Strangeness in Nuclei and Neutron Stars

Laura Tolós

based on
Laura Tolos and Laura Fabbietti,
Prog. Part. Nucl. Phys. 112 (2020) 103770, 2002.09223 [nucl-ex]
Strangeness Hyperons in Nuclei and Neutron Stars

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Outline

- Hyperons and where to find them
- YN and YY interactions
- Hypernuclei
- Hyperons in matter
- Hyperons and Neutron Stars
- Present and Future
A hyperon is a baryon containing one or more strange quarks.

| Hyperon | Quarks | I(J^P)       | Mass (MeV) |
|---------|--------|--------------|------------|
| Λ       | uds    | 0(1/2^+)    | 1115       |
| Σ⁺      | uus    | 1(1/2^+)    | 1189       |
| Σ⁰      | uds    | 1(1/2^+)    | 1193       |
| Σ⁻      | dds    | 1(1/2^+)    | 1197       |
| Ξ⁺      | uss    | 1/2(1/2^+)  | 1315       |
| Ξ⁻      | dss    | 1/2(1/2^+)  | 1321       |
| Ω⁻      | sss    | 0(3/2^+)    | 1672       |

credit: I. Vidana
A hyperon is a baryon containing one or more strange quarks. The study of hypernucleus allows for:

- new spectroscopy
- information on strong and weak interactions between hyperons and nucleons

| Hyperon | Quarks | I(J^P) | Mass (MeV) |
|---------|--------|--------|------------|
| Λ       | uds    | 0(1/2^+) | 1115       |
| Σ⁺      | uus    | 1(3/2^+) | 1189       |
| Σ⁰      | uds    | 1(1/2^+) | 1193       |
| Σ⁻      | dds    | 1(3/2^-) | 1197       |
| Ξ⁺      | uus    | 1/2(1/2^+) | 1315      |
| Ξ⁻      | dss    | 1/2(3/2^-) | 1521      |
| Ω⁻      | sss    | 0(5/2^-) | 1672       |
In Neutron Stars

YN and YY interactions
YN and YY interactions

- Study strangeness in nuclear physics
- Provide input for hypernuclear physics and astrophysics

**Scarce YN scattering data** due to the short life of hyperons and the low-density beam fluxes

\( \Lambda N \) and \( \Sigma N \): < 50 data points
\( \Xi N \) very few events

\( NN \): > 5000 data for \( E_{\text{lab}} < 350 \text{ MeV} \)

**Data from hypernuclei:**

- more than 40 \( \Lambda \)-hypernuclei (\( \Lambda N \) attractive)
- few \( \Lambda \Lambda \)-hypernuclei (\( \Lambda \Lambda \) weak attraction)
- few \( \Xi \)-hypernuclei (\( \Xi N \) attractive)
- no evidence of \( \Sigma \)-hypernuclei (\( \Sigma N \) repulsive)
Theoretical approaches to YN and YY

- **Meson exchange models (Juelich/Nijmegen models)**
  To build YN and YY from a NN meson-exchange model imposing SU(3)$_{\text{flavor}}$ symmetry
  - **Juelich**: Holzenkamp, Holinde, Speth ‘89; Haidenbauer and Meißner ‘05
  - **Nijmegen**: Maesen, Rijken, de Swart ‘89; Rijken, Nagels and Yamamoto ‘10

- **Chiral effective field theory approach (Juelich-Bonn-Munich group)**
  To build YN and YY from a chiral effective Lagrangian similarly to NN interaction
  - **Juelich-Bonn-Munich**: Polinder, Haidenbauer and Meißner ‘06; Haidenbauer, Petschauer, Kaiser, Meißner, Nogga and Weise ‘13
  - Kohno ‘10; Kohno ‘18

- **Quark model potentials**
  To build YN and YY within constituent quark models
  Fujiwara, Suzuki, Nakamoto ‘07
  Garcilazo, Fernandez-Carames and Valcarce ‘07 ‘10

- **$V_{\text{low } k}$ approach**
  To calculate a “universal” effective low-momentum potential for YN and YY using RG techniques
  Schaefer, Wagner, Wambach, Kuo and Brown ‘06

