Charge-exchange scattering to IAS and implications for the nuclear symmetry energy

Dao T. Khoa[1], B.M. Loc[1], and R.G.T. Zegers[2]
[1] Institute for Nuclear Science & Technology, VINATOM.
[2] NSCL and Department of Physics and Astronomy, MSU.

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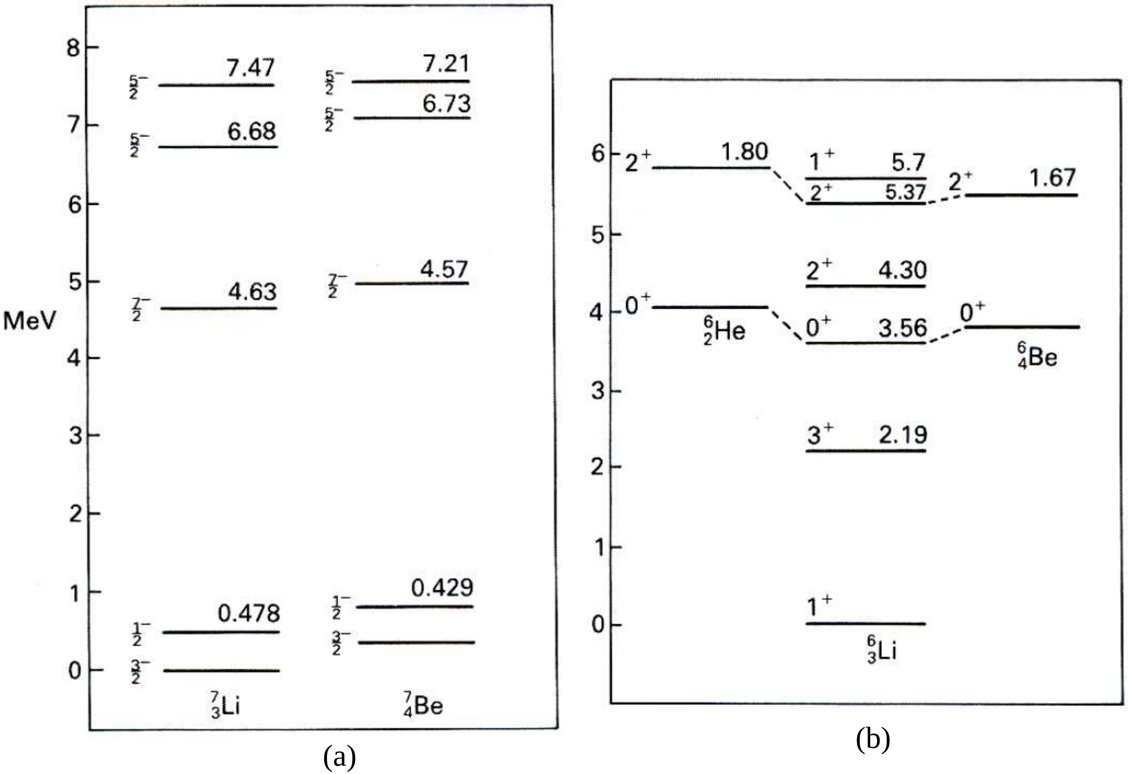


Figure : Isobaric analog states in the mirror nuclei ^{7}Li and ^{7}Be, and in the isobars $A = 6$

Back
Close

The Fermi transition ($\Delta L = \Delta S = 0$ and $\Delta T = 1$) between the isobaric analog states (IAS), induced by the charge-exchange (p, n) or (^{3}He,t) reaction, can be considered as "elastic" scattering of proton or ^{3}He by the isovector part of the OP that flips the projectile isospin

- A.M. Lane, Phys. Rev. Lett. **8**, 171 (1962)
- G.R. Satchler, *Isospin in Nuclear Physics* (Ed. D.H. Wilkinson, North-Holland Pub., Amsterdam, 1969) p390

In the folding model, the isovector part of the OP is determined exclusively by the neutron-proton difference in the nuclear densities and the isospin dependence of the effective NN interaction.

