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Abstract

Neutron skin is an exotic structure present in unstable atomic nuclei that produces various effects during nuclear reaction processes. Studies employing different theoretical models have revealed that neutron skin thickness influences numerous physical observables in nucleus-nucleus collisions, including neutron removal cross-section, light particle yield ratios, heavy fragment yield ratios, and photon production cross-section, and also exhibits close correlations with nuclear cluster structure, surface diffuseness, and temperature. Investigations in high-energy heavy-ion collisions have similarly demonstrated clear manifestations of neutron skin effects. Experimentally, radioactive ion beam facilities can generate unstable nuclei featuring neutron skin structures; by measuring neutron-skin-sensitive observables from their reactions with stable nuclei, the neutron skin thickness can be extracted or determined. In conjunction with nuclear theoretical models, this approach can further constrain the equation of state of asymmetric nuclear matter and related properties of nuclear astrophysics.

Full Text

Preamble

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Neutron Skin Structure and Its Effects in Nuclear Reactions

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Abstract

Neutron skin is an exotic structure that exists in unstable atomic nuclei and produces various effects during nuclear reaction processes. Theoretical studies using different models have found that neutron skin thickness influences several physical quantities in nucleus-nucleus collisions, including neutron removal cross-section, light particle yield ratios, heavy fragment yield ratios, and photon production cross-section. It also exhibits close relationships with nuclear cluster structure, surface width, and temperature. Research in high-energy heavy-ion collisions has revealed clear effects of neutron skin as well. Experimentally, unstable nuclei with neutron skin structures can be produced using radioactive nuclear beam facilities. By measuring observables sensitive to neutron skin in reactions with stable nuclei, the neutron skin thickness can be extracted or determined. Combined with nuclear theoretical models, this can further constrain the equation of state of asymmetric nuclear matter and related properties of nuclear astrophysics.

Keywords: Neutron skin, Radioactive nuclear beam, Equation of state of asymmetric nuclear matter

Abstract

The physics of radioactive nuclear beams represents one of the frontiers of nuclear physics, where new phenomena and physics emerge in exotic nuclei far from the β-stability line. Neutron skin is an exotic phenomenon in unstable nuclei that is closely correlated with the properties of the equation of state (EOS) of asymmetric nuclear matter and neutron stars. This study examines previous research on the effects of neutron skin in nucleus-nucleus collisions to identify suitable observables for determining neutron skin thickness, which could in turn be used to investigate the EOS of asymmetric nuclear matter. Various theoretical models are employed to study neutron skin effects in nuclear collisions. The statistical abrasion-ablation (SAA) and isospin-dependent quantum molecular dynamics (IQMD) models are used to investigate neutron abrasion cross-section, neutron/proton ratios, and t/3He ratios. Nuclear structure models are applied to explore the relationship between neutron skin and α-cluster formation, α-decay, nuclear surface properties, and nuclear temperature. Strong correlations have been identified between neutron skin thickness and neutron abrasion cross-section, neutron/proton ratios, t/3He ratios, photon production, and other quantities. By measuring observables that exhibit strong correlation with neutron skin, the skin thickness can be obtained. The EOS of asymmetric nuclear matter and properties of neutron stars can then be studied or constrained using the obtained neutron skin data. Further investigations are necessary to identify observables useful for determining neutron skin thickness from experimental measurements.

Key words: Neutron skin, Radioactive nuclear beam, Equation of state of asymmetric nuclear matter

Introduction

Atomic nuclei represent an important hierarchical level of matter's microscopic structure. Approximately 300 stable nuclei exist in nature, while theoretical predictions suggest that 8,000–10,000 nuclei may exist, with over 3,000 discovered experimentally to date. Traditional nuclear physics, through extensive studies of stable nuclei, has established a relatively complete theoretical framework. For instance, nuclear radius is proportional to the cube root of the nucleon number (A), and nucleons occupy energy level orbitals calculated from the shell model in ascending order. However, as more unstable nuclei are discovered experimentally, their properties are found to differ significantly from stable nuclei, revealing many new phenomena and physics [1–4]. Examples include neutron halo and neutron skin structures; changes in shell structures predicted by the shell model near the drip lines, where traditional magic numbers disappear and new ones emerge; exotic radioactive modes in extremely proton-rich nuclei; and the appearance of multi-nucleon cluster structures.

