Polarised Deuteron Breakup as a Probe of the Nuclear Symmetry Energy

Zichen Luo[1]

[1] *2022080183, Physics 21, Department of Physics, Tsinghua University, Haidian, Beijing, China*

18 July 2025

ABSTRACT

The Nuclear Equation of State (EoS) provides a fundamental link between nuclear physics and astrophysics, yet its predictive power is limited by our incomplete understanding of the nuclear symmetry energy, $E_{\text{sym}}(\rho)$. This critical component, which quantifies the energy cost of proton–neutron asymmetry, is well constrained at the saturation density found in stable nuclei, but remains a major uncertainty at the sub-saturation and supra-saturation densities relevant to neutron stars. This uncertainty leads to significant discrepancies in astrophysical models, particularly those predicting the mass–radius relationship of neutron stars.

This research outlines a novel laboratory experiment designed to directly constrain the symmetry energy, reducing our reliance on rare astrophysical observations. The core of the approach is to use the Improved Quantum Molecular Dynamics (ImQMD) framework to model the peripheral collision of a polarised deuteron with a heavy, neutron-rich target. The isovector force — a component of the strong nuclear interaction that distinguishes between protons and neutrons — acts attractively on the deuteron's proton and repulsively on its neutron. These opposing forces cause the two nucleons to scatter at different angles.

The resulting difference in scattering angle serves as a highly sensitive probe of the symmetry energy's "stiffness", a property parameterised by the variable γ in the model. By measuring the differential cross-sections of the outgoing protons and neutrons in an experiment conducted at RIKEN's Radioactive Isotope Beam Factory (RIBF) using the SAMURAI spectrometer, the data can be compared to a library of ImQMD simulations. This comparison enables the determination of the γ value that best fits the experimental results, providing a new and precise constraint on the nuclear symmetry energy — and ultimately refining our understanding of nuclear matter, from the laboratory to the cosmos.

Keywords: Nuclear Equation of State (EoS), Nuclear matter, Neutron stars, Symmetry energy, Proton–neutron asymmetry, Saturation density, Isovector force, Deuteron, Scintillator

---

I. INTRODUCTION

Understanding how nuclear matter behaves under extreme density and temperature is important in both nuclear physics and astrophysics. A key quantity in this context is the nuclear equation of state (EoS), which describes the thermodynamic properties of nuclear matter. The EoS influences the structure of neutron stars, the dynamics of supernovae, and the outcomes of neutron star mergers. One of the main uncertainties in the EoS is the density dependence of the nuclear symmetry energy, $E_{\text{sym}}(\rho)$.

The symmetry energy measures how much energy is required to move away from equal numbers of protons and neutrons. It affects the proton fraction and composition of neutron-rich systems. At nuclear saturation density ($\rho_0 \approx 0.16$ fm^{-3}), $E_{\text{sym}}(\rho_0)$ is fairly well known from measurements of nuclear masses and neutron skin thicknesses. However, neutron star interiors span a wide range of densities—from below saturation in the crust to several times ρ_0 in the core—where predictions for $E_{\text{sym}}(\rho)$ differ widely. A rapidly increasing (stiff) symmetry energy allows more massive neutron stars, while a slowly increasing (soft) one limits their maximum size and mass. This uncertainty affects how we interpret data from gravitational waves, such as the GW170817 event, which placed constraints on how neutron stars deform under tidal forces.

To reduce this uncertainty, many experiments have aimed to constrain $E_{\text{sym}}(\rho)$. Heavy-ion collisions have been widely used, where observables like isospin diffusion, neutron-to-proton ratios, and meson production give indirect information about the high-density regime. However, these observables are influenced by the complex, non-equilibrium nature of the collisions and require detailed transport model simulations. Differences between models lead to large uncertainties, showing the need for cleaner, more direct experimental methods.

This work presents a recent approach that aims to probe the symmetry energy at sub-saturation densities with high sensitivity and minimal model dependence[1, 2, 3]. The method is based on the isovector reorientation (IVR) effect, which occurs in peripheral collisions between a polarised deuteron and a heavy, neutron-rich target. In such systems, the isovector part of the nuclear potential—repulsive for neutrons and attractive for protons—exerts a torque on the deuteron, rotating its spin axis before it breaks up.

The resulting angular correlation between the emitted proton and neutron is highly sensitive to the isovector interaction, and thus to the symmetry energy[2]. Because both nucleons come from the same deuteron, many of the isoscalar effects cancel out, making the isovector signal easier to isolate. This self-cancellation reduces model dependence and increases sensitivity to the quantity of interest.

