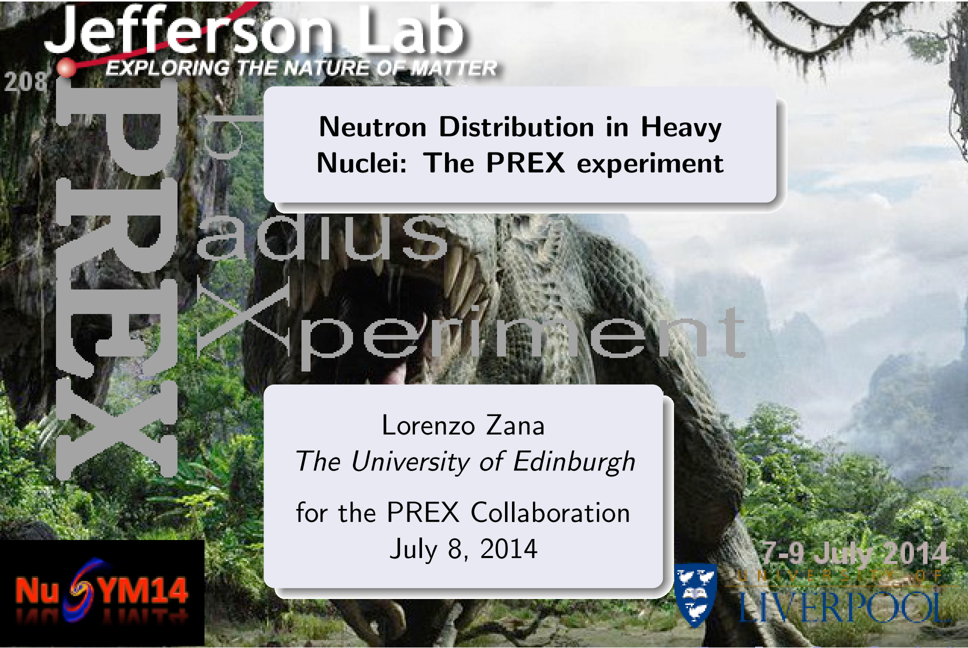


Neutron Distribution in Heavy Nuclei: The PREX experiment

Lorenzo Zana
The University of Edinburgh

for the PREX Collaboration

July 8, 2014

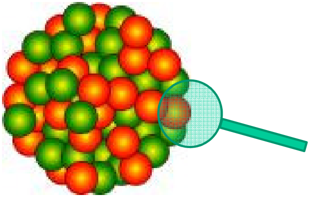
Nucleon Radius and Neutron skin

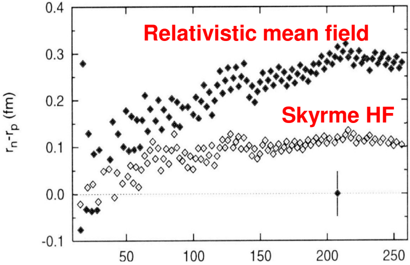
Nucleon Radius comparison

- A qualitative feature of fundamental importance of nuclear structure in heavy atoms is that the radius of neutron is assumed to be 0.25 fm more than proton radius, this is known as neutron skin.
- Neutron skin is never measured cleanly in stable nucleus.

Nucleon Radius and Neutron skin

- Our knowledge of the shape of stable nuclei is presently incomplete





e.g. ^{208}Pb RMS charge radius accuracy < 0.001 fm
RMS neutron radius accuracy ~0.2 fm !!

Horowitz et al. PRC63 025501 (2001)
Piekarewicz et al. NPA 778 (2006)

Nucleon Radii in heavy nuclei

- Measurements are important to understanding the strong nuclear force
- Calculations are difficult due to non-pQCD regime complicated by many-body physics
- Interesting for:
  - Fundamental nuclear structure
  - Isospin dependence and nuclear symmetry
  - Dense nuclear matter and NEUTRON STARS
- Proton radius is relatively easy - electromagnetic probes
- Neutron radius is difficult
  - Weakly couples to electroweak probes
  - Hadronic probes have considerable uncertainty
  - Theory has range of $R_n - R_p$ for Pb of $0.0 - 0.4$ fm

PV Asymmetry. The PREX COLLABORATION:

Published in Phys.Rev.Lett. 108 (2012) 112502

Measurement of the Neutron Radius of 208Pb Through Parity–Violation in Electron Scattering