Neutron skin is defined as the difference between the neutron radius and proton radius of an atomic nucleus. Since protons are charged, their distribution radius can be measured precisely through various methods such as electron and proton scattering. However, no satisfactory experimental method currently exists for measuring neutron distribution radius, and the precision of neutron radius measurements remains much poorer than that of proton radius [2].

The energy of nuclear matter can be expressed in terms of the system's density and asymmetry, which constitutes the equation of state (EOS) of nuclear matter. The EOS can be expanded into contributions from symmetric and asymmetric nuclear matter. The EOS of symmetric nuclear matter has been studied extensively and systematically, and its properties are well understood. For asymmetric nuclear matter, however, different nuclear forces or interaction potentials in theoretical models yield different density dependencies of symmetry energy, which can be either soft or hard, introducing significant uncertainties. Currently, the EOS of asymmetric nuclear matter represents an important research focus in nuclear physics.

Theoretical studies have revealed clear dependencies between certain parameters in the EOS of asymmetric nuclear matter (such as symmetry energy and its slope) and the neutron skin thickness of atomic nuclei. If neutron skin size can be measured precisely, it can be used to determine or constrain these parameters. Additionally, neutron stars consist primarily of neutron matter, and their structure is intimately related to the EOS of asymmetric nuclear matter, with different interaction potentials or theories yielding different mass-radius relationships for neutron stars [9–10]. Therefore, precise knowledge of atomic neutron skin can also constrain the specific properties of neutron stars.

Neutron skin produces various effects that differ from stable nuclei due to the larger radius of neutron density distribution compared to proton density distribution. These effects manifest in both reaction processes and structural characteristics. The following discussion examines specific effects of neutron skin through various physical quantities in nuclear reactions and certain nuclear structural features, focusing on relationships between neutron skin and neutron removal cross-section, light particle yield ratios, projectile fragmentation reactions, photon production, cluster structure, nuclear surface width, nuclear temperature, and neutron skin effects in high-energy heavy-ion collisions.

1.1 Relationship Between Neutron Skin and Neutron Removal Cross-Section

The statistical abrasion-ablation model is a relatively successful phenomenological nuclear reaction model capable of calculating nuclear reaction cross-sections and yields from projectile fragmentation reactions. References [11–12] investigated the dependence of neutron removal cross-section on neutron skin using this model. Neutron removal cross-section is defined as the sum of production cross-sections for all fragments with the same proton number as the projectile. Studies revealed a clear proportional relationship between neutron removal cross-section and neutron skin thickness. A similar approach yields proton removal cross-section, defined as the sum of production cross-sections for all fragments with the same neutron number as the projectile. Results show that proton removal cross-section is inversely proportional to neutron skin thickness—the thicker the neutron skin, the smaller the proton removal cross-section, as illustrated in Figure 1 [Figure 1: see original paper] [12]. Therefore, experimental measurement of neutron removal cross-section can be used to extract the neutron skin size of projectile nuclei. Taking the ratio of neutron to proton removal cross-sections can eliminate systematic experimental errors and improve precision in determining neutron skin thickness. This ratio exhibits an excellent linear relationship with neutron skin thickness. Reference [13] theoretically investigated the relationship between neutron skin and neutron removal cross-section for tin isotopes, also finding neutron removal cross-section to be a physical quantity sensitive to neutron skin thickness that can constrain symmetry energy through experimental measurement.

