Exploration of In-Medium Hyperon-Nucleon Interactions

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HYP2022, Prague, Czech Republic, June 27-July 1, 2022

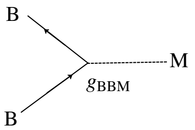
HYP 2022 PRAGUE
14th International Conference on Hypernuclear and Strange Particle Physics
June 27 – July 1, 2022
Prague, Czech Republic

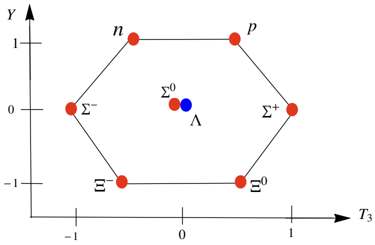
Motivation

- Astrophysical Applications: "Hyperonization puzzle"
- Present Experimental Analysis: heavy-ion collisions, hypernuclear experiments (J-PARC, MAMI, J-Lab, KEK etc.)
- Investigation on SU(3) symmetry limit

Exploring medium effect

- Using baryon-baryon scattering data and SU(3) constraints to build OBE potential → Medium effect by G-matrix calculation → input for hypernuclear density functional and structure calculations → This talk
- Using nucleon-data and G-matrix calculations → deriving effective in-medium coupling constants using SU(3) relations for baryon vertices → Talk by Horst Lenske, 30.06.22, 11 am





Bare Interaction

- SU(3) Flavour Interaction Lagrangian

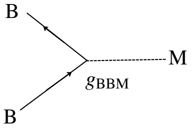
$$\mathcal{L} = -g\alpha\, Tr([B, \bar{B}]\ \phi)$$

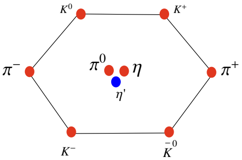
$$+g(1\text{-}\alpha)\, Tr(\{\bar{B}, B\}\ \phi)$$

- SU(3) One-Boson-Exchange Potential (OBEP) formed used to solve 3D Lippman-Schwinger Equation

Model Parameters

$$\mathcal{L}_{int} = -g\alpha Tr([B, \bar{B}]\ \phi) + g(1-\alpha) Tr(\{\bar{B}, B\}\ \phi)$$



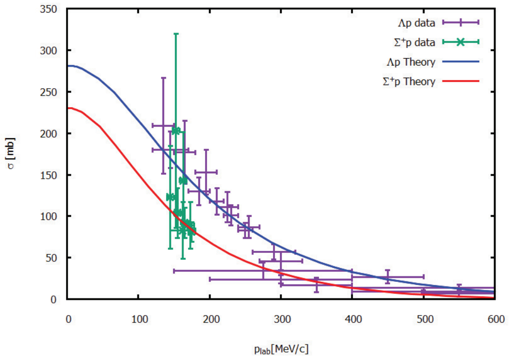


1. **Mass of the meson (m)** $\Rightarrow$ PDG
2. **Coupling strength of BBM vertex (g, α)**
3. Mixing angle (θ)
4. Cut-off (Λ_c)

Free model parameters: g_8, g_1, α, θ, Λ_c
$\Rightarrow$ Fixed by data fit and SU(3) flavour symmetry
$\Rightarrow$ Effective 'hybrid' approach: Theory + phenomenology

Fit to World Data

$\Sigma^+ p$ and Λp calculated cross section (theory) plotted compared to bubble chamber data



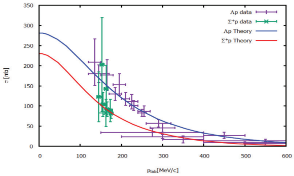
Fit Result

- χ^2 : 6.68, $\frac{\chi^2}{data} = 0.42$

[Data: Eisele et al.(1971), Hauptmann et al.(1977), Kadyk et al.(1971), Alexander et al.(1968)]

Fit to World Data

$\Sigma^+ p$ and Λp calculated cross section (theory) plotted compared to bubble chamber data



