CREX: Measurements of the Neutron Radius of ^{48}Ca

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for the CREX Collaboration

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Outline

- Introduction and Update
- Motivation
- Setup and Experiment
- Results and Uncertainties

Main Motivation

- Both proton and neutron distributions are important to understanding nuclear matter
- Calculations are difficult due to non-pQCD regime complicated by many-body physics
- Interesting for
  - Fundamental nuclear structure
  - Isospin dependence and nuclear symmetry energy
  - Dense nuclear matter and neutron stars
- Isovector properties not well constrained by binding energies - must look at distributions within nuclei
- Proton distribution is relatively easy - electromagnetic probes
- Neutron distribution is difficult
  - Weakly couples to electroweak probes
  - Hadronic probes have considerable uncertainty
  - Theory has range of $R_n - R_p$ for various nuclei

Why ^{48}Ca and ^{208}Pb?

- 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

- Require neutron excess
- Require spin-0
- Must have very long lifetime
- Require large inelastic state separation(3.8 MeV for ^{48}Ca)

No other nuclei meet these criteria

- Both nuclei will provide two points over a broad mass range and provide powerful tests when done together

New Developments since PAC39

- Successful theory workshop with over 20 presentations

http://www.jlab.org/conferences/crex/

J. Piekarewicz: *A three-legged "isovector" stool:* $R_n[^{48}Ca]$;$R_n[^{208}Pb]$; $\alpha_D[^{208}Pb]$

Organizing Committee: C. Horowitz (Indiana), K. Kumar (UMass), R. Michaels (JLab), W. Nazarewicz (UTK/ORNL), J. Piekarewicz (FSU)

New Developments since PAC39 (2)

- Neutron skin measurements on ^{208}Pb *and* ^{48}Ca highlighted as important program

NSAC Subcommittee Report

Jefferson Lab uses a faint signal arising from parity violation induced by the weak interaction to measure the radius of the neutron distribution of stable lead and calcium nuclei. Studies of neutron skins in heavy nuclei at both FRIB and Jefferson Lab, and investigations of high-frequency nuclear oscillations and intermediate energy nuclear reactions with a range of proton and neutron-rich nuclei will help pin down the behavior of nuclear matter at densities below twice typical nuclear density

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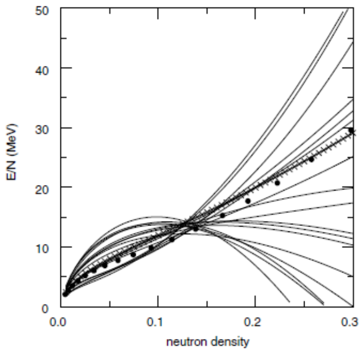
- Refined systematic errors and simulations with deeper analysis
- Updated projected uncertainty from 0.03 $\rightarrow$ 0.02 fm

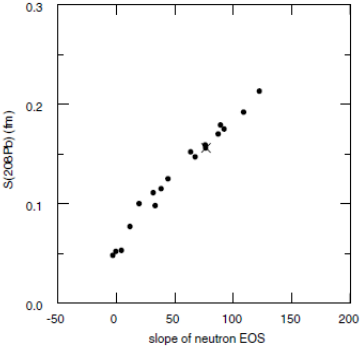
Importance of Neutron Densities

- Constraints on neutron EOS

E vs. ρ



^{208}Pb Skin vs. $dE/d\rho|_{\rho=0.1\ \mathrm{fm}^{-1}}$

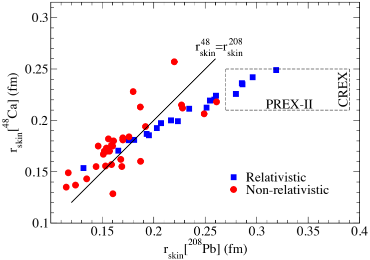


B. Alex Brown, PRL 85, 5296 (2000)

- Slope of EOS can be used to constrain DFTs
- Correlated to ρ dependence of symmetry energy

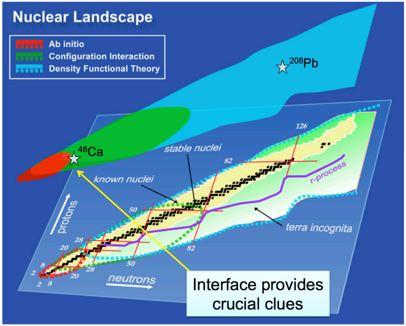
Density Functional Theory

- PREX constrains slope of symmetry energy
- A correlation is predicted between ^{48}Ca and ^{208}Pb, but needs to be tested in DFT framework



- Model spans suggest values between Ca and Pb, need to be tested, correlation isn't good, may have systematic assumptions across all models
- A successful test would build confidence in extending isovector observables across the periodic table
- Disagreement would mean something is missing - isovector and surface energy contribution strengths not well understood? models incomplete?