The experiment will be conducted at the SAMURAI facility at RIKEN, and the procedure will be explained step by step[3]. My contribution involved using Geant4 simulations to study and select suitable materials for the polarimeter, which is crucial for measuring the polarization of the deuteron before it hits the target. This work supports the overall detector design to ensure accurate polarisation measurements.

By offering a more direct constraint on a key part of the nuclear EoS, this method improves our ability to describe matter from the scale of atomic nuclei to that of neutron stars.

II. THEORETICAL FRAMEWORK

A. Nuclear Symmetry Energy and Its Astrophysical Significance

The properties of nuclear matter under extreme conditions are described by the nuclear equation of state (EoS). For asymmetric nuclear matter, neutron and proton densities ρ_n and ρ_p define the total baryon density $\rho = \rho_n + \rho_p$, and the isospin asymmetry parameter is

$$\delta = \frac{\rho_n - \rho_p}{\rho}.$$

Using the commonly applied parabolic approximation, the energy per nucleon expands as

$$E(\rho, \delta) \approx E_0(\rho) + E_{\text{sym}}(\rho)\,\delta^2 + \mathcal{O}(\delta^4),$$

where $E_0(\rho)$ is the energy per nucleon in symmetric nuclear matter ($\delta = 0$). $E_{\text{sym}}(\rho)$ at ρ_0 is fairly well constrained by experimental data such as nuclear masses and neutron skin thicknesses, but the density dependence of $E_{\text{sym}}(\rho)$ beyond ρ_0 remains uncertain.

This uncertainty significantly impacts astrophysics, especially the modelling of neutron stars. The structure of a static, spherically symmetric neutron star is governed by the Tolman–Oppenheimer–Volkoff (TOV) equations, which require the EoS expressed as pressure versus density.

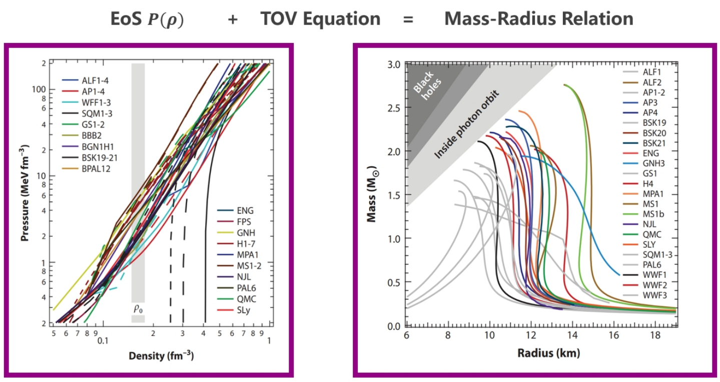

Figure 1: Predicted neutron star mass-radius (M-R) relations for several different theoretical Equations of State (EoS). Stiffer EoS models (which can result from a stiff symmetry energy) generally permit larger maximum masses and radii. The divergence highlights the need for experimental constraints. **Image adapted from Ozel & Freire [4].**

A stiff symmetry energy, rising quickly with density, produces a stiffer EoS, allowing higher maximum neutron star masses and larger radii. Conversely, a soft symmetry energy leads to a softer EoS, restricting maximum masses and resulting in more compact stars. This variation, illustrated in Fig. 1, translates into a broad range of predicted mass-radius relations, complicating interpretations of observational data from X-ray binaries, pulsar timing, and gravitational wave detections like GW170817. Therefore, constraining the density dependence of the symmetry energy is key to connecting nuclear physics with astrophysical phenomena.

B. Nuclear Dynamics Simulation with ImQMD

To probe the symmetry energy's influence on nuclear reactions, we use the Improved Quantum Molecular Dynamics (ImQMD) model. This semi-classical transport approach represents each nucleon as a Gaussian wave packet whose centroid evolves via Hamilton's equations under a self-consistent mean field and two-body collisions.

The local potential energy density arises from a Skyrme-type effective interaction. Importantly, the isovector (symmetry) part is parameterised to allow systematic variation of the symmetry energy's density dependence, while the isoscalar part remains fixed. The symmetry energy is expressed as

$$E_{\text{sym}}(\rho) = \frac{C_{s,k}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma},$$

where the first term represents the kinetic contribution (Fermi gas model), and the second term is the potential contribution controlled by the exponent γ. Smaller γ values correspond to a softer density dependence; larger γ produce a stiffer rise[1].