- DTK, W. von Oertzen, A.A. Ogloblin, Nucl. Phys. A **602**, 98 (1996)
- DTK, E. Khan, G. Colò, N.V. Giai, Nucl. Phys. A **706**, 61 (2002)
- DTK, B.M. Loc, D.N. Thang, Eur. Phys. J. A **50**: 34 (2014)

Lane potential and isospin coupling in the charge-exchange scattering to the IAS

Given the same isospin $t = 1/2$, the central nucleon-nucleus or ^{3}He-nucleus OP for the elastic scattering on a nonzero-isospin target can be written as

$$U(R) = U_0(R) + 4U_1(R)\frac{\boldsymbol{t}.\boldsymbol{T}}{aA}, \tag{1}$$

where $\boldsymbol{t}$ is the isospin of the projectile and $\boldsymbol{T}$ is that of the target with mass number A, and $a = 1$ and 3 for nucleon and ^{3}He, respectively. The second term is the **symmetry term** of the OP, and U_1 is known as the **Lane potential** that contributes to both the elastic and charge-exchange scattering. The knowledge of U_1 is of **fundamental interest in the study of the isovector mode of direct nuclear reaction.**

Given the isospins $\boldsymbol{t}$ and $\boldsymbol{T}$ for the projectile and target $\Rightarrow$ $T_z = (N-Z)/2$ and $\tilde{T}_z = T_z - 1$ for the target A and its **isobaric analog** $\tilde{A}$, respectively. Denoting the state formed by adding proton or ^{3}He to A is $|aA>$, and that formed by adding a neutron or triton to $\tilde{A}$ is $|\tilde{a}\tilde{A}> \Rightarrow$ Form factor of the **charge-exchange scattering** to the IAS

$$F_{\rm cx}(R) =< \tilde{a}\tilde{A}|4U_1(R)\frac{\boldsymbol{t}.\boldsymbol{T}}{aA}|aA>= \frac{2}{aA}\sqrt{2T_z}U_1(R). \tag{2}$$

In the two-channel approximation

$$\Psi = |aA> \chi_{aA}(\boldsymbol{R}) + |\tilde{a}\tilde{A}> \chi_{\tilde{a}\tilde{A}}(\boldsymbol{R}). \tag{3}$$

The elastic and charge-exchange scattering cross sections are obtained from the solutions of the **coupled-channel Lane equations**

$$[K_a + U_a(R) - E_a]\,\chi_{aA}(\boldsymbol{R}) = -F_{\rm cx}(R)\chi_{\tilde{a}\tilde{A}}(\boldsymbol{R}), \tag{4}$$

$$[K_{\tilde{a}} + U_{\tilde{a}}(R) - E_{\tilde{a}}]\,\chi_{\tilde{a}\tilde{A}}(\boldsymbol{R}) = -F_{\rm cx}(R)\chi_{aA}(\boldsymbol{R}). \tag{5}$$

G.R. Satchler, *Direct Nuclear Reactions* (Oxford Univ. Press, 1983)

Folding model

Central nucleon-nucleus or nucleus-nucleus optical potential U is evaluated as a Hartree-Fock-type potential

$$U = \sum [< ij|v_{\rm D}|ij > + < ij|v_{\rm EX}|ji >], \tag{6}$$

Using explicit proton (ρ_p) and neutron (ρ_n) densities, nucleon-nucleus or nucleus-nucleus OP is obtained in terms of the **isoscalar** ($U_{\rm IS}$) and **isovector** ($U_{\rm IV}$) parts as

$$U(E, \boldsymbol{R}) = U_{\rm IS}(E, \boldsymbol{R}) \pm U_{\rm IV}(E, \boldsymbol{R}), \tag{7}$$

where - sign pertains to the proton or ^{3}He OP, and + sign to the neutron or triton OP ⇒ FF for both the (p, n) and $(^3\text{He},t)$ scattering to the IAS

$$F_{\rm cx}(R) = \frac{2}{aA}\sqrt{2T_z}U_1(R) = \sqrt{\frac{2}{T_z}}U_{\rm IV}(R). \tag{8}$$

