Asymmetric Nuclear Matter in Relativistic *ab initio* Theory in the Full Dirac Space

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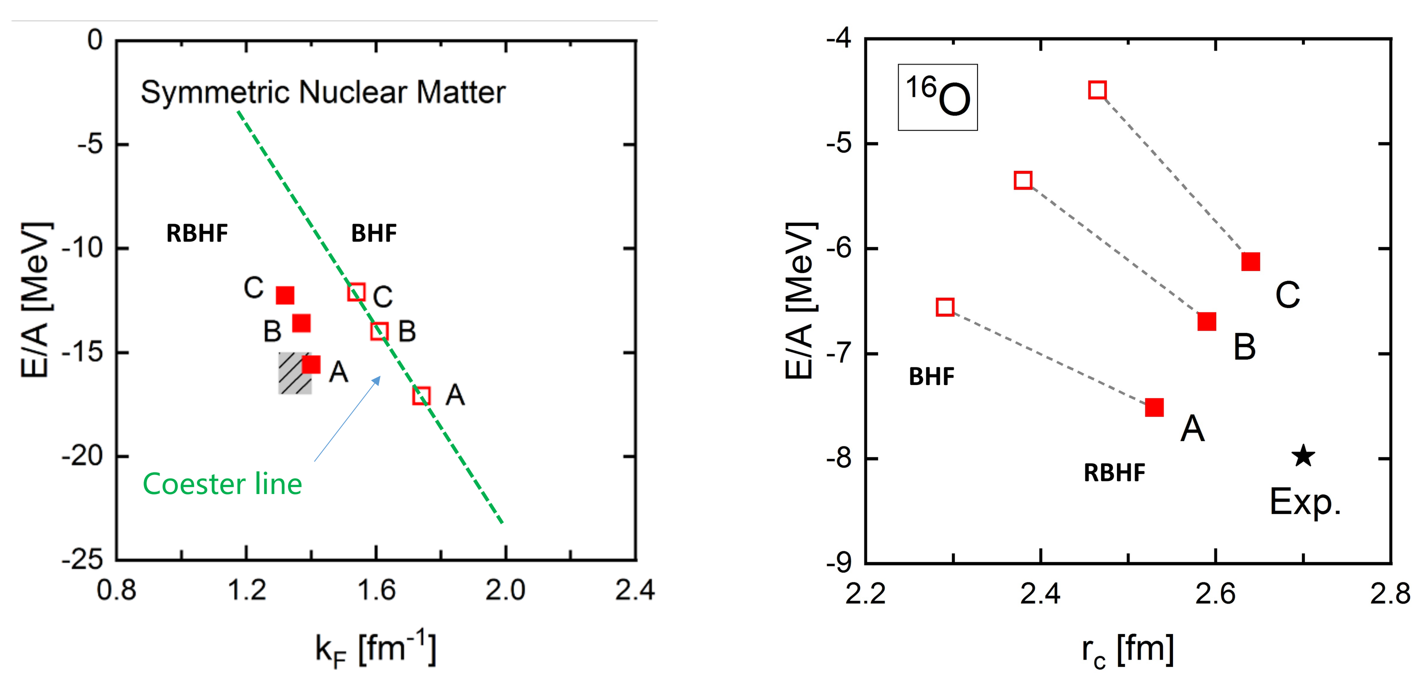
The ***relativistic Brueckner-Hartree-Fock*** equations are solved self-consistently for ***asymmetric nuclear matter*** with the Bonn-A potential in the ***full Dirac space***. The momentum and isospin dependence of the in-medium ***nucleon Dirac mass*** are determined uniquely. The long-standing controversy between the projection method and the momentum-independence approximation has been solved. The ***symmetry energy*** and its ***slope parameter*** at the saturation density are ***33.1*** and ***65.2*** MeV, respectively, in harmony with empirical and experimental values.

Introduction

- Symmetry energy and its density dependence play a crucial role in both nuclear physics and astrophysics.
  M. Baldo and G.F. Burgio, PPNP **91**, 203 (2016)
- Calculations based on *ab initio* methods are expected to give important predictions.
  G. Taranto, M. Baldo, and G.F. Burgio, PRC **87**, 045803 (2013)
- Advantages of the relativistic Brueckner-Hartree-Fock (RBHF) theory:
  S. Shen *et al.*, PPNP **109**, 103713 (2019)



In this work, the RBHF theory in the full Dirac space is developed to study asymmetric nuclear matter.

