MREX: The Mainz Radius EXperiment

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Neutron Skin

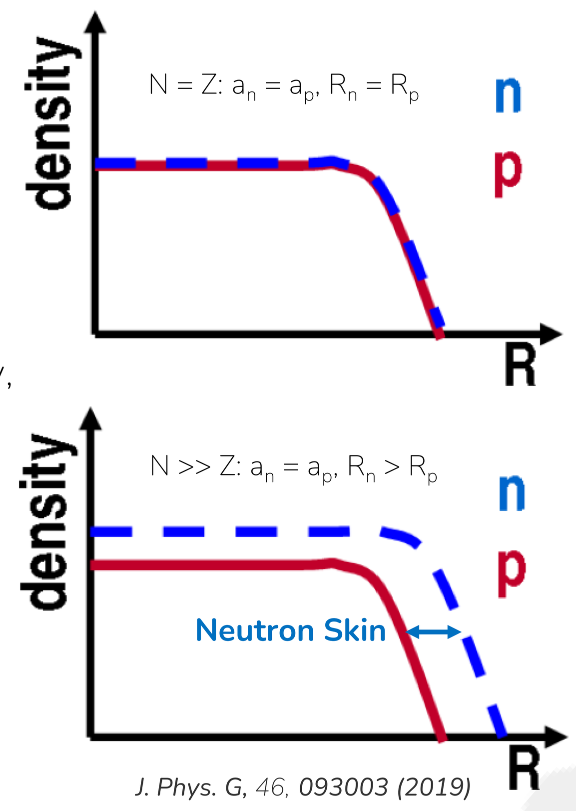
Neutron and proton density in nuclei are well approximated by 2-parameter Fermi distribution:

$$\rho(r) = \frac{\rho_0}{1+\exp\left[(r-C)/a\right]}$$

When N = Z, ρ_n and ρ_p are almost the same. In heavier nuclei with N >> Z neutrons are pushed towards the nuclear periphery, creating neutron skin (NS). It is characterized by **NS thickness**:

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

Experimentally and theoretically produced R_{skin} in ^{208}Pb have had large systematic uncertainties. But precise study of NS is crucial to restricting the Nuclear Equation of State.



J. Phys. G, 46, 093003 (2019)

Nuclear Equation of State

Nuclear Equation of State (EOS) describes the density dependence of the nuclear energy per nucleon:

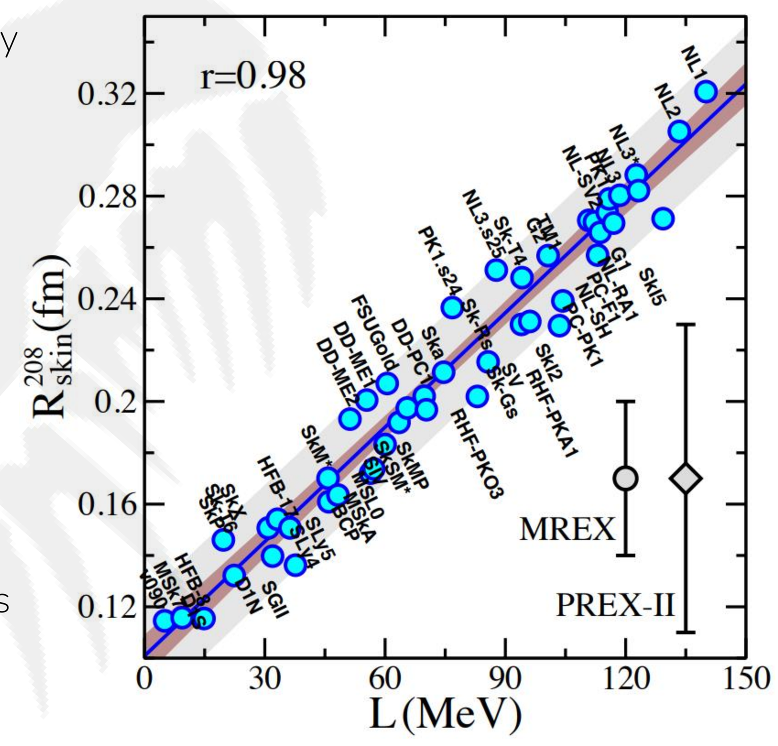
$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\rm SNM}(\rho) + \alpha^2\mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

where $\alpha \equiv (\rho_n - \rho_p)/(\rho_n + \rho_p)$ and $S(\rho)$ is **symmetry energy**. Performing Taylor series around saturation density ρ_0:

$$\mathcal{S}(\rho) = J + Lx + \frac{1}{2}K_{\rm sym}x^2 + \ldots,$$

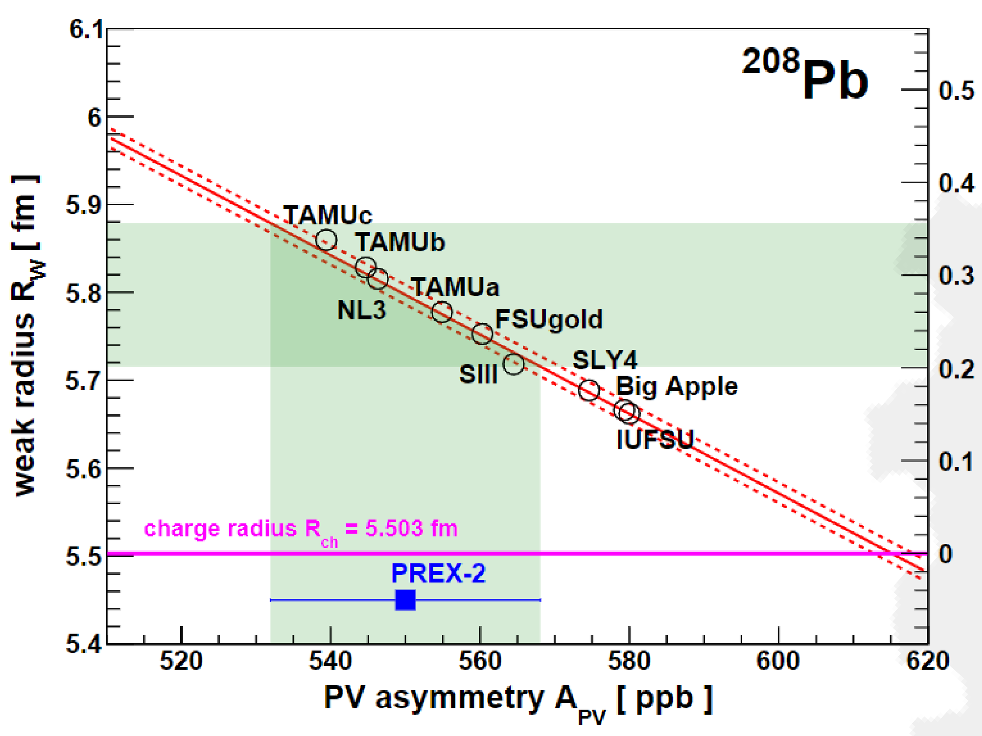
where $x = (\rho - \rho_0)/3\rho_0$ and $L \equiv 3\rho_0 \left(\frac{\partial S}{\partial \rho}\right)\Big|_{\rho_0}$

Here L is a **symmetry energy slope parameter**. L has strong correlation with R_{skin}, allowing for its model independent extraction from neutron skin thickness measurement.



Phys Today 72 (7), 30 (2019)

Bridge between nuclear physics and astrophysics



Phys. Rev. Lett. 126 (17), 172502 (2021)

Electron weakly couples to neutrons better than to protons, and coupling depends on polarization. Thus, R_n from asymmetry in **parity-violating electron scattering**:

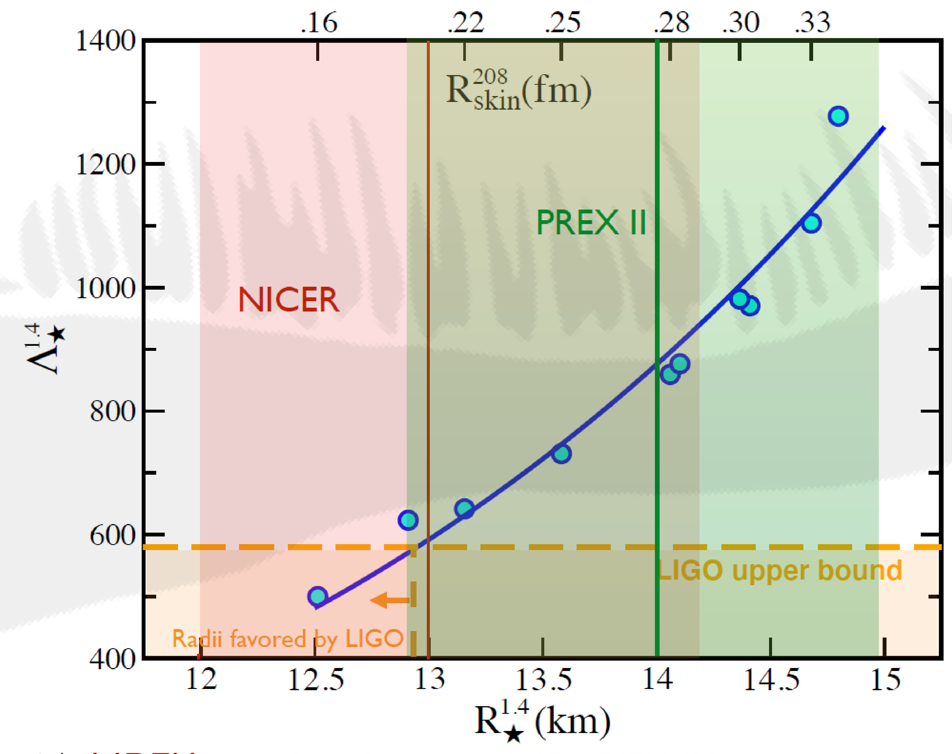
$$A_{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z}\frac{F_W(Q^2)}{F_{\rm ch}(Q^2)}$$

