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Neutron Skins in Sn and Pb Nuclei

Khin Nyan Linn*

Abstract

The Relativistic Mean Field (RMF) theory is applied to calculate the root mean square (rms) radii of the neutron and proton density distributions. The NL3 and NL-Z2 effective interactions are used in the mean field Lagrangian. The RMF theory predicts the existence of neutron skins in Sn and Pb nuclei from the observation of the density profile and the rms radii of the proton and neutron density distribution. We compared our calculated results on rms proton and neutron radii with some available experimental data. The neutron skin thickness of Sn and Pb nuclei are presented. Neutron skin is observed at ^{102}Sn and beyond ^{132}Sn. For Pb isotopes, neutron skin builds up beyond ^{208}Pb.

Introduction

In the area of theoretical and experimental nuclear physics the investigation of exotic nuclei is of central importance. Exotic nuclei are nuclei in which the ratios of N/Z are very different from those of ordinary nuclei. Exotic nuclei are highly unstable with weak binding of the outer nucleons and after some time they decay into stable nuclei. As a consequence of the weak neutron binding the existence of the new effects of nuclear halos and neutron skin among neutron rich nuclei becomes possible. In the realm of heavier nuclei, a related phenomenon can be predicted in which the steadily increasing neutron excess gives rise to the neutron skin on the outside of the nucleus. In normal matter, the proton and neutron radii are similar and their distributions overlap. As the other extreme pure neutron matter is only found in neutron stars (with a small fraction of protons present). Analyzing the difference in the root mean square (rms) radii of the neutron and proton density distributions can be used to quantitatively describe the existence of halos or skins. Experimental evidence of effects ascribed to a neutron halo or a neutron skin has been observed in several nuclei near the neutron drip line. The neutron skin of the nucleus has been one of central issues of nuclear structure. A thick neutron skin has been observed experimentally only in quite light nuclei ^{6}He and ^{8}He. A neutron skin does not emerge in nuclei near the β stability line, but a neutron skin with more than 10 neutrons can be formed in nuclei far from the stability line.

In the present paper, we calculated the rms radii of the neutron and proton distribution of isotopic chain of Sn and Pb isotopes with the application Relativistic Mean Field (RMF) theory. We analyzed the neutron skin thickness of Sn and Pb nuclei.

Materials and Methods

The Formalism of Relativistic Mean Field Theory

A widespread approximation method for the ground state properties of the finite nuclei is the microscopic self-consistent relativistic mean field theory applying effective interactions. In the present work, we employ the relativistic mean-field (RMF) theory in mean-field approximation and no-sea approximation. Starting from an effective relativistic meson-baryon Lagrangian density and non-relativistic Hartree-Fock (HF) theory with effective interactions, NL3 extended versions NL-Z2, the meson-baryon couplings of RMF theory have been applied. Another well-known feature in the RMF theory is that the proper spin-orbit interaction and associated nuclear shell structure comes out naturally. The proper spin-orbit coupling arises directly from the relativistic nature of the meson-nucleon interactions.

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In the walecka-type model, the protons and neutrons are described as Dirac particles interacting in a relativistic covariant manner through the exchange of various mesons including the isoscalar-scalar σ meson, the isoscalar-vector ω meson, the isovector-vector ρ meson and the photon. In the walecka-type model, the dynamics of a nuclear system which contains the corresponding fields ψ(x) for nucleons, $\sigma^{\mu}(x)$, $\omega^{\mu}(x)$, $\rho^{\mu}(x)$ for mesons and A^{μ} for photons, is determined through the Lagrangian density $\mathcal{L}$,

