A possible probe to neutron-skin thickness by fragment parallel momentum distribution in projectile fragmentation reactions

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Abstract

In the framework of the Lanzhou Quantum Molecular Dynamics (LQMD) model, a possible probe to the neutron-skin thickness (δnp) of neutron-rich 48Ca is studied in 140A MeV 48Ca + 9Be projectile fragmentation reaction based on parallel momentum distribution (p//) of residual fragments.The Fermi-type density distribution is employed to initiate the neutron density distributions in the LQMD simulation. A combined Gaussian function with different width parameters for the left side (ΓL) and the right side (ΓR) in distribution are used to describe the p// of residual fragments. The value of ΓL, taking neutron-rich sulfur isotopes as examples, shows a sensitive correlation to δnp of 48Ca, which is suggested to be a probe to determine the neutron-skin thickness of the projectile nucleus.

Full Text

A Possible Probe for Neutron-Skin Thickness via Fragment Parallel Momentum Distribution in Projectile Fragmentation Reactions

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Abstract. Neutron-skin thickness is a key parameter for neutron-rich nuclei, yet it remains difficult to determine experimentally. Within the framework of the Lanzhou Quantum Molecular Dynamics (LQMD) model, we investigate a possible probe for the neutron-skin thickness (δnp) of neutron-rich 48Ca in the 140A MeV 48Ca + 9Be projectile fragmentation reaction, based on the parallel momentum distribution (p//) of residual fragments. A Fermi-type density distribution is employed to initialize the neutron density distributions in the LQMD simulations. The p// distributions are described using a combined Gaussian function with different width parameters for the left side (ΓL) and right side (ΓR). Using neutron-rich sulfur isotopes as examples, ΓL shows a sensitive correlation with δnp of 48Ca and is proposed as a probe for determining the neutron-skin thickness of the projectile nucleus.

Keywords: Neutron-skin thickness, Projectile fragmentation, Parallel momentum distribution, Neutron-rich nucleus, Quantum molecular dynamics model

INTRODUCTION

The neutron-skin thickness, defined as the difference between the root-mean-square radii of the neutron and proton density distributions of a nucleus, δnp rn2 1/2 − rp2 1/2, is an important parameter for neutron-rich nuclei. With the advanced capabilities of new rare isotope facilities to produce nuclei near the proton and neutron drip lines, a new era has commenced for studying nuclei with exotic structures, particularly neutron-rich isotopes at extremes [1, 2]. The exact value of δnp is crucial for research on nuclear symmetry energy [3] and neutron stars [4], and it becomes even more important to study δnp for extreme nuclei because they may have significantly different density distributions in the surface region compared to stable nuclei.

Throughout the history of studying δnp in neutron-rich nuclei, many probes have been proposed based on different theoretical frameworks and experimental approaches. Projectile fragmentation reactions induced by neutron-proton asymmetric nuclei, as one type of heavy-ion reaction, serve as typical experimental tools to investigate properties of neutron-rich nuclei. Various observables have been proposed as probes to study the neutron skin of projectile nuclei with varying degrees of success, including light particle emissions [5, 6], fragment production ratios [7, 8], and fragment mass or charge distributions through information entropy analysis [9, 10]. Due to the inherent difficulties in measuring neutron density distributions directly, the neutron-skin thickness of asymmetric nuclei is usually determined experimentally through indirect probes such as the giant dipole resonance [11, 12], spin dipole resonance [13], neutron-removal cross section [14], and parity-violating electron scattering (for 208Pb [15, 16] and 48Ca [17]).

The momentum distribution of nucleons is widely used to study the structure and properties of atomic nuclei [18–21]. The short-range correlation between nucleons can be experimentally investigated by detecting the high-momentum tail of the nucleon momentum distribution using bremsstrahlung γ rays in heavy-ion nuclear reactions [22–24]. The parallel momentum distribution (p//) of fragments in breakup or few-body reactions often provides the first evidence for halo or skin nuclei, as demonstrated in studies of 11Li [18], 29P [25], 23Al

[26], and 31Ne [27]. Thus, p// of residual fragments can also be employed to determine δnp within the framework of optical models [28–30]. Experimentally, the p// of fragments is typically used to determine their yields or cross sections after integration [31], which directly connects the fragment yields to the nuclear density (and neutron-skin thickness) of the projectile nucleus. This suggests that p// of fragments could serve as a probe for δnp of the projectile nucleus.

