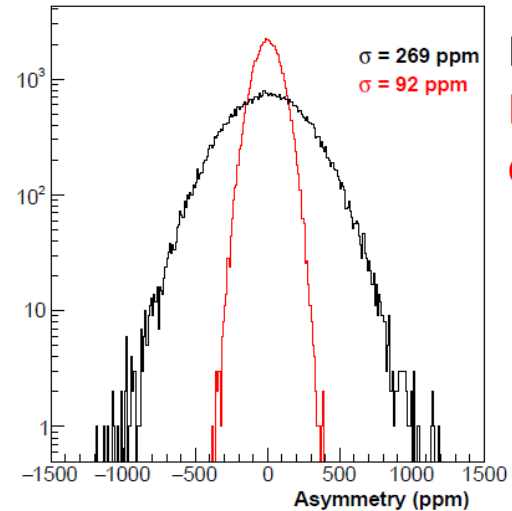
$$N_{\text{coil}} \geq N_{\text{BPM}}.$$

Lagrange -- a combination of the above two

$$\mathcal{L} = \chi^2 + \sum_{\mu} \lambda_{\mu} \left(\frac{\partial D}{\partial C_{\mu}} - \sum_i \beta_i \frac{\partial M_i}{\partial C_{\mu}} \right),$$

χ^2 minimization with beam modulation sensitivities constraints:

$$\frac{\partial \mathcal{L}}{\partial \beta_i} = 0, \quad \frac{\partial \mathcal{L}}{\partial \lambda_{\mu}} = 0$$



Raw
Beam-
corrected

Paul Souder, Tao Ye, Kent Paschke, Cameron Clarke, Ye Tian, Victoria Owen



Extracting the Weak Form Factor

Comparing PREX (^{208}Pb) and CREX (^{48}Ca) to Theory