$$\mathcal{L} = \bar{\Psi}\left(i\gamma_{\mu}\partial^{\mu} - m\right)\Psi + \frac{1}{2}\left(\partial_{\mu}\hat{\sigma}\partial^{\mu}\hat{\sigma} - m_{\sigma}^{2}\hat{\sigma}^{2}\right) - \frac{1}{2}\left(\frac{1}{2}\hat{G}_{\mu\nu}\hat{G}^{\mu\nu} - m_{\omega}^{2}\hat{\omega}_{\mu}\hat{\omega}^{\mu}\right)$$
$$-\frac{1}{2}\left(\frac{1}{2}\hat{\vec{B}}_{\mu\nu}\hat{\vec{B}}^{\mu\nu} - m_{\rho}^{2}\hat{\vec{\rho}}_{\mu}\hat{\vec{\rho}}^{\mu}\right) - \frac{1}{4}\hat{F}_{\mu\nu}F^{\mu\nu} - g_{\sigma}\hat{\sigma}\hat{\bar{\Psi}}\hat{\Psi} - g_{\omega}\hat{\omega}_{\mu}\hat{\bar{\Psi}}\gamma^{\mu}\hat{\Psi}$$
$$- g_{\rho}\hat{\vec{\rho}}_{\mu}\hat{\bar{\Psi}}\vec{\tau}\gamma^{\mu}\hat{\Psi} - e\hat{A}_{\mu}\hat{\bar{\Psi}}\frac{1+\tau_{3}}{2}\gamma^{\mu}\hat{\Psi} - \frac{1}{2}m_{\sigma}^{2}\hat{\sigma}^{2} - \frac{1}{3}b_{2}\hat{\sigma}^{3} - \frac{1}{4}b_{3}\hat{\sigma}^{4}$$

Here, the usual relativistic units of $\hbar = c = 1$ are used for the discussion of this model. M, m_{σ}, m_{ω}, m_{ρ} are the nucleon-, the σ-, ω-, ρ-meson masses respectively, while g_{σ}, g_{ω}, g_{ρ} and $e^2/4\pi = 1/137$ are the corresponding coupling constants for the mesons and photon. In non-linear versions of the Lagrangian, the coupling is supplemented by a non-linear self coupling of the σ meson, first introduced by Boguta and Bodmer to improve the compressibility of nuclear matter and to obtain a quantitative description of nuclei.

Neutron Skin Thickness

The large difference between the proton and neutron density distribution in unstable nuclei is the question of interest among new phenomena concerning exotic nuclei. The presence of neutron skin in stable nuclei has been discussed since the mid 1950s [10]. No evidence of thick neutron skin in stable nuclei has been observed, even if many of them have a large neutron excess (N-Z). Thick neutron skins (~ 0.9 fm) have been reported by Tnaihata and et al., in the He isotopes. Another formation of the neutron skin in unstable neutron-rich nuclei has been observed in Na isotopes. From the RMF theory, the neutron skin thickness (r_n-r_p) increases from -0.076 fm for ^{100}Sn to 0.508 fm for ^{140}Sn. The neutron skin thickness (r_n-r_p) increases from 0.046 fm for ^{180}Pb to 0.382 fm for ^{222}Pb.

Results and Discussion

The observation of nucleon density distribution provides basic and important information in nuclear structure. Neutron density distribution for several Sn isotopes in the calculation of RMF theory with two different parameter sets are displayed in Figure 4. From the density profile there is a tail in the neutron density distribution between ^{100}Sn and ^{102}Sn. And another tail near the neutron density distribution beyond ^{132}Sn is observed. In the case of Sn isotopes, an extremely thick neutron skin builds up at ^{102}Sn, the nuclei next to the doubly magic nuclei ^{100}Sn. It leads to a sudden jump in the neutron rms radii. The rms proton and neutron radii for Sn isotopes can be observed in Figure 1. These results are in good agreement with experimental data. And a quite large neutron skin thickness can also be found beyond ^{132}Sn, another doubly magic nuclei leading a sudden jump in the neutron rms radii. At A = 132 of Sn isotope, $1h_{11/2}$ shell is filled and paring does not contribute. The neutron 3p subshells become populated at larger masses of Sn isotopes. Weak binding allow a large extension of valence wave functions into the exterior, thus producing this extremely thick neutron skin. According to Figure 1, the rms neutron radii of Sn isotope increases suddenly at A = 132 while the proton rms radius increases steadily.

The neutron skin thickness are clearly visible in Figure 2 and 3 for Sn and Pb isotopes where the difference of the proton and neutron radii is shown. In these figures, the neutron skin thickness for Sn and Pb isotopes are mentioned from the calculation of the RMF theory with two different parameter sets.