Intermediate Mass Nuclei as a Bridge

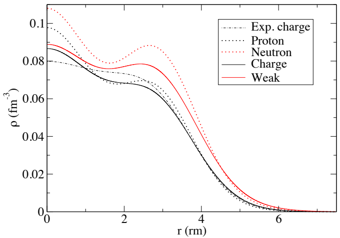


Theory TAC Review

...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

Coupled Cluster Models



G. Hagen *et al.*,

Phys. Rev. Lett 109 032502 (2012)

- Coupled cluster models just becoming computationally feasible, but are still preliminary
- G. Hagen of ORNL awarded early-career award to do these calculations
- 3-neutron forces have an effect on isovector properties, such as the neutron skin
- Agreement with calculations would increase confidence in such calculations to be applied to other nuclei and is a test of such models
- Disagreement would mean something is missing, such as important terms in the expansion and models need to be refined

Accessing Neutron Radii in Nuclei

Hadronic Probes

- Elastic pN, $\vec{p}N$, nN, $\pi^{\pm}N$
- Alpha scattering
- Antiproton scattering

Have uncertainty in extraction due to strong force interactions

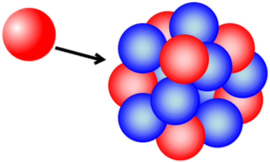
Complementary Methods

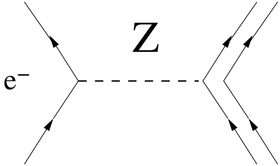
- GDR/dipole polarizability

Electroweak Probes

- Parity violating electron scattering
- Atomic parity violation
- "Clean" measurements, fewer systematics

Technically challenging due to small weak force interactions





Parity Violating Electron Scattering

- e^- also exchange Z, which is parity violating
- Primarily couples to neutron:

$$Q_{\mathrm{weak}}^{\mathrm{proton}} \propto 1 - 4\sin^2\theta_{\mathrm{W}} \approx 0.076, \quad Q_{\mathrm{weak}}^{\mathrm{neutron}} \propto -1$$

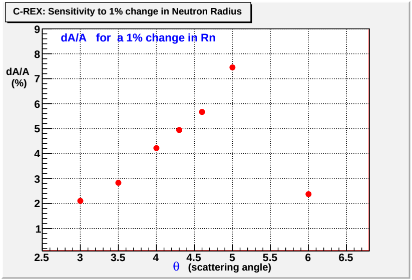
- Detectable in parity violating asymmetry of electrons with different helicity
- In Born approximation, $Q^2 \ll M_Z^2$, from $\gamma - Z$ interference:

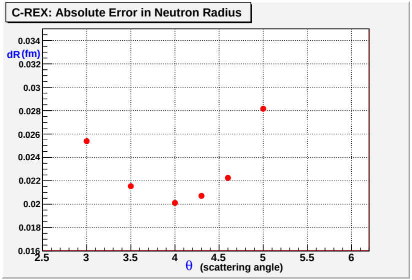
$$A_{\mathrm{PV}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

- For fixed target exp., typical $A_{\mathrm{PV}} \sim 10^{-7} - 10^{-4}$

Optimize Kinematics

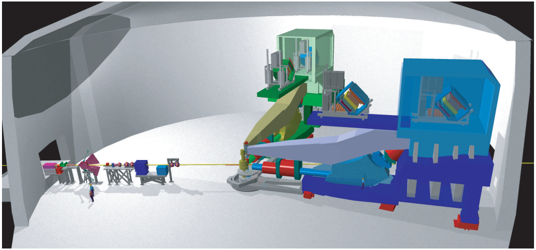
- Compete against falling rates with higher asymmetry as Q^2 grows
- Need to optimize to sensitivity of A to marginal changes in radius