PREX-2 utilized this method to determine R_{skin} in ^{208}Pb to be 0.28 ± 0.07 fm.

This is in tension with theory when combined with CREX result for R_{skin} in ^{48}Ca.

R_{skin} can also be restricted with astrophysical observables:

- Tidal deformability of a neutron star $\Lambda_\star$ from **LIGO-Virgo** GW170817 observation gives upper limit on R_{skin} when combined with nuclear models
- Neutron star radius $R_\star$ from **NICER** x-ray observatory measurement of the pulsar PSR J0030+0451 and corresponding L gives prediction for R_{skin}



Phys. Rev. Lett. 120 (17), 172702 (2018)

These results are in **tension** with PREX-2, providing motivation to reproduce the measurement with **MREX**.

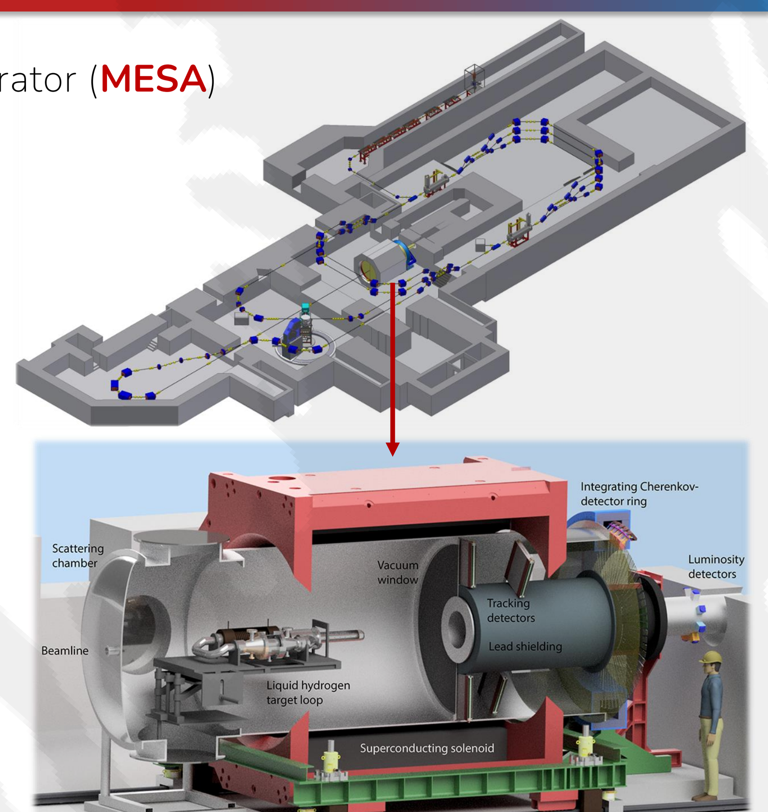
MESA, P2 and MREX

Mainz Energy-Recovering Superconducting Accelerator (**MESA**) will provide us with:

- 155 MeV beam kinetic energy
- 150 μA beam current
- 85% beam polarization
- < 1% systematic uncertainty from beam monitors (polarization etc.)

The **P2** experiment plans high-precision measurement of $\sin^2\theta_W$ through parity-violating electron scattering on liquid hydrogen target.

By exchanging hydrogen with ^{208}Pb target, MREX can use the same detector set-up to measure A_{PV} at the **same kinematics** as PREX-2.



