



# PROBING THE NEUTRON SKIN PUZZLE IN $^{208}\text{Pb}$ : PRECISION POLARIZED ELECTRON SCATTERING AT MAINZ\*

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*Received 7 November 2025, accepted 3 February 2026,*

*published online 31 March 2026*

The determination of the neutron skin thickness of  $^{208}\text{Pb}$  from the PREX-II measurement of the parity-violating asymmetry  $A_{\text{PV}}$  has generated considerable discussion within the nuclear physics community, revealing notable discrepancies with previous experimental results and theoretical predictions. PREX also reported a beam-normal single-spin asymmetry  $A_n$  for  $^{208}\text{Pb}$ , a key background to  $A_{\text{PV}}$ , that deviates from contemporary calculations — a discrepancy now known as the PREX anomaly. We present a new measurement of  $A_n$  in elastic electron scattering from natural lead performed at MAMI and discuss its implications for solving the PREX anomaly. We also outline the concept of the forthcoming Mainz Radius EXperiment (MREX) at MESA, designed to deliver an independent measurement of  $A_{\text{PV}}$  in  $^{208}\text{Pb}$  with twice the precision of PREX-II.

DOI:10.5506/APhysPolBSupp.19.1-A34

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\* Presented at the XXXVIII Mazurian Lakes Conference on Physics, Piaski, Poland, August 31–September 6, 2025.

## 1. Introduction

The Neutron Skin (NS), which is a phenomenon of an increased neutron-to-proton density ratio in the periphery of neutron-rich nuclei, is a prominent probe of the nuclear equation of state (EoS), bridging nuclear physics and astrophysics [1]. In particular, the NS in  $^{208}\text{Pb}$  has been the great focus for experimental and theoretical studies. The latest experimental measurement of NS in  $^{208}\text{Pb}$  performed by the PREX-II experiment [2] via parity-violating electron scattering (PVeS) has prompted significant discussion in the field. This result was obtained by measuring the parity-violating asymmetry defined as

$$A_{\text{PV}} = (\sigma_{\text{R}} - \sigma_{\text{L}})/(\sigma_{\text{R}} + \sigma_{\text{L}}), \quad (1)$$

where  $\sigma_{\text{R}}$  and  $\sigma_{\text{L}}$  denote scattering cross sections for right- and left-handed polarized electrons, utilizing its model-independent sensitivity to the neutron distribution. The PREX-II result indicated a larger NS than obtained from hadronic probes [3], implying a relatively stiff nuclear EoS [4]. This finding is, however, somewhat at odds with EoS constraints derived from astrophysical observations, including tidal deformability from neutron-star mergers [5] and neutron-star radii from X-ray spectroscopy [6]. *Ab-initio* calculations [7] and collective flow measurements in ultrarelativistic  $^{208}\text{Pb}$ – $^{208}\text{Pb}$  collisions at the LHC [8] similarly favor a thinner neutron skin. Furthermore, the PREX-II result shows tension with theory predictions when considered jointly with the CREX measurement on  $^{48}\text{Ca}$  [9].

Although PREX-II achieved very low systematic uncertainty in  $A_{\text{PV}}$ , its statistical precision limited the accuracy of the extracted neutron radius  $R_n$ . Reducing this uncertainty is essential to enable direct comparison of nuclear EoS parameters derived from PVeS with those inferred from astrophysical data. This motivates a new determination of the NS thickness of  $^{208}\text{Pb}$  at higher precision — the goal of the forthcoming Mainz Radius EXperiment.

A precise determination of the neutron skin via PVeS requires excellent control over false asymmetries. In particular, the beam-normal single-spin (transverse) asymmetry  $A_n$  could bias parity-violating measurements due to imperfect longitudinal electron spin alignment. It is defined as

$$A_n = (\sigma_{\uparrow} - \sigma_{\downarrow}) / (\sigma_{\uparrow} + \sigma_{\downarrow}), \quad (2)$$

where  $\sigma_{\uparrow}$  and  $\sigma_{\downarrow}$  are the cross sections for spin orientations parallel and antiparallel to the scattering plane normal vector  $\hat{n} = (\vec{k} \times \vec{k}')/|\vec{k} \times \vec{k}'|$  with  $\vec{k}$  and  $\vec{k}'$  the momenta of the incoming and scattered electrons. At leading order,  $A_n$  arises from the imaginary part of the interference between one- and two-photon exchange amplitudes [10]. Two-photon exchange (TPE) effects, though typically percent-level corrections, play an increasingly im-

portant role in precision measurements, influencing proton form-factor extractions [11],  $\gamma$ - $Z$  box corrections in PVeS [12], and atomic charge radius determinations [13]. Since  $|A_n|$  typically exceeds  $|A_{\text{PV}}|$  by an order of magnitude, precise knowledge of  $A_n$  is essential to control background contributions in PVeS.

