

Hard photon production as a probe to study the surface properties of proton-rich nuclei

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Abstract

Based on the isospin- and momentum-dependent Boltzmann-Uehling-Uhlenbeck transport model, this paper simulates the hard photon emission produced by neutron-proton bremsstrahlung in peripheral collisions of proton-rich systems $^{48,50,52,54,56,58}\text{Ni} + ^{58}\text{Ni}$ at a beam energy of 50 MeV/nucleon. The study incorporates nucleon-nucleon short-range correlation effects into the extended Thomas-Fermi approximation (ETF*) of the nucleon kinetic energy density in finite nuclei, which leads to the existence of a neutron skin in momentum space for proton-rich nuclei.

The results indicate that as the proton skin thickness of the neutron-deficient Ni projectiles increases, the multiplicity of emitted hard photons gradually decreases. However, when surface terms are considered in the extended Thomas-Fermi approximation, the emission of hard photons (especially high-energy hard photons) is significantly enhanced, and this effect is much larger than the influence of the proton skin in coordinate space. Therefore, when inferring the proton skin thickness of a specific isotope from other known neutron-deficient isotopes, the effects of short-range correlations and the surface terms in the extended Thomas-Fermi approximation must be taken into account.

Full Text

Preamble

Abstract

This paper presents a comprehensive study on the integration of advanced machine learning techniques within the framework of modern scientific research. As the volume of experimental data continues to grow exponentially across various disciplines, traditional analytical methods are increasingly being supplemented

or replaced by deep learning architectures. We investigate the theoretical foundations and practical applications of these models, focusing on their ability to extract meaningful patterns from high-dimensional datasets. Our results demonstrate that by employing specialized neural network configurations, researchers can achieve significantly higher predictive accuracy and computational efficiency compared to conventional statistical approaches. Furthermore, we discuss the implications of these findings for future developments in automated discovery and data-driven modeling.

1. Introduction

The rapid evolution of computational power and algorithmic sophistication has ushered in a new era of data-driven science. Machine learning, particularly deep learning, has emerged as a transformative force, enabling the analysis of complex systems that were previously considered intractable. From genomic sequencing to astrophysical simulations, the capacity to process and interpret vast quantities of information is now a fundamental requirement for scientific progress.

In this context, the development of robust models that can generalize across diverse domains is of paramount importance. While early applications of machine learning were often limited by data scarcity and hardware constraints, contemporary researchers have access to massive repositories of labeled data and high-performance computing clusters. This shift has facilitated the transition from simple linear models to intricate deep neural networks capable of capturing non-linear relationships and hierarchical features.

2. Methodology

2.1 Data Acquisition and Preprocessing

The efficacy of any machine learning model is fundamentally dependent on the quality and representativeness of the training data. In this study, we utilized a multi-source dataset comprising both experimental observations and high-fidelity simulations. To ensure consistency, all raw data underwent a rigorous preprocessing pipeline, including normalization, outlier detection, and feature scaling.

Let the input feature vector be denoted by $x \in \mathbb{R}^n$ and the corresponding target variable by y . The normalization process can be expressed as:

$$x' = \frac{x - \mu}{\sigma}$$

where μ represents the mean and σ denotes the standard deviation of the feature set. This transformation ensures that all input variables contribute equally to the model's learning process, preventing features with larger magnitudes from dominating the gradient updates.

2.2 Model Architecture

We implemented a deep residual network (ResNet) architecture to address the challenges of vanishing gradients in deep architectures. The core component of this model

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Hard Photon Production as a Probe for Studying the Surface Properties of Proton-Rich Nuclei

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Abstract: Hard photon production is investigated as a potential probe for characterizing the surface properties of proton-rich nuclei. By analyzing the emission mechanisms and cross-sections of high-energy photons in nuclear reactions involving proton-rich isotopes, we demonstrate how these observables correlate with the underlying nuclear structure, specifically the proton skin thickness and surface density distributions. Our findings suggest that hard photons, being insensitive to the strong interaction during their escape from the nuclear medium, provide a clean signal for probing the spatial distribution of protons in nuclei far from the line of stability.

Key words: hard photon production; proton-rich nuclei; nuclear surface properties; proton skin

1 Introduction

The study of nuclei far from the line of stability is a central frontier in modern nuclear physics. In particular, the surface properties of proton-rich nuclei, such as the formation of proton skins or halos, offer critical insights into the nuclear force and the equation of state (EoS) of asymmetric nuclear matter. Unlike stable nuclei, proton-rich isotopes exhibit unique structural features due to the competition between the long-range Coulomb repulsion and the short-range nuclear attraction.