Raytracing

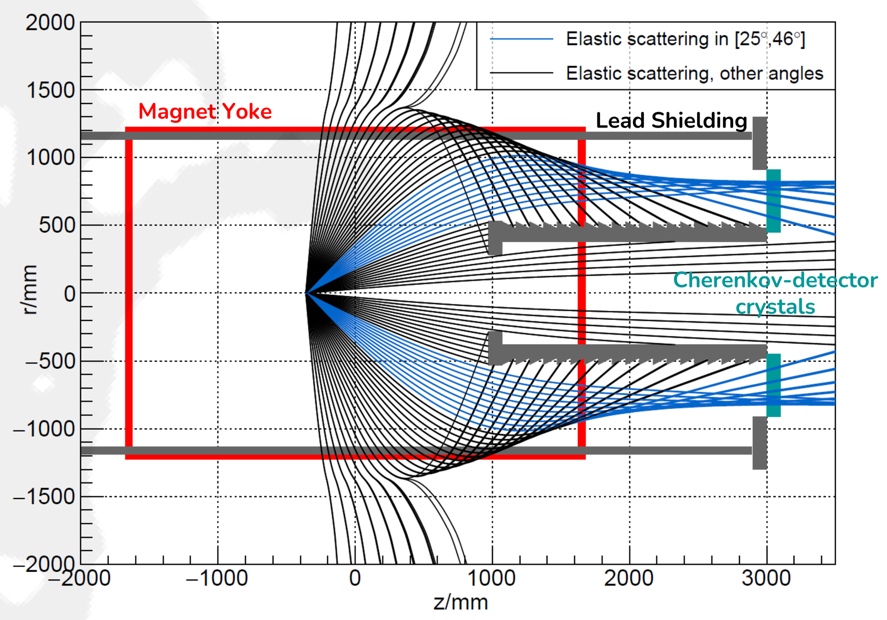
To simulate the tracks of the scattered electrons inside the detector set-up, the raytracing tool is used. **Target position** is chosen to:

- Match the average momentum transfer of PREX-2: <Q²> = 0.00616 (GeV/c)²
- Maximize signal from elastic electrons
- Minimize signal from inelastic events and secondary produced particles

Magnetic field is chosen to be 0.7T to bend most of inelastically scattered electrons.

The preliminary position of potential additional shielding is also chosen with raytracing.

B = 0.70 T, target center @ z = -360 mm



Monte-Carlo simulation

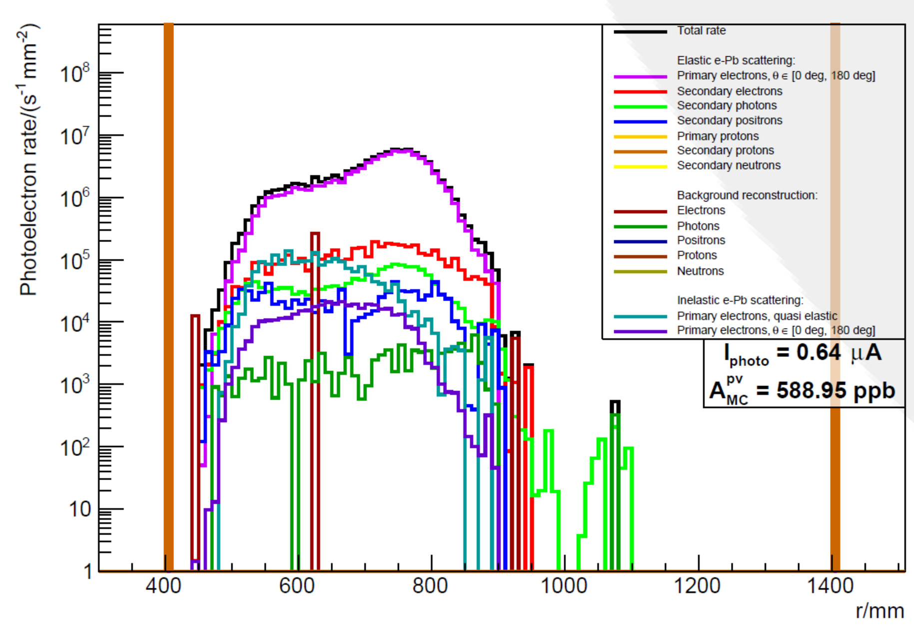
General information

The P2 simulation framework[1] was modified for MREX. It uses **Geant4** to simulate interaction of:

- Electron beam with target
- Generated scattered electrons and secondary produced particles with the detector set-up

It also includes the Cherenkov-detector response function.