This parametrisation enables controlled studies of how variations in the isovector interaction affect macroscopic observables. Since the isovector potential acts oppositely on neutrons and protons in neutron-rich matter, its strength directly relates to $E_{\text{sym}}(\rho)$. By adjusting γ, we isolate the impact of the symmetry energy on reaction dynamics, especially at sub-saturation densities relevant to neutron star crusts[1].

C. The Isovector Reorientation Effect as a Sensitive Probe

Our focus is on the Isovector Reorientation (IVR) effect, a sensitive experimental probe of the symmetry energy at sub-saturation densities. It involves peripheral collisions of a polarised deuteron with a neutron-rich heavy target (e.g. ^{124}Sn or ^{208}Pb). As the deuteron grazes the neutron-rich surface, the proton and neutron experience different components of the isovector potential—attractive for the proton and repulsive for the neutron—creating a torque that reorients the deuteron's spin before breakup. The torque's magnitude depends directly on the strength of the isovector force, and thus on the stiffness parameter γ. After breakup, the angular correlations between emitted proton and neutron encode information about this reorientation and hence the symmetry energy.

Several observables quantify the IVR effect. One approach introduces the correlation angle α, based on relative momenta of breakup fragments[1]. Another refines this using $\delta\theta = \theta_p - \theta_n$, the difference between proton and neutron scattering angles within an event[2]. This differential measure cancels common-mode effects—especially the dominant isoscalar potential—making $\delta\theta$ a clean probe of the isovector interaction, as demonstrated by the distinct scattering angle distributions shown in Fig. 2.

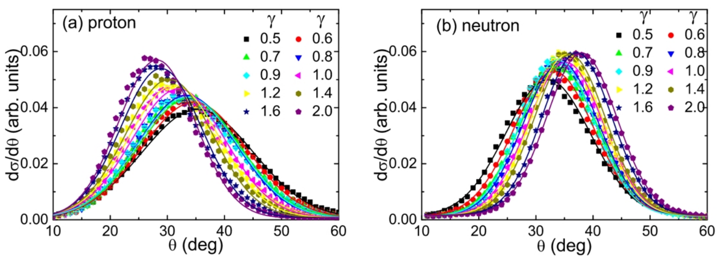

Figure 2: Simulated distributions of the scattering angle difference, $\delta\theta = \theta_p - \theta_n$, from ImQMD calculations. Each curve corresponds to a different value of the symmetry energy stiffness parameter, γ. The clear separation between the curves demonstrates the observable's high sensitivity to the isovector potential. **Image from Liang et al. [2].**

Experimentally, we use the asymmetry ratio

$$R = \frac{N(P_x^p > P_x^n)}{N(P_x^p < P_x^n)},$$

where P_x is the momentum component in the reaction plane. This ratio captures the transverse momentum imbalance caused by IVR-induced torque. Comparing measured R to ImQMD simulations across γ values allows constraints on the symmetry energy stiffness with minimal model dependence[3].

This method provides a direct, experimentally accessible link between nuclear observables and fundamental properties of dense matter, offering valuable benchmarks for nuclear theory and astrophysics.

III. EXPERIMENTAL SETUP AND METHOD

The experiment will take place at the Radioactive Isotope Beam Factory (RIBF) at the RIKEN Nishina Center, using the SAMURAI spectrometer—a large-acceptance superconducting magnetic spectrometer designed for high-resolution studies of rare isotope beams[3]. The main aim is to measure angular correlations between protons and neutrons emitted from the elastic breakup of a tensor-polarized deuteron beam after peripheral collisions with heavy targets, using the setup illustrated in Fig. 3. This measurement directly probes the Isovector Reorientation (IVR) effect, which provides information about the density-dependent symmetry energy at sub-saturation densities.

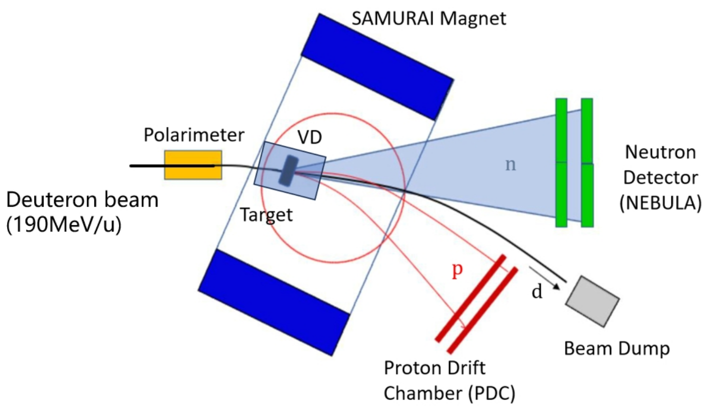

Figure 3: A schematic overview of the SAMURAI spectrometer setup for the proposed experiment. The polarised deuteron beam enters from the left, interacts with the target, and the resulting proton and neutron fragments are detected by the PDC and NEBULA detectors, respectively.