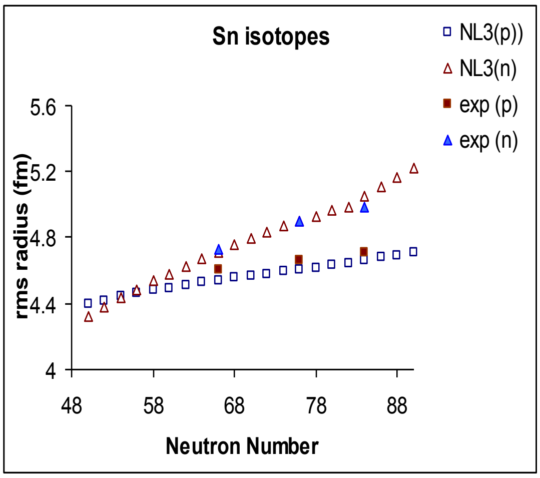

Figure 1(a) Neutron and Proton rms radii for Sn isotopes (NL3)

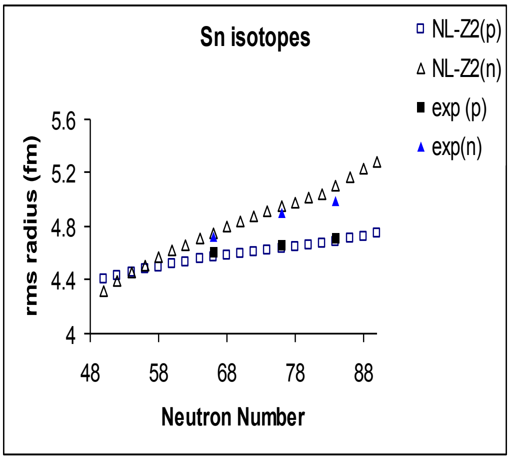

Figure 1 (b) Neutron and Proton rms radii for Sn isotopes (NL-Z2)

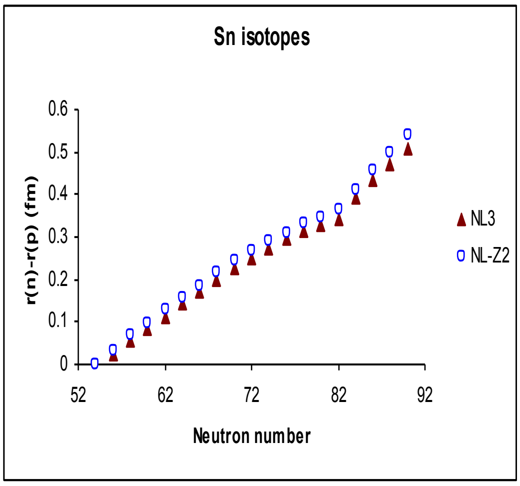

Figure 2 Neutron skin thickness(r_n-r_p) for Sn isotopic chain.

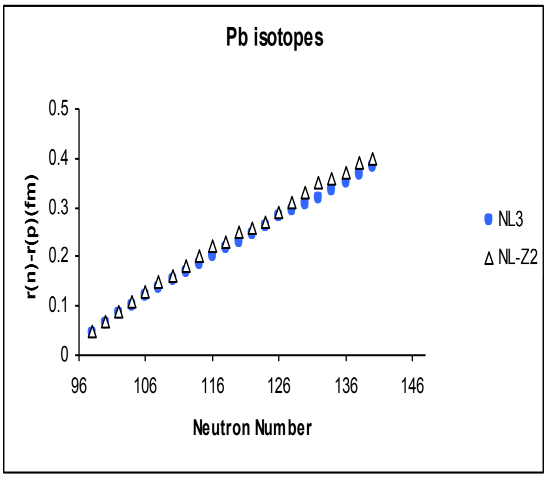

Figure 3 Neutron skin thickness (r_n-r_p) for Pb isotopic chain.

The density profile of Pb isotopes is shown in Figure (5). The neutron density distribution of Pb isotope exhibits an extremely thick neutron skin is building up for isotopes beyond doubly magic nuclei ^{208}Pb is in prolate shape (β_2 ~ 0.2). Because of the shape transitions, Pb isotopes beyond ^{208}Pb have large neutron distributions leading to an extremely thick neutron skin.