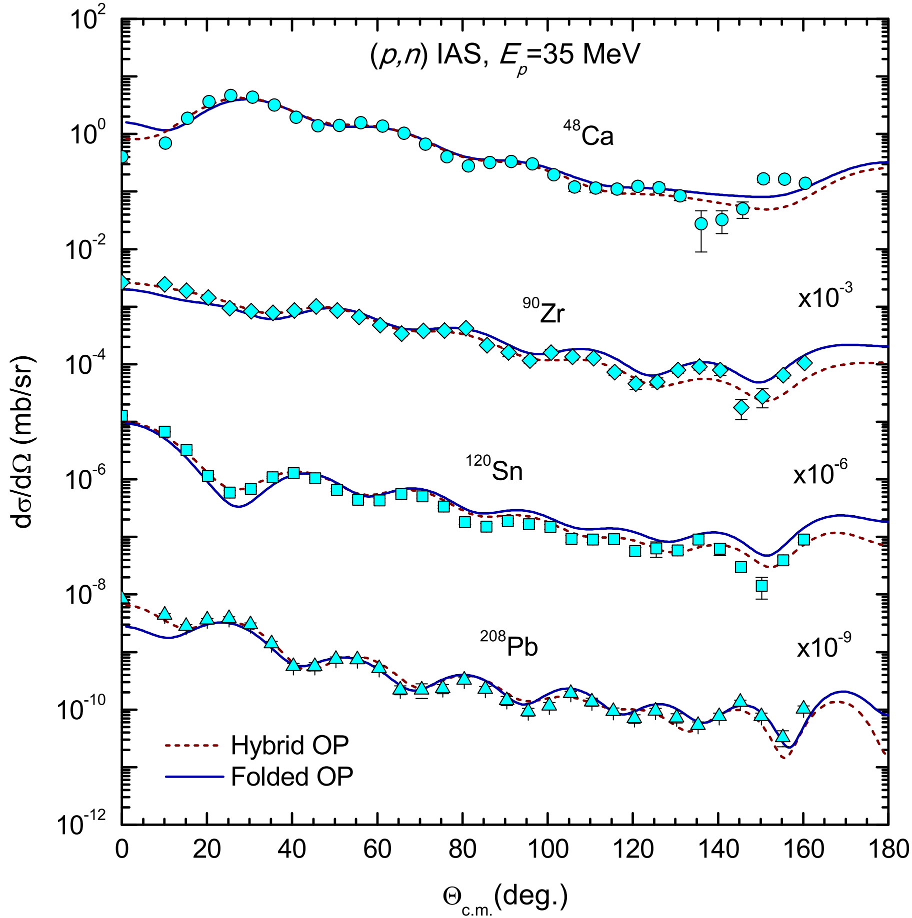


Figure : CC description of the (p, n) scattering to the IAS of different targets at $E_p = 35$ MeV. MSU data by R.R. Doering, D.M. Patterson, A. Galonsky, Phys. Rev. C **12**, 378 (1975).

Implication for the nuclear symmetry energy

The folding + CC analysis of the charge-exchange scattering is helpful for the study of the NM symmetry energy, when the same density- and isospin dependent effective NN interaction is used in the HF calculation of the total NM energy density $\mathcal{E}$

$$\mathcal{E} = \mathcal{E}_{\rm kin} + \frac{1}{2}\sum_{kk'}[\langle \boldsymbol{k}\boldsymbol{k}'|v_{\rm D}|\boldsymbol{k}\boldsymbol{k}'\rangle + \langle \boldsymbol{k}\boldsymbol{k}'|v_{\rm EX}|\boldsymbol{k}'\boldsymbol{k}\rangle],$$

where $|\boldsymbol{k}\rangle$ are plane waves. The total NM energy per particle E

$$\frac{\mathcal{E}}{\rho} = E(\rho,\delta) = E(\rho,\delta=0) + S(\rho)\delta^2 + O(\delta^4) + ..., \ \delta = \frac{\rho_n - \rho_p}{\rho}. \quad (9)$$

The folding model analysis of the (p,n) scattering to the IAS has put some constraint on the nuclear symmetry energy $S(\rho)$ at $\rho \lesssim \rho_0$, within the empirical boundaries deduced from experiments.