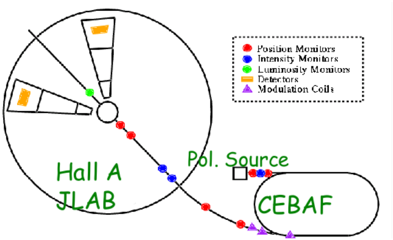


- For 2.2 GeV standard-energy beam, $\theta \approx 4^\circ$
- $\delta R_n \approx 0.02\ \mathrm{fm}$ with 35 days beamtime and anticipated systematics

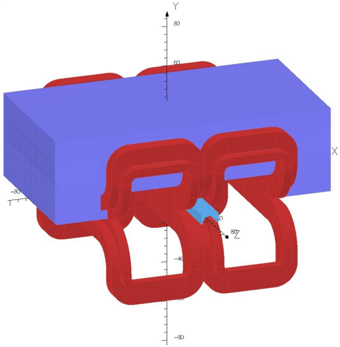
Experimental Configuration

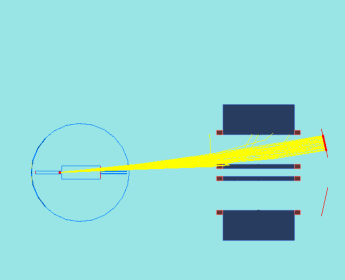


- HRS's run simultaneously and symmetrically
- $A_{\mathrm{PV}} \sim 2$ ppm, comparable to previous generation HAPPEX-II
- Much less challenging than 0.5 ppm PREX



Septum Magnet



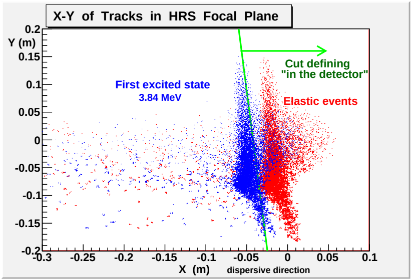


Septum Magnet Requirements

- HRS only go to 12.5°, require septum to reach 4°
- Sufficient hardware resolution must be maintained, need pure dipole
- Need to reach 1350 $\mathrm{A/cm^2}$ with 2-coil configuration
- Require new power supply, LCW pumps
- Target must be moved back for 4° acceptance, room is available without major reworking

HRS and Quartz Detectors

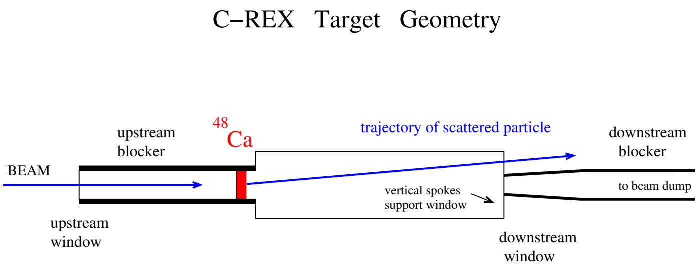
- HRS has hardware resolution 10^{-3}, use to separate inelastic states



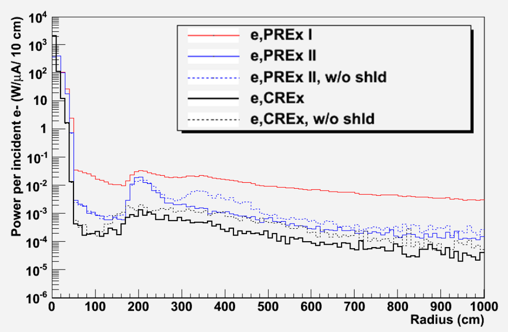
- Place quartz Cerenkov detectors to minimize inelastics
- Several states, but kept to $< 0.5\%$. Asymmetries calculable to some level and are expected to be benign

^{48}Ca Target

- 1 $\mathrm{g/cm^2}$, 5% radiator (much less than PREX!)
- Factor 20 safety margin in beam current to avoid target melting due to higher conductance, smaller dE/dx, and higher melting point
- Oxidizes when exposed to air, must remain isolated
- Al end windows contribute background, must remove from acceptance
- Collimators degrade e^- energy by $> 20\ \mathrm{MeV}$
- Test with ^{40}Ca target during PREx-II