S. Abrahamyan, Z. Ahmed, H. Albataineh, K. Aniol, D. S. Armstrong, W. Armstrong, T. Averett, B. Babineau, A. Barbieri, V. Bellini, R. Beminiwattha, J. Benesch, F. Benmokhtar, T. Bielarski, W. Boeglin, A. Camsonne, M. Canan, P. Carter, G. D. Cates, C. Chen, J.–P. Chen, O. Hen, F. Cusanno, M. M. Dalton, R. De Leo, K. de Jager, W. Deconinck, P. Decowski, X. Deng, A. Deur, D. Dutta, A. Etile, D. Flay, G. B. Franklin, M. Friend, S. Frullani, E. Fuchey, F. Garibaldi, E. Gasser, R. Gilman, A. Giusa, A. Glamazdin, J. Gomez, J. Grames, C. Gu, O. Hansen, J. Hansknecht, D. W. Higinbotham, R. S. Holmes, T. Holmstrom, C. J. Horowitz, J. Hoskins, J. Huang, C. E. Hyde, F. Itard, C.–M. Jen, E. Jensen, G. Jin, S. Johnston, A. Kelleher, K. Kliakhandler, P.M. King, S. Kowalski, K. S. Kumar, J. Leacock, J. Leckey IV, J. H. Lee, J. J. LeRose, R. Lindgren, N. Liyanage, N. Lubinsky, J. Mammei, F. Mammoliti, D.J. Margaziotis, P. Markowitz, A. McCreary, D. McNulty, L. Mercado, Z.–E. Meziani, R. W. Michaels, M. Mihovilovic, N. Muangma, C. Muñoz–Camacho, S. Nanda, V. Nelyubin, N. Nuruzzaman, Y. Oh, A. Palmer, D. Parno, K. D. Paschke, S. K. Phillips, B. Poelker, R. Pomatsalyuk, M. Posik, A.J.R. Puckett, B. Quinn, A. Rakhman, P. E. Reimer, S. Riordan, P. Rogan, G. Ron, G. Russo, K. Saenboonruang, A. Saha, B. Sawatzky, A. Shahinyan, R. Silwal, S. Sirca, K. Slifer, P. Solvignon, P. A. Souder, M. L. Sperduto, R. Subedi, R. Suleiman, V. Sulkosky, C. M. Sutera, W. A. Tobias, W. Troth, G. M. Urciuoli, B. Waidyawansa, D. Wang, J. Wexler, R. Wilson, B. Wojtsekhowski, X. Yan, H. Yao, Y. Ye, Z. Ye, V. Yim, L. Zana, X. Zhan, J. Zhang, Y. Zhang, X. Zheng, P. Zhu (collapse list)

Why parity violating asymmetry?

Z^0 of weak interaction : sees the neutrons

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

T.W. Donnelly, J. Dubach, I. Sick
Nucl. Phys. A 503, 589, 1989

C. J. Horowitz, S. J. Pollock, P. A. Souder, R. Michaels
Phys. Rev. C 63, 025501, 2001

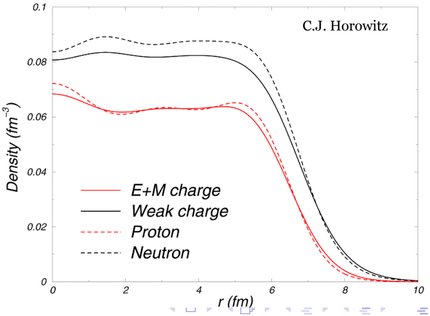
^{208}Pb

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_N(r)$$

Parity Violating Asymmetry

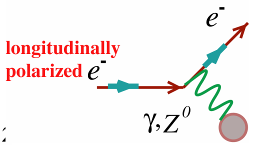
$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$



Parity violating asymmetry

Weak Neutral Current (WNC) Interactions at $Q^2 << M_Z^2$

Longitudinally Polarized Electron Scattering off Unpolarized Fixed Targets

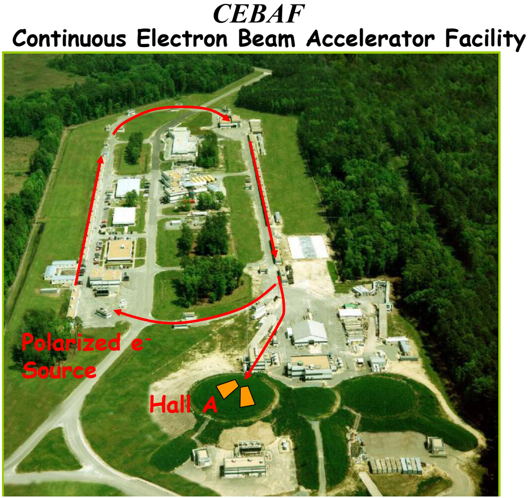


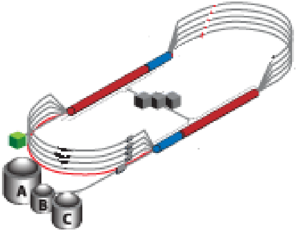
$$\sigma \propto |A_\gamma + A_{weak}|^2$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} (g_A^e g_V^T + \beta g_V^e g_A^T)$$

- *The couplings g depend on electroweak physics as well as on the weak vector and axial-vector hadronic current*
- *With specific choice of kinematics and targets, one can probe new physics at high energy scales*
- *With other choices, one can probe novel aspects of hadron structure*

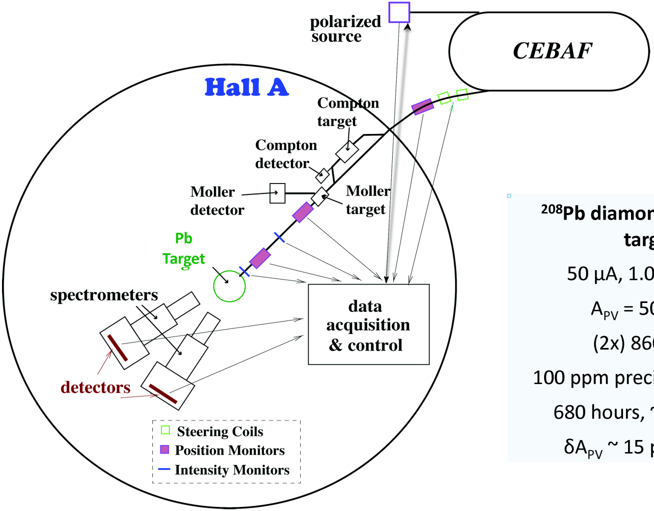
Thomas Jefferson National Accelerator Faciity