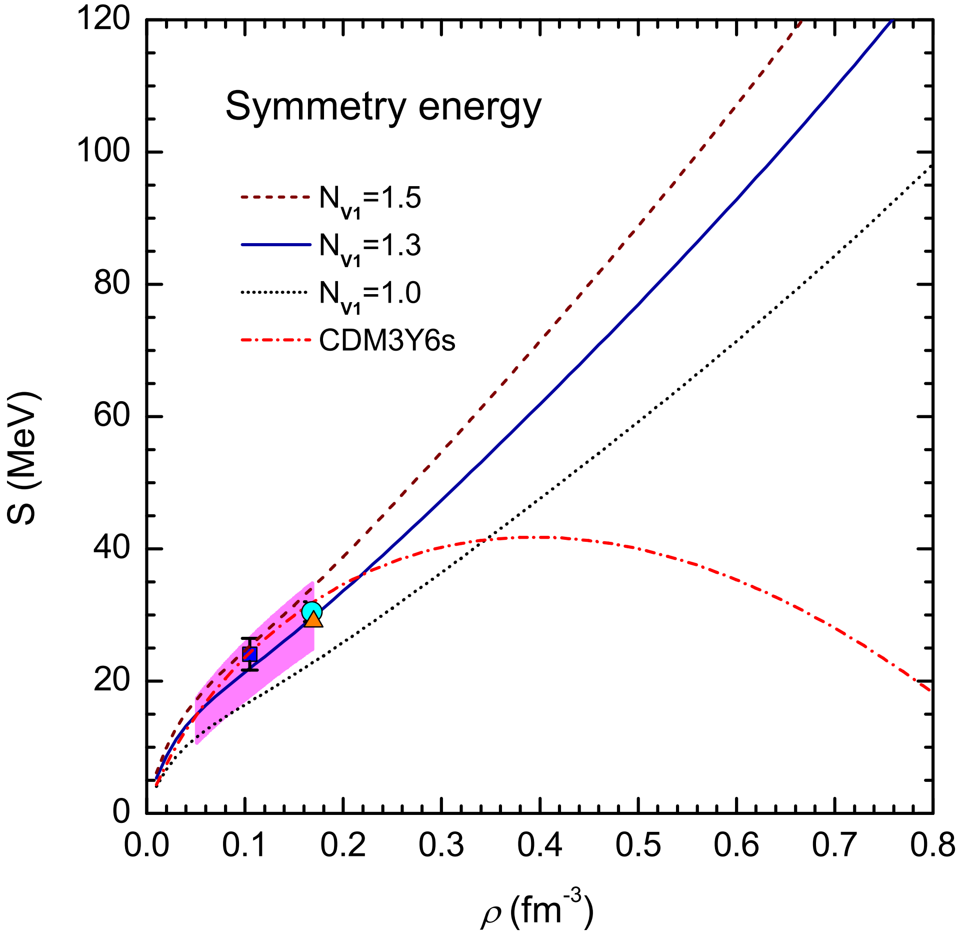
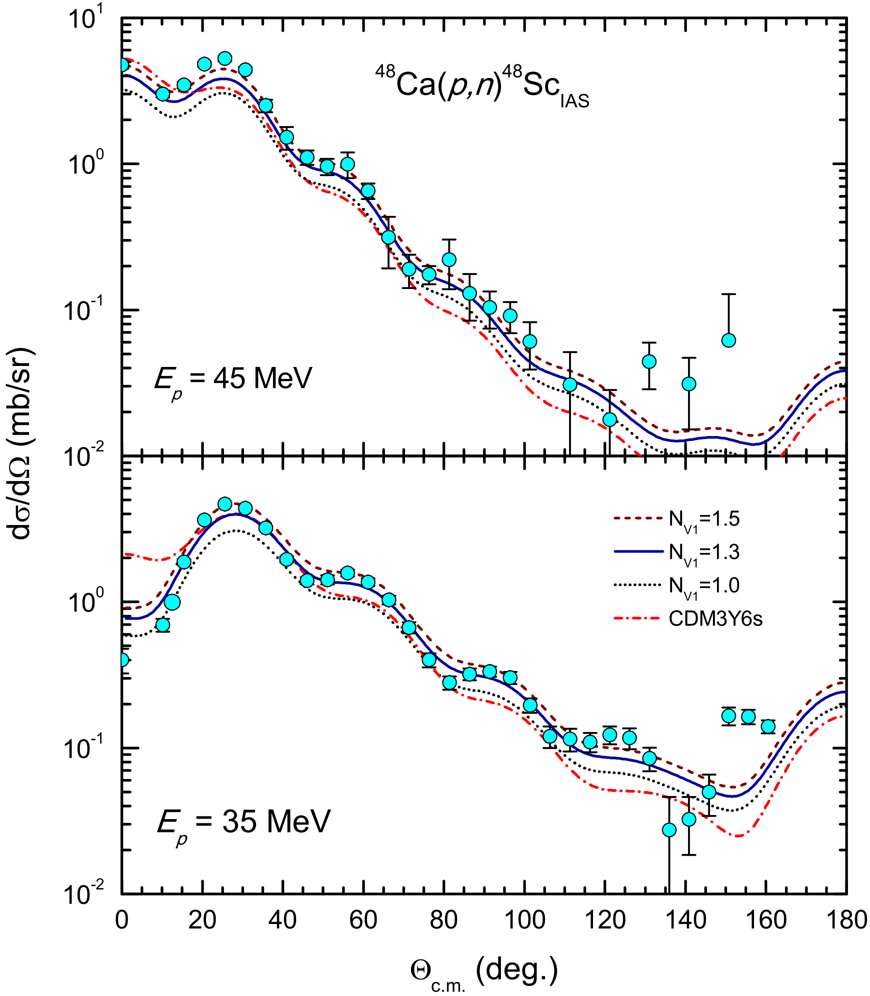