In this study, we investigate the p// of residual fragments in projectile fragmentation reactions using the Lanzhou quantum molecular dynamics (LQMD) model [32, 33]. Our results suggest that the width of the p// distribution for fragments produced in peripheral collisions is sensitive to δnp and could serve as a probe for the neutron-skin thickness of the projectile nucleus.

II. MODEL DESCRIPTION

A. The LQMD Model

The LQMD model is an isospin- and momentum-dependent transport model that includes all possible elastic and inelastic collision reaction channels during charge exchange. The temporal evolution of nucleons, hyperons, and mesons in a reaction system under a self-consistently generated mean field is governed by Hamilton' s equations of motion [32–35]. Based on the Skyrme interactions, isospin-, density-, and momentum-dependent Hamiltonians were constructed [34]. The Hamiltonian of baryons consists of the relativistic energy, effective interaction potential, and momentum-related components:

$$H = \sum_i \sqrt{p_i^2 + m_i^2} + U_{\text{int}} + U_{\text{mom}}$$

where p_i and m_i denote the momentum and mass of the baryons, respectively. U_{int} comprises the Coulomb interaction and the local interaction potential. The local interaction potential is expressed as follows:

$$U_{\text{loc}} = \int V_{\text{loc}}[\rho(\mathbf{r})]d\mathbf{r}$$

derived from the Skyrme energy density functional. $V_{\text{loc}}(\rho)$ can be written as:

$$V_{\text{loc}}(\rho) = \alpha\rho^2 + \beta\rho^{2+\gamma} + g_{\text{sur}}(\nabla\rho)^2 + g_{\text{iso}}^{\text{sur}}[\nabla(\rho_n - \rho_p)]^2 + E_{\text{sym}}^{\text{loc}}(\rho)\rho\delta^2$$

where ρ_n, ρ_p, and $\rho = \rho_n + \rho_p$ are the neutron, proton, and total densities, respectively, and $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry. The coefficients α, β, γ, g_{sur}, $g_{\text{iso}}^{\text{sur}}$, and ρ_0 were set to -215.7 MeV, 142.4 MeV, 1.322, 23 MeV$\cdot$fm^2, -2.7 MeV$\cdot$fm^2, and 0.16 fm^{-3}, respectively. $E_{\text{sym}}^{\text{loc}}(\rho)$ is the local part of the symmetry energy, which can be adjusted to mimic the predictions of the symmetry energy calculated using microscopic or phenomenological many-body theories:

$$E_{\rm sym}^{\rm loc}(\rho) = C_{\rm sym}(\rho/\rho_0)^{\gamma_s}$$

The values of $C_{\rm sym}$ and γ_s are 52.5 MeV and 2.0, respectively, which correspond to hard-symmetry energy with a baryon density [34].

$U_{\rm mom}$ takes the form:

$$U_{\rm mom} = \sum_{i,j,j\neq i}\sum_{\tau,\tau'} C_{\tau,\tau'}\delta_{\tau,\tau_i}\delta_{\tau',\tau_j}\int d\mathbf{p}\,d\mathbf{p}'\,d\mathbf{r}\times f_i(\mathbf{r},\mathbf{p},t)\ln[\epsilon(\mathbf{p}-\mathbf{p}')^2+1]f_j(\mathbf{r},\mathbf{p}',t)$$

where $C_{\tau,\tau} = C_{\rm mom}(1+x)$, $C_{\tau,\tau'} = C_{\rm mom}(1-x)$ $(\tau \neq \tau')$, and the isospin symbols τ (τ') represent protons and neutrons, respectively. The parameters $C_{\rm mom}$ and ϵ were determined by fitting the real part of the optical potential as a function of incident energy from proton-nucleus elastic scattering data, yielding values of 1.76 MeV and 500 c^2/GeV^2, respectively. Thus, the effective mass of the nuclear medium at saturation density is $m^*/m = 0.75$. The parameter x represents the strength of isospin splitting, for which a value of -0.65 is adopted in this study, and the mass splitting is $m_n^* > m_p^*$ in the nuclear medium [36].