Radiation Impact



- CREX is at higher beam energy (more forward peaked), target is half rad. thickness
- Radiation simulations show several times smaller than PREX-II (about order of magnitude per electron)
- Further simulations will be performed to optimize any shielding

Beam Request and Proposed Data

Energy	2.2 GeV
Current	150 μA
Polarization	Full, $\sim$ 85%

Production	35 days
Commissioning	5 days
Pol, calib., A_T	5 days

- 150 μA available with $\sim$ 50 μA for remaining halls
- Require full longitudinal and (vertically) transverse beam

Measured Asymmetry (p_e A)	2 ppm
Scattering Angle	4°
Detected Rate (each HRS)	140 MHz
Statistical Uncertainty of A_{PV}	2.1%
Systematic Uncertainty of A_{PV}	1.2%
Statistical Uncertainty of A_T	0.4 ppm

Systematic Uncertainties

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%

- Statistics dominate total uncertainty
- CREX more sensitive to Q^2 uncertainty than PREX, angular resolution demonstrated using elastic *ep*

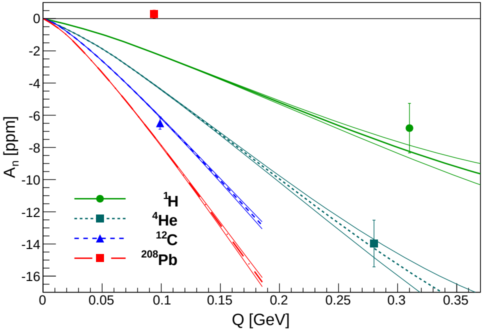
Conclusion

- Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics
- Having these measurements available for a broad range of masses is important to constraining isovector properties
- Parity-violating electron scattering provides a clean method to measure such a distribution
- The CREX measurement aims to measure δR_n to a precision of 0.02 fm with 45 days

BACKUP

Transverse Asymmetries

- Vertically transverse beam asymmetries sensitive to two photon effects
- Asymmetries are highly suppressed, few ppm for $Q^2 \sim 10^{-2}\ \mathrm{GeV}^2$



- Dispersion calculations: agreement with low Z nuclei
- ^{208}Pb is significantly off - Coulomb distortions?

High Current Running

Three main current limitation issues:

- Halls A and C have 1 MW power limit at beam dump (90 μA at 11 GeV)
- Injector RF power limits total current output to 200 μA
- Linac RF power limits total beam current to 465 μA

For 1 pass, 150 μA beam, this leave 50 μA to the remaining halls
Q_{weak} ran with 180 $\mu\mathrm{A}$ at parity-quality with much higher demands

Power Deposited in Target Assembly

In blocker and window

	Stand. [W/μA]	Tapered [W/μA]
Total Deposited	0.40	0.19
Radiated out	1.64	0.03

For 150 μA, this corresponds to 60 or 30 W (20 W in window and 10-40 W in blocker)

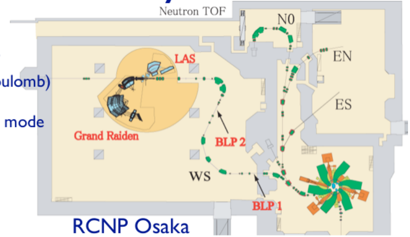
Dipole Polarizability

Dipole Polarizability α_D

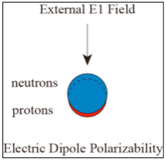
Polarized proton inelastic scattering

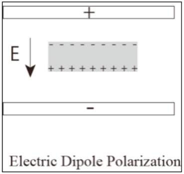
Integrate the electric dipole (E1) response of Pb-208 at very small angles < 2.5° (purely Coulomb)

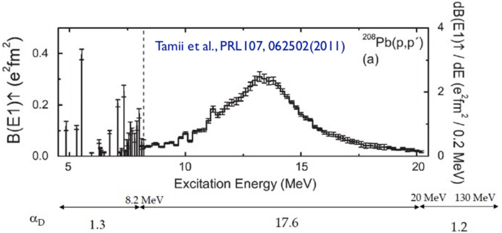
Electromagnetic probe, independent of decay mode