- **Lattice calculations (HALQCD/NPLQCD)**
  To solve YN and YY interactions on the lattice
  - **HALQCD**: Ishii, Aoki, Hatsuda ‘07; Aoki, Hatsuda and Ishii ‘10; Aoki et al ‘12
  - **NPLQCD**: Beane, Orginos and Savage ‘11; Beane et al ‘12
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**YN (and YY) meson-exchange models**

Built from a **NN meson-exchange model imposing SU(3)\text{\textsubscript{flavor}} symmetry**

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**NIJMEGEN**

*(Nagels, Rijken, de Swart, Timmermans, Maessen..*)

- Based on Nijmegen NN potential
- Momentum and Configuration Space
- Exchange of pseudoscalar, vector and scalar nonets
- SU(3) symmetry to relate YN to NN vertices
- Gaussian form factors

**JUELICH**

*(Holzenkamp, Reube, Holinde, Speth, Haidenbauer, Meissner, Melnitchouck..*)

- Based on Bonn NN potential
- Momentum Space, Full Energy Dependence & Non-localities
- Exchange of single mesons and higher order processes
- SU(6) symmetry to relate YN to NN vertices
- Dipolar form factors
ΛN and ΣN scattering

\[ T = V + V \frac{1}{E_0 - H_0 + i\eta} T \]

New results from femtoscopy for Σ⁰p

\[ C(k^*) = \mathcal{N} \times \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} \]

\[ k^* = \frac{1}{2} \times | \mathbf{p}_1^* - \mathbf{p}_2^* | \]

S. Acharya et al. 2019
YN (and YY) interactions in $\chi$EFT

Baryon-Baryon interaction in SU(3) $\chi$EFT a la Weinberg (1990);

- **power counting** allowing for a systematic improvement by going to higher order
- derivation of **two- and three-baryon forces** in a consistent way

Degrees of freedom: **octet of baryons** (N, Λ, Σ, Ξ) & **pseudoscalar mesons** ($\pi, K, \eta$)

Diagrams: **pseudoscalar-meson exchanges and contact terms**

credit: Haidenbauer

\[
\begin{align*}
\nu &= 2 - B + 2L + \sum_i v_i \Delta_i, \\
\Delta_i &= d_i + \frac{1}{2} b_i - 2,
\end{align*}
\]

B: number of incoming (outgoing) baryons
L: number of Goldstone boson loops
$v_i$: number of vertices with dimension $\Delta_i$
$d_i$: derivatives
$b_i$: number of internal baryons at vertex

LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244

NLO: J.H., N. Kaiser, U.-G. Meißner, A. Nogga, S. Petschauer, W. Weise, NPA 915 (2013) 24
ΛN and ΣN scattering

\[ T = V + V \frac{1}{E_0 - H_0 + i\eta} T \]

New results from femtoscopy for Σ^0p

\[ C(k^*) = N \times \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} \]

\[ k^* = \frac{1}{2} \times |P_1^* - P_2^*| \]

S. Acharya et al. 2019
$\Xi N$ scattering

$T = V + V \frac{1}{E_0 - H_0 + i\eta} T$

$\Xi N$ cross sections are small
J. Haidenbauer and
U.G. Meißner EPJA 55 (2019) 23

Scarce experimental information.
New results from femtoscopy

S. Acharya et al. 2019
Hypernuclei

\( \Lambda \) hypernuclei

- Strangeness exchange: \( n(K^-, \pi^-)\Lambda \)
- Associated production: \( n(\pi^+, K^+)\Lambda \)
- Electroproduction: \( p(\gamma, K^+)\Lambda \)

Double \( \Lambda \) hypernuclei

- PANDA@FAIR

credit: A. Sanchez-Lorente

Also \( \Xi \) hypernuclei @ BNL, KEK

\[ 12C(K^-, K^+) 12_{\Xi^-}Be \]

\[ K^- + p \rightarrow \Xi^- + K^+ \]
Physics that can be addressed:
- YN and YY interactions
- YN→NN weak decay
- Hypernuclear structure

credit: Axel Perez-Obiol
Binding energy of different hypernuclei as function of the mass number

Binding energy saturates at about -30 MeV for large nuclei

Single-particle model reproduces the data quite well  

Conflicting measurements by STAR and ALICE of the hypertriton lifetime triggered the revived experimental and theoretical interest
Hyperons in matter