- Two RF superconducting linacs: $E_e = 1 - 6 GeV$
- High quality polarized beam, $P_e = 85 - 90\%$

PREX in Hall-A



^{208}**Pb diamond-sandwich target**

50 μA, 1.05 GeV, 5°

A_{PV} = 500 ppb

(2x) 860 MHz

100 ppm precision at 15 Hz

680 hours, ~35M pairs

δA_{PV} ~ 15 ppb (3%)

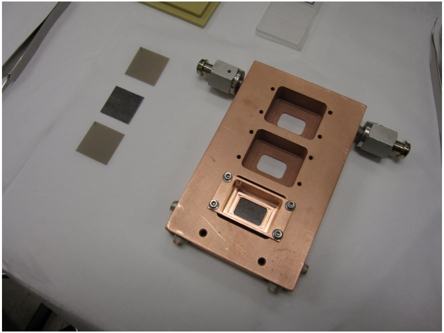
PREX key equipments

Several pieces of instrumentation were important

- Upgrades in polarimetry
  - Non-invasive Compton, $\sim 1\%$
  - Invasive Moller, $\sim 1\%$
- Pb/D targets
- Quartz Cerenkov detectors
- Integrating ADCs
- Beamline monitoring components

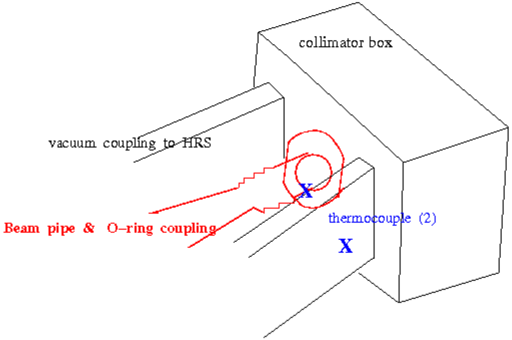
Lead/Diamond target(s)

- 0.15 mm thick diamond, 0.5 mm thick Pb
- Cryogenically cooled frame (30 W)
- Beam is rastered by two fast magnets upstream to diffuse beam on surface



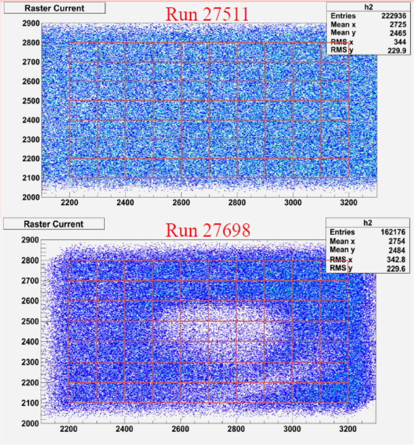
Experimental Issues

- Several issues prevented full experimental program
  - Large amounts of radiation were dumped in the experimental hall damaging electronics
  - Mistune of septum field - loss of some small angle statistics
  - Destruction of scattering chamber rubber O-rings

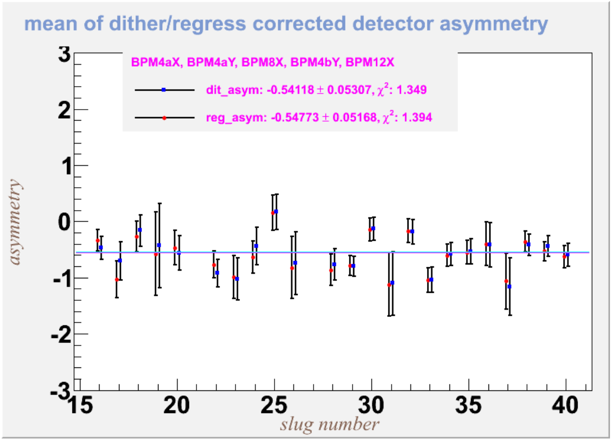


Experimental Issues - Target

- Targets were destroyed over periods of time by beam
- Loss of material $\sim$ 10%
- Thicker diamond targets were more successful - Lasted 4 days at 70 μA
- Thickest diamond contributes 8% background - manageable

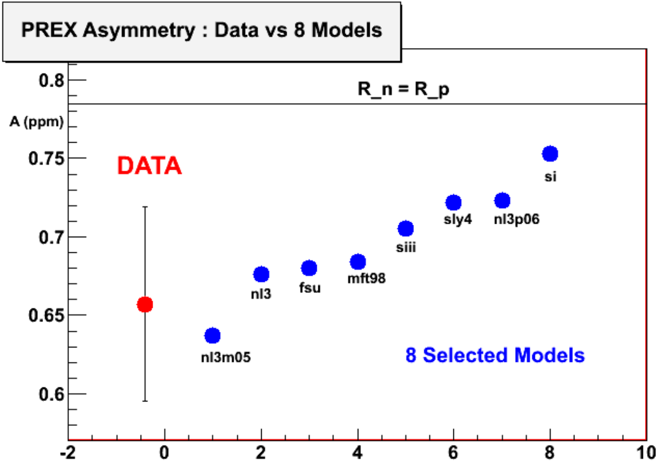


Data Quality



- Measured asymmetries relatively stable over run

Results



- Set 95% CL on existence of neutron skin
- $R_n - R_p = 0.34 + 0.15 - 0.17 \text{ fm}$