While  $A_n$  was extensively measured across light nuclei, the unexpected vanishing of  $A_n$  observed in  $^{208}\text{Pb}$  by PREX [14] and later confirmed by PREX-II/CREX [15] contradicted all theoretical expectations, challenging current understanding of TPE dynamics. Motivated by this anomaly, a dedicated measurement program using the A1 high-resolution spectrometers [16] at MAMI [17] was initiated to map  $A_n$  across a range of nuclei [18, 19]. Measurements on  $^{12}\text{C}$ ,  $^{28}\text{Si}$ , and  $^{90}\text{Zr}$  agreed with theory predictions [20], and no comparable suppression was seen, leaving the lead anomaly unresolved.

## 2. $A_n$ measurement with a natural lead target at MAMI

To prepare for a first benchmark of the vanishing  $A_n$  measured by PREX and CREX in  $^{208}\text{Pb}$ , the transverse asymmetry in elastic electron scattering from a natural lead target was measured using the A1 experimental setup at MAMI. The custom data acquisition (DAQ) system was developed for the experiment to measure at rather low scattering rates compared to those in previously performed campaigns [21]. The presented experiment served as a test of the new DAQ, which was later used for the subsequent high-precision measurement on the isotopically pure  $^{208}\text{Pb}$  [22].

### 2.1. Experimental setup

A vertically polarized electron beam with an energy of 570 MeV and a current of 20  $\mu\text{A}$  provided by the MAMI accelerator was rastered and directed onto an actively cooled natural lead foil of 0.5 mm thickness, corresponding to approximately one-tenth of a radiation length. Two high-resolution magnetic spectrometers (A and B) were positioned symmetrically around the beam line at forward scattering angles of approximately  $20^\circ$ , defining an average momentum transfer of  $Q^2 \approx 0.04 \text{ GeV}^2/c^2$ . The elastically scattered electrons were detected in fused-silica Čerenkov detectors installed in the focal planes of both spectrometers and read out by multiple photomultiplier tubes.

The polarity reversal pattern was generated using pseudo-random sequences synchronized to the 50 Hz grid frequency, which effectively suppressed periodic false asymmetries, forming 20 ms time intervals with equal contributions from both polarities, referred to as events. A half-wave plate in the optical system at the beam source was used to periodically reverse the

beam polarization independently of the electronics to test for possible hidden instrumental asymmetries. Beam current, position, angle, and energy were continuously monitored via voltage-to-frequency converters (VFCs). A series of calibration runs was performed throughout the beamtime to ensure the stability of all beam monitor responses. The beam polarization was determined from the Møller polarimeter at the beginning campaign and cross-calibrated with Mott measurements throughout data collection, yielding an effective polarization of  $P_n = 80.57\%$  with conservatively assigned 10% uncertainty.

## 2.2. Data analysis and results

The data analysis followed the established A1 methodology for beam-normal single-spin asymmetry studies. First, runs with incomplete data or evident beam instabilities were excluded. Next, all beam monitors were calibrated: position and energy monitor responses were fitted with linear scaling relations derived from dedicated calibration runs at the beginning of the beamtime, while multiple runs performed every three hours during data taking were used for beam current monitor calibration and the PMT count offset determination. Then, quality cuts were imposed on individual events, excluding outliers with unexpectedly large fluctuations of beam parameters.

For each spectrometer, the raw experimental asymmetry  $A_{\text{raw}}$  was corrected for polarity-correlated fluctuations in beam current, energy, and trajectory using a linear regression model

$$A_n = \frac{1}{P_n} \left( A_{\text{raw}} - c_I A_I - \sum_i \frac{\partial \sigma}{\partial x_i} \Delta x_i \right), \quad (3)$$

where  $x_i \in \{X, Y, X', Y', E\}$  denote horizontal and vertical beam position, angle, and energy parameters, and  $c_I$  represents the correlation coefficient for polarity-correlated differences in beam current  $A_I$ . The coefficients were determined by fitting the measured asymmetry against the polarity-dependent beam parameters. Each PMT's contribution to the asymmetry measured by each spectrometer was weighted by its statistical significance.