Λ and Σ in dense matter

\[ k_F = 1.35 \text{ fm}^{-1} (\rho_0 = 0.166 \text{ fm}^{-3}) \]

|          | EFT LO | EFT NLO |
|----------|--------|---------|
| \( \Lambda \) [MeV] | 550 \cdots 700 | 500 \cdots 650 |
| \( U_\Lambda(0) \) | -38.0 \cdots -34.4 | -28.2 \cdots -22.4 |
| \( U_\Sigma(0) \) | 28.0 \cdots 11.1 | 17.3 \cdots 11.9 |

- Empirical value of Λ binding in nuclear matter ~27-30 MeV

- \( \Sigma N \) (I=3/2): \( ^3S_1 - ^3D_1 \) decisive for Σ properties in nuclear matter. YN data can be reproduced with attractive and repulsive \( ^3S_1 - ^3D_1 \) interaction. It is chosen to be repulsive in accordance to data on \( \Sigma^- \) atoms and \( (\pi^-, K^+) \) inclusive spectra for \( \Sigma^- \) formation in heavy nuclei. Lattice* supports repulsion!

* Nemura et al EPJ Web of Conferences 175 (2018) 05030

Haidenbauer and Meißner, NPA 936 (2015) 29
Improving on the calculation by using $\chi$EFT NN interaction and continuous choice in Brueckner-Hartree-Fock approach while investigating isospin-asymmetric matter

S. Petschauer, J. Haidenbauer, N. Kaiser, U.G. Meißner and W. Weise EPJA 52 (2016) 15

Symmetric nuclear matter

Neutron matter

$\Lambda$ single-particle potential at NLO turns repulsive $k \sim 2$ fm$^{-1}$

Strong isospin dependence of the $\Sigma N$ interaction

$\Sigma$-nuclear potential is moderately repulsive for LO and NLO
Moderately attractive $\Xi$-nuclear interaction, with $U_\Xi(0,k_{F0}) \sim -3$ to $-5$ MeV.
Smaller than $U_\Xi(n_0) \sim 14$ MeV Khaustov et al'00
and in line with other BHF studies with phenomenological $\Xi N$ potentials.
Λ in dense matter: including three-body forces

Three-body forces are required to reproduce few-nucleon binding energies, scattering observables and nuclear saturation in non-relativistic many-body approaches.

To use it in many-body calculations, such as BHF, one has to construct a density-dependent two-body interaction.

Λ in dense matter

symmetric matter

neutron matter

χEFT gives little attraction or even repulsion for \( n > n_0 \)

In neutron stars, hyperons will appear at high density!!

Solution of the Hyperon Puzzle?

J. Haidenbauer, U.G. Meißner, N. Kaiser and W. Weise EPJA 53 (2017) 121
Hyperons and Neutron Stars

- produced in core collapse supernova explosions, usually observed as pulsars

- usually refer to compact objects with $M \approx 1\text{–}2 \, M_\odot$ and $R \approx 10\text{–}12 \, \text{Km}$

- extreme densities up to $5\text{–}10 \, \rho_0$ ($n_0 = 0.16 \, \text{fm}^{-3} \Rightarrow \rho_0 = 3 \times 10^{14} \, \text{g/cm}^3$)

- magnetic field: $B \sim 10^{8..16} \, \text{G}$

- temperature: $T \sim 10^{6...11} \, \text{K}$

- observations: masses, radius (?), gravitational waves, cooling…
GW170817
Abbot et al. (LIGO-VIRGO) '17 ‘18

NICER
PSR J0030+0451
R_{eq}=12.71_{-1.19}^{+1.14} \text{ km}
M=1.34_{-0.16}^{+0.15} \text{ M}_\odot
Riley et al. ‘19

R_{eq}=13.02_{-1.06}^{+1.24} \text{ km}
M=1.44_{-0.14}^{+0.15} \text{ M}_\odot
Miller et al. ‘19

..also GW250419?
• **primary ingredient:**
  EoS: $\varepsilon(n)$, $P(n)$, $P(\phi)$
  in charge neutral $\beta$-stable matter