Results

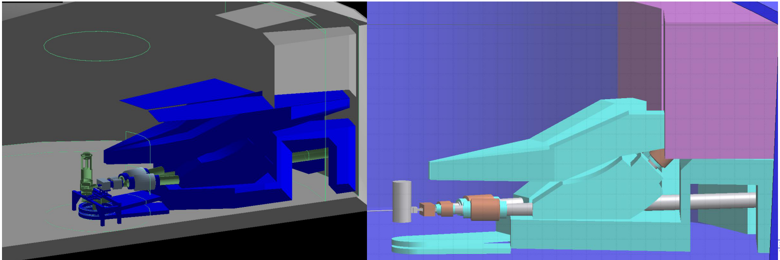
$$A_{\mathrm{PV}} = 0.6571 \pm 0.0604 \pm 0.0130 \text{ ppm}$$
$$\pm 9.22\% \text{ (stat)} \quad \pm 1.98\% \text{ (sys)}$$

	abs (ppm)	rel (%)
Polarization	0.0071	1.1
Detector Lin.	0.0071	1.1
Beam Corrections	0.0072	1.1
Q^2	0.0028	0.4
$^{12}\mathrm{C}$ Asymmetry	0.0025	0.4
Transverse Pol.	0.0012	0.2
BCM Lin.	0.0010	0.1
Target Thick	0.0006	0.1
Rescattering	0.0001	0.0
Inelastic Cont.	0.0000	0.0

- Systematic of $\sim 2\%$ achieved!
- Completely statistics dominated

Future plans: PREXII

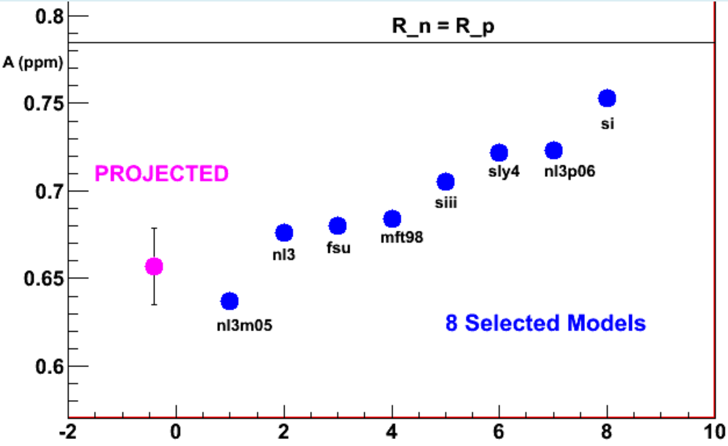
- New proposal to complete measurements appoved with A-rating from PAC
- Measurement of APV to 3% (combined with PREX-I) with 35 days
- Several improvements to prior experiment:
  - Improved metal O-rings
  - Additional radiation mitigation



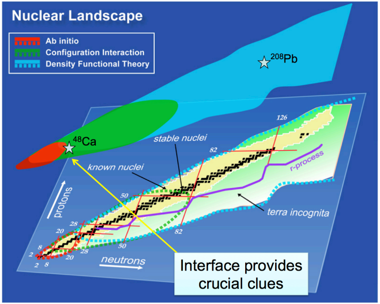
Future plans: PREXII - expected inpact

PREX-II Approved by PAC (Aug 2011)

"A" Rating 35 days run in 2013 / 2014



Future plans: CREX ^{48}Ca target



Theory TAC Review

...this and the complementary one in ^{208}Pb are important measurements for constraining, on the one hand, inputs to nuclear DFT phenomenologies and, on the other, inputs to nuclear dynamics–the modeling of three-neutron forces–in microscopic approaches.

- Data from medium-sized nuclei can act as a bridge between light-nuclei ab initio calculations and heavy nuclei DFT
- Iso*vector* observables are not easily accessible and typically poorly constrained
- Facilities like FRIB will study nuclei with very large neutron skins and halos, need CREX and PREX to reliably anchor those measurements

Future plans: PREX and CREX program comparison

With 30 days for PREX: 3% stat, 35 days for CREX 2% stat

PREX, $E = 1.1$ GeV, $A = 0.6$ ppb

Charge Normalization	0.1%
Beam Asymmetries	1.1%
Detector Non-linearity	1.0%
Transverse	0.2%
Polarization	1.1%
Inelastic Contribution	$< 0.1\%$
Effective Q^2	0.4%
Total	2%

CREX, $E = 2.2$ GeV, $A = 2$ ppm

Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	0.3%
Transverse	0.1%
Polarization	0.8%
Inelastic Contribution	0.2%
Effective Q^2	0.8%
Total	1.2%

- Polarimetry errors could improve with planned advances for Moller and SoLID
- CREX more sensitive to Q^2 uncertainty than PREX, angular resolution demonstrated using elastic *ep*

Why ^{48}Ca and ^{208}Pb and not something else?