1.2 Relationship Between Neutron Skin and Light Particle Yield Ratios

References [14–15] studied the relationship between neutron skin and light particle yield ratios using the isospin-dependent quantum molecular dynamics (IQMD) model. For nuclei with neutron skin structure, the neutron density distribution radius exceeds that of protons, producing various effects in nuclear reactions that differ from stable nuclei. By investigating neutron-to-proton yield ratios from reactions of 50Ca impinging on Be targets, a proportional relationship with neutron skin thickness was observed from central to peripheral collisions, with particularly clear linear dependence in peripheral reactions. Consequently, neutron skin thickness can be extracted experimentally by measuring proton-to-neutron ratios. Since neutron measurement is experimentally challenging, heavier charged particles—triton (t) and 3He—were further investigated. These nuclei differ by one neutron versus one proton after removing identical nucleons. Studies revealed that the t/3He yield ratio is essentially proportional to the neutron-to-proton yield ratio, as shown in Figure 2 [Figure 2: see original paper] [15]. Taking the ratio of t/3He yield ratio to neutron-to-proton yield ratio yields approximately a constant across different neutron skin thicknesses. Therefore, both neutron-to-proton ratio and t/3He ratio can be used experimentally to extract neutron skin thickness, but since both triton and 3He are charged particles, they are easier to measure and can yield higher-precision experimental results.

1.3 Effects of Neutron Skin in Projectile Fragmentation Reactions

In addition to light particles, nuclear reactions also produce heavy fragments. Extensive research exists on heavy fragment production in projectile fragmentation reactions, such as isoscaling phenomena where isotope yields from two collision systems with different isospins exhibit linear relationships on logarithmic coordinates. The isoscaling slope for light particles is essentially constant and proportional to symmetry energy, enabling symmetry energy extraction through isoscaling parameters. In projectile fragmentation reactions, isoscaling phenomena have also been observed for heavy fragments.

Reference [16] investigated the effect of neutron skin thickness on isoscaling phenomena in projectile fragmentation reactions using the IQMD model by varying the neutron skin size of projectiles. Results showed that different neutron skin thicknesses alter the isoscaling parameter, which exhibits anti-correlation with neutron skin thickness. This indicates that neutron skin thickness can be extracted by measuring the isoscaling parameter of heavy fragments in fragmentation reactions, which can further constrain the nuclear matter EOS and its important parameters.

Reference [17] also examined various observables in fragmentation reactions, including neutron abrasion cross-section, charge-changing cross-section, and interaction cross-section, finding that these quantities all depend on neutron skin thickness. This suggests that nuclear matter EOS and neutron star properties could potentially be constrained through these observables. The dependence of charge-changing cross-section on neutron skin thickness is shown in Figure 3 [Figure 3: see original paper] [17]. Additionally, studies have found that information entropy-related observables from fragmentation reaction fragment production cross-sections exhibit clear dependence on neutron skin thickness [18–19].

1.4 Relationship Between Neutron Skin and Photon Production

Reference [20] calculated direct photon yield ratios from 50Ca+12C and 50Ca+40Ca reactions using the IQMD model to investigate neutron skin thickness effects on photon production. The ratio of central to peripheral collision yields (Rcp) shows relatively clear dependence on neutron skin thickness, with energy dependence that yields better linear relationships at higher energies. Neutron skin thickness also significantly influences the relationship between Rcp and rapidity. For 40Ca targets, the largest differences appear at zero rapidity, while for 12C targets, differences are greater at target-like rapidity. Deeper theoretical investigation is needed to extract neutron skin thickness from photon yields. However, compared to previously studied quantities, photons represent a cleaner probe and may become an ideal experimental observable.

1.5 Relationship Between Neutron Skin and Nuclear Structure Properties

Reference [21] studied carbon isotopes from 12C to 18C with varying neutron skin thicknesses, finding that neutron skin size affects the probability of α-cluster formation within nuclei, with similar phenomena observed in tin isotopes. In α-decay of heavy nuclei, references [22–23] found clear dependence between daughter nucleus neutron skin size and α-decay lifetime. Larger neutron skin reduces α-decay probability, as shown in Figure 4 [Figure 4: see original paper] [22].

Theoretical studies have revealed dependence between neutron skin and nuclear surface width [24]. By varying nuclear potentials, different density distributions and neutron skin thicknesses can be obtained for atomic nuclei. Based on macroscopic models such as the liquid drop model, density distributions can be described by two-parameter Fermi distributions, enabling investigation of correlations between neutron skin thickness and surface diffuseness widths for neutrons and protons. Therefore, neutron skin can be obtained from microscopic theoretical calculations of density distributions, which can in turn determine nuclear surface diffuseness widths in macroscopic models.