Theoretical framework

- Dirac equation.--The single-particle motion of a nucleon with rest mass M, momentum $\boldsymbol{p}$ and single-particle energy $E_{\boldsymbol{p},\tau}$ is depicted by the Dirac equation

$$[\boldsymbol{\alpha}\cdot\boldsymbol{p}+\beta\,(M+\mathcal{U}_\tau)]\,u_\tau(\boldsymbol{p},s)=E_{\boldsymbol{p},\tau}u_\tau(\boldsymbol{p},s),\qquad \tau=n,p.$$

$\mathcal{U}_\tau$ represents the single-particle potential

$$\mathcal{U}_\tau(\boldsymbol{p})=U_{S,\tau}(p)+\gamma^0U_{0,\tau}(p)+\boldsymbol{\gamma}\cdot\hat{\boldsymbol{p}}U_{V,\tau}(p)$$

Scalar pot. | Timelike vector pot. | Spacelike vector pot.

Effective quantities:

$$\boldsymbol{p}^*_\tau=\boldsymbol{p}+\hat{\boldsymbol{p}}U_{V,\tau}(p),\quad M^*_{\boldsymbol{p},\tau}=M+U_{S,\tau}(p),\quad E^*_{\boldsymbol{p},\tau}=E_{\boldsymbol{p},\tau}-U_{0,\tau}(p)$$

- Thompson equation.--The effective interactive G matrix is the solution of the in-medium covariant Thompson equation

$$G_{\tau\tau'}(\boldsymbol{q}',\boldsymbol{q}|\boldsymbol{P},W)=V_{\tau\tau'}(\boldsymbol{q}',\boldsymbol{q}|\boldsymbol{P})+\int\frac{d^3k}{(2\pi)^3}V_{\tau\tau'}(\boldsymbol{q}',\boldsymbol{k}|\boldsymbol{P})\times\frac{M^*_{\boldsymbol{P}+\boldsymbol{k},\tau}M^*_{\boldsymbol{P}-\boldsymbol{k},\tau'}}{E^*_{\boldsymbol{P}+\boldsymbol{k},\tau}E^*_{\boldsymbol{P}-\boldsymbol{k},\tau'}}\frac{Q_{\tau\tau'}(\boldsymbol{k},\boldsymbol{P})}{W-E_{\boldsymbol{P}+\boldsymbol{k},\tau}-E_{\boldsymbol{P}-\boldsymbol{k},\tau'}}G_{\tau\tau'}(\boldsymbol{k},\boldsymbol{q}|\boldsymbol{P},W)$$

The starting energy W is referred to PRC **103**, 054319 (2019).

- Single-particle potentials.--In the full Dirac space, $U_{s,\tau}$, $U_{0,\tau}$, and $U_{V,\tau}$ can be determined uniquely through

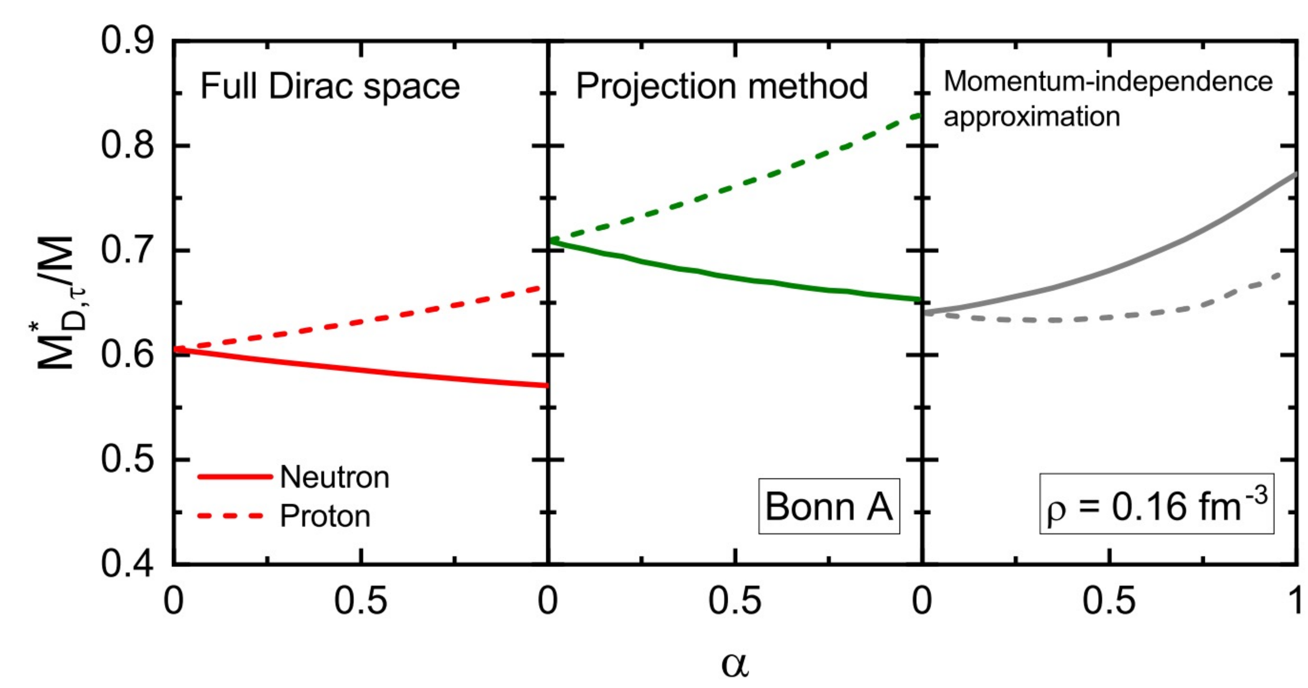
$$U_{S,\tau}(p)=\frac{\Sigma^{++}_\tau(p)-\Sigma^{--}_\tau(p)}{2},$$
$$U_{0,\tau}(p)=\frac{E^*_{\boldsymbol{p},\tau}}{M^*_{\boldsymbol{p},\tau}}\frac{\Sigma^{++}_\tau(p)+\Sigma^{--}_\tau(p)}{2}-\frac{p^*_\tau}{M^*_{\boldsymbol{p},\tau}}\Sigma^{-+}_\tau(p),$$
$$U_{V,\tau}(p)=-\frac{p^*_\tau}{M^*_{\boldsymbol{p},\tau}}\frac{\Sigma^{++}_\tau(p)+\Sigma^{--}_\tau(p)}{2}+\frac{E^*_{\boldsymbol{p},\tau}}{M^*_{\boldsymbol{p},\tau}}\Sigma^{-+}_\tau(p)$$

