Nuclear structure IV:
Nuclear physics and Neutron stars

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Nuclear astrophysics:

- What’s the relation between nuclear physics and neutron stars?
- What are the composition and properties of neutron stars?
- How do supernovae explode?
- How are heavy elements formed?
$^{208}\text{Pb}$, $\sim 10^{-15}$ m, $10^{-25}$ kg
Nuclei and neutron stars

$^{208}Pb$, $\sim 10^{-15}$ m, $10^{-25}$ kg

neutron star, $\sim 10$ Km, $10^{30}$ kg ($2 M_{\text{solar}}$)
Can we really describe nuclei and neutron stars starting from the same forces???
TOV equations:

\[
\frac{dP}{dr} = -\frac{G[m(r) + 4\pi r^3 P/c^2][\epsilon + P/c^2]}{r[r - 2Gm(r)/c^2]}, \quad \frac{dm(r)}{dr} = 4\pi \epsilon r^2,
\]

Boundary conditions: \( P(r = 0) = P_c \) and \( P(r = R_{\text{max}}) = 0 \) (surface). An equation of state \( P(\rho) \) is needed.
Neutron matter and neutron star structure

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Other useful quantities to know:

\( \epsilon(\rho) = \rho \left[ E(\rho) + m_N \right] \) energy density

\( P(\rho) = \rho^2 \frac{\partial E}{\partial \rho} \) pressure

The total mass of the star is given by

\[ M(R) = \int_0^R dr \ 4\pi r^2 \epsilon(r) \]
Neutron matter and neutron star structure

$$n/n_s$$

$$M (M_\odot)$$

$$R (\text{km})$$

maximum mass

J. Lattimer
Equation of state of neutron matter

Many many EOS of neutron matter exist! Just "some":

Özel, Freire, arXiv (2016)

Which one(s) (if any) support neutron stars observations?
The main constrain: maximum mass.


**Neutron star structure test the EOS!**
Neutron star radius sensitive to the EOS at nuclear densities. Maximum mass depends mostly to the composition.
Accurate measurement of $E_{sym}$ put a constraint to the radius of neutron stars, OR observation of M and R would constrain $E_{sym}$!
Neutron star observations can be used to ‘measure’ the EOS and constrain $E_{sym}$ and $L$. (Systematic uncertainties still under debate...)
Neutron star matter really matters!

$E_{\text{sym}} = 33.7 \text{ MeV}$

$E_{\text{sym}} = 32 \text{ MeV}$

Polytropes

Quark matter

Steiner, Gandolfi, PRL (2012), Gandolfi et al. EPJA (2014)
Fundamental questions in nuclear physics

- What is the equation of state of dense matter?
- What is the composition of neutron stars?
- How do supernovae explode?
- How are heavy elements formed?
Neutron stars

- Atmosphere: atomic and plasma physics
- Crust: physics of superfluids (neutrons, vortex), solid state physics (nuclei)
- Inner crust: deformed nuclei, pasta phase
- Outer core: nuclear matter
- Inner core: hyperons? quark matter? $\pi$ or $K$ condensates? ...

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Let’s discuss only one possible scenario: hyperons
If chemical potential large enough ($\rho \sim 2 - 3\rho_0$), heavier particles form, i.e. $\Lambda$, $\Sigma$, ...

For example: it might be energetically convenient to change a neutron(ddu) into a $\Lambda$(uds).
In order to infer the hyperon-nucleon interactions, *hypernuclei* can be created in experiments!

\[ K^- \{ \bar{u} \}_{s} \rightarrow \bar{u}^+ d \rightarrow \bar{u}^- d \rightarrow \pi^- \]

\[ (K^-, \pi^-) \text{ reaction} \]

\[ n \{ d \}_{s} \rightarrow s \rightarrow d \rightarrow \Lambda \]

\[ (\pi^+, K^+) \text{ reaction} \]

\[ e \{ u \}_{s} \rightarrow \gamma^* \rightarrow \bar{s} \rightarrow \bar{u} \rightarrow K^+ \]

\[ (e, e' K^+) \text{ reaction} \]
Few thousands of binding energies for normal nuclei are known. Only few tens for hypernuclei.
Hypernuclei and hypermatter:

\[
H = H_N + \frac{\hbar^2}{2m_\Lambda} \sum_{i=1}^{A} \nabla_i^2 + \sum_{i<j} v_{ij}^\Lambda + \sum_{i<j<k} V_{ijk}^\Lambda
\]

\(\Lambda\)-binding energy calculated as the difference between the system with and without \(\Lambda\).
\( \Lambda \) hypernuclei

\( \nu^{\Lambda N} \) and \( \nu^{\Lambda NN}(I) \) are phenomenological (Usmani).

\( V^{\Lambda NN}(I) \) is a new form where the parameters have been fine tuned. As expected, the role of \( \Lambda NN \) is crucial for saturation.


\( V^{\Lambda NN}(II) \) is a new form where the parameters have been fine tuned. As expected, the role of \( \Lambda NN \) is crucial for saturation.
Neutrons and $\Lambda$ particles:

$$\rho = \rho_n + \rho_\Lambda, \quad x = \frac{\rho_\Lambda}{\rho}$$

$$E_{\text{HNM}}(\rho, x) = \left[ E_{\text{PNM}}((1-x)\rho) + m_n \right] (1-x) + \left[ E_{\text{P\Lambda M}}(x\rho) + m_\Lambda \right] x + f(\rho, x)$$

where $E_{\text{P\Lambda M}}$ is the non-interacting energy (no $\nu_{\Lambda\Lambda}$ interaction),

$$E_{\text{PNM}}(\rho) = a \left( \frac{\rho}{\rho_0} \right)^\alpha + b \left( \frac{\rho}{\rho_0} \right)^\beta$$

and

$$f(\rho, x) = c_1 \frac{x(1-x)\rho}{\rho_0} + c_2 \frac{x(1-x)^2 \rho^2}{\rho_0^2}$$
Λ-neutron matter

EOS obtained by solving for \( \mu_\Lambda(\rho, x) = \mu_n(\rho, x) \)

Lonardoni, Lovato, Pederiva, Gandolfi, PRL (2015)

No hyperons up to \( \rho = 0.5 \text{ fm}^{-3} \) using \( \Lambda NN \) (II)!!!
Drastic role played by $\Lambda NN$. Calculations can be compatible with neutron star observations.

Note: no $v_{\Lambda\Lambda}$, no protons, and no other hyperons included.
Hyperons

Understanding hyperon-nucleon interactions is crucial, but very few experimental data available:

- \( \sim 4500 \) NN scattering data available, \( \sim 30 \Lambda N \)
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Future, more ΛN experiments and/or **Lattice QCD**. Example: phase-shifts calculated with Lattice QCD.

Future, more $\Lambda N$ experiments and/or Lattice QCD. Example: attempt to extract the potential with Lattice QCD:

HAL QCD collaboration.
Stay tuned...

Remember, hyperons in dense matter is only **one possible** scenario. Very active field...
Summary of this lecture before the general summary:

- Neutron star structure from the EOS
- Maximum mass and radii
- Hyperons and dense matter
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Wrap up...

- Fundamental Symmetries (BSM)
- e⁻ and ν scattering
- QCD
- NUCLEAR REACTIONS
- HYPERNUCLEI
- NUCLEAR MATTER
- ELECTROWEAK INTERACTIONS
- NUCLEAR INTERACTIONS
- Neutron stars/ supernovae
- Dark matter
- β and ββ decay
- Computational physics
The last but very important lesson.
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Always acknowledge the funding agencies!!!