Figure : HF prediction of $S(\rho)$ compared to empirical data by M.B. Tsang *et al.* Prog. Part. Nucl. Phys. **66**, 400 (2011); L. Trippa *et al.* Phys. Rev. C **77**, 061304(R) (2008); DTK, H.S. Than, Phys. Rev. C **71**, 044601 (2005).



$^{48}Ca(p,n)^{48}Sc_{IAS}$
E_p = 45 MeV
E_p = 35 MeV
N_{V1}=1.5
N_{V1}=1.3
N_{V1}=1.0
CDM3Y6s
dσ/dΩ (mb/sr)
$\Theta_{c.m.}$ (deg.)

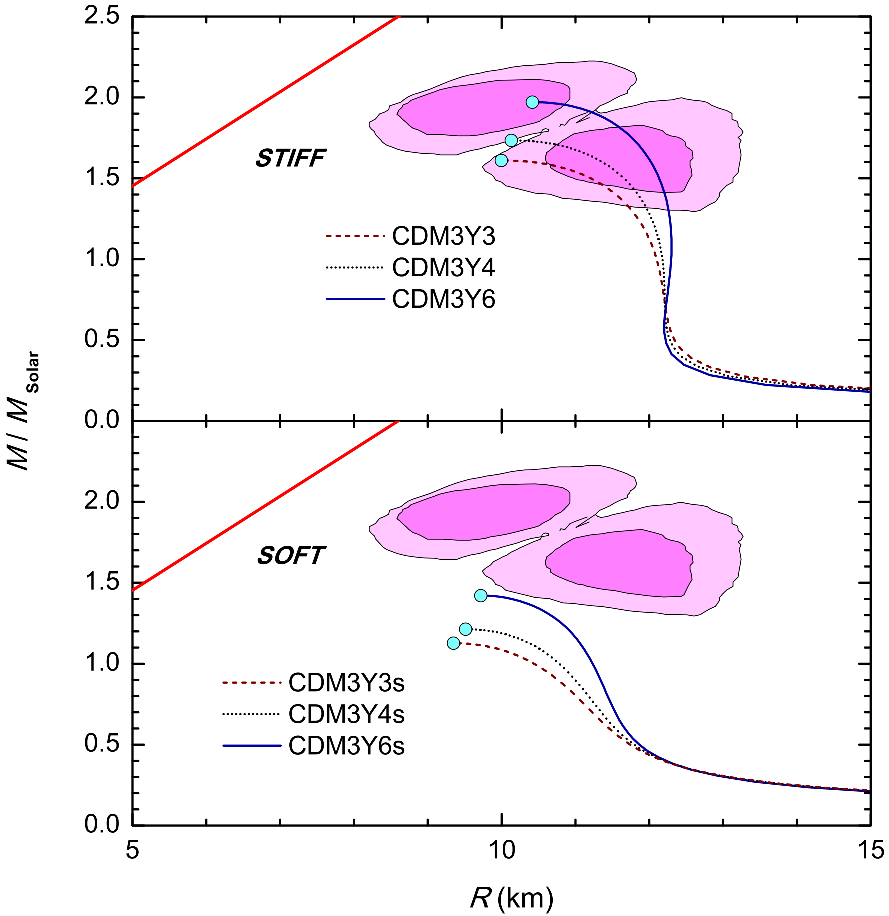


Figure : NS gravitational mass vs. its radius obtained with the EOS's given by the stiff- and soft type NN interactions. HF results from D.T. Loan, N.H. Tan, DTK, J. Margueron, Phys. Rev. C **83**, 065809 (2011), empirical data (x-ray burster 4U 1608-52) deduced by A.W. Steiner, J.M. Lattimer, E.F. Brown, Astrophys. J. **722**, 33 (2010).

(^{3}He,t) scattering to the IAS at medium energies

The experimental resolution of (^{3}He,t) experiment is now much higher than that of (p, n) reaction [Y. Fujita, B. Rubio, W. Gelletly, Prog. Part. Nucl. Phys. **66**, 549 (2011).]

The difference between the neutron and proton densities or the **neutron skin** ΔR_{np} of the target can be well probed in the folding model analysis of the charge-exchange (^{3}He,t) scattering to IAS at medium energies (when the two-step processes can be neglected, and the $t-$matrix interaction can be used in the folding calculation).

$$\Delta R_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}, \tag{10}$$

was found by the structure studies to be **strongly correlated with the slope of the symmetry energy of nuclear matter** $\Rightarrow$ Information on the density dependence of the symmetry energy.
M.B. Tsang *et al.*, Phys. Rev. C **86**, 015803 (2012)