where $\Sigma^{++++}_\tau=\int G^{++++}$, $\Sigma^{-+}_\tau=\int G^{-+++}$, $\Sigma^{--}_\tau=\int G^{-+-+}$.

RBHF equations are solved in a self-consistent manner.

Dirac mass in the full Dirac space

- The in-medium nucleon Dirac masses $M^*_{D,\tau}=M+U_{S,\tau}$ as functions of the asymmetry parameter $\alpha=(\rho_n-\rho_p)/(\rho_n+\rho_p)$.

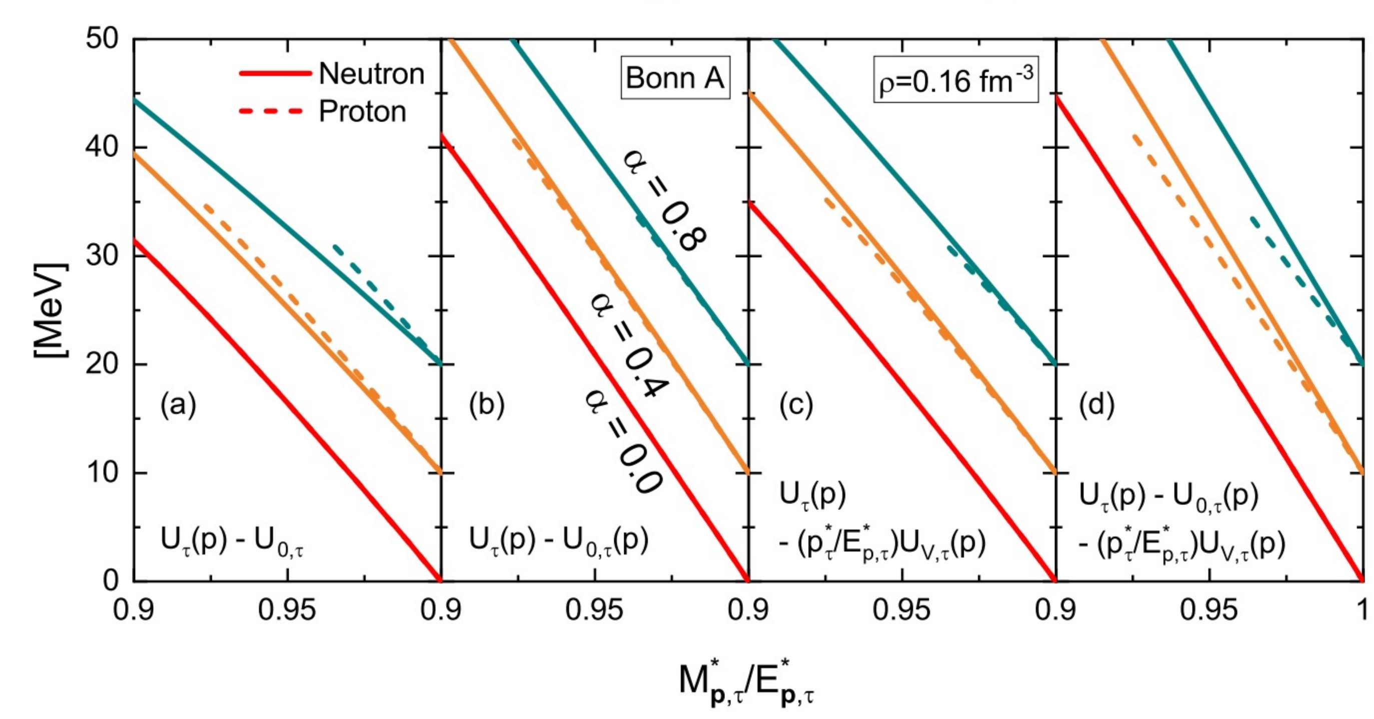


✓ $M^*_{D,n}<M^*_{D,p}$ is found in the full Dirac space;