Systematic uncertainties were evaluated by varying analysis parameters, such as calibration intervals, event selection cuts, beam monitor subsets, fit constraints, *etc.* Additional contributions from gate-length asymmetry and autocalibration offsets were explicitly assessed. The overall uncertainty was dominated by the beam polarization. The final results for the beam-normal single-spin asymmetry in elastic electron scattering from natural lead are summarized as

$$\text{Spek A : } A_n = (+11.6 \pm 4.3_{\text{stat}} \pm 0.4_{\text{syst}} \pm 1.2_{\text{pol}}) \text{ ppm}, \quad (4)$$

$$\text{Spek B : } A_n = (-5.9 \pm 7.5_{\text{stat}} \pm 0.6_{\text{syst}} \pm 0.6_{\text{pol}}) \text{ ppm}. \quad (5)$$

The two spectrometers yield asymmetries of opposite sign, as expected from the symmetric scattering geometry. The absence of significant polarity-dependent offsets demonstrates the robustness of the employed procedure. The results hint at a potential non-zero transverse asymmetry in natural lead and provide a solid foundation for the subsequent high-precision  $A_n$  measurement with an isotopically pure  $^{208}\text{Pb}$  target [22]. The consistent understanding of the latter is particularly crucial for the forthcoming Mainz Radius EXperiment (MREX).

### 3. The Mainz Radius EXperiment

MREX aims to determine the neutron radius of  $^{208}\text{Pb}$  via PVeS at a four-momentum transfer  $Q^2 = 0.00616 \text{ (GeV}/c)^2$  identical to that of PREX-II. The measurement will employ the forthcoming Mainz Energy-Recovering Superconducting Accelerator (MESA), providing electron beams of 55 MeV or 155 MeV with currents up to 150  $\mu\text{A}$  and polarization near 85%. The systematic uncertainty from beam monitoring is expected to remain below 1%, dominated by the polarization measurement.

#### 3.1. Experimental setup

MREX will use the P2 experiment apparatus [23], which features a 0.7 T solenoidal magnet, tracking detectors for  $Q^2$  determination in low-current mode, and an integrating Cerenkov detector for scattered electrons detection. The liquid-hydrogen target of P2 will be replaced with a 0.5 mm-thick  $^{208}\text{Pb}$  foil (10% of a radiation length), chosen to optimize the elastic event rate while limiting radiative losses and thermal load [24]. To reproduce the PREX-II  $Q^2$ , average scattering angles of approximately  $91^\circ$  and  $29^\circ$  at beam energies of 55 MeV and 155 MeV must be achieved, respectively. Due to the solenoid geometry, only the higher-energy configuration is feasible, as it prevents excessive spiraling of electrons with large transverse momentum. The position of the target along the beam line is optimized to match the required  $Q^2$  at the maxed-out magnetic field strength of the solenoid magnet.

The solenoid design ensures wide angular coverage, enhancing statistics, but also increases acceptance for non-elastically scattered electrons and secondary particles. These include contributions from quasielastic scattering and electroexcitation of resonances and low-lying nuclear states. Since the P2 tracking detectors cannot fully distinguish elastic from inelastic events

on an event-by-event basis, accurate modeling of these processes is essential. The total measured asymmetry can be expressed as

$$A^{\text{meas}} = \left(1 - \sum_i f_i\right) A^{\text{el}} + \sum_i f_i A_i, \quad (6)$$

where  $f_i$  and  $A_i$  denote the rate fraction and asymmetry of each non-elastic process. The elastic asymmetry is then obtained as

$$A^{\text{el}} = \frac{A^{\text{meas}} - \sum_i f_i A_i}{1 - \sum_i f_i}. \quad (7)$$

The accuracy of  $A_{\text{PV}}$  extraction thus depends on the precision of  $f_i$  and  $A_i$  values obtained from detailed Monte Carlo simulations.

### 3.2. Simulation framework

The developed Geant4-based Monte Carlo simulation framework extends the P2 experiment simulation [23] to better describe electron– $^{208}\text{Pb}$  scattering. It includes realistic beam–target interactions, sampling scattering vertex distributions, and generation of the scattered electrons with cross sections and asymmetries corresponding to each process. Transport through the full detector geometry accounts for multiple scattering, Bremsstrahlung, secondary particle production, and other potential sources of background.