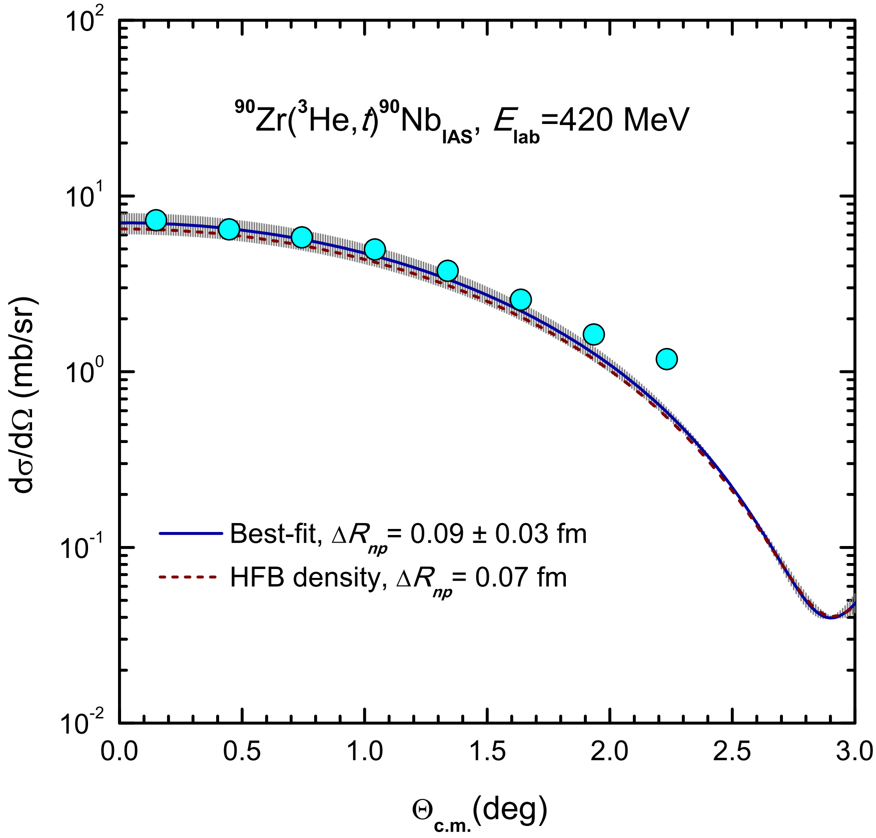


Figure : Folding model analysis of $^{90}Zr(^{3}He,t)^{90}Nb^{*}_{IAS}$ data [R.G.T. Zegers *et al.*, Phys. Rev. Lett. **99**, 202501 (2007)] given by the charge-exchange FF based on the empirical density by Ray *et al.*, Phys. Rev. C **18**, 1756 (1978), and HFB density by M. Grasso *et al.