✓ There is a sharp conflict between predictions by the mom.-ind. app. and that in the full Dirac space as well as that with the projection method.

- The left side of the following equation as functions of $M^*_{\boldsymbol{p},\tau}/E^*_{\boldsymbol{p},\tau}$. The slope at each point on the line is the value of $U_{S,\tau}$.

$$U_\tau(p)-U_{0,\tau}(p)-\frac{p^*_\tau}{E^*_{\boldsymbol{p},\tau}}U_{V,\tau}(p)=\frac{M^*_{\boldsymbol{p},\tau}}{E^*_{\boldsymbol{p},\tau}}U_{S,\tau}(p)$$



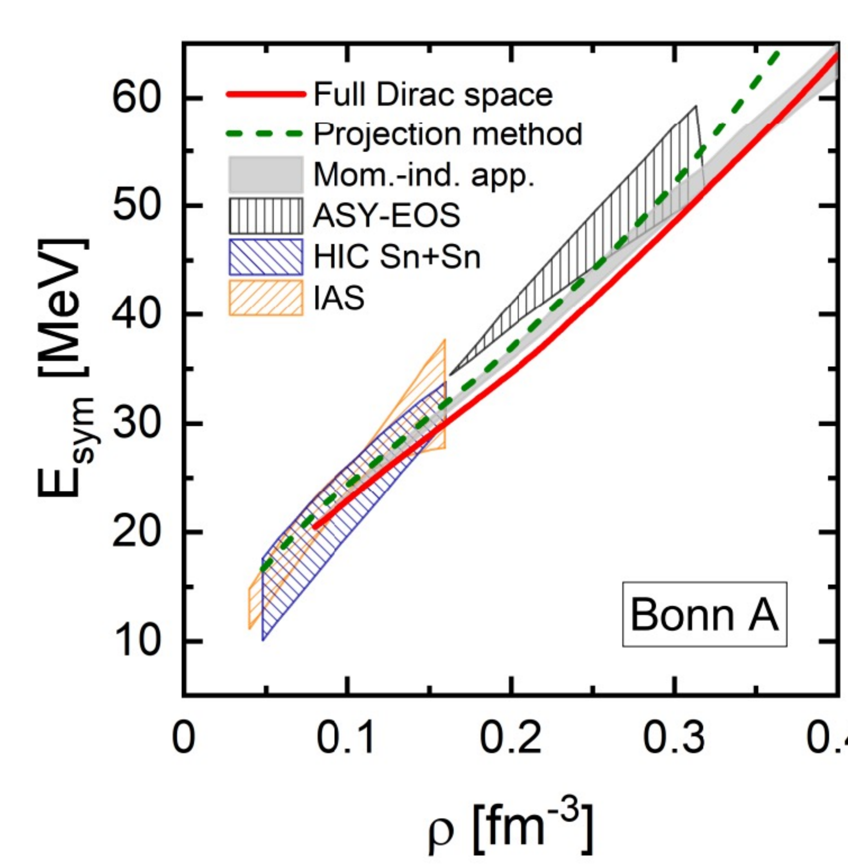
✓ The momentum dependence of the single-particle potentials and U_V are important to get the correct relative size of $U_{S,n}$ and $U_{S,p}$.

Symmetry energy in the full Dirac space

- The Symmetry energy E_{sym} as a function of the density ρ calculated by the RBHF theory in the full Dirac space, in comparison with other theoretical calculations and experimental constrains.

	E_{sym}(MeV)	L(MeV)
This work	***33.1***	***65.2***
Empirical	31.7 ± 3.2	58.7 ± 28.1

M. Oertel *et al.*, RMP **89**, 015007 (2017)



Summary

- The relativistic Brueckner-Hartree-Fock theory in the full Dirac space is developed to study asymmetric nuclear matter.
- The Dirac mass $M^*_{D,n}<M^*_{D,p}$ is determined uniquely, and the long-standing controversy between the projection method and the momentum-independence approximation is solved.
- $E_{\text{sym}}=33.1$ MeV, $L=65.2$ MeV, in harmony with empirical values.