The response of the Čerenkov detector is simulated to determine photoelectron yields, from which the rate-weighted asymmetry  $A^{\text{meas}}$  is constructed. Similarly, the average momentum transfer of elastically scattered electrons is calculated. However, the cross section and asymmetry distributions used during the generation of each of the particle types have associated uncertainties, leading to additional systematic uncertainty in the extraction of the elastic asymmetry, and must be carefully defined.

### 3.3. Uncertainty from the correction for non-elastic contribution

Uncertainties associated with the non-elastic rate fractions and asymmetries propagate into the extracted elastic asymmetry via

$$\Delta A_i^f = \frac{A^{\text{el}} - A_i}{1 - \sum_i f_i} \Delta f_i, \quad (8)$$

$$\Delta A_i^A = \frac{f_i}{1 - \sum_i f_i} \Delta A_i, \quad (9)$$

where  $\Delta f_i$  and  $\Delta A_i$  are the uncertainties in the photoelectron rate fraction and asymmetry for each scattering process included in the simulation.

We use the expected uncertainty in the experimental data or model predictions used in the simulation generator as the cross section or asymmetry distribution to define  $\Delta f_i$  and  $\Delta A_i$ . As shown in Table 1, the largest rate uncertainties are associated with quasielastic electron scattering and electroexcitation of higher-order nuclear states. The absence of experimental data for non-elastic electrons scattering  $A_{\text{PV}}$  results in high asymmetry uncertainty for all contributing processes, as only simplified estimations and models are used for asymmetry predictions [24, 25].

Table 1. Systematic uncertainties of asymmetry and rate fraction of different non-elastic processes contributions to the Čerenkov detector signal.  $3^-$ ,  $2^+$  denote the first two low-lying excited states, MR — multipole resonances, Inel — other low-lying excited states, QE — quasielastic scattering, TBG and Secondary — uncertainties from secondary particle production before and after generation at the vertex.

Type $i$	$3^-, 2^+$	MR	Inel	QE	TBG	Secondary
$\Delta A_i$	$0.6 A_{\text{el}}$	$0.6 A_{\text{el}}$	$1.5 A_{\text{el}}$	$2  A_{\text{QE}} $	0	$ A_{\text{el}} - A_{\text{sec}} $
$\Delta f_i/f_i$	20%	50%	100%	100%	10%	10%

Using the defined uncertainties and simulated  $f_i$  and  $A_i$  values, the additional systematic uncertainty from non-elastic contributions is estimated at 0.37%, dominated by quasielastic and resonance channels. This uncertainty can be reduced to 0.25% by shifting the target upstream and installing a 10 cm-thick conical lead collimator 20 cm downstream from the target, which suppresses lower-energy inelastic electrons by allowing for longer travel in the magnetic field while preserving  $Q^2$ . Even though such a collimator also reduces the total number of detected elastic electrons, it allows for a reduction of measuring time necessary to reach 0.5% uncertainty in the extracted neutron radius from approximately 2300 h to 1500 h, assuming the beam parameters described above and an additional 1% systematic uncertainty from beam monitors.

## 4. Conclusions

The initial beam-normal single-spin asymmetry measurement with a natural lead target verified the feasibility of performing high-precision lead transverse asymmetry studies at MAMI using the newly developed DAQ system with the A1 spectrometers. The target composition and preliminary nature of the measurement did not allow for concluding the  $A_n$  value in electron- $^{208}\text{Pb}$  scattering, but provided a strong ground for the following

campaigns with an isotopically pure target [22]. In combination, the results show the necessity for a better understanding of TPE dynamics, which is also crucial for the restriction of parity-conserving background at MREX.

The described initial Monte-Carlo simulations of the MREX experiment, aimed to determine the neutron radius of  $^{208}\text{Pb}$  via PVeS, show that the goal of 0.5% in  $R_n$  extraction is feasible. In the future, the description of inelastic electron scattering is planned to be improved by employing updated theoretical predictions for inelastic rates and asymmetries in the generator, reducing the associated systematic uncertainty. Furthermore, the potential impact of radiative corrections on elastic parity-violating asymmetry must be accounted for [26].

This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) — project number: 514321794 (CRC1660: Hadrons and Nuclei as Discovery Tools) and by the PRISMA+ (Precision Physics, Fundamental Interactions and Structure of Matter) Cluster of Excellence.

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