What further measurements could be done?

Why ^{48}Ca and ^{208}Pb and not something else?

What further measurements could be done?

These are the only choices available for such a program

Why ^{48}Ca and ^{208}Pb and not something else?

What further measurements could be done?
These are the only choices available for such a program

Reasons:

- Require neutron excess
- Require large inelastic state separation, doubly-magic (3.8 MeV for ^{48}Ca)
- Must have very long lifetime

Why ^{48}Ca and ^{208}Pb and not something else?

What further measurements could be done?
These are the only choices available for such a program

Reasons:

- Require neutron excess
- Require large inelastic state separation, doubly-magic (3.8 MeV for ^{48}Ca)
- Must have very long lifetime

Importance of the experiments on both targets

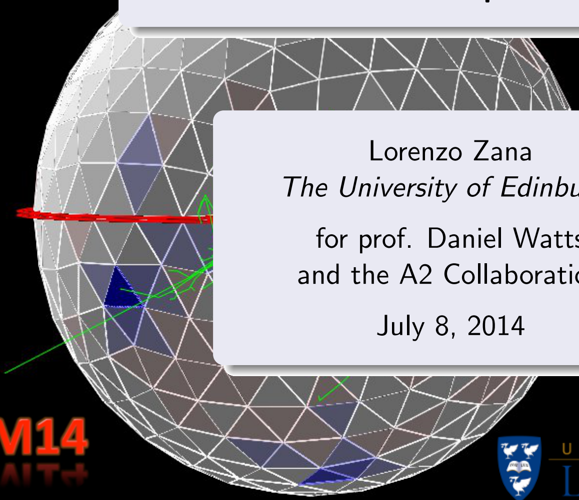
- No other nuclei meet these criteria
- Both nuclei will provide two points over a broad mass range and provide powerful tests when done together

Neutron Distribution in Heavy Nuclei: Coherent Pion Photoproduction

Lorenzo Zana
The University of Edinburgh

for prof. Daniel Watts
and the A2 Collaboration

July 8, 2014



7-9 July 2014

Coherent Pion Photoproduction. A2 Collaboration:

PRL 112, 242502 (2014) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Neutron Skin of ^{208}Pb from Coherent Pion Photoproduction

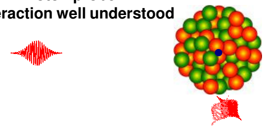
C. M. Tarbert,[1] D. P. Watts,[1,*] D. I. Glazier,[1] P. Aguar,[2] J. Ahrens,[2] J. R. M. Annand,[3] H. J. Arends,[2] R. Beck,[2,4] V. Bekrenev,[5] B. Boillat,[6] A. Braghieri,[7] D. Branford,[1] W. J. Briscoe,[8] J. Brudvik,[9] S. Cherepnya,[10] R. Codling,[3] E. J. Downie,[3] K. Foehl,[1] P. Grabmayr,[11] R. Gregor,[12] E. Heid,[2] D. Hornidge,[13] O. Jahn,[2] V. L. Kashevarov,[10] A. Knezevic,[14] R. Kondratiev,[15] M. Korolija,[14] M. Kotulla,[6] D. Krambrich,[2,4] B. Krusche,[6] M. Lang,[2,4] V. Lisin,[15] K. Livingston,[3] S. Lugert,[12] I. J. D. MacGregor,[3] D. M. Manley,[16] M. Martinez,[2] J. C. McGeorge,[3] D. Mekterovic,[14] V. Metag,[12] B. M. K. Nefkens,[9] A. Nikolaev,[2,4] R. Novotny,[12] R. O. Owens,[3] P. Pedroni,[7] A. Polonski,[15] S. N. Prakhov,[9] J. W. Price,[9] G. Rosner,[3] M. Rost,[2] T. Rostomyan,[7] S. Schadmand,[12] S. Schumann,[2,4] D. Sober,[17] A. Starostin,[9] I. Supek,[14] A. Thomas,[2] M. Unverzagt,[2,4] Th. Walcher,[2] L. Zana,[1] and F. Zehr[6]
(Crystal Ball at MAMI and A2 Collaboration)

[1]*SUPA, School of Physics, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[2]*Institut für Kernphysik, University of Mainz, Germany*
[3]*SUPA, Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[4]*Helmholtz-Institut für Strahlen- und Kernphysik, University Bonn, Germany*
[5]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[6]*Institut für Physik, University of Basel, Basel, Switzerland*
[7]*INFN Sezione di Pavia, Pavia, Italy*
[8]*Center for Nuclear Studies, The George Washington University, Washington, D.C. 20052, USA*
[9]*University of California at Los Angeles, Los Angeles, California 90095, USA*
[10]*Lebedev Physical Institute, Moscow, Russia*
[11]*Physikalisches Institut Universität Tübingen, Tübingen, Germany*
[12]*II. Physikalisches Institut, University of Giessen, Germany*
[13]*Mount Allison University, Sackville, New Brunswick E4L 1E6, Canada*
[14]*Rudjer Boskovic Institute, Zagreb, Croatia*
[15]*Institute for Nuclear Research, Moscow, Russia*
[16]*Kent State University, Kent, Ohio 44240, USA*
[17]*The Catholic University of America, Washington, D.C. 20064, USA*

(Received 2 February 2014; published 18 June 2014)

Coherent Pion Photoproduction

Photon probe ✓
Interaction well understood



π^0 meson – produced with ~equal probability on protons *AND* neutrons.