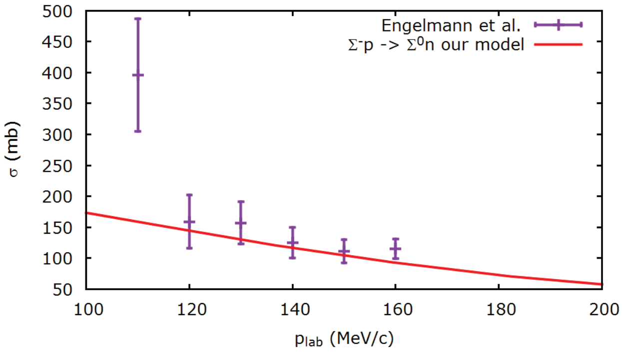
Data Fit Result (χ^2 : 6.68)

	$\frac{g_8}{\sqrt{4\pi}}$	$\frac{g_1}{\sqrt{4\pi}}$	α	θ	Λ_c
pseudoscalar	3.795	0.1913	0.355	-23	1.3
scalar	1.2274	3.5434	0.96053	37.05	2
vector	1.1566	3.4431	1.0	35.26	1.7

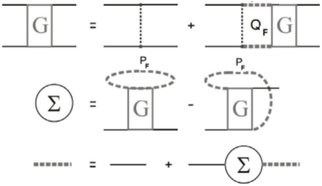
scalar and vector theta : close to ideal mixing angle, pseudoscalar reflects $\eta - \eta'$ mixing.

S = -1

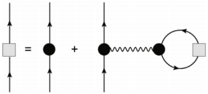
$\Sigma^- p \Rightarrow \Sigma^0 n$ cross section



$\Rightarrow$ Good description of data.



Derive Vertex Functionals

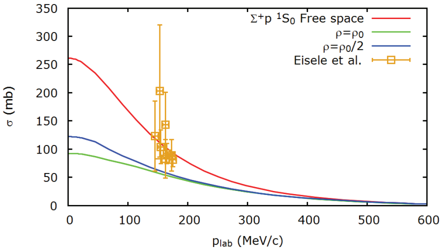


$$\Gamma_{BB'a}(q_s, k_F) \simeq \frac{1}{1 - \int dq' V_a \mathcal{G}^* Q_F}\bigg|_{BB'} g_{BB'a}.$$

How to Study medium effect?

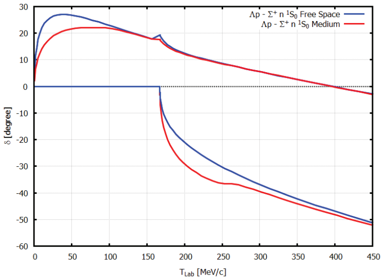
- 1. Through Pauli Blocking in Bethe-Goldstone equation $T = V + \int VQGT$
- Interactions are in nested manner to all orders into propagators, G-matrix equations, and self-energies
- Density dependence mainly caused by Pauli-blocking

Medium effect on channel mixing and cross section



$\Sigma^+ p \quad {}^1S_0$ cross section

- Medium weakens the strength of the interaction
- Mainly by NN Pauli-Blocking



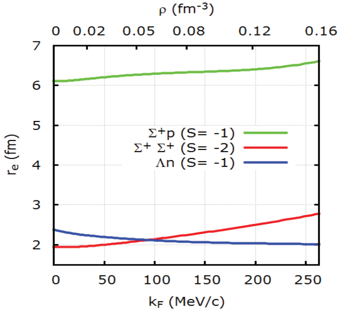
$\Lambda p \rightarrow \Sigma^+ n \ {}^1S_0$ phase shift in vacuum (blue) and nuclear matter (red)

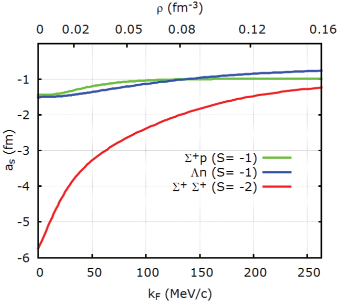
Medium affects 'cusp' and channel mixing

Low Energy Parameters

$\lim_{q\to 0} q\cot\delta \approx -\frac{1}{a_s} + \frac