Traditionally, nuclear radii and surface thicknesses have been probed using electron scattering or hadronic probes. However, hadronic probes are subject to complex final-state interactions (FSI) that can obscure the initial structural information. In contrast, hard photons—defined as photons with energies exceeding several tens of MeV—are produced during the early stages of intermediate-energy heavy-ion collisions. Since photons do not participate in the strong interaction, they can escape the reaction zone relatively unhindered, carrying

pristine information about the dynamic environment and the spatial distribution of nucleons at the moment of their production.

In this work, we explore the feasibility of using hard photon production as a diagnostic tool for the surface properties of proton-rich nuclei. We focus on the bremsstrahlung process arising from individual proton-neutron (pn) collisions, which is the dominant source of hard photons in the intermediate energy regime. By modeling the density profiles of proton-rich nuclei and simulating the collision dynamics, we establish a relationship between the hard photon yield and the

摘要：基于同位旋和动量依赖的 Boltzmann-Uehling-Uhlenbeck 输运模型，本文模拟了在 50 MeV/nucleon 束流

This study investigates the emission of hard photons produced by neutron-proton bremsstrahlung during peripheral collisions in proton-rich systems, specifically $^{48,50,52,54,56,58}\text{Ni} + ^{58}\text{Ni}$. The research incorporates nucleon-nucleon short-range correlation (SRC) effects into the extended Thomas-Fermi approximation (ETF*) of the nucleon kinetic energy density within finite nuclei. This inclusion leads to the existence of a neutron skin in momentum space for proton-rich nuclei. The results demonstrate that as the proton skin thickness of neutron-deficient Ni projectiles increases, the multiplicity of emitted hard photons gradually decreases. However, when surface terms are considered in the extended Thomas-Fermi approximation, the emission of hard photons—particularly high-energy ones—is significantly enhanced. This enhancement effect far outweighs the influence of the proton skin in coordinate space. Consequently, when inferring the proton skin thickness of a specific isotope based on other known neutron-deficient isotopes, it is essential to account for both short-range correlation effects and the influence of surface terms within the extended Thomas-Fermi approximation.

Keywords: hard photons; proton-rich nuclei; proton skin; short-range correlation

The distribution of nucleons within the atomic nucleus serves as a critical window for studying nuclear interactions and the nuclear matter equation of state (EoS) [?, ?]. In particular, it is essential for describing the symmetry energy, which characterizes how the specific binding energy of nucleons varies with the neutron-proton asymmetry [?]. For neutron-rich nuclei, where the number of neutrons exceeds the number of protons, a neutron skin structure is expected to form. The thickness of this skin, ΔR_{np} , is defined as the difference between the root-mean-square radii of neutrons and protons. This significant structural phenomenon has been extensively investigated using various nuclear theoretical models, including Skyrme-Hartree-Fock calculations [?, ?], relativistic mean-field models [?], and shell models.

方法 [12-14] 等方法。在实验方面，人们为测量中子皮厚度

Considerable efforts have also been dedicated to this field, including photoproduction of π mesons and experiments on pionic and antiprotonic atoms at CERN [?, ?, ?], as well as parity-violating electron scattering experiments (PREX and CREX) at the Jefferson Laboratory [?, ?, ?].

Furthermore, final-state observables in intermediate-energy [?, ?, ?] and relativistic heavy-ion collisions [?, ?, ?, ?] have been utilized to investigate the neutron skin thickness of neutron-rich nuclei. Despite the flourishing research on neutron skins and the significant advancements in radioactive beam technologies, studies on the proton skin of proton-rich (neutron-deficient) nuclei remain relatively underdeveloped. Therefore, to achieve a comprehensive understanding of nuclear structure across the entire nuclide map, it is urgent to conduct systematic research on the proton skin structure in proton-rich nuclei.

Analogous to the definition of neutron skin thickness in neutron-rich nuclei, the proton skin thickness in proton-rich nuclei is defined as the difference between the root-mean-square (rms) radii of protons and neutrons, namely $\Delta R_{pn} = \langle r^2 \rangle_p^{1/2} - \langle r^2 \rangle_n^{1/2}$. Consequently, the most direct method for investigating proton skin thickness is to measure the density distributions of neutrons and protons within the nucleus. While electron scattering...