RCNP Osaka



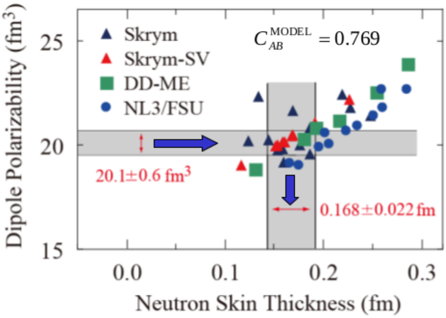




Dipole Polarizability

CREX WS, March 17-19, 2013

Correlation Between Dipole Polarizability and Neutron Skin Thickness



(0.168 ± 0.022) fm in ^{208}Pb

J. Piekarewicz, W. Nazarewicz, et al., PRC85, 041302(2012)

Precision given Beam Time/Current

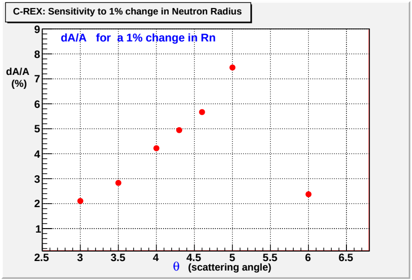
Current [μA]	Beam Time [days]	δA_{PV} [%]	dR [fm]
200	35	2.2	0.018
150	35	2.4	0.020
100	35	2.8	0.023
100	30	3.0	0.024

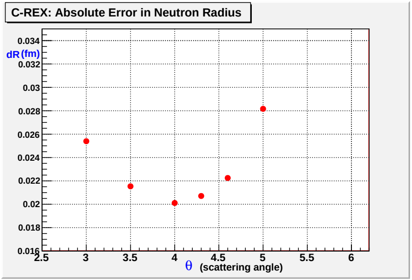
- 1 MW power limit to A and C
- RF power on the R100 cavity at injector has maximum 200 μA
- RF power to linacs limit the total beam current in any linac to 465 μA

For 150 $\mu\mathrm{A}$ 1-pass 2.2 GeV to Hall A, that leaves up to 50 $\mu\mathrm{A}$ 5-pass for the remaining halls

Optimize Kinematics

- Compete against falling rates with higher asymmetry as Q^2 grows
- Need to optimize to sensitivity of A to marginal changes in radius



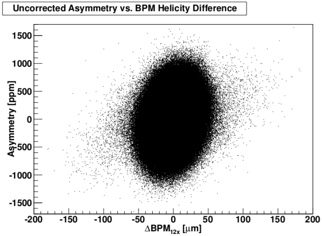


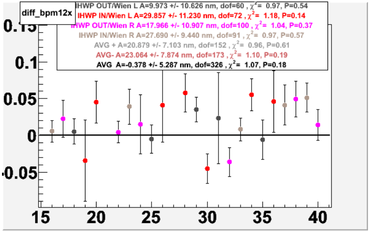
$$\mathrm{FOM} = R \times A^2 \times \left(\frac{dA/A}{dR_n/R_n} \right)^2$$

- Nominally maintain same Q^2 if considering different angle
- $\theta = 4.5^\circ$, $E = 1.96$ GeV

Parity Quality Beam

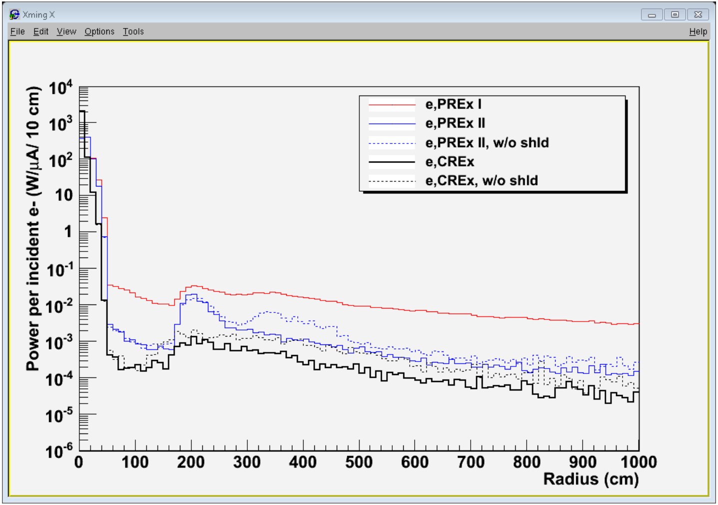
- Requirements less strict than PREx
  - Higher Q^2 ($\times 2$), larger asymmetry ($\times 4$)
  - Cross section changes $\times 6$ more slowly with angle
- Requirements less strict than Q_{weak}, also high current