During the initialization of the projectile nucleus in LQMD, the initial coordinates of the nucleons are obtained by random sampling according to the two-parameter Fermi-type density distribution [38]:

$$\rho_i(r) = \frac{\rho_0}{1+\exp\left(\frac{r-C_i}{t_i/4.4}\right)}, \quad i = n, p$$

where ρ_0 is a normalization constant that ensures the integrated density distribution equals the number of protons or neutrons, f_i is a parameter for adjusting the diffuseness [7, 39], t_i is the diffuseness parameter, and C_i is the half-density radius. Nuclei with reliable stability and expected neutron-skin thickness were selected as collision candidates, with δnp values of 0.111, 0.120, 0.136, 0.168, and 0.186 fm for the corresponding initial 48Ca nuclei after LQMD initialization (see [Figure 1: see original paper]). Fragments were analyzed in phase space at $t = 300$ fm/c in the LQMD simulation, and nucleons with a relative distance smaller than 3.0 fm and a relative momentum smaller than 200 MeV/c were considered in the coalescence model [33].

B. Parallel Momentum Distribution

The p// of fragments produced in projectile fragmentation reactions exhibits a nonsymmetric distribution in experiments, which can be fitted by a combined Gaussian function [31]:

$$f(p) = \begin{cases} S \times \exp\left(-\frac{(p-p_0)^2}{2\Gamma_L^2}\right) & \text{if } p \leq p_0 \\ S \times \exp\left(-\frac{(p-p_0)^2}{2\Gamma_R^2}\right) & \text{if } p > p_0 \end{cases}$$

In this combined Gaussian function, the left and right halves share the same peak position but have different widths. Here, S is the normalization factor, p_0 is the peak position of the distribution, and Γ_L and Γ_R denote the widths of the left and right sides of the combined Gaussian distribution, respectively.

III. RESULTS AND DISCUSSION

The p// of a fragment is generally influenced by the incident energy of the reaction, the nuclear density of the reaction system, the impact parameter, and the fragment itself (such as its isospin). The experimental δnp determined from proton elastic scattering for 40Ca was $-0.010^{+0.022}_{-0.024}$ fm [37], while for 48Ca it was $0.121 \pm 0.026(\mathrm{exp}) \pm 0.024(\mathrm{model})$ fm from the parity-violating method [17]. To compare the sensitivity of p// to the projectile nuclear density distribution, we simulated 33P production in the 140A MeV 40Ca + 9Be (δnp = -0.030 fm for 40Ca) and 48Ca + 9Be (δnp = 0.168 fm for 48Ca) reactions and fitted the results using Eq. (7), as shown in [Figure 2: see original paper]. The p// for 33P in the symmetric 40Ca-induced reaction is symmetric in ΓL and ΓR, whereas ΓL is larger than ΓR for 33P in the asymmetric 48Ca-induced reaction, indicating a neutron-skin effect for the neutron-rich projectile.

With varying impact parameters in projectile fragmentation reactions, the p// of a specific fragment is also influenced by the significant change in nuclear density from central to peripheral collisions [23], and the p// of a fragment thus carries substantial information about the reaction, such as the nuclear density distribution and nucleon-nucleon cross section [1]. The p// values of the neutron-proton symmetric fragment 24Mg produced in the 140A MeV 48Ca + 9Be reaction within impact parameter ranges $b = [0-2]$, $[2-4]$, $[4-6]$, and $[6-8]$ fm are plotted in [Figure 3: see original paper]. From central to peripheral collisions, the p// for 24Mg shifts from the low-momentum side to the high-momentum side as b increases. Both ΓL and ΓR depend on the impact parameter. For different p// distributions, the value of ΓL tends to decrease with increasing b, with ΓL > ΓR (see [Figure 3: see original paper]) and the uncertainty of ΓR larger than that of ΓL, particularly for central collisions. While ΓR remains constant when $b < 6$ fm, ΓL decreases with increasing b. The reason for ΓL > ΓR may be related to differences in collision centrality; that is, the larger the centrality, the deeper the collision with the target, resulting in greater p// loss and a wider ΓL.

Finally, we studied the p// values for isotopic fragments with different isospins to determine whether they are sensitive to the neutron-skin thickness of the projectile. The neutron skin of an asymmetric nucleus primarily influences the products of peripheral collisions. The p// of fragments was simulated for peripheral collisions of 140A MeV 48Ca + 9Be within $b = [6-8]$ fm. To compare p// values for isotopic fragments with different mass numbers, we examined the p// per nucleon (p///A). Based on the different δnp values for 48Ca shown in [Figure 1: see original paper], the p///A distributions for neutron-rich sulfur isotopes (from 33S to 36S) are plotted in [Figure 4: see original paper] together with fitting results from Eq. (7). The ΓL values for p// were extracted, and the correlations between ΓL for sulfur isotopes and δnp of 48Ca are shown in [Figure 5: see original paper], fitted using a decaying exponential function. A strong exponential dependence of ΓL for neutron-rich sulfur isotopes on δnp of the projectile nucleus 48Ca is observed, indicating that ΓL can serve as an effective probe for the neutron-skin thickness of the projectile nucleus in projectile fragmentation reactions.

