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Influence of the treatment of initialization and mean-field potential on the neutron to proton yield ratios

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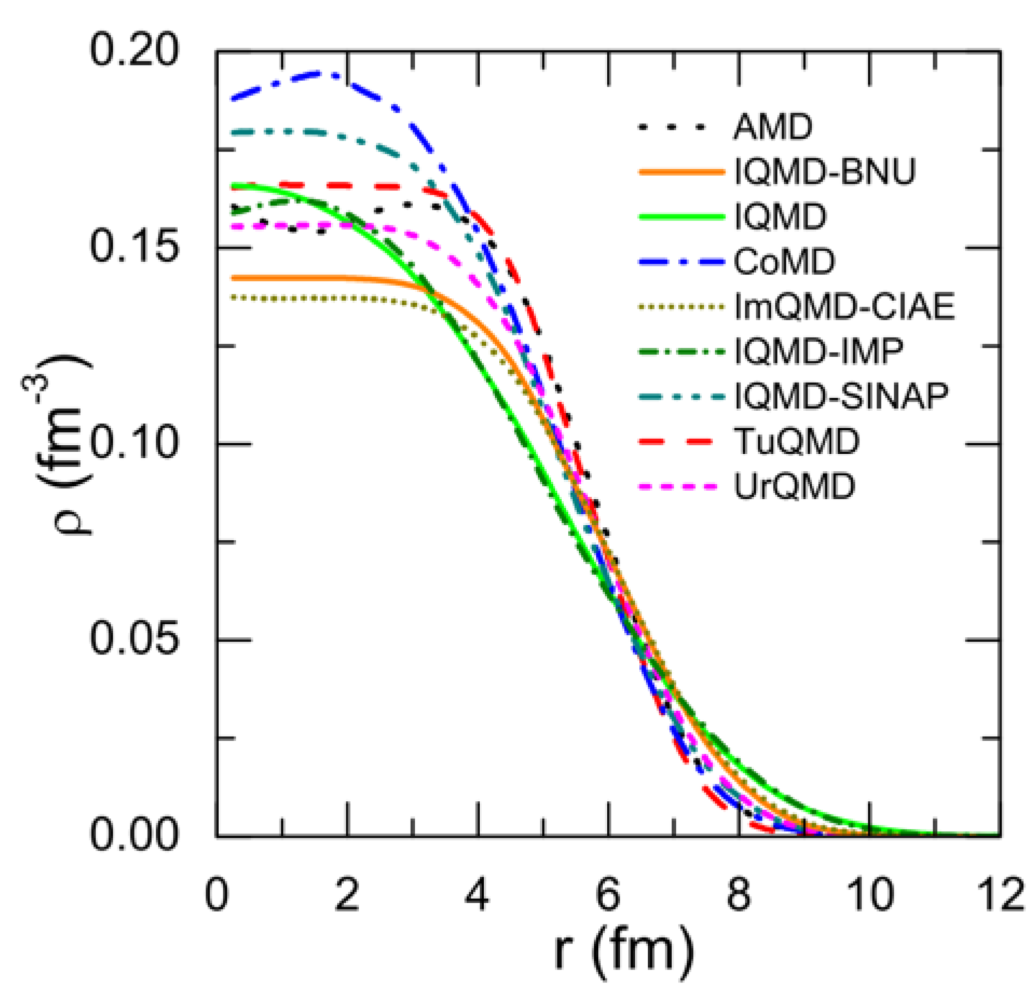
Details can be found in PhysRevC.104.024605

Acknowledgements: This work was partly inspired by the TMEP, and it was supported by NSFC No. 11875323, 11705163, 11790320, 11790323, U1867212, 114222548, and 11961141003, the National Key R&D Program of China under Grant No. 2018YFA0404404, the CBSR Project (No. WDJC-2019-13,BJ20002501), Innovation Project of Guangxi Graduate Education No. XYCSZ2018060, and the funding of China Institute of Atomic Energy. The work was carried out at National Supercomputer Center in Tianjin, and the calculations were performed on TianHe-1 (A).

Abstract

In this work, we firstly investigate how to reproduce and how well one can reproduce the Woods Saxon density distribution of initial nuclei in the ImQMD model. Then, we propose a new treatment for the initialization of nuclei which is correlated with the nucleonic mean-field potential by using the same potential energy density functional. In the mean field potential, the three-body force term is accurately calculated. Based on the new version of the model, the influences of precise calculations of the three-body force term, the width of the wave packet, and the quantities related to the strength of symmetrical energy on the neutron to proton yield ratios are discussed. In the case where the neutron-proton effective mass splitting is fixed, R(n/p) at high kinetic energy can also be used to learn the symmetry energy at suprasaturation density.