Select reactions which leave nucleus in ground state

Reconstruct π^0 from $\pi^0 \rightarrow 2\gamma$ decay

- Angular distribution of π^0 $\rightarrow$ PWIA contains the matter form factor

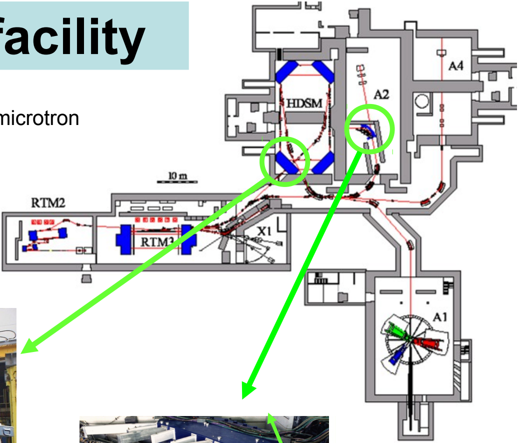
$$d\sigma/d\Omega(\mathrm{PWIA}) = (s/m_N^2)\, A^2\, (q_\pi^*/2k_\gamma)\, F_2(E_\gamma^*,\theta_\pi^*)^2\, |F_m(q)|^2 \sin^2\theta_\pi^*$$

- π^0 final state interactions - use latest complex optical potentials tuned to π-A scattering data. Corrections modest at low pion momenta

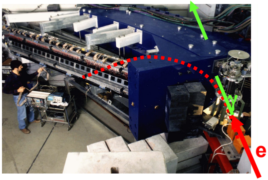
Mami: The Mainzer Microtron

The MAMI facility

- 100% duty factor electron microtron
- MAMI-C 1.5 GeV upgrade
  (MAMI-B 0.85 GeV)

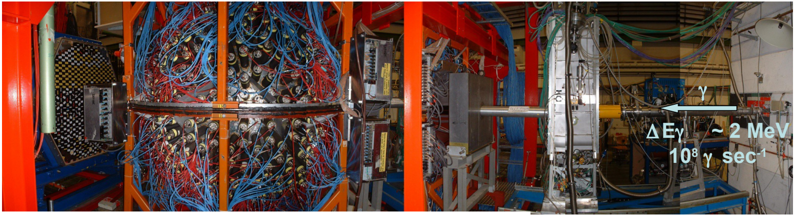


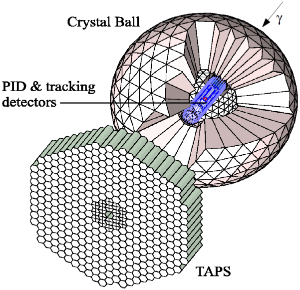

One of the MAMI-C magnets



Mami: The Photon Beamline

The MAMI photon beamline





<u>Crystal Ball:</u>
672 NaI(Tl) crystals
93,3% of total solid angle
Each crystal equipped with PMT

$$\frac{\sigma}{E_\gamma} = \frac{2\%}{(E_\gamma/GeV)^{0.25}} \qquad \sigma(\theta) = 2^\circ \ldots 3^\circ$$

$$\Delta t = 2.5 \text{ ns FWHM} \qquad \sigma(\phi) = \frac{2^\circ \ldots 3^\circ}{\sin(\theta)}$$

<u>TAPS:</u>
Up to 510 BaF_2 crystals
Polar acceptance: 4-20°

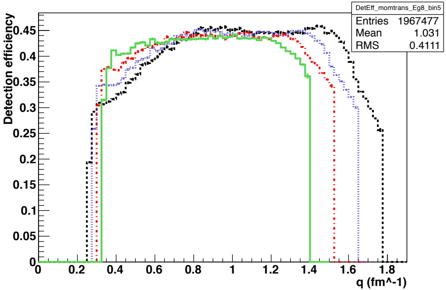
$\Delta t = 0.5$ ns FWHM

$$\frac{\sigma}{E_\gamma} = \frac{0{,}79\%}{\sqrt{E_\gamma/GeV}} + 1{,}8\%$$

Coherent Pion Photoproduction Analysys

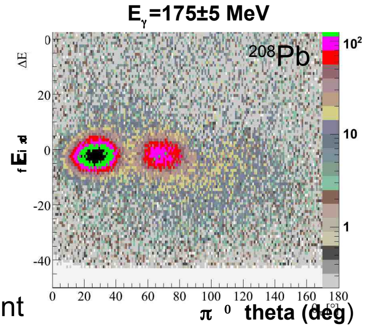
Previous (γ, π^0) measurements for ^{208}Pb did not achieve the precision needed to study the neutron skin mainly because they used π^0 detection systems with too low an efficiency (10%) and too large a dependence on pion energy and angle.