Further simulations of fragment de-excitation were performed using the GEMINI code [40]. Compared with the clear correlation between ΓL and δnp in the LQMD simulations, ΓL becomes constant as δnp varies in the LQMD + GEMINI simulations, indicating that the GEMINI de-excitation erases the correlation between ΓL and δnp. It is also noted that the correlation between ΓL and δnp represents an indirect probe for the neutron-skin thickness of the projectile nucleus because fragments are obtained after the compression-expansion process of the colliding system. Further investigations are needed to study the ΓL δnp correlation, including de-excitation effects, since they may modify the intermediate-mass fragments in projectile fragmentation reactions, as found in Refs. [7, 8].

Based on the eikonal distorted-wave impulse approximation (DWIA) explanation by Ogata et al. [30], the high-momentum side reflects the phase-volume effect due to energy and momentum conservation, whereas the low-momentum side reflects the momentum shift caused by the attractive potential of the residual nucleus when the incident energy is not very high (below 200A MeV). Because the impact parameters are restricted to $b = [6-8]$ fm, the width of ΓL reflects the Heisenberg uncertainty principle in quantum mechanics; that is, from $\Delta x \cdot \Delta p \geq h/4\pi$, Δx is inversely correlated with Δp [21]. Thus, it can be considered that the larger the ΓL, the closer the nucleons contained in the fragment are to the center of the nucleus. In contrast, the smaller the ΓL, the closer the nucleons in the fragment are to the edge of the nucleus. With increased neutron-skin thickness, the valence neutrons are pushed further away from the center of the nucleus, resulting in a narrower ΓL as observed in [Figure 4: see original paper] for the neutron-rich sulfur fragments.

IV. SUMMARY

In summary, we have studied a possible probe for the neutron-skin thickness of a neutron-rich projectile nucleus by simulating the 140A MeV 48Ca + 9Be reaction within the LQMD model. The neutron-skin thickness of 48Ca was adjusted by varying the diffuseness of the neutron density distributions. A combined Gaussian function with different widths for the left (ΓL) and right (ΓR) halves was employed to fit the p// distributions of fragments. The p// values of fragments are influenced by the projectile nucleus, impact parameters, and the isospin of the isotopes. We found that ΓL of the p// distribution for projectile-like fragments produced in peripheral collisions is sensitive to δnp of the projectile nucleus. Given that p// of fragments is easy to measure experimentally, the correlation between ΓL of projectile-like fragments and δnp of the projectile nucleus potentially provides a new probe for the neutron-skin thickness of neutron-rich projectile nuclei.

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REFERENCES

[1] C. W. Ma, H. L. Wei, X. Q. Liu et al., Nuclear fragmentation reactions in projectile fragmentation reactions, Prog. Part. Nucl. Phys. 121, 103911 (2021). DOI:10.1016/j.ppnp.2021.103911

[2] X. B. Wei, H. L. Wei, Y. T. Wang et al., Multiple-models predictions for drip line nuclides in projectile fragmentation of 40,48Ca, 58,64Ni, and 78,86Kr at 140 MeV/u, Nucl. Sci. Tech. 33, 155 (2022). DOI:10.1007/s41365-022-01051-9

[3] L. Li, F. Y. Wang, Y. X. Zhang, Isospin effects on intermediate mass fragments at intermediate energy heavy ion collisions, Nucl. Sci. Tech. 33, 58 (2022). DOI:10.1007/s41365-022-01050-w

[4] W. J. Xie, Z. W. Ma, J. H. Guo, Bayesian inference of the crust-core transition density via the neutron-star radius and neutron-skin thickness data, Nucl. Sci. Tech. 34, 91 (2023). DOI:10.1007/s41365-023-01239-7

[5] X. Y. Sun, D. Q. Fang, Y. G. Ma et al., Neutron/proton ratio of nucleon emissions as a probe of neutron skin, Phys. Lett. B 682, 396 (2010). DOI:10.1016/j.physletb.2009.11.031