Motivation

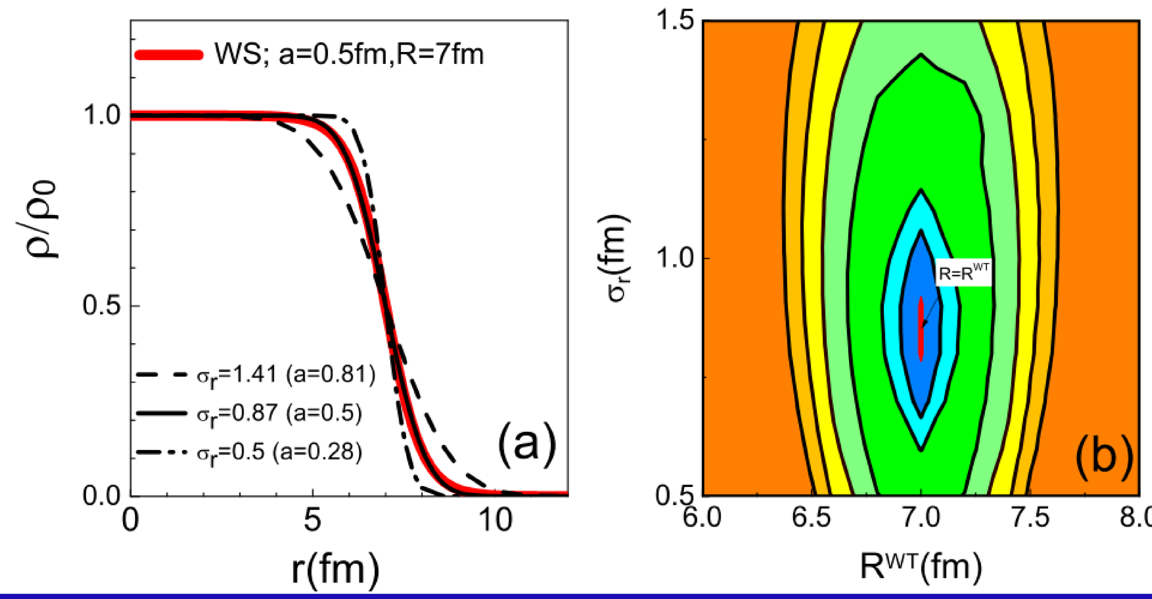


[1] J. Xu, L.-W. Chen, ManYee B. Tsang, H. Wolter, Y.-X. Zhang, J. Aichelin,M. Colonna, D. Cozma, P. Danielewicz, Z.-Q. Feng, A.L. Fevre, T. Gaitanos, C. Hartnack, K. Kim, Y. Kim, et al. Phys. Rev. C. 93, 044609 (2016).

- **In QMD type models, it is hard to reproduce the WS density distribution!**
- **Q1: Can we reproduce the Woods-Saxon density distribution in QMD type models?**
- **Q2: How to correlated to the initial density distribution with the nucleonic mean field potential?**

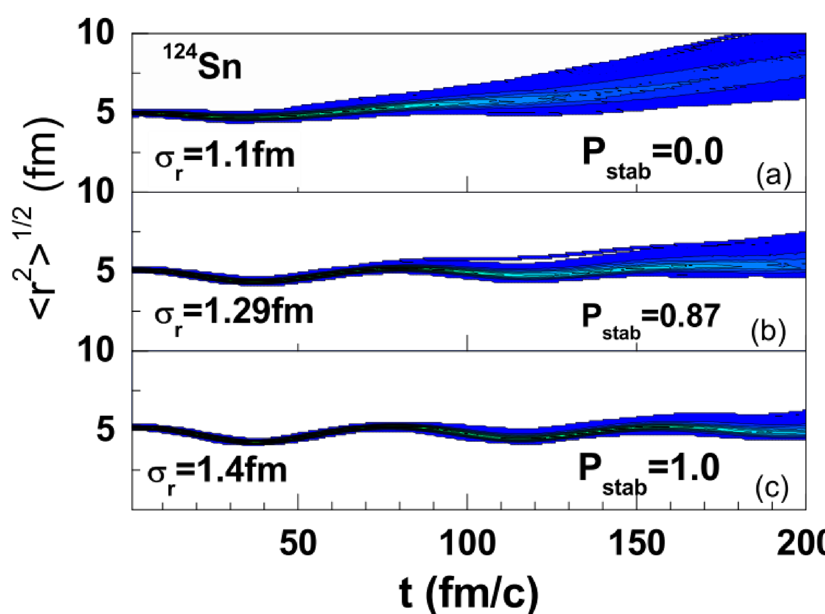
Conditions for reproducing WS density distribution with Gaussian