[1] *Eur. Phys. J. A 54, 208 (2018)*

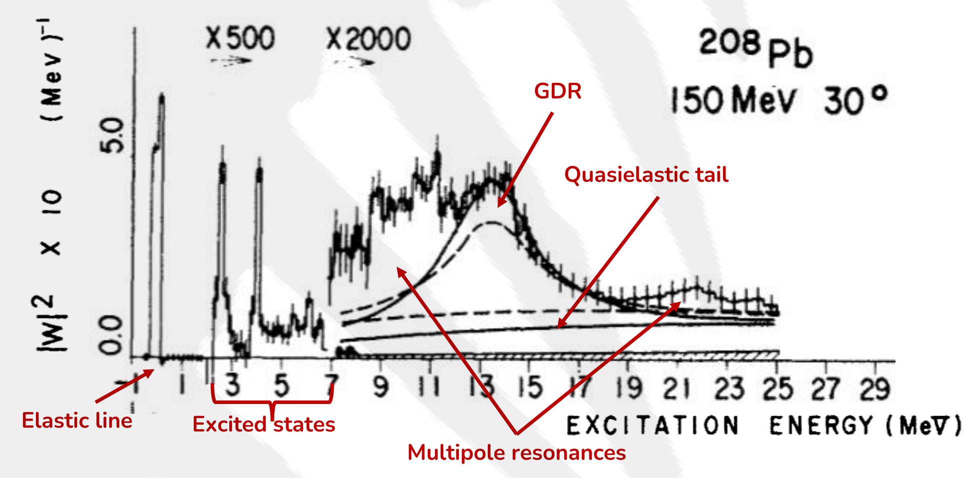


Inelastic and quasielastic scattering

Solenoid geometry leads to 25 MeV **excitation energy acceptance**. Precise modeling of non-elastic lines is necessary.

Cross section and asymmetry of quasielastic electron scattering at low Q² is uncertain.

Moving target upstream and **adding shielding** allow to reduce the acceptance and the rate of non-elastic events.



Phys. Rev. C 15(1), 217 (1977)

Measuring time

Simulation combined with theoretical predictions[2] for A_{PV} and ε show the achievable measuring time to be:

- **110 hours** to reach 1% uncertainty for R_n (PREX-2)
- **1500 hours** to reach 0.5% uncertainty for R_n

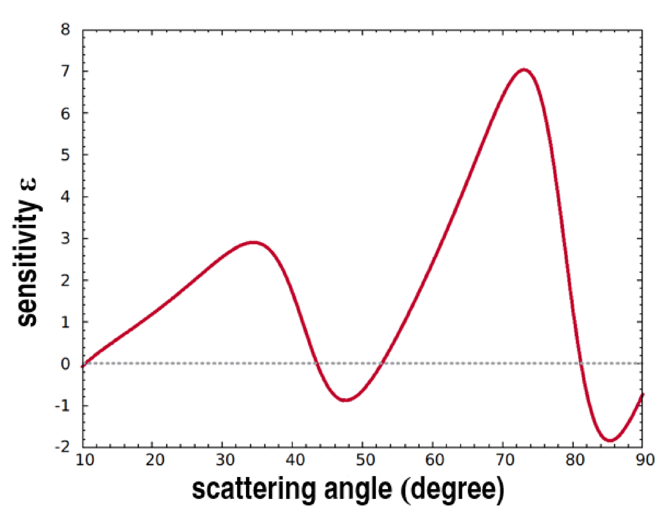
The exact measuring time depends largely on beam monitoring and quasielastic contribution, predictions for which will be improved in the future.

[2] *C. J. Horowitz*

$$\varepsilon = \frac{{\rm d}\ln(A^{\rm PV})}{{\rm d}\ln(R_n)} = \frac{R_n}{A^{\rm PV}}\frac{\delta A^{\rm PV}}{\delta R_n}$$

$$\mathrm{FOM} = \frac{{\rm d}\sigma}{{\rm d}\Omega}\times\left(A^{\rm PV}\right)^2\times\varepsilon^2$$

$$\frac{\Delta_{\rm syst}A_{\rm PV}}{A_{\rm PV}} = 1.1\%$$



Conclusion

Precise determination of NS thickness in ^{208}Pb is a great tool for bridging Nuclear Physics and Astrophysics. The results of the Monte-Carlo simulation of the forthcoming MREX show that it can be done in Mainz. We calculate corresponding systematic uncertainties and explore possibilities to reduce them, resulting in the reachable measuring time of 110 and 1500 hours to match or double PREX-2 uncertainty.