[6] D. Q. Fang, Neutron skin thickness and its effects in nuclear reactions, Nucl. Tech. 46, 155 (2023). (In Chinese) DOI:10.11889/j.0253-3219.2023.hjs.46.080016

[7] Z. T. Dai, D. G. Fang, Y. G. Ma et al., Triton/3He ratio as an observable for neutron-skin thickness, Phys. Rev. C 89, 014613 (2014). DOI:10.1103/PhysRevC.89.014613

[8] Z. T. Dai, D. Q. Fang, Y. G. Ma et al., Effect of neutron skin thickness on projectile fragmentation, Phys. Rev. C 91, 034618 (2015). DOI:10.1103/PhysRevC.91.034618

[9] C. W. Ma, Y. P. Liu, H. L. Wei et al., Determination of neutron-skin thickness using configurational information entropy, Nucl. Sci. Tech. 33, 6 (2022). DOI:10.1007/s41365-022-00997-0
[10] H. L. Wei, X. Zhu, C. Yuan, Configurational information entropy analysis of fragment mass cross distributions to determine the neutron skin thickness of projectile nuclei, Nucl. Sci. Tech. 33, 111 (2022). DOI:10.1007/s41365-022-01096-w
[11] A. Krasznahorkay, J. Bacelar, J. A. Bordewijk et al., Excitation of the isovector giant dipole resonance by inelastic α scattering and the neutron skin of nuclei, Phys. Rev. Lett. 66, 1287 (1991). DOI:10.1103/PhysRevLett.66.1287
[12] M. Csatlós, A. Krasznahorkay, D. Sohler et al., Measurement of neutron-skin thickness in 208Pb by excitation of the GDR via inelastic α-scattering, Nucl. Phys. A 719, 304c (2003). DOI:10.1016/S0375-9474(03)00937-0
[13] C. Gaarde, J. Rapaport, T. N. Taddeucci et al., Excitation of giant spin-isospin multipole vibrations, Nucl. Phys. A 369, 258 (1981). DOI:10.1016/0375-9474(81)90019-1
[14] D. Q. Fang, Y. G. Ma, X. Z. Cai et al., Effects of neutron skin thickness in peripheral nuclear reactions, Chin. Phys. Lett. 28, 102102 (2011). DOI:10.1088/0256-307X/28/10/102102
[15] S. Abrahamyan, Z. Ahmed, H. Albataineh et al., Measurement of the neutron radius of 208Pb through parity violation in electron scattering, Phys. Rev. Lett. 108, 112502 (2012). DOI:10.1103/PhysRevLett.108.112502
[16] D. Adhikari, H. Albataineh, D. Androic et al. (PREX Collaboration), Accurate determination of the neutron skin thickness of 208Pb through parity-violation in electron scattering, Phys. Rev. Lett. 126, 172502 (2021). DOI:10.1103/PhysRevLett.126.172502
[17] D. Adhikari, H. Albataineh, D. Androic et al. (CREX Collaboration), Precision Determination of the Neutral Weak Form Factor of 48Ca, Phys. Rev. Lett., 129, 042501 (2022). DOI:10.1103/PhysRevLett.129.042501
[18] I. Tanihata, H. Hamagaki, O. Hashimoto et al., Measurements of interaction cross sections and nuclear radii in the light p-shell region, Phys. Rev. Lett. 55, 2676 (1985). DOI:10.1103/PhysRevLett.55.2676
[19] E. Hanelt, A. Grewe, K. H. Schmidt et al., Momentum distributions of projectile fragments produced in the cold and hot fragmentation of relativistic 136Xe and 197Au projectiles, Z. Phys. A 346, 43 (1993). DOI:10.1007/BF01290780
[20] Y. G. Ma, R. Wada, K. Hagel et al., Sequential decay distortion of Goldhaber model widths for spectator fragments, Phys. Rev. C 65, 051602 (2002). DOI:10.1103/PhysRevC.65.051602
[21] M. Q. Ding, D. Q. Fang, Y. G. Ma, Effects of neutron-skin thickness on light-particle production, Phys. Rev. C 109, 024616 (2024). DOI:10.1103/PhysRevC.109.024616
[22] O. Hen, G. A. Miller, E. Piasetzky et al., Nucleon-nucleon correlations, short-lived excitations, and the quarks within, Rev. Mod. Phys. 89, 045002 (2017). DOI:10.1103/RevModPhys.89.045002
[23] Y. H. Qin, Q. L. Niu, D. Guo et al., Probing high-momentum component

in nucleon momentum distribution by neutron-proton bremsstrahlung γ-rays in heavy ion reactions, Phys. Lett. B 850, 138514 (2024). DOI:10.1016/j.physletb.2024.138514