Reference [25] investigated the relationship between neutron skin and nuclear temperature using HF+BCS theory. Studies of nuclei at finite temperature revealed that both proton and neutron radii increase with temperature. As temperature rises, BCS pairing correlations cause a phase transition from superfluid to normal state at a transition temperature proportional to pairing energy—approximately 0.6–0.7 MeV (about 0.6 times the pairing energy). Research found that neutron skin size gradually increases above the transition temperature but is actually smaller at the transition temperature itself.

1.6 Neutron Skin Effects in High-Energy Heavy-Ion Collisions

Relativistic heavy-ion collisions constitute an important field in nuclear physics, primarily investigating properties of hot and dense nuclear matter [26–27]. In recent years, effects of nuclear structure such as neutron skin or deformation have become research topics in this field [28]. Reference [29] studied neutron skin effects in high-energy heavy-ion collisions using two collision systems with identical nucleon numbers but different proton and neutron numbers. By employing different nuclear potentials to obtain varying neutron skin thicknesses, studies based on different theoretical models such as AMPT, UrQMD, and Hijing [29] revealed proportional relationships between charged particle multiplicity yield ratios and neutron skin thickness, demonstrating that neutron skin thickness can also be investigated through high-energy heavy-ion collisions.

Experimental Methods for Probing Neutron Halo and Neutron Skin Structures

2.2 Experimental Measurement Methods for Halo Structures

Unstable nuclei in experimental studies are primarily produced using radioactive beam facilities [30]. Currently, two main methods exist worldwide for producing unstable nuclei: Projectile Fragmentation (PF) and Isotope Separation On-Line (ISOL), as schematically shown in Figure 5 [Figure 5: see original paper] [31]. The projectile fragmentation method uses stable nuclear beams from heavy-ion accelerators to bombard targets, producing fragments with various charge and mass numbers. These fragments are then selected, transported, and focused to experimental terminals through subsequent secondary beam lines. The advantage of projectile fragmentation is its ability to produce very short-lived unstable nuclei, including many secondary beams near neutron and proton drip lines. Secondary beam energies are essentially similar to the projectile energy, and can be reduced using degraders when lower energies are required. The ISOL method uses beams from heavy-ion accelerators to bombard thick targets, where most or all of the beam energy is deposited. Various particles produced from beam-target reactions are separated and extracted using isotope separation techniques at low energies. When higher energies are required, secondary beams can be re-accelerated before delivery to experimental terminals. The ISOL method's advantage lies in its high secondary beam intensity, though producing very short-lived nuclides is difficult. These two methods possess complementary characteristics.

Nuclei with halo structures exhibit different properties from stable nuclei in many aspects, with two most important characteristics: significantly larger radii compared to stable nuclei, and much narrower momentum distributions for the outermost valence nucleons. Various methods exist for experimentally measuring nuclear radii, particularly charge radii of long-lived nuclei through electron scattering, proton scattering, and isotope shift measurements. A commonly used method measures nuclear matter radius through nuclear reaction total cross-section. Under high-energy approximations, the nuclear reaction total cross-section (σR) can be expressed by a relatively simple formula: $\sigma\mathrm{R} = \pi(\mathrm{Rp} + \mathrm{RT})^2$, essentially proportional to the square of the sum of projectile and target radii multiplied by π. In reality, nuclear reaction total cross-section depends on energy, and various theoretical models such as the Glauber model can describe its energy dependence reasonably well.

Based on the nuclear reaction total cross-section formula, since target radii are known for stable nuclei, measuring σR experimentally allows determination of projectile nuclear radius or density distribution through the formula or theoretical models—this constitutes the principle of nuclear radius measurement. In practice, the transmission method is typically employed [32–33]. When a beam passes through a target, the number of incident particles (N0) and the number of unreacted particles after passing through the target (N1) relate to target thickness (t) and nuclear reaction total cross-section through N1 = N0exp($-\sigma$Rt). Rearranging yields the expression for nuclear reaction total cross-section: σR = ln(N1/N0)/t. With known target thickness, only two counts need measurement experimentally: incident particle number N0 and outgoing unreacted particle number N1. Placing detectors before and after the target measures these quantities to obtain nuclear reaction total cross-section. However, practical measurements are complicated because incident beams also react with all detectors. Generally, empty-target measurements are added to correct errors from reactions in detectors.