- **a) R^{WT} = R,**
- **b) σ_r = 0.01564 + 1.71217a**



Situation for selecting the width in ImQMD

- a) Since the σ_r is same for all nucleons in the system, it means $a_n = a_p$ in density distribution in the QMD model. It is different than the reality for neutron rich system.
- b) The values of σ_r in the QMD type models are larger than the values extracted from the relation, σ_r= 0.01564 + 1.71217a.



Correlate the initialization and propagation with the same nucleonic potential

- **Energy density functional used in the initialization and mean field propagation**

$$u(\boldsymbol{r})_{sky} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^{\eta}} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{sur,iso}}{\rho_0}[\nabla(\rho_n-\rho_p)]^2 + A_{sym}\frac{\rho^2}{\rho_0}\delta^2 + B_{sym}\frac{\rho^{\eta+1}}{\rho_0^{\eta}}\delta^2$$

$+$

$$u_{md}(\boldsymbol{r},\boldsymbol{p}_i-\boldsymbol{p}_j)= C_0\sum_{ij}\int d^3p d^3p' f_i(\mathbf{r},\mathbf{p})f_j(\mathbf{r},\boldsymbol{p}')(\mathbf{p}-\boldsymbol{p}')^2 + D_0\sum_{ij\in n}\int d^3pd^3p' f_i(\mathbf{r},\mathbf{p})f_j(\mathbf{r},\mathbf{p}')(\mathbf{p}-\mathbf{p}')^2 + D_0\sum_{ij\in p}\int d^3pd^3p' f_i(\boldsymbol{r},\boldsymbol{p})f_j(\boldsymbol{r},\boldsymbol{p}')(\boldsymbol{p}-\boldsymbol{p}')^2$$

$+$ u_{coul}

- **Restricted Density Variational method for calculating initial :**

Given the WS density distribution:

$$\rho_i = \rho_{0i}\frac{1}{1+e^{\left(\frac{r-R_i}{a_i}\right)}}, i=n,p$$

Under the condition of the conservation of particle number in the system, the value of ρ_{0n},ρ_{0p}, R_n, R_p, a_n, and a_p are obtained by minimizing the total energy of the system given by,

$$E=\int\mathcal{H}dr=\int\left\{\frac{\hbar^2}{2m}[\tau_n(r)-\tau_p(r)]+u_{sky}+u_{md}+u_{coul}\right\}dr$$

- **Update the mean field with accurate solution of three-body force term in propagation**

$$\frac{\beta}{\eta+1}\Sigma_i < \frac{\rho^{\eta}}{\rho_0^{\eta}} >_i \approx \frac{\beta}{\eta+1}\Sigma_i < \frac{\rho}{\rho_0} >_i^{\eta} + O(\rho)$$

The old treatment: $\frac{\beta}{\eta+1}\Sigma_i < \frac{\rho}{\rho_0} >_i^{\eta} \Rightarrow \dot{\boldsymbol{P}}_i = -\frac{\partial U_3}{\partial \boldsymbol{r}_i} = -\frac{\beta}{\eta+1}\frac{\partial}{\partial \boldsymbol{r}_i}\Sigma_{j=1}^{N}\frac{<\rho>_j^{\eta}}{\rho_0^{\eta}}$

The new treatment: $\frac{\beta}{\eta+1}\Sigma_i < \frac{\rho^{\eta}}{\rho_0^{\eta}} >_i \Rightarrow \dot{\boldsymbol{P}}_i = -\frac{\partial U_3}{\partial \boldsymbol{r}_i} = -\beta\rho_0\int\frac{\rho^{\eta}}{\rho_0^{\eta}}\frac{\rho_i}{\rho_0}\frac{\boldsymbol{r}-\boldsymbol{r}_i}{\sigma_r^2}d^3\boldsymbol{r}$

(the 11-point Gauss-Legendre quadrature method)

Updated initialization with the same Skyrme EDF

a) The values of B, Rn, and Rp are calculated based on the RDV with the same Skyrme energy density functional as that used in the mean-field propagation of the ImQMD-L model.

b) the centroids of the wave packet for neutrons and protons are sampled within the half-density radii Rn and Rp, and the binding energy of the sampled nucleus is in the range of B±0.2MeV.