- Use double-Wien, HWP insertions to control systematics
- PREX demonstrated corrections < 40 ppb, $\delta x < 4$ nm
- Polarization monitored to 1% with Moller and Compton

Radiation: e^-



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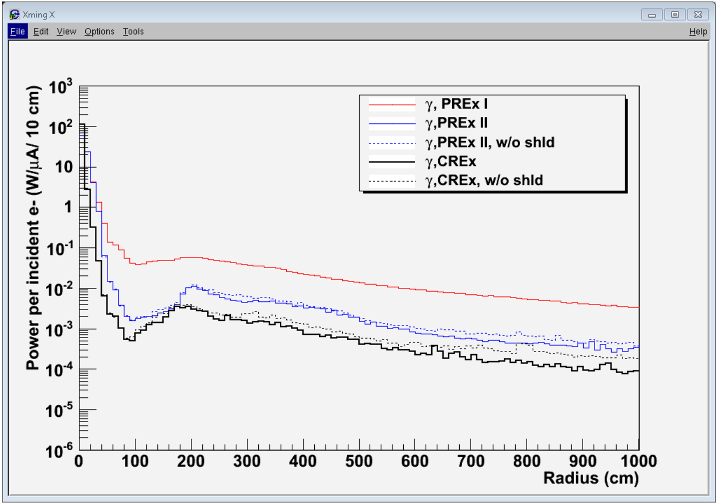
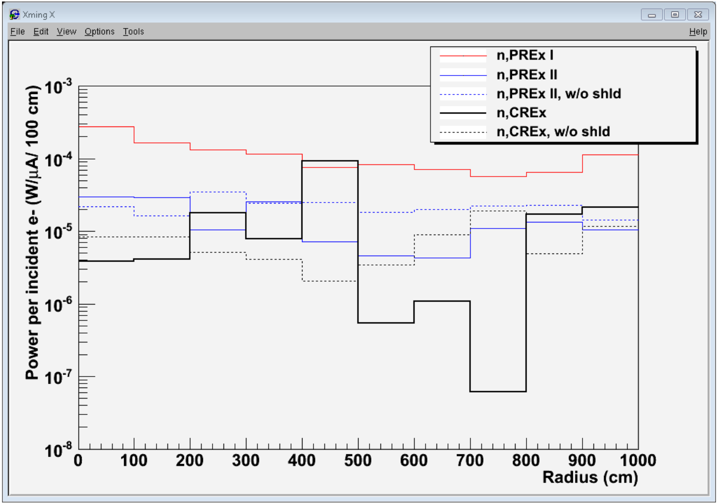
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
100
200
300
400
500
600
700
800
900
1000
Radius (cm)

Radiation: γ



Radiation: *n*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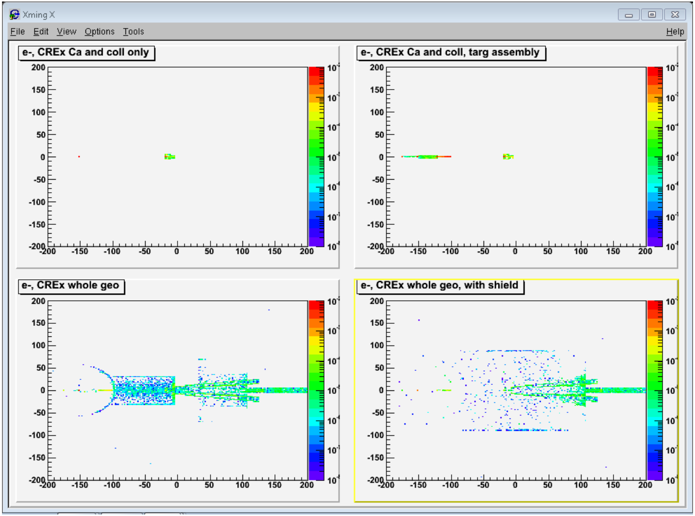
10^{-6}
10^{-7}
10^{-8}
0 100 200 300 400 500 600 700 800 900 1000
Radius (cm)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