*, Phys. Rev. C **64**, 064321 (2001).

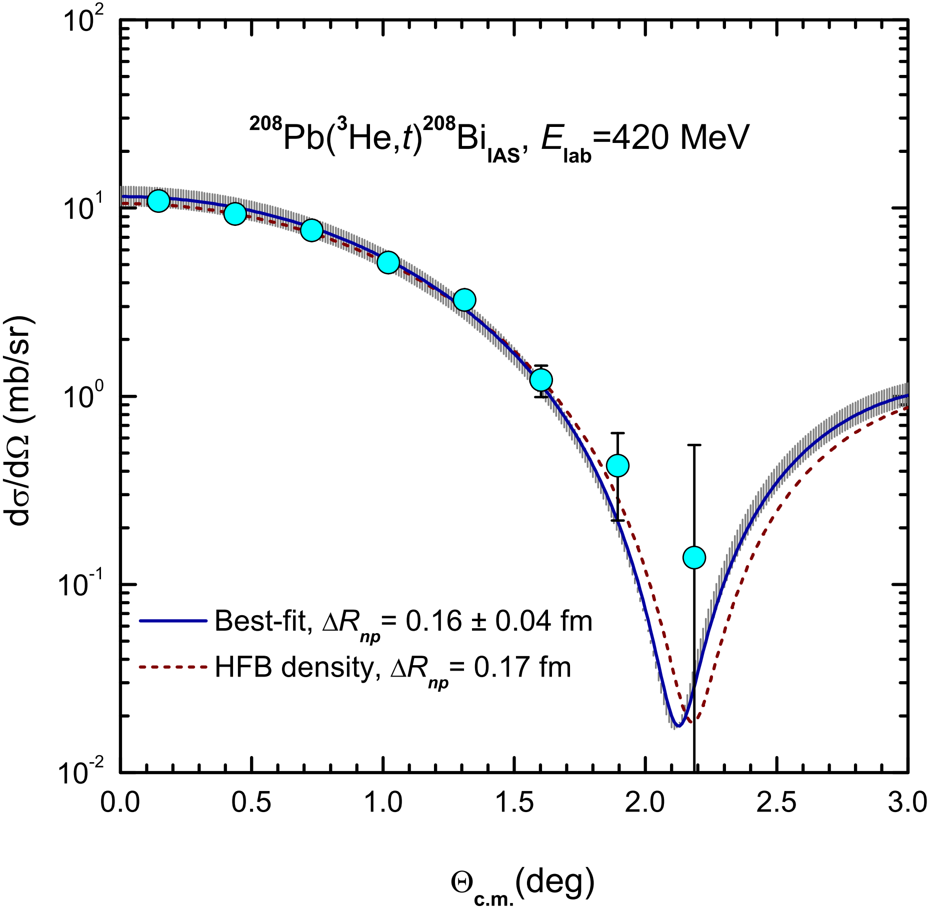


Figure : Folding model analysis of ^{208}Pb(^{3}He,t)^{208}Bi$^{*}_{IAS}$ data [R.G.T. Zegers *et al.*, Phys. Rev. Lett. **99**, 202501 (2007)]. See details in B.M. Loc, DTK, R.G.T. Zegers, Phys. Rev. C **89**, 024317 (2014).