- **new treatment of 3-body fore term、correlate the initialization and propagation with the same nucleonic potential ⟹ImQMD-L model**

Results and discussions

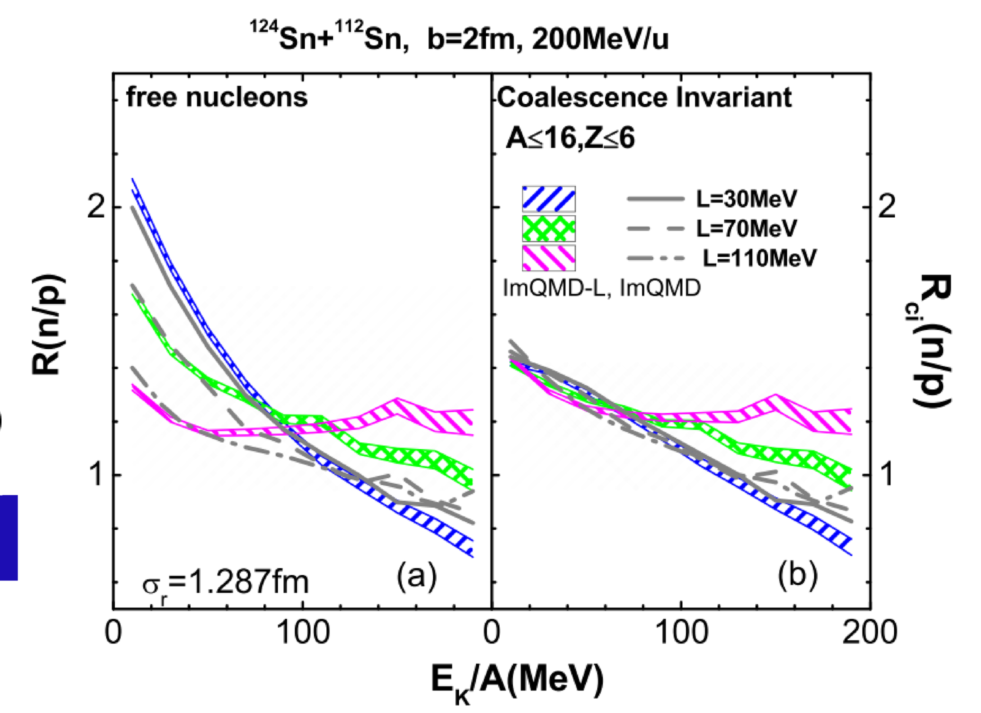


FIG. 4. Panels (a) and (b) are R(n/p) for emitted free nucleons and for coalescence invariant nucleons, respectively. Color shaded regions are the results from the new treatment of three-body force, and gray lines are the results from the old method.

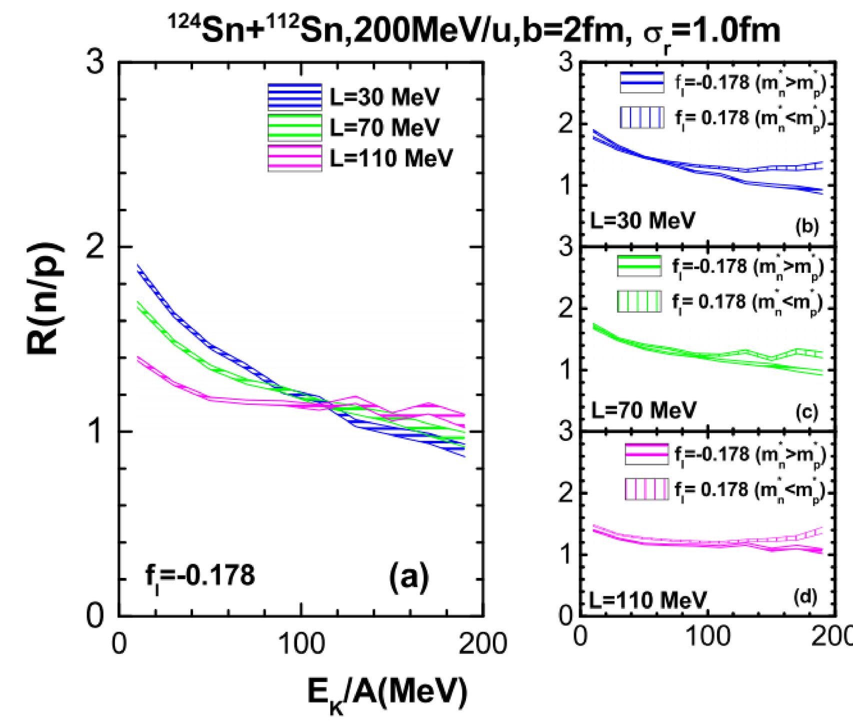


FIG. 6. Panels (a)-(d) are the neutron to proton yield ratios for emitted free nucleons obtained with different L and different f_I at σ_r=1.0 fm.