The procedure consists of five key stages: beam production and acceleration, in-flight polarization monitoring, target interaction, fragment detection, and event selection. Each stage is optimised to maintain beam quality, maximise signal sensitivity, and reduce background.

A. Beam Production and Acceleration

The experiment starts by producing a tensor-polarized deuteron beam at the Polarised Ion Source (PIS). The spin orientation, specifically the tensor polarization, is precisely controlled using a Wien filter, which selects deuterons with a defined spin state. The beam is then accelerated through RIKEN's multi-stage accelerator complex.

Acceleration occurs in three phases: first through the Azimuthal Varying Field (AVF) cyclotron, then the RIKEN Ring Cyclotron (RRC), and finally the Superconducting Ring Cyclotron (SRC). Single-turn extraction is used at each stage to minimise depolarisation effects and preserve spin coherence, achieving around 80% of the theoretical maximum tensor polarization.

The beam exits the SRC at 190 MeV per nucleon (380 MeV total) and is transported to the SAMURAI experimental hall. This energy is chosen to favour peripheral reactions while limiting unwanted secondary processes.

B. Polarization Monitoring

Before reaching the main target, the beam passes through an in-flight polarimeter that continuously monitors the tensor polarization components $p_{z'z'}$ and $p_{y'y'}$, ensuring the spin state remains stable during data collection. A small portion of the beam is scattered off a thin polyethylene (CH_2) target, and scattered deuterons are detected by an array of scintillators.

Known analysing powers for deuteron-proton elastic scattering at this energy allow extraction of the beam polarization from angular asymmetries. This real-time feedback is essential for normalising the IVR signal and correcting for any polarization drifts.

C. Target Interaction and Isovector Reorientation

After polarization verification, the main beam strikes the primary reaction target located about 3 metres upstream of the SAMURAI dipole magnet. To isolate the isovector nuclear force from the Coulomb effect and check model dependencies, measurements are carried out with neutron-rich targets: ^{124}Sn and ^{208}Pb

In peripheral collisions with impact parameters around 7–9 fm, the deuteron grazes the neutron-rich surface of the target. The neutron and proton within the deuteron experience different potentials: the proton is attracted by the isovector field, the neutron repelled. This difference produces a torque that reorients the deuteron's spin axis, the key signature of the IVR effect.

Selected events correspond to elastic breakup ($d + A \to p + n + A$), with the target nucleus remaining in its ground state. The angular correlation between the emitted proton and neutron retains information about this reorientation, reflecting the strength of the isovector interaction.

D. Fragment Detection and Momentum Reconstruction

Charged and neutral breakup fragments are detected in coincidence using systems within the SAMURAI setup:

- Proton detection: The positively charged proton is bent by the SAMURAI magnet's 1.2 T dipole field, oriented at 30° to the beam axis. Its trajectory is reconstructed with high precision by the Proton Drift Chamber (PDC), a low-material, multi-wire chamber downstream of the magnet. A plastic scintillator time-of-flight (TOF) wall behind the PDC provides timing and triggers.
- Neutron detection: The neutral neutron passes undeflected through the magnetic field and is detected by the NEBULA array, a segmented plastic scintillator system 7.3 metres from the target. NEBULA's large angular coverage and precise timing enable accurate neutron direction and TOF measurement.
- Beam handling: Unreacted deuterons are deflected by the SAMURAI magnet into a shielded, water-cooled beam dump, reducing background and radiation in the experimental area.

Together, the PDC and NEBULA allow full three-dimensional momentum reconstruction of the breakup nucleons in coincidence, enabling precise determination of angular correlations such as $\delta\theta = \theta_p - \theta_n$ and transverse momentum asymmetry R.

E. Event Trigger and Background Suppression

A three-fold coincidence trigger selects clean elastic breakup events:

1. Signal in the proton TOF wall indicating a charged fragment,
2. Coincident signal in the NEBULA array indicating a neutron,
3. No signal in the Active Veto Barrel (AVB), a cylindrical plastic scintillator array surrounding the target.

