Neutron skin thickness in ^{208}Pb and its connection to nuclear equation of state, and neutron star structure

Pratap Roy[1, 2,7,*] R. Kanungo[1,3], E. Haettner[2], Y. Tanaka[2,4], S. Bagchi[5], T. Dickel[2], D. Kostyleva[2], J. Zhao[2], H. Geissel[2], C. Scheidenberger[2], I. Tanihata[6] and the SuperFRS Collaboration.

[1]*Astronomy and Physics Department, Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada.*
[2]*GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany.*
[3]*TRIUMF, Vancouver, British Columbia V6T 4A3, Canada.*
[4]*RIKEN Nishina Center, Wako, Saitama 351-0198, Japan.*
[5]*Department of Physics, Indian Institute of Technology (ISM), Dhanbad - 826004, India.*
[6]*RCNP, Osaka University, Mihogaoka, Ibaraki, Osaka 567 0047, Japan*
[7]*Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata - 700064, India*

* *email: roypratap@vecc.gov.in*

Heavy nuclei tend to develop a neutron skin due to an excess of neutrons and the influence of the Coulomb barrier, which reduces the proton density at the surface. A quantitative description of this skin thickness (Δr_{np}) in a nucleus is given by the difference between the root mean square radii (rms) for the neutron (R_n) and proton distributions (R_p). The formation of a neutron skin in heavy nuclei depends on the pressure (P) of neutron matter at sub-saturation densities [1]. A higher P pushes neutrons outward against surface tension, increasing R_n. Remarkably, the same pressure supports a neutron star against gravity. The neutron skin thickness in heavy nuclei is thus critically linked to the nuclear equation of state (EoS: pressure-energy density relation) and neutron star structure. It is astonishing that two quantities, the radius of a heavy nucleus and that of a neutron star, differing by nearly 18 orders of magnitude, are intricately connected and depend on our incomplete understanding of the equation of state of neutron-rich matter. Therefore, determining the neutron skin's precise thickness could play a pivotal role in constraining the nuclear EoS and, in turn, enhancing our understanding of neutron star structures.

In this context, one system of particular interest is the doubly magic nucleus ^{208}Pb, which has 44 more neutrons than protons. The probability of the wavefunctions of some of these extra neutrons are expected to be found on the surface, contributing to the neutron skin. The value of the neutron skin thickness in ^{208}Pb carries significant implications for models of nuclear structure and their applications in atomic physics and astrophysics [1,2]. Several authors have highlighted a strong correlation between Δr_{np} of ^{208}Pb (henceforth defined as $^{208}\Delta r_{np}$) and the density derivative (slope parameter L) of the nuclear symmetry energy S [1-3]. Symmetry energy represents the energy difference between pure neutron matter and symmetric nuclear matter and stands as a major source of uncertainty in determining the nuclear EoS [4]. A precise value of $^{208}\Delta r_{np}$ is also critical for understanding neutron star cooling mechanisms and placing constraints on its tidal polarizability [5,6]. Given its far-reaching consequences, measuring the neutron skin thickness in ^{208}Pb has been a top priority for researchers in recent times.

The determination of Δr_{np} poses an experimental challenge, primarily due to the difficulty in accurately measuring R_n. Proton distribution radii in nuclei are measured with high precision (typically with an uncertainty of 0.02 fm or less) through electromagnetic interactions (*e.g.*, electron scattering) [7,8]. In contrast, accurately determining the neutron distribution radii in a model-independent manner has been a demanding task. Extensive efforts have been invested in determining $^{208}\Delta r_{np}$ using various strong and electromagnetic probes like proton and pion scattering, coherent pion photo-production, antiproton annihilation, isospin diffusion, and complete electric dipole response measurement. Most of these studies suggest a value of $\Delta r_{np} \approx 0.15 - 0.2$ fm for ^{208}Pb [9], which is consistent with the astrophysical constraints [10]. However, recent measurements of $^{208}\Delta r_{np}$ through parity-violating electron scattering by the PREX collaboration reported a significantly thicker neutron skin for ^{208}Pb ($0.33^{+0.16}_{-0.18}$ fm for PREX-I and 0.283 ± 0.071 fm for PREX-II) [11,12]. These measurements, considered highly model-independent, have left the scientific community puzzled, as the thick neutron skin for ^{208}Pb does not align with many previous measurements and displays some