Regarding the relationship between valence nucleon momentum distribution and density, from quantum mechanical wave functions, momentum distribution is essentially the Fourier transform of density distribution. When coordinate space density distribution is broad, its transformation to momentum space becomes narrow, and vice versa. To measure valence nucleon momentum distributions experimentally, nuclei with halo or exotic structures are typically considered as consisting of a core plus valence nucleons. In the projectile rest frame, core momentum equals valence nucleon momentum in magnitude but opposite in direction. Therefore, measuring valence nucleon momentum distribution only requires measuring core momentum distribution. Particularly for neutron-rich nuclei where valence nucleons are neutrons and difficult to measure experimentally, core momentum distribution after valence neutron stripping is typically measured. The time-of-flight method is commonly employed experimentally: with known flight distance, measured flight time determines particle velocity and momentum [32–33].

2.3 Experimental Measurement Methods for Neutron Skin Structure

Measuring nuclear reaction total cross-section yields the total matter radius of a nucleus. To measure neutron skin thickness, both proton radius and neutron radius must be known. Among nuclear reaction cross-sections, charge-changing cross-section directly relates to proton radius. Simultaneous experimental measurement of nuclear reaction total cross-section and charge-changing cross-section can determine both nuclear radius and proton radius, thereby establishing neutron skin thickness [34]. Additionally, measuring neutron removal cross-section, neutron-to-proton yield ratio, and triton-to-3He yield ratio may also be viable methods. All quantities discussed previously that exhibit clear dependence on neutron skin could serve as observables. However, actual experimental implementation requires more systematic research to clarify each physical quantity's sensitivity to neutron skin. Only when extracted neutron skin thickness precision meets expectations can they be considered ideal experimental observables. Estimates suggest that if neutron-to-proton yield ratio measurement precision reaches 5%, the resulting neutron skin thickness precision can achieve approximately 0.1 fm [14]. Beyond observables in intermediate-energy nuclear reactions, high-energy heavy-ion collisions also offer potential probes for neutron skin thickness. Currently, high-energy heavy-ion collisions primarily study stable nuclei, but if high-energy collisions with unstable nuclei become possible in the future, better probes from high-energy nuclear physics could also be employed to investigate neutron skin structure.

In addition to these methods, significant attention is focused on parity-violation experiments in electron scattering proposed by Jefferson Laboratory, considered a weak-electromagnetic interaction-based detection scheme capable of high-precision neutron skin thickness measurement. The first experiment targeted 208Pb neutron skin measurement, with additional experiments for 48Ca. The 208Pb experiment has completed two phases: Phase I yielded a neutron skin thickness of 0.33+ (0.16–0.18) fm [35], while Phase II resulted in (0.283 $\pm$ 0.071) fm [36]. Determining EOS parameters of asymmetric nuclear matter, such as symmetry energy slope parameter (L) and symmetry energy at saturation density (J), using the latest 208Pb neutron skin data differs significantly from most previous heavy-ion collision results [37], requiring further experimental and theoretical investigation to resolve this discrepancy.

Compared to stable nuclei where neutron and proton distribution radii are relatively similar, neutron skin structure represents a common structural feature in neutron-rich nuclei far from the stability line. Its magnitude is intimately related to single-particle orbitals and the evolution of shell structure with isospin. Systematic investigation of neutron skin structure is crucial for deeply understanding the nature of nuclear forces. Simultaneously, neutron skin structure is closely related to the EOS of isospin-asymmetric nuclear matter, with clear dependencies on many important EOS parameters. Neutron skin can be used to determine or constrain symmetry energy and other physical quantities with considerable precision. Furthermore, the EOS of asymmetric nuclear matter is intimately connected to properties of nuclear astrophysical objects such as neutron stars, with different EOS yielding different neutron star mass-radius relationships. Therefore, neutron skin represents an important physical quantity not only in nuclear structure and reaction studies but also in nuclear astrophysics, constituting one of the current frontiers and hot topics in nuclear physics research.

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Note: Figure translations are in progress. See original paper for figures.