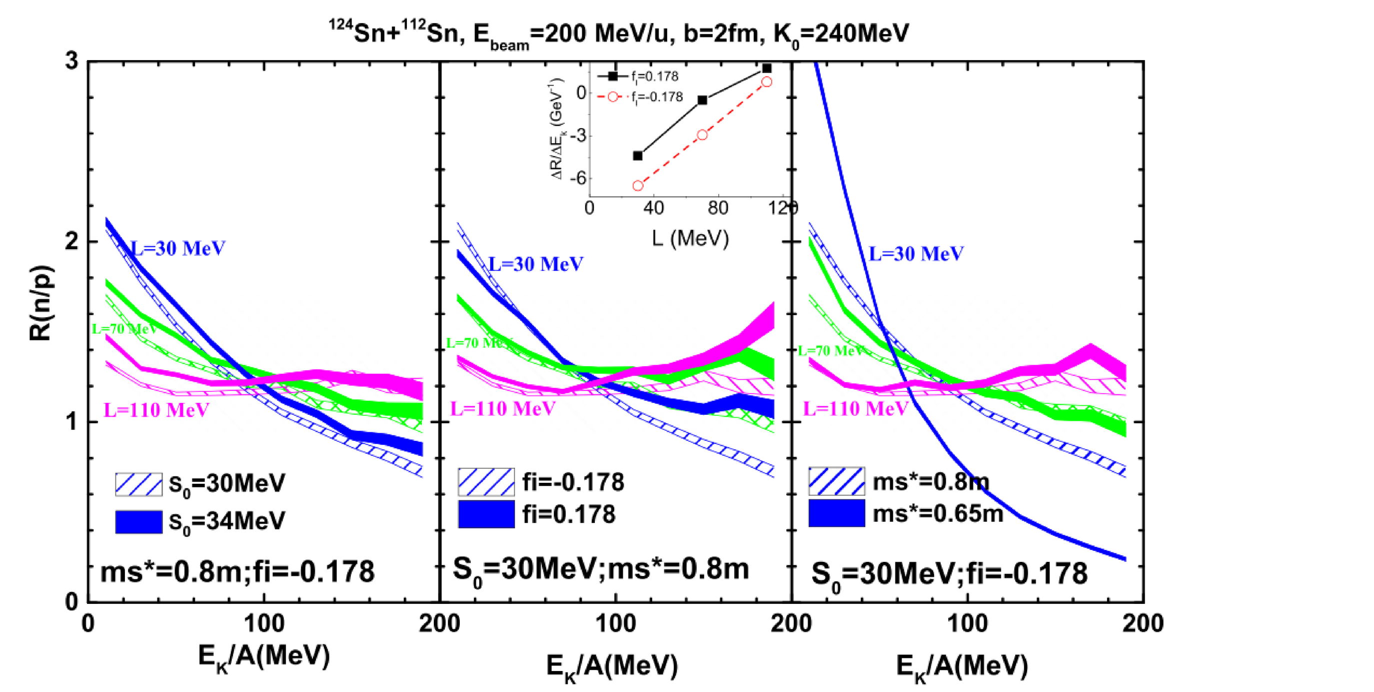


FIG.5. (Color online) The neutron to proton yield ratios for emitted free nucleons; different colors are for different L. Panel (a) is for different S_0 , panel (b) is for different f_I , and panel (c) is for different m_s^*.

Conclusion

- **Based on the inverse Weierstrass transformation, Theoretically, the Woods-Saxon density distribution can be reproduced within a certain accuracy range(σ_r = 0.01564 + 1.71217a); however, it cannot be realized in the model.**
- **The ImQMD-L calculations show that the R(n/p) in the high kinetic energy region can be used to probe the symmetry energy above the saturation density if f_I is fixed. The current calculations show that the analysis of spectra of R(n/p) on the L and f_I parameter space is necessary in future to tightly constrain the symmetry energy.**