The AVB vetoes events where the target nucleus is excited or fragmented, ensuring only events with an intact target (elastic breakup) are accepted.

This selection effectively suppresses background from inelastic processes and secondary reactions, producing a clean sample sensitive to the IVR effect. The measured angular and momentum correlations then provide a direct, low-background probe of the isovector nuclear force with minimal model dependence.

IV. VETO DETECTOR AND POLARIMETER

Two key components of the experimental setup are the veto detector and the polarimeter. Both play a crucial role in event selection and in extracting polarisation information about the incoming deuteron beam[3]. My contributions to this project focused on the simulation and testing of these two subsystems.

A. Veto Detector

The veto detector is designed to identify and reject events where the deuteron has undergone inelastic or unwanted interactions before reaching the target. It consists of 32 plastic scintillators arranged in a cylindrical geometry, coaxial with the beam path. In a clean event, the deuteron travels through the centre without interacting. The detection of hits in multiple scintillator bars signifies an inelastic interaction, causing the event to be vetoed.

During the autumn 2024 semester, the construction of this detector took place. After assembly, we tested the system using cosmic rays. These natural background particles provided a convenient way to verify the detector's response. I assisted in the analysis of the resulting data to verify the functionality of the individual detector modules and the system as a whole. This included identifying clean cosmic ray tracks, such as the example shown in Fig. 4, and visualising the response of the individual scintillators to confirm the expected behaviour of the system.

B. Polarimeter

The polarimeter serves as a critical subsystem for measuring the vector polarisation of the incoming deuteron beam prior to its interaction with the primary target. It consists of four detector modules positioned at distinct azimuthal angles around the beam axis. The polarimeter operates by analysing deuteron scattering off a thin polyethylene (CH_2) target, with scattered protons detected by these modules. The resulting angular distribution of scattered particles carries information about the beam's polarisation, which can be inferred by examining asymmetries in the scattering pattern. Each detector module is composed of a plastic scintillator coupled to a silicon photomultiplier (SiPM), providing the necessary timing and energy resolution for this measurement.

During the academic semester, my principal technical contribution was the execution of comprehensive simulations using the Geant4 toolkit to evaluate the scintillator response under irradiation by deuteron beams at 190 MeV per nucleon. The objective of these simulations was to inform the selection of an optimal scintillator material and geometry for the polarimeter modules, ensuring sufficient energy deposition to generate detectable scintillation light while avoiding saturation of the SiPM readout.

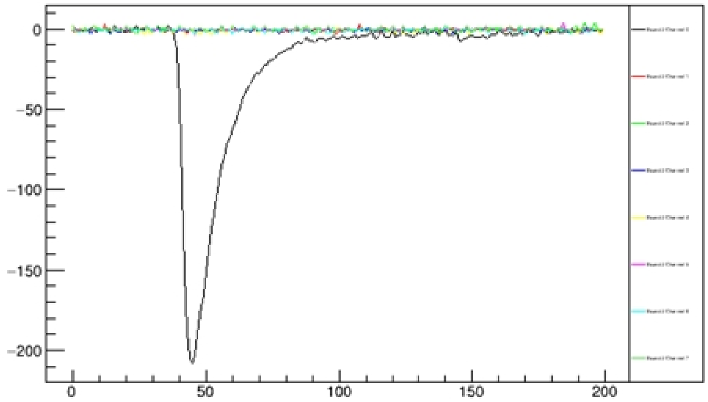

Figure 4: An example of a cosmic ray event registered by the veto detector during testing. The pattern of activated scintillator bars allows for the reconstruction of the particle's trajectory, confirming the detector's functionality.

The simulations were performed on the research group's Ubuntu server, employing a simplified but representative detector geometry. Specifically, I modelled a cubic scintillator block irradiated by a monoenergetic deuteron beam aligned along the beam axis. A total of eleven scintillator materials were examined, spanning common plastic scintillators such as polyvinyltoluene-based plastics, as well as higher-density inorganic crystals including LYSO (Lutetium Yttrium Orthosilicate), $LaBr_3$ (Lanthanum Bromide), and BGO (Bismuth Germanate). For each material, five thicknesses ranging from 1 cm to 5 cm in 1 cm increments were simulated. Each configuration consisted of 1000 independent events, and the total energy deposited in the scintillator volume was recorded for each event.

The electromagnetic physics processes relevant to MeV-scale deuteron ionisation and energy loss were included using Geant4's standard electromagnetic physics lists. Post-processing of the simulation outputs was conducted with custom C++ scripts that extracted key statistics including the mean energy deposition and the shape of the energy deposition distributions.