[24] D. W. Si, Y. Zhou, S. Xiao et al., Measurement of the high energy γ-rays from heavy ion reactions using Čerenkov detector, Nucl. Sci. Tech. 35, 24 (2024). DOI:10.1007/s41365-024-01368-7

[25] Y. B. Wei, Y. G. Ma, X. Z. Cai et al., Parallel momentum distribution of 28Si Fragments from 29P, Chin. Phys. Lett. 22, 61 (2005). http://iopscience.iop.org/0256-307X/22/1/018

[26] D. Q. Fang, W. Guo, C. W. Ma et al., Studies on the exotic structure of 23Al, Chin. Phys. C 32, 34 (2008). http://csnsdoc.ihep.ac.cn/article/id/68c4071e-1596-4366-8926-9446db4e3d07

[27] S. Y. Zhang, S. S. Zhang, X. X. Sun et al., Study of the deformed halo nucleus 31Ne with Glauber model based on microscopic self-consistent structures, Sci. China: Phys. Mech. Astron. 65, 262011 (2022). DOI:10.1007/s11433-022-1919-2

[28] B. Abu-Ibrahim, Y. Ogawa, Y. Suzuki et al., Cross section calculations in Glauber model: I. Core plus one-nucleon case, Comp. Phys. Commun. 151, 369 (2003). DOI:10.1016/S0010-4655(02)00734-8

[29] K. Hencken, G. Bertsch, H. Esbensen, Breakup reactions of the halo nuclei 11Be and 8B, Phys. Rev. C 54, 3043 (1996). DOI:10.1103/PhysRevC.54.3043

[30] K. Ogata, K. Yoshida, K. Minomo, Asymmetry of the parallel momentum distribution of (p, pN) reaction residues, Phys. Rev. C 92, 034616 (2015). DOI:10.1103/PhysRevC.92.034616

[31] M. Mocko, M. Andronenko, F. Delaunay et al., Projectile fragmentation of 40Ca, 48Ca, 58Ni, and 64Ni at 140 MeV/nucleon, Phys. Rev. C 74, 054612 (2006). DOI:10.1103/PhysRevC.74.054612

[32] Z. Q. Feng, Momentum dependence of the symmetry potential and its influence on nuclear reactions, Phys. Rev. C 84, 024610 (2011). DOI:10.1103/PhysRevC.84.024610

[33] Z. Q. Feng, Effects of isospin dynamics on neck fragmentation in isotopic nuclear reactions, Phys. Rev. C 94, 014609 (2016). DOI:10.1103/PhysRevC.94.014609

[34] Z. Q. Feng, Nuclear in-medium effects and collective flows in heavy-ion collisions at intermediate energies, Phys. Rev. C 85, 014604 (2012). DOI:10.1103/PhysRevC.85.014604

[35] Y. F. Guo, P. H. Chen, F. Niu et al., Isospin effect in peripheral heavy-ion collisions at Fermi energies, Chin. Phys. C 42, 124106 (2018). DOI:10.1088/1674-1137/42/12/124106

[36] Z. Q. Feng, Nuclear in-medium and isospin effects on subthreshold kaon production in heavy-ion collisions, Phys. Rev. C 87, 064605 (2013). DOI:10.1103/PhysRevC.87.064605

[37] J. Zenihiro, H. Sakaguchi, S. Terashima et al., Direct determination of the neutron skin thicknesses in 40,48Ca from proton elastic scattering at $E_p = 295$ MeV, arXiv:1810.11796 (2018). DOI:10.48550/arXiv.1810.11796

[38] W. D. Myers, K. H. Schmidt, An update on droplet-model charge distributions, Nucl. Phys. A 410, 61 (1983). DOI:10.1016/0375-9474(83)90401-3

[39] C. W. Ma, Y. Fu, D. Q. Fang et al., A possible experimental observable for the determination of neutron skin thickness, Chin. Phys. B 17, 1216 (2008). DOI:10.1088/1674-1056/17/4/011

[40] R. J. Charity, M. A. McManhan, G. J. Wozniak et al., Systematics of complex fragment emission in niobium-induced reactions, Nucl. Phys. A 483, 371 (1988). DOI:10.1016/0375-9474(88)90542-8

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