Strangeness in nuclei and neutron stars: a challenging puzzle

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Outline

✓ Strangeness in neutron stars:
  ▪ the hyperon puzzle

✓ Strangeness in nuclei:
  ▪ hypernuclei & experimental inputs

✓ The project:
  ▪ Auxiliary Field Diffusion Monte Carlo (AFDMC)
  ▪ hyperon-nucleon interaction

✓ Results:
  ▪ hypernuclei
  ▪ hyper-neutron matter → neutron stars

✓ Conclusions & Perspectives
Strangeness in neutron stars

- $E$ vs $\rho_b$
- $M$ vs $R$
- PNM
- TOV
- $R \sim 12\,\text{km}$
- $M \sim 1.4\,M_\odot$
Strangeness in neutron stars

\[ \mu_\Lambda = \mu_n \]

\[ \rho_\Lambda^{th} \sim 2 \div 3 \rho_0 \]

\[ R \sim 12 \text{ km} \]
\[ M \sim 1.4 \, M_\odot \]

\[ npe\mu \]
\[ \Lambda \, \Sigma \, \Xi \]
\[ \pi_c \, K_c \, q_p \]

\( 940 \text{ MeV} \)
\( 1116 \text{ MeV} \)
\( 1200 \text{ MeV} \)
\( 1300 \text{ MeV} \)
Strangeness in neutron stars

- Theoretical indication for hyperons in NS core: softening of the EoS
- Observation of massive NS: stiff EoS
- Magnitude of the softening: strongly model dependent
- Interactions poorly known
- Non trivial many-body problem: very dense system, strong interactions

Hyperon puzzle

$\mu_\Lambda = \mu_n$

$\rho_\Lambda^{th} \sim 2/3 \rho_0$

$\mu = \mu_n$

$M > 2.0M_\odot$

$M < 2.0M_\odot$

obs: $\sim 2M_\odot$

$E \rightarrow HNM$

$E \rightarrow \rho_b$

$M \rightarrow TOV$

$R \rightarrow 12\ km$

$\mu_\Lambda = \mu_n$

$\rho_\Lambda^{th} \sim 2/3 \rho_0$
Strangeness in nuclei

binding energies: scattering data:

\begin{align*}
\text{nuc} & : \sim 3340 \\
\Lambda \text{ hyp} & : \sim 41 \\
\Lambda \Lambda \text{ hyp} & : \sim 5 \\
\Sigma \text{ hyp} & : \sim (1) \\
NN & : \sim 4300 \\
\Lambda N & : \sim 52 \\
\end{align*}

✓ Interactions poorly known

✓ Non trivial many-body problem: very dense system, strong interactions
The project: AFDMC

✓ Diffusion Monte Carlo

\[
|\psi(\tau + d\tau)\rangle = e^{- (H - E_T)d\tau} |\psi(\tau)\rangle \quad \tau \rightarrow \infty \quad \text{ground state}
\]

\[
P \sim e^{- \frac{1}{2} \lambda d\tau \mathcal{O}^2} \quad \Rightarrow \quad |\psi(\tau + d\tau)\rangle \sim 2^A \quad \text{components}
\]

✓ Auxiliary Field Diffusion Monte Carlo

Idea: single particle wave function + Hubbard-Stratonovich transformation

\[
|\psi\rangle \sim \bigotimes_i |\varphi_i\rangle \sim A \quad \Rightarrow \quad e^{- \frac{1}{2} \lambda \mathcal{O}^2} = \frac{1}{\sqrt{2\pi}} \int dx \ e^{-\frac{x^2}{2} + \sqrt{-\lambda} x \mathcal{O}}
\]

AFDMC:

finite systems: \( A \sim 90 \)

infinite systems: \( A \sim 140 \)

✓ Interactions poorly known

✓ Non trivial many-body problem: very dense system, strong interactions
The project: hyperon-nucleon interaction

Quantum Monte Carlo (Auxiliary Field Diffusion Monte Carlo)

- 2b+3b nucleon-nucleon phenom. interaction: Argonne & Urbana
- 2b+3b hyperon-nucleon phenom. interaction: Argonne like

Bodmer, Usmani, Carlson et al.