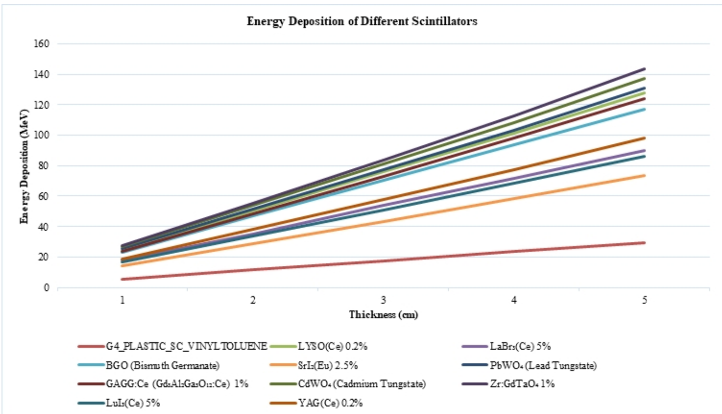

Figure 5: Mean energy deposition in various scintillator materials as a function of thickness, based on my Geant4 simulations of a 190 MeV/u deuteron beam. Higher-density inorganic materials like LYSO and BGO show significantly greater energy deposition compared to plastic scintillators.

The results, summarised in Fig. 5, demonstrated that high-density scintillator materials such as LYSO and BGO exhibit substantially greater energy deposition over shorter thicknesses compared to plastic scintillators. This characteristic is advantageous for maximising scintillation yield but must be balanced against the dynamic range and saturation limits of the SiPM detectors. The detailed data provide a quantitative basis for selecting scintillator materials and thicknesses that optimise the polarimeter's performance within these constraints.

While the final choice of scintillator material will be determined by senior members of the collaboration, conducting these simulations has significantly deepened my understanding of the interplay between material properties, detector response, and readout limitations. Moreover, this work has enhanced my practical skills in applying Geant4 for detector development, enabling informed design decisions prior to experimental commissioning.

V. CONCLUSION

This experiment aims to provide a precise measurement of the Isovector Reorientation (IVR) effect through the elastic breakup of a tensor-polarized deuteron beam on neutron-rich targets. By investigating the angular correlations between emitted protons and neutrons, the experiment seeks to constrain the density dependence of the nuclear symmetry energy at sub-saturation densities—a key quantity influencing both nuclear structure and neutron star physics. The outcome will enhance our understanding of the isovector nuclear force and help bridge nuclear theory with astrophysical observations.

My contributions have focused on two essential subsystems: the veto detector and the polarimeter. For the veto detector, I was involved in its detailed design and construction, including optimising the cylindrical arrangement of 32 plastic scintillators coaxial with the beamline. I conducted extensive cosmic ray testing to validate detector performance, analysing event data to confirm reliable operation and effective background rejection. Regarding the polarimeter, I performed comprehensive Geant4 simulations to evaluate the response of various scintillator materials to deuteron irradiation. These simulations guided the selection of materials that balance energy deposition with SiPM readout limitations, ensuring optimal detector performance for polarisation measurements.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Professor Xiao Zhigang, for his invaluable guidance, support, and encouragement throughout this project. His expertise was instrumental in the development of this work.

REFERENCES

[1] Li Ou et al. "Dynamic Isovector Reorientation of Deuteron as a Probe to Nuclear Symmetry Energy". In: *Phys. Rev. Lett.* 115 (21 Nov. 2015), p. 212501. DOI: 10.1103/PhysRevLett.115.212501. URL: https://link.aps.org/doi/10.1103/PhysRevLett.115.212501.

[2] Xiao Liang, Li Ou, and Zhigang Xiao. "New probe to study the symmetry energy at low nuclear density with the deuteron breakup reaction". In: *Phys. Rev. C* 101 (2 Feb. 2020), p. 024603. DOI: 10.1103/PhysRevC.101.024603. URL: https://link.aps.org/doi/10.1103/PhysRevC.101.024603.

[3] Baiting Tian et al. *Simulation studies of the isovector reorientation effect of deuteron scattering on heavy target*. arXiv:2506.15738v2 [physics.ins-det]. 2025. arXiv: 2506.15738v2 [physics.ins-det].

[4] Feryal Ozel and Paulo Freire. "Masses, Radii, and the Equation of State of Neutron Stars". In: *Annual Review of Astronomy and Astrophysics* 54.1 (2016), pp. 401–440. DOI: 10.1146/annurev-astro-081915-023322.