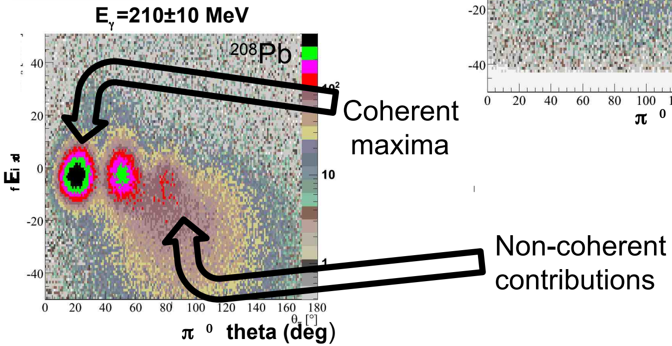
With Crystal Ball, Glasgow Photon Tagger and MAMI



Coherent Pion Photoproduction Analysys

$$E_\pi^{diff} = E_\pi^{measured} - E_\pi^{calc}$$





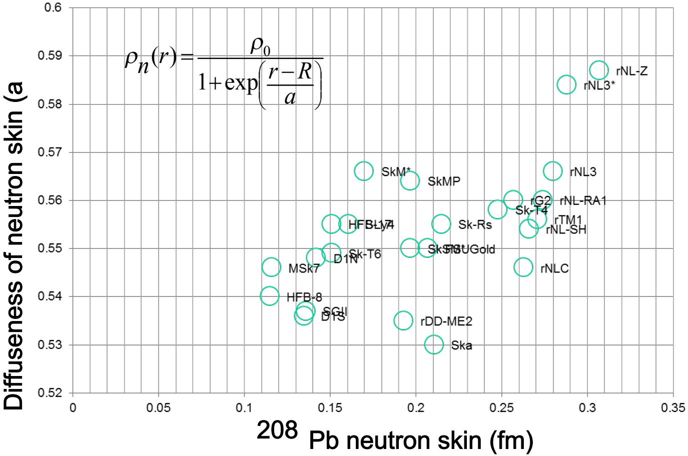
Coherent Pion Photoproduction Analysys

To obtain cross sections the yield was corrected for the π^0 detection efficiency.

- This is calculated by analysing pseudo-data from a GEANT4 simulation of the detector apparatus using the same procedure as for the real data.
- The detection efficiency for the current measurement shows no sharp dependencies on pion angle and was typically around 40%.
- The yield was also corrected for the photon tagging efficiency ($\sim$40%).
- The contribution of pions not originating from the ^{208}Pb target was found to be less than $\sim$1% in additional runs with the target removed and was subtracted from the yield.

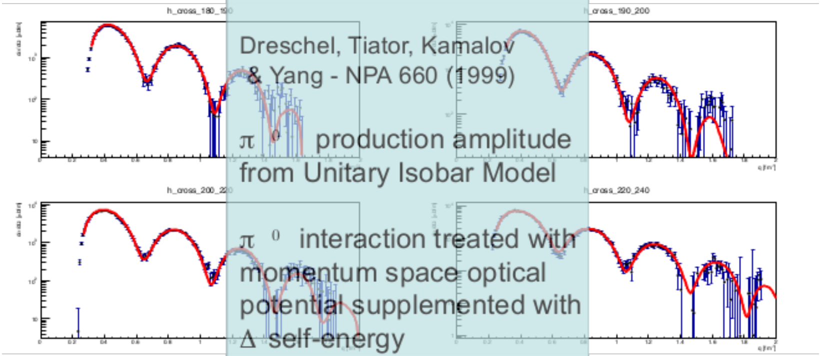
Coherent Pion Photoproduction Analysys

Existing data and parameters



M. Centelles et. al.

Coherent Pion Photoproduction Analysys



Theoretical prediction

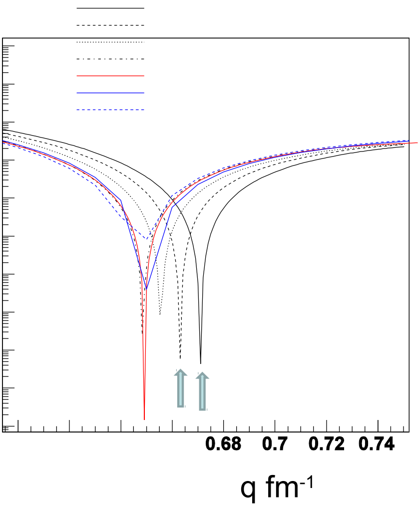
Dreschel, Tiator, Kamalov & Yang - NPA 660 (1999)

π^0 production amplitude from Unitary Isobar Model

π^0 interaction treated with momentum space optical potential supplemented with Δ self-energy

Coherent Pion Photoproduction Analysys

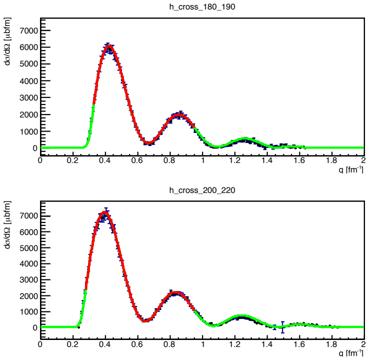
1st minima in $^{208}Pb(\gamma, \pi^0)$ for varying skin thickness



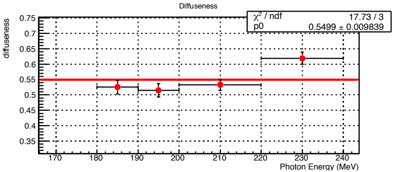
0.1 fm skin corresponds to shift in q of ~0.01 fm-1