- pion exchange model
- local in coordinate space
- explicit 2-body and 3-body terms
- hard-core repulsion
- charge symmetry breaking terms

\[ H = T_N + V_{NN} + V_{NNN} \]
\[ + T_\Lambda + V_{AN} + V_{ANN} \]

VMC calculations: light hypernuclei
CVMC calculations: A=17

suitable for AFDMC calculations
The project: hyperon-nucleon interaction

Quantum Monte Carlo (Auxiliary Field Diffusion Monte Carlo)

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VMC calculations: light hypernuclei

CVMC calculations: A=17

$\Lambda N$ scattering data
$A = 4$ asymmetry

no unique form: fit on exp data

$B_\Lambda = E^{(A-1)} - E^{(\Lambda Z)}$
Results: hypernuclei

![Graph showing the binding energy $B_\Lambda$ vs. $A^{-2/3}$ for various hypernuclei with $\Lambda$ binding energies from VMC. The graph includes data points for $^{91}\Lambda$Zr, $^{41}\Lambda$Ca, $^{17}\Lambda$O, $^{13}\Lambda$C, $^{7}\Lambda$He, $^{6}\Lambda$He, and $^{5}\Lambda$He, along with experimental (exp), $\Lambda N$ (red circles), and $\Lambda N + \Lambda NN$ (I) (blue diamonds) curves.]


Results: hypernuclei

Results: hypernuclei

\[ B_\Lambda \text{ [MeV]} \]

\[ A^{-2/3} \]

\begin{tabular}{cccccccccc}
0.0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 \\
0.0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5
\end{tabular}

\( B_\Lambda \) vs. \( A^{-2/3} \)

- Emulsion
- \((K^\prime,\pi^-)\)
- \((\pi^+,K^+)\)
- \((e,e'K^+)\)

\[ 208 \]
\[ 89 \]
\[ 40 \]
\[ 28 \]
\[ 16 \]
\[ 12 \]
\[ 9 \]
\[ 7 \]
\[ 6 \]
\[ 5 \]
\[ 4 \]
\[ 3 \]

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Results: hypernuclei

D. L., S. Gandolfi, F. Pederiva, in preparation

\[ B_\Lambda [\text{MeV}] \]

\[ A^{-2/3} \]

emulsion

\((K^-,\pi^-)\)

\((\pi^+,K^+)\)

\((e,e'K^+)\)

AFDMC
Results: hyper-neutron matter

\[ \mu_\Lambda(\rho_b, x_\Lambda) = \mu_n(\rho_b, x_\Lambda) \]

\[ x_\Lambda \equiv x_\Lambda(\rho_b) \]

EoS
\[
\begin{align*}
E_{\text{HNM}} & \equiv E_{\text{HNM}}(\rho_b) \\
\mathcal{E}_{\text{HNM}} & \equiv \mathcal{E}_{\text{HNM}}(\rho_b) \\
P_{\text{HNM}} & \equiv P_{\text{HNM}}(\rho_b)
\end{align*}
\]

AFDMC: neutrons + lambdas

\[ E_{\text{HNM}} \equiv E_{\text{HNM}}(\rho_b, x_\Lambda) \]
Results: hyper-neutron matter

\[ \rho_{\Lambda}^{th} = 0.24(1) \, \text{fm}^{-3} \]

\[ \rho_{\Lambda}^{th} = 0.34(1) \, \text{fm}^{-3} \]

Results: hyper-neutron matter

Results: hyper-neutron matter

no hyperon formation for \( \Lambda NN \) (II) up to \( \rho \sim 0.56 \) fm\(^{-3}\)
Results: hyper-neutron matter

Dramatic effect of three-body hyperon-nucleon potential

No hyperon formation for $\Lambda NN$ (II) up to $\rho \sim 0.56$ fm$^{-3}$

Conclusions & Perspectives

✓ Status

› development of a Quantum Monte Carlo algorithm for hypernuclear systems
› the three-body hyperon-nucleon interaction plays a fundamental role in both finite and infinite hypernuclear systems
› more constraints on the nature of hyperon-neutron forces are needed before drawing any conclusion on the role played by hyperons in neutron stars
› *hyperon puzzle* still not solved

✓ Needs & Developments

› experimental inputs: scattering data, energy spectrum (gs+exc), CSB effect, exotic neutron rich hypersystems
› NN(N) and YN(N) different potentials: Nijmegen, chiral, (isospin projected)
› benchmark calculations
› realistic (hyper)nuclear matter in beta equilibrium