Trajectory in 2D plot of IS and IV densities of ^{48}Ca and ^{208}Pb†

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Recently, the neutron skin thicknesses of doubly closed shell nuclei $^{208}_{82}$Pb$_{126}$ and $^{48}_{20}$Ca$_{28}$ have been investigated intensively. Theoretical studies with modern energy density functionals (EDFs) indicate that the thickness of the neutron skin, $\Delta r_{np} \equiv r_n - r_p$, embodies the stability of pure neutron matter and provides important information on the symmetry energy of neutron matter equation of states (EoS), which is a sum of the well-known EoS of the symmetric nuclear matter and the symmetry energy. The two EoSs govern the formation of not only nuclei but also astrophysical phenomena such as neutron stars and supernova explosions.

In this paper, we propose a model to examine the details of the symmetry energy by using the isoscalar (IS) and isovector (IV) density distributions. The neutron skin is an integrated quantity extracted from neutron and proton density distributions. However, the radial density distributions will provide more information to elucidate quantitatively the EoS of both nuclear matter and neutron matter. To this end, it is essential to study the radial dependence of IS and IV densities, which can be extracted from neutron and proton densities.

The IS and IV densities are defined as $\rho_{\mathrm{IS}}(r) = \rho_n(r) + \rho_p(r)$ and $\rho_{\mathrm{IV}}(r) = \rho_n(r) - \rho_p(r)$, respectively. Experimental IS and IV densities of ^{48}Ca[1)] are plotted in Fig. 1. The solid black curve sandwiched by the dotted lines is the experimental trajectory of IS versus IV densities at different radii r. The equi-energy contour lines of HF EDF, $\varepsilon(\rho_n, \rho_p) = \varepsilon(\rho_{\mathrm{IS}}, \rho_{\mathrm{IV}}) =$ constant, are calculated using SAMi-J27 and plotted for the values from 3 MeV at $\rho_{\mathrm{IS}} = \rho_{\mathrm{IV}} \approx 0$ to -15 or -16 MeV at the saturation density $\rho_{\mathrm{IS}} \approx 0.16$ fm^{-3} with an energy step of 1 MeV.

The dashed lines correspond to the constant IV density line $\rho_{\mathrm{IV}} = \rho_{\mathrm{IS}}(N-Z)/A$ of the asymmetric nuclear matter. The experimental trajectory is above the constant density limit in the surface region. This feature suggests a strong IV pressure to push the IV density towards the surface region rather than the interior of nucleus. The Fermi liquid of a finite nucleus may fill the valley determined by EDF from the bottom at approximately $\rho_{\mathrm{IS}} = 0.16$ fm^{-3} to the top of valley at $\rho_{\mathrm{IS}} = \rho_{\mathrm{IV}} = 0.0$ fm^{-3}. The trajectory plots are started from the right-hand side at $r = 0$ fm and ends at the left corner at $r = 6$ fm. The dots on the solid line indicate different radius points with $r = 0, 1, 2, 3, \ldots$ fm from the right to the left. The positive IV density at $r = 0$ fm reflects a larger neutron density than that of protons at the central region corresponding to $r = 0$ fm. Keeping the ρ_{IS} almost constant, the experimental curve rises to the surface region at $r = 3$ fm, where the dots are separated largely because of a rapid change in the IV density. This can be understood qualitatively from a flat contour map around the IS density $\rho = 0.16$ fm^{-3} so that the IV density can have large freedom within the limit of the equi-energy contour line.

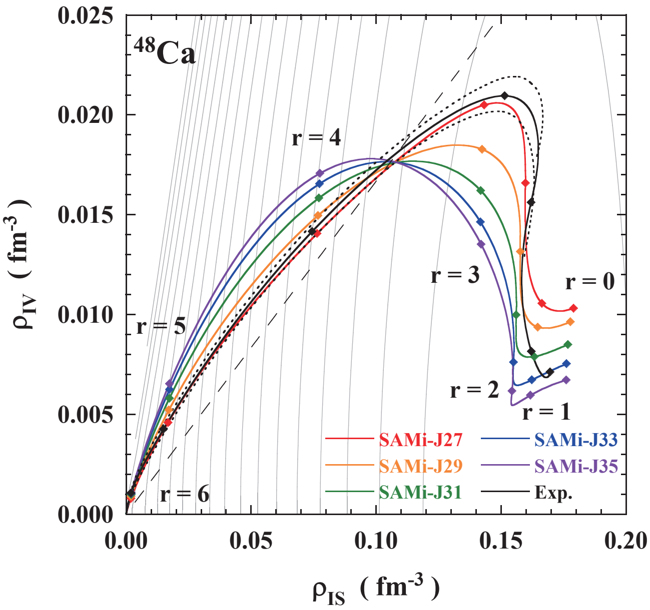

Fig. 1. Trajectories of isoscalar (IS) and isovector (IV) densities of ^{48}Ca. The experimental curve (black solid line) is compared with theoretical ones with Skyrme interactions. The equi-energy contour lines are calculated using the SAMi-J family. The equi-energy contour lines are plotted for SAMi-J27. See the text for details.

We can see a clear J-dependence for the enhancement of IV density at $r = 4$ fm; a larger J value yields a greater neutron density at the surface. Compared with the experimental data, SAMi-J27 shows the best agreement in the entire region of this plot.

In summary, we propose a new 2D plotting method of IS-IV densities to extract not only the empirical symmetry energy coefficients J, L, and K_{sym}, but also the asymmetric isospin term K_τ in the nuclear incompressibility. We found strong correlations between the curvature of the 2D density at the density $\rho_{\mathrm{IS}} = 0.1$ fm^{-3} and the symmetry energy coefficients J, L, and K_τ. The optimal values are found to be $J = 27.2$ MeV, $L = 31.6$ MeV, $K_{\mathrm{sym}} = -154.7$ MeV, and $K_\tau = -300.6$ MeV for the SAMi-J EDF from the IS-IV density plots of ^{48}Ca and ^{208}Pb.

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Reference
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