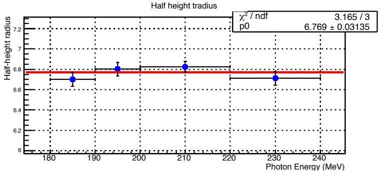
Results

Fits in each bin



Results





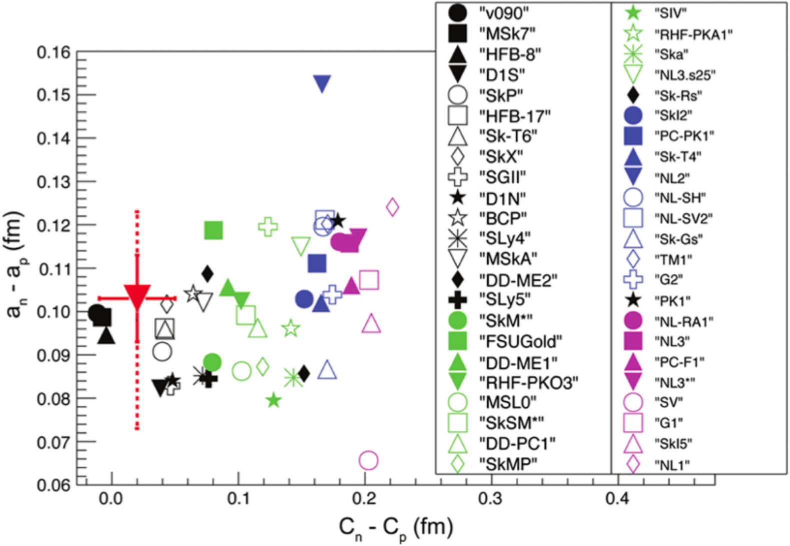
Results

$$\text{Diffusenes} = 0.55^{+0.01(stat)+0.02(sys)}_{-0.01(stat)-0.03(sys)}\text{fm}$$

$$\text{Half-Height Radius} = 6.70^{+0.03(stat)+0.01(sys)}_{-0.03(stat)-0.01(sys)}\text{fm}$$

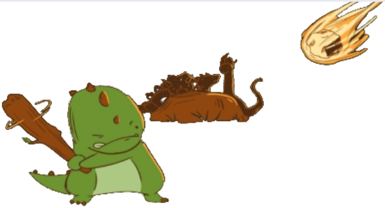
$$\text{Neutron Skin} = 0.15^{+0.03(stat)+0.01(sys)}_{-0.03(stat)-0.03(sys)}\text{fm}$$

Results

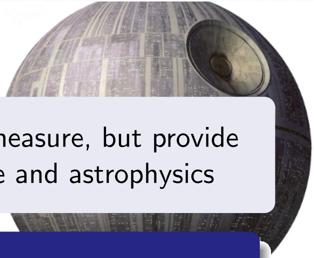

"v090"
"MSk7"
"HFB-8"
"D1S"
"SkP"
"HFB-17"
"Sk-T6"
"SkX"
"SGII"
"D1N"
"BCP"
"SLy4"
"MSkA"
"DD-ME2"
"SLy5"
"SkM*"
"FSUGold"
"DD-ME1"
"RHF-PKO3"
"MSL0"
"SkSM*"
"DD-PC1"
"SkMP"
"SIV"
"RHF-PKA1"
"Ska"
"NL3.s25"
"Sk-Rs"
"SkI2"
"PC-PK1"
"Sk-T4"
"NL2"
"NL-SH"
"NL-SV2"
"Sk-Gs"
"TM1"
"G2"
"PK1"
"NL-RA1"
"NL3"
"PC-F1"
"NL3*"
"SV"
"G1"
"SkI5"
"NL1"
$a_n - a_p$ (fm)
$C_n - C_p$ (fm)
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.0
0.1
0.2
0.3
0.4

Conclusions

Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics



Conclusions

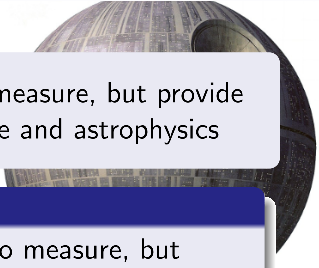


Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics

π^0 photoproduction

- Coherent pion photoproduction provides a measurement of neutron radii with an electromagnetic probe has potential to provide a $<1\%$ measurement of skin
- The Neutron Skin in ^{208}Pb show a profile charachterized by an halo (diffuseness $\gg$0)

Conclusions



Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics

PV Asymmetry

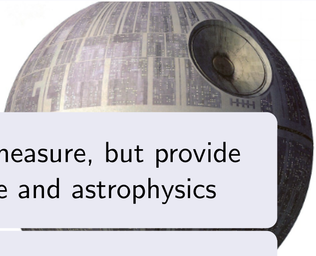
- Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics
- Parity-violating electron scattering provides a clean method to measure such a distribution
- The PREX and CREX measurements aim to measure δR_n to a precision of 0.06 and 0.02 with 35 and 30 production days respectively

Conclusions

Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics

BOTH METHODS have active future programme of measurements planned on further nuclei, skin evolution across isotopic chains

Conclusions



Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics

BOTH METHODS have active future programme of measurements planned on further nuclei, skin evolution across isotopic chains

Thank You for your time