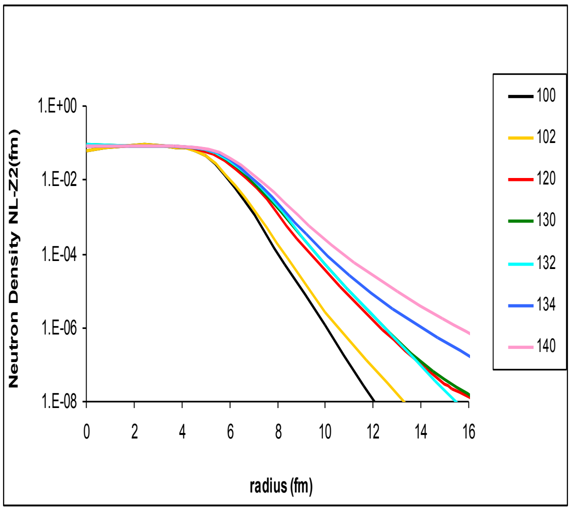

Figure 4 (a) Neutron density distribution [100-140]Sn isotopes (with NLZ2)

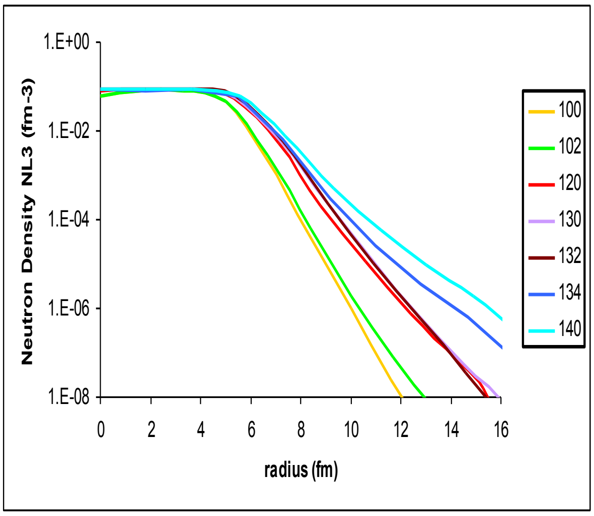

Figure 4(b) Neutron density distribution for for [100-140]Sn isotopes (with NL3)

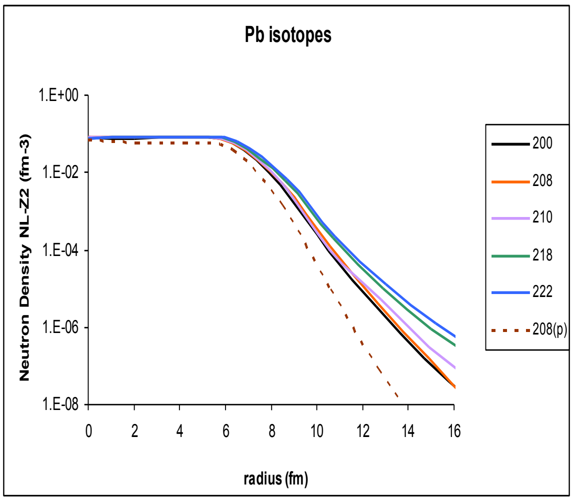

Figure 5 (a) Neutron density distribution for Pb isotopes (with NLZ2)

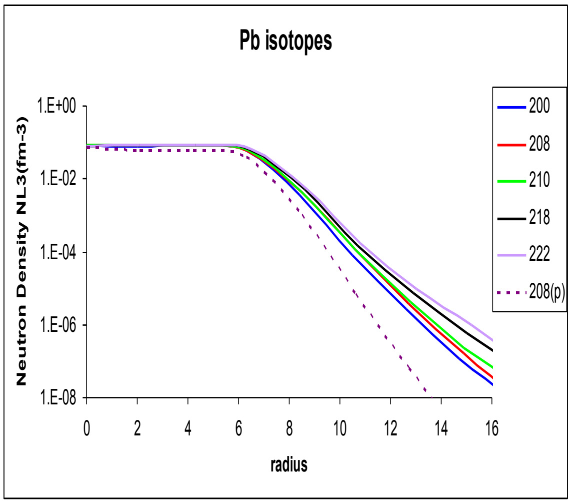

Figure 5 (b) Neutron density distribution for Pb isotopes (with NL3)

Conclusion

The rms proton and neutron radii are calculated with the application of the Relativistic Mean Field Theory with two different parameter sets. The calculation on two different parameter sets are in good agreement with each other. Our calculated results are reliable agreement with some available experimental data. The neutron skin thickness are predicted from the calculation of the density distribution and the difference between the rms neutron and proton radii. Neutron skin is appeared beyond the doubly magic nuclei in Sn and Pb nuclei. In conclusion, the existence of neutron skin thickness comes out from the shape transition among Sn and Pb isotopes.

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