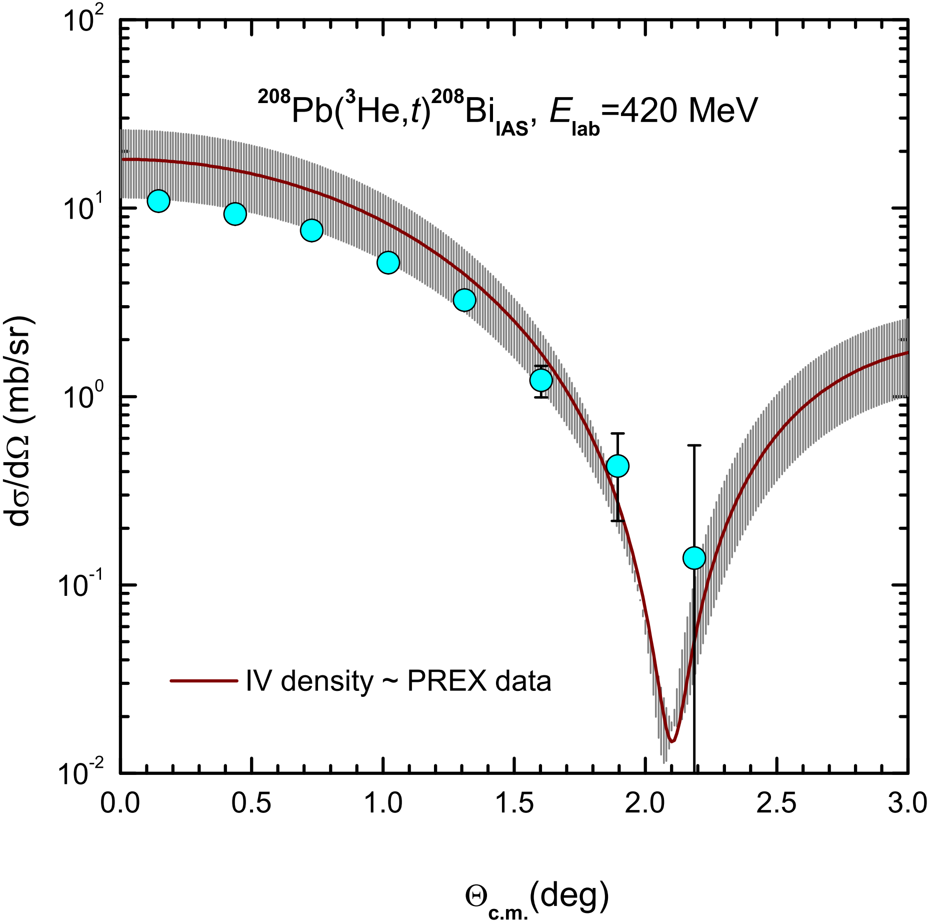


Figure : Folding model analysis of ^{208}Pb(^{3}He,t)^{208}Bi$^*_{\rm IAS}$ data given by the charge-exchange FF based on the empirical density adjusted to reproduce the PREX data $\Delta R_{np} \approx 0.33^{+0.16}_{-0.18}$ fm [S. Abrahamyan *et al.* (PREX Collaboration), Phys. Rev. Lett. **108**, 112502 (2012)].

Back
Close

Conclusion

- The consistent folding model study of the charge-exchange (p, n) scattering to the IAS has been done using the isospin dependent OP and charge-exchange FF given by the density dependent CDM3Y6 interaction
- Some preference for the stiff behavior of the nuclear symmetry energy with the increasing NM density has been established.
- The folding model analysis of the $(^3\mathrm{He}, t)$ scattering the IAS of ^{90}Zr and ^{208}Pb at $E_{\mathrm{lab}} = 420$ MeV has been done to deduce the neutron skin for these nuclei. The best-fit neutron skin values found by our analysis are in a good agreement with the existing database.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