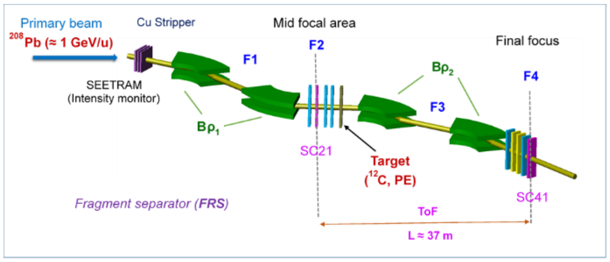

Fig. 1. A schematic of the experimental setup

disparities with astrophysical observations [13]. A thick neutron skin (e.g., > 0.25 fm) would suggest a stiff EoS, which otherwise is considered relatively soft.

Hence, it is crucial to emphasize that the issue of the neutron skin in ^{208}Pb remains unresolved and demands further investigation using unexplored methodologies. To address this, we conducted an experiment to determine Δr_{np} in ^{208}Pb by measuring the total interaction cross-sections for the ^{208}Pb + ^{12}C and ^{1}H reactions at ~900A MeV incident energy. The total interaction cross-section, σ_I, is a valuable tool for deriving the matter radius, R_m [14,15]. Combining this information with the known rms proton distribution radius allows us to determine Δr_{np} accurately.

This experiment was carried out using the FRS fragment separator [16] at GSI, Darmstadt, Germany, with a primary beam of ^{208}Pb bombarded on ^{12}C (2.52 gm/cm^2) and PE $(CH_2)_n$ (0.93 gm/cm^2) reaction targets located at the mid-focal area F2 (see Fig. 1). We determined the cross-section for the ^{208}Pb + ^{1}H reaction from the PE target data using the measured cross-section for the ^{208}Pb + ^{12}C reaction.

The reaction products post-target were identified using event-by-event magnetic rigidity (Bρ), time of flight (ToF), and energy loss (dE) data. The Z identification was provided by two multisampling ionization chambers (MUSIC) [17] at the final focus F4, and time of flight measurements were obtained using two plastic scintillator detectors at F2 and F4. The scintillator at F2 also served as the trigger for the data acquisition system. Position-sensitive time projection chambers (TPCs) [18] at F2 and F4 were employed for beam tracking and defining particle trajectories before and after the reaction. Event-by-event Bρ for the particles was determined by combining the position information with the central magnetic rigidity of the dipoles.

The interaction cross-section is measured based on the method of transmission where the unreacted ^{208}Pb nuclei after the reaction target are identified and counted. The ratio between the unreacted and incident ^{208}Pb nuclei is used to determine the interaction cross-section. The separation and identification after the target were done by employing the *Bρ-ToF-dE* technique using the second half of the fragment separator as an analyzer. It should be emphasized here that measuring σ_I through the transmission method for heavy nuclei is exceptionally challenging due to the possible complications arising from the mixture of different charge states. Hence, such measurements have so far been limited to light and medium-mass nuclei.

The preliminary analysis of the data has been completed. To enhance the accuracy of our findings, we performed an exhaustive beam transmission simulation utilizing the MOCADI code to account for the transmission losses. Presently, we are in the final stages of refining the theoretical calculations required to extract the neutron skin thickness from the measured cross-sections.

A comprehensive overview of the current state of research in this field will be presented during the upcoming symposium. Furthermore, the detail of our experiment, including the challenges faced and the innovative data analysis techniques employed, will also be discussed.

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