• **some constraints:**
  - Schwarzschild limit (GR)
    \[ R \geq 2 \frac{GM}{c^2} \]
  - causality limit for EoS
    \[ R \geq 2.9 \frac{GM}{c^2} \]
  - mass-shedding limit
    \[ R < \left( \frac{GM}{2\pi} \right)^{1/3} / \nu^{2/3} \]

**Need of simultaneous mass-radius measurements to constrain EoS !!!**

---

\[
\frac{dP}{dr} = -\frac{Gm\varepsilon}{c^2r^2} \left( 1 + \frac{P}{\varepsilon} \right) \left( 1 + \frac{4\pi r^3 P}{c^2 m} \right) \left( 1 - \frac{2Gm}{c^2r} \right)^{-1} \\
\frac{dm}{dr} = \frac{4\pi r^2 \varepsilon}{c^2}
\]
The Nucleonic Equation of State

The Equation of State (EoS) is a relation between thermodynamic variables describing the state of matter

**Microscopic Ab-initio Approaches:**
- based on solving the many-body problem starting from two- and three-body interactions
- Variational method: APR, CBF,..
- Quantum Montecarlo: AFDMC..
- Coupled cluster expansion
- Diagrammatic: BBG (BHF), SCGF..
- Relativistic DBHF
- RG methods: SRG from $\chi$EFT..
- Lattice methods

**Phenomenological Approaches:**
- based on density-dependent interactions adjusted to nuclear observables and neutron star observations
- Non-relativistic EDF: Skyrme..
- Relativistic Mean-Field (RMF) and Relativistic Hartree-Fock (RHF)
- Liquid Drop Model: BPS, BBP,..
- Thomas-Fermi model: Shen
- Statistical Model: HWN, RG, HS..

**Advantage:** systematic addition of higher-order contributions
**Disadvantage:** applicable up to? ($SRG \text{ from } \chi EFT \sim 1-2 n_0$)

**Advantage:** applicable to high densities beyond $n_0$
**Disadvantage:** not systematic
First proposed in 1960 by Ambartsumyan & Saakyan

Traditionally neutron stars were modeled by a uniform fluid of neutron rich matter in $\beta$-equilibrium

but more exotic degrees of freedom are expected, such as hyperons, due to:

• high value of density at the center and
• the rapid increase of the nucleon chemical potential with density

Hyperons might be present at $n \sim (2-3)n_0$ !!!
**β-stable hyperonic matter**

$\mu_N$ is large enough to make $N \rightarrow Y$ favorable

\[
\begin{align*}
n + n & \rightarrow n + \Lambda \\
p + e^- & \rightarrow \Lambda + \nu_e \\
n + n & \rightarrow p + \Sigma^- \\
n + e^- & \rightarrow \Sigma^- + \nu_e
\end{align*}
\]

\[
\mu_i = b_i \mu_n - q_i \mu_e
\]

\[
\sum_i x_i q_i = 0
\]
Inclusion of hyperons....

softening of the EoS by the presence of hyperons

..... induces a strong softening of the EoS that leads to $M_{\text{max}} < 2M_{\odot}$

Chatterjee and Vidana '16
Vidana '18
The Hyperon Puzzle

Scarce experimental information:

- data from several single \( \Lambda \) and few \( \Xi \) hypernuclei, and few double \( \Lambda \) hypernuclei

- few YN scattering data (\( \sim 50 \) points) due to difficulties in preparing hyperon beams and no hyperon targets available

- YN data from femtoscopy

The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the EoS that leads to maximum neutron star masses \( < 2M_\odot \).

Solution?

- stiffer YN and YY interactions
- hyperonic 3-body forces
- push of Y onset by \( \Delta \)-isobars or meson condensates
- quark matter below Y onset
- dark matter, modified gravity theories…
Future: space missions to study the interior of NS

Constraints from pulse profile modelling of rotation-powered pulsars with eXTP and multimessenger astronomy
A lot of experimental, observational and theoretical effort has been invested to understand **hyperons in nuclei and neutron stars**.

**Hyperon-nucleon and hyperon-hyperon interactions** are crucial for hypernuclear physics and the physics of compact objects, such as neutron stars.

**Neutron stars** provide a unique scenario for testing hyperons at extreme densities.

The **future of hyperon physics** relies on particle and nuclear experiments as well as X-ray and multimessenger astronomy.