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Measuring the spatial distribution of particles is particularly challenging due to the influence of complex strong interactions. Notably, research programs targeting nucleon distributions in unstable nuclei have been initiated at the Facility for Antiproton and Ion Research (FAIR) at GSI [?] and the COMBAS facility at the Dubna Radioactive Ion Beam complex (FLNR-DRIBs) [?]. Furthermore, final-state observables in heavy-ion collisions across energy ranges from low to relativistic energies are sensitive to the initial phase-space distribution of nucleons or quarks and gluons within the colliding nuclei. For instance, yield ratios such as n/p , ${}^3\text{H}/{}^3\text{He}$, and π^-/π^+ , as well as hard photon emission, have been proposed as probes for nuclear deformation and neutron skin thickness [?, ?]. It is also important to note that among all observables in heavy-ion reactions, photons serve as one of the cleanest and least disturbed probes of the early stages of the nuclear reaction. This is because they interact with nuclear matter only through electromagnetic interactions, unlike hadrons, which undergo complex final-state interactions on their path to the detector. Consequently, photon emission in heavy-ion collisions represents a sensitive probe for detecting the proton skin thickness of proton-rich nuclei.

In recent years, nucleon-nucleon short-range correlations (SRC) caused by the tensor component and the repulsive core of the nuclear force have received extensive attention [?]. These correlations lead to the emergence of a high-momentum tail in the single-nucleon momentum distribution of the nucleus. By incorpo-

rating SRC effects into an extended Thomas-Fermi model, Cai et al. discovered the coexistence of a proton skin in momentum space and a neutron skin in coordinate space within neutron-rich nuclei. They further demonstrated an inverse relationship between the root-mean-square radii in coordinate and momentum space, satisfying $\langle r^2 \rangle \langle k^2 \rangle \equiv \text{const}$, a correlation governed by Liouville's theorem and the Heisenberg uncertainty principle [?]. Conversely, research indicates that proton-rich nuclei exhibit the coexistence of a neutron skin in momentum space and a proton skin in coordinate space. This occurs because, under the influence of SRC, neutrons typically possess higher velocities than protons in the proton skin region of heavy nuclei. Literature [?] has explored how the coordinate-space proton skin and momentum-space neutron skin jointly influence the yield ratios of neutrons and protons in proton-rich nuclei [?]. Understanding the role of nucleon-nucleon SRC in nuclear structure, nuclear reaction dynamics, and the properties of neutron stars remains one of the core challenges in nuclear physics. Therefore, investigating the impact of the momentum-space neutron skin induced by SRC on the detection of proton skin thickness is crucial, as it provides key information for understanding the deep structure of atomic nuclei.

In this work, we apply the extended Thomas-Fermi approximation of nucleon kinetic energy density, which includes short-range correlation effects, to the Isospin- and Momentum-Dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model [?]. We investigate the correlation between proton skin thickness and hard photon emission in reactions induced by proton-rich Ni isotopes, specifically $^{48,50,52,54,56,58}\text{Ni} + ^{58}\text{Ni}$, at a beam energy of 50 MeV/nucleon. Additionally, this paper explores the influence of the surface term of the nucleon kinetic energy density, modified by the inclusion of SRC, on the detection of the proton skin thickness in these proton-rich Ni isotopes.

2 理论框架

In this study, we employ an upgraded BUU transport model based on the IBUU04 model [?]. The initial density distributions of nucleons within the projectile and target nuclei are generated using a two-parameter Fermi distribution (2pF):

$$\rho_J(r) = \rho_{J,0} \{1 + \exp[(r - c_J)/a_J]\}^{-1}$$

where c_J and a_J represent the half-density radius and the diffuseness parameter, respectively.

Considering that the nucleon momentum distribution exhibits a high-momentum tail (HMT) due to short-range correlations between nucleons, we have incorporated the parameterized nucleon momentum distribution provided in references [?, ?] into the IBUU model. The specific form is as follows:

The kinetic energy density distribution of nucleons in finite nuclei can be modified as [?]:

$$\tau_J(r) = \alpha_\infty \rho_J^{5/3}(r) \Phi_J + \eta_J \frac{[\nabla \rho_J(r)]^2}{\rho_J(r)} + \Delta \rho_J(r)$$

In the first term, $\alpha_\infty = (3/5)(3\pi^2)^{2/3}$ represents the bulk component, corresponding to nucleons in infinite nuclear matter, where $\Phi_J = 1 + C_J(5\phi_J + 3/\phi_J - 8) > 1$ is determined by the properties of the high-momentum tail. In neutron-deficient systems, the enhancement of the bulk kinetic energy density is more pronounced for neutrons than for protons. This occurs because a relatively larger fraction of neutrons is depleted from the Fermi sea to form a “neutron skin” in momentum space within the high-momentum tail. This phenomenon is analogous to the proton skin in momentum space observed in neutron-rich nuclei, as discussed in reference [?]. The second term, originally proposed by Weizsäcker [?], is referred to in this study as the surface term, as it is highly sensitive to the surface properties of finite nuclei. Although the strength factor η_J for this parameter remains a subject of debate, studies have shown that it significantly influences the halo and skin properties at the surface of heavy nuclei [?, ?]. This factor can be determined using the density distribution and the average nucleon kinetic energy $\langle E_{kin,J} \rangle$.

实验信息进行约束 [53]。由于核表面的光滑性，涉及拉普

The third term of the Laplace operator is negligible. Based on the above description, the parameters Φ_J and η_J corresponding to different Ni isotopes can be obtained; specific values are provided in Table 1 of Ref. [37].

We adopt the same formulation as in Ref. [36] to describe the neutron skin in the momentum space of neutron-deficient nuclei. This method is analogous to measuring the neutron skin in coordinate space, which is defined as the difference between the root-mean-square (rms) radii of neutrons and protons, $\Delta R_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$. In momentum space, we consider the difference between the average kinetic energies of neutrons and protons, denoted as $\Delta E_{kin}^{np} \equiv \langle E_{kin}^n \rangle - \langle E_{kin}^p \rangle$, where $\langle E_{kin}^J \rangle \equiv \int E_{kin}(r) \rho_J(r) dr / \int \rho_J(r) dr \equiv \langle k_J^2 \rangle / 2M$. The momentum distribution is given by $n_J(k, \rho, \delta) = C_J(\theta(k_F^J - |k|) + \phi_J(k_F^J)^4 / |k|^4 \theta(|k| - k_F^J))$, where k_F^J is the Fermi momentum of nucleon J . The parameter Δ_J represents the depletion of the Fermi sea relative to the step-function distribution of a free Fermi gas. The parameters Δ_J , C_J , and ϕ_J are linearly related to the isospin asymmetry $\delta = (\rho_n - \rho_p) / \rho$, with the general expression $Y_J = Y_0(1 + Y_1 \tau_3^J \delta)$, where $\tau_3^n = +1$ and $\tau_3^p = -1$ [43-45]. The amplitude C_J and the high-momentum cutoff coefficient ϕ_J together determine the fraction of nucleons in the high-momentum tail (HMT), $x_{HMT} = 3C_J(1 - \phi_J^{-1})$. These parameters satisfy the normalization condition $[2/(2\pi)^3] \int n_J(k, \rho, \delta) d\mathbf{k} = (k_F^J)^3 / 3\pi^2$ and are consistent with the equation of state for pure neutron matter provided by microscopic many-body theories [46-51], as well as experimental analyses of the HMT fraction and its impact on symmetry energy [42,52-53]. In this study, we use the HMT-exp parameter set [36]: $x_{HMT}^{SNM} = 28\%$ and $x_{HMT}^{PNM} = 4\%$, corresponding to $C_0 = 0.161$, $C_1 = -0.25$, $\phi_0 = 2.38$, and $\phi_1 = -0.56$. Based on this momentum distribution, a proton skin in momentum space has been observed in the neutron-rich nucleus ^{208}Pb , with its thickness increasing as isospin asymmetry increases [36]. Further discussions

on the effects of short-range correlations and the HMT on nuclear symmetry energy and neutron star properties can be found in Ref. [54]. By incorporating short-range correlation effects into the extended Thomas-Fermi approximation, this study employs the following isospin- and momentum-dependent mean-field single-nucleon potential [58]:

$$U(\rho, \delta, \mathbf{p}, \tau) = A_u(x) \frac{\rho_{\tau'}}{\rho_0} + A_l(x) \frac{\rho_{\tau}}{\rho_0} + B \left(\frac{\rho}{\rho_0} \right)^{\sigma} (1 - x\delta^2) + \frac{2C_{\tau, \tau}}{\rho_0} \int \frac{f_{\tau}(\mathbf{p}') d^3 \mathbf{p}'}{1 + (\mathbf{p} - \mathbf{p}')^2 / \Lambda^2} + \frac{2C_{\tau, \tau'}}{\rho_0} \int \frac{f_{\tau'}(\mathbf{p}') d^3 \mathbf{p}'}{1 + (\mathbf{p} - \mathbf{p}')^2 / \Lambda^2}$$

where $\tau = 1/2$ ($-1/2$) corresponds to neutrons (protons), and δ is the isospin asymmetry defined previously. The parameters $A_u(x)$, $A_l(x)$, B , $C_{\tau, \tau}$, $C_{\tau, \tau'}$, σ , and Λ have been updated after including short-range correlation effects by fitting the empirical properties of nuclear matter, such as the saturation density $\rho_0 = 0.16 \text{ fm}^{-3}$, binding energy $E_0 = -16 \text{ MeV}$, incompressibility $K_0 = 230 \text{ MeV}$, and the nucleon effective mass $m_s^* = 0.7m$. Here, $f_{\tau}(\mathbf{r}, \mathbf{p})$ is the phase-space distribution function at coordinate \mathbf{r} and momentum \mathbf{p} . Different x parameters can be used to reflect various forms of symmetry energy predicted by different many-body theories without altering the properties of symmetric nuclear matter or the symmetry energy at normal density [59]. Furthermore, for nucleon-nucleon scattering, an isospin-dependent, in-medium reduced nucleon-nucleon cross section is employed [60].

Hard photon production in intermediate-energy heavy-ion reactions has been investigated in numerous early theoretical and experimental works [61-68]. This study considers only hard photons with energies of 10-100 MeV produced via the bremsstrahlung reaction channel $p + n \rightarrow p + n + \gamma$, excluding photons from collective giant resonances and statistically emitted thermal photons. Although the reaction cross section for the $p + n \rightarrow p + n + \gamma$ process remains model-dependent [69-72], calculations from theoretical reaction models can reasonably reproduce all qualitative features of experimental hard photon data [63]. In this work, we use a neutral scalar σ -meson exchange model based on quantum field theory to calculate the probability of hard photon production [69], expressed as follows:

$$\frac{d^2 P}{d\Omega dE_{\gamma}} = 1.671 \times 10^{-7} \frac{1}{E_{\gamma}} (1 - y^2)^{\alpha}$$

where $y = E_{\gamma}/E_{max}$, $\alpha = 0.7319 - 0.5898\beta_i$, E_{γ} is the emitted photon energy, E_{max} is the total energy available in the proton-neutron center-of-mass system, and β_i is the initial velocity of the nucleons. Our calculations also account for the Pauli blocking effect in the final state of the $p + n \rightarrow p + n + \gamma$ process [62]. Assuming that photons are emitted isotropically in the proton-neutron center-of-mass system, the single differential probability of the photon is obtained by averaging over a 4π solid angle:

$$\frac{dP}{dE_{\gamma}} = 2.1 \times 10^{-6} \frac{1}{E_{\gamma}} (1 - y^2)^{\alpha}$$

In the IBUU transport model, since the cross section for photon production via bremsstrahlung is approximately one-thousandth of the proton-neutron elastic

scattering cross section, we introduce the photon reaction channel using a perturbative method by multiplying the nucleon elastic scattering channel by the probability of photon bremsstrahlung production.

3 结果和讨论

When simulating heavy-ion collisions using the IBUU model, the initial density distribution of nucleons within the colliding nuclei is characterized by a two-parameter Fermi (2pF) distribution. The half-density radius c_J and the diffuseness parameter a_J are adopted from Ref. [?]. [Figure 1: see original paper] illustrates the relationship between the average local densities of neutrons and protons as a function of radius for the neutron-deficient isotopes $^{48,50,52,54,56,58}\text{Ni}$. The results demonstrate that as the neutron number decreases in these neutron-deficient Ni isotopes, the discrepancy between the proton and neutron density distributions at the nuclear surface becomes increasingly pronounced. Furthermore, a distinct proton skin in coordinate space is clearly observed in $^{48,50,52}\text{Ni}$.

These density distributions are fundamentally consistent with the results obtained using the Skyrme-Hartree-Fock method with SkM* parameterization as reported in Ref. [?]. Based on the difference between the root-mean-square radii of protons and neutrons, we calculated the proton skin thickness ΔR_{pn} for the $^{48,50,52,54,56,58}\text{Ni}$ isotopes. The resulting values are 0.276, 0.205, 0.147, 0.097, 0.055, and 0.004 fm, respectively.

To compare the effects of nucleon short-range correlation (SRC) and the surface terms of kinetic energy density, Figure 2 [Figure 2: see original paper] and Figure 3 [Figure 3: see original paper] illustrate the neutron and proton density distributions (color online) for various neutron-deficient Ni isotopes, both with and without the inclusion of nucleon kinetic energy. Furthermore, when the surface terms are excluded from the nucleon energy density, the local momentum distributions of nucleons within these different Ni isotopes are presented.

Figures 2 and 3 illustrate the relationship between the local momentum of nucleons and the radius r for the isotopes $^{48,50,52,54,56,58}\text{Ni}$ under conditions where the surface term of the kinetic energy density is considered. The average local momentum of a nucleon, k_{loc} , is defined via the local kinetic energy per nucleon as $\langle E_{loc}(r) \rangle / \rho_J(r) \equiv [k_{loc}(r)]^2 / 2M$.

[Figure 2: see original paper]

As shown in Figure 2, for the proton-rich isotopes $^{48,50,52}\text{Ni}$, the local momentum of protons is greater than that of neutrons across the entire radial range because the proton density exceeds the neutron density. However, when the surface term of the nucleon kinetic energy density—which incorporates short-range correlation (SRC) effects—is taken into account, a different behavior emerges.

[Figure 3: see original paper]

As demonstrated in Figures 3(a), (b), and (c), neutrons in the surface region of proton-rich nuclei exhibit a higher local momentum than protons. The inclusion of the surface term results in the local momenta of both neutrons and protons in the nuclear surface region being higher than in cases where the surface term is absent from the kinetic energy density. Consequently, this enhancement in local momentum will increase the probability of hard photon emission through the $p + n \rightarrow p + n + \gamma$ process.

high local momentum. This is because the Weizsäcker surface term $(\nabla\rho_J/\rho_J)^2$ for neutrons in proton-rich nuclei is numerically larger. According to Eq. (3), one can approximate the local momentum in the surface region as $k_{p/n}(r) \approx (\nabla\rho_{p/n})/(36M\rho_{p/n}) \approx 1/(36Ma_{p/n})$. Since the neutron surface diffuseness a_n in proton-rich nuclei is typically much smaller than the proton surface diffuseness a_p , this leads to $k_{loc}^n(r) > k_{loc}^p(r)$.

More interestingly, by comparing [Figure 1: see original paper] and [Figure 3: see original paper], we find a coexistence phenomenon in proton-rich nuclei: a neutron skin in momentum space exists alongside a proton skin in coordinate space. This is analogous to the phenomenon observed in neutron-rich nuclei reported in Ref. [?]. It reflects an inverse relationship between the root-mean-square (rms) radius in coordinate space and the rms radius in momentum space, expressed as $\langle r_j^2 \rangle \langle k_j^2 \rangle = \text{const}$. This relationship can be derived from the Heisenberg uncertainty principle and Liouville's theorem.

Utilizing this relationship facilitates the experimental use of momentum-space information to more accurately constrain coordinate-space structures. Consequently, this allows for a better determination of the proton skin structure in proton-rich nuclei or the neutron skin structure in neutron-rich nuclei. Within the current extended Thomas-Fermi (ETF) approximation, short-range correlation (SRC) effects are primarily incorporated into the first term of the nucleon kinetic energy density. This inclusion leads to a slight increase in the local momentum of protons, making it more comparable to the local momentum of neutrons, particularly in the internal regions of the nucleus.

[Figure 1: see original paper]

(Color online) Evolution of hard photon multiplicity ($E_\gamma = 10 - 100$ MeV) as a function of reaction time in peripheral $^{48,50,52,54,56,58}\text{Ni} + ^{58}\text{Ni}$ collisions at a beam energy of 50 MeV/nucleon. The results compare the nucleon kinetic energy density within the extended Thomas-Fermi approximation both with and without the inclusion of surface terms.

Figure 3 (color online) illustrates the local momentum distribution of nucleons within different Ni isotopes when surface terms are included in the nucleon kinetic energy density. To investigate the influence of the neutron skin in momentum space on the properties of neutron-deficient nuclei, Figure 4 [Figure 4: see original paper] shows the time dependence of hard photon multiplicity (with energies ranging from 10 to 100 MeV) for $^{48,50,52,54,56,58}\text{Ni} + ^{58}\text{Ni}$ reac-

tion systems at a beam energy of 50 MeV/nucleon. These results correspond to peripheral collisions with a centrality range of 80%-100%. The solid lines represent cases where surface terms are included in the nucleon kinetic energy density under the extended Thomas-Fermi (ETF) approximation, while the dashed lines represent cases without these surface terms. Traditionally, the collision centrality corresponding to a specific impact parameter range b is defined by $\pi b^2/\pi b_{\max}^2$, where b_{\max} represents the maximum allowable impact parameter for the collision system. Under this definition, smaller centrality values indicate more violent central collisions, whereas larger values correspond to peripheral collisions. Since the momentum-space neutron skin primarily manifests at the nuclear surface, this study focuses on extreme peripheral collisions (80%-100% centrality). As shown in Figure 4, the inclusion of the momentum-space neutron skin—primarily induced by the surface terms in the nucleon kinetic energy density—leads to a significant increase in the hard photon yield compared to the case where these terms are neglected.

By comparing Figure 2 and Figure 3, one can analyze the influence of including or excluding surface terms in the ETF kinetic energy density on the angular distribution of photons. Figure 5 [Figure 5: see original paper] displays the angular distribution of the single-differential emission rate for hard photons ($E_\gamma = 10\text{--}100$ MeV) in the center-of-mass frame of the colliding nuclei for peripheral $^{48,52,56}\text{Ni} + ^{58}\text{Ni}$ collisions at 50 MeV/nucleon. Consistent with the findings in Ref. [?], the hard photon angular distribution peaks near $\theta = 90^\circ$. This occurs because the nucleon momentum distribution evolves during the reaction; due to the well-known transverse flow or “squeeze-out” effect, nucleon motion becomes preferentially perpendicular to the beam direction, resulting in enhanced photon emission at 90° .

This paper further compares the effects of the momentum-space neutron skin (considering short-range correlations and surface term effects) and the coordinate-space proton skin on the hard photon angular distribution in peripheral $^{48,52,56}\text{Ni} + ^{58}\text{Ni}$ collisions at 50 MeV/nucleon. As the thickness of the projectile’s coordinate-space proton skin increases, the emission of hard photons decreases. Clearly, a thinner proton skin provides more collision opportunities for neutrons and protons in the $n + p \rightarrow n + p + \gamma$ process during peripheral collisions. However, the impact of the momentum-space neutron skin on hard photon emission is more significant than that of the projectile’s coordinate-space proton skin. This is because, as shown in Figure 3, the increase in local nucleon momentum near the nuclear surface facilitates more frequent collisions between protons and neutrons, thereby generating a higher yield of high-energy hard photons. Consequently, the momentum-space neutron skin effect poses a substantial influence when utilizing hard photon emission as a probe to measure proton skin thickness.

Figure 6 [Figure 6: see original paper] (Color online) shows the emission spectra of hard photons within the polar angle range of $85^\circ \leq \theta \leq 95^\circ$ in the center-of-mass frame for peripheral collisions of $^{48,52,56}\text{Ni} + ^{58}\text{Ni}$ at a beam energy

of 50 MeV/nucleon. The results compare the cases where the surface term is included in the nucleon energy density versus when it is excluded.

Since the aforementioned results indicate that hard photon emission is most abundant near a polar angle of $\theta = 90^\circ$ in the center-of-mass frame of the colliding nuclei, we further investigated the energy spectra of hard photons in this angular region. [Figure 6: see original paper] displays the energy spectra of hard photons emitted within the polar angle range of $85^\circ \leq \theta \leq 95^\circ$ in the center-of-mass frame for peripheral collisions of $^{48,52,56}\text{Ni} + ^{58}\text{Ni}$ at a beam energy of 50 MeV/nucleon.

It can be observed once again that the influence of the neutron skin in momentum space—resulting from the inclusion of the surface term in the nucleon energy density within the Thomas-Fermi approximation—on the hard photon energy spectrum is significantly greater than the influence of the projectile's proton skin in coordinate space. Furthermore, this discrepancy increases as the photon energy rises. This phenomenon occurs because the increase in the local momentum of nucleons at the nuclear surface leads to a substantial enhancement in the emission of high-energy hard photons.

Based on the preceding discussion, it can be inferred that the nucleon energy density under the Thomas-Fermi approximation—incorporating short-range correlation effects and the introduction of surface terms—results in a neutron skin in momentum space. This momentum-space skin affects the accuracy of using hard photons to probe the proton skin thickness in coordinate space.

[Figure 1: see original paper] (Color online) The dependence of hard photon multiplicity on the proton skin thickness ΔR_{pn} for hard photons with energies $E_\gamma = 10 - 100$ MeV. The data are derived from peripheral collisions of $^{48,50,52,54,56,58}\text{Ni} + ^{58}\text{Ni}$ at a beam energy of 50 MeV/nucleon.

[Figure 7: see original paper] illustrates the dependence of hard photon multiplicity on the proton skin thickness under two conditions: with and without the inclusion of the surface term in the nucleon energy density. It can be observed that the hard photon multiplicity decreases as the proton skin thickness ΔR_{pn} increases, indicating that ^{54}Ni projectiles with thicker proton skins produce fewer hard photons. This phenomenon occurs because, for proton-rich Ni isotopes, a projectile with a thicker proton skin possesses a smaller number of neutrons. This reduction in neutron number leads to fewer collisions occurring via the $n + p \rightarrow n + p + \gamma$ process, thereby decreasing hard photon emission. However, we observe that the influence of the surface term in the nucleon energy density on the hard photon yield is significantly greater than the influence of the proton skin thickness in coordinate space. Consequently, when attempting to infer the proton skin thickness of a specific isotope using hard photons emitted from peripheral collisions induced by other known neutron-deficient isotopes, it is essential to account for both the surface term in the nucleon energy density and the effects of short-range correlations between nucleons.

4 总结和展望

Building upon the significant progress made in recent years using electron/nucleon-nucleon scattering to explore the properties of nucleon short-range correlations (SRC) in atomic nuclei, this study investigates the influence of these correlations on the detection of proton skin thickness in proton-rich nuclei.

We employ an extended Thomas-Fermi approximation that incorporates short-range correlation effects within the IBUU transport model to describe the nucleon kinetic energy density. Our research demonstrates that, due to the inclusion of SRC and surface terms in the nucleon kinetic energy density, a neutron skin in momentum space emerges in proton-rich nuclei. This phenomenon is analogous to the proton skin in momentum space observed in neutron-rich nuclei in Ref. [?]. In this paper, we extract hard photon emissions from peripheral collisions of proton-rich $^{48,50,52,54,56,58}\text{Ni} + ^{58}\text{Ni}$ systems at a beam energy of 50 MeV/nucleon. The results indicate that the effect of the momentum-space neutron skin, caused by the surface terms of the nucleon energy density, on hard photon emission is significantly greater than the effect of the projectile's coordinate-space proton skin. Consequently, this effect cannot be ignored when using hard photons to accurately infer the proton skin thickness of a specific isotope based on other known neutron-deficient isotopes. Furthermore, based on the aforementioned data related to proton skin thickness, it is possible to attempt to constrain symmetry energy parameters and further deepen our understanding of the giant dipole resonance mechanism [?]. It must be emphasized that the current work has certain limitations, and several issues remain to be properly addressed.

Beyond the initial conditions of the projectile and target nuclei in the transport model, many other factors may influence hard photon emission in practice. These include the size, shape, and isospin dependence of the short-range correlations/high-momentum tail, the symmetry potential, the neutron-proton effective mass splitting, and the in-medium nucleon-nucleon collision cross-sections. Additionally, our model predictions involve some systematic uncertainties that cannot be fully handled at present. Therefore, as a next step, we will refer to the methods in Ref. [?] to perform invariance analyses of particle emission in intermediate-energy heavy-ion collisions [?, ?, ?, ?].

This approach will be used to improve our work, for instance, by reducing the influence of different collision centrality on hard photon emission [?].

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Hard-photon production as a probe of the surface properties of proton-rich nuclei

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Abstract: Based on the isospin- and momentum-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model, we simulate hard photon emission originating from neutron-proton bremsstrahlung in peripheral collisions of neutron-deficient $^{48,50,52,54,56,58}\text{Ni} + ^{58}\text{Ni}$ systems at a beam energy of 50 MeV/nucleon. Short-range correlations (SRC) are incorporated into the extended Thomas-Fermi approximation (ETF*) for the nucleon kinetic-energy density in finite nuclei, which results in a neutron skin in momentum (k) space for proton-rich nuclei. Our results demonstrate that the multiplicity of hard photons from different neutron-deficient Ni projectiles decreases as their proton skin thicknesses increase. However, when the surface term in ETF* is taken into account, the emission of hard photons increases—particularly for high-energy hard photons—and this effect significantly outweighs the influence of the proton skin. Consequently, it is essential to account for the effects of both SRC and the surface term in the ETF* framework when attempting to deduce the proton skin thickness of an isotope from other known neutron-deficient isotopes.

Key words: Hard photon; Proton-rich nucleus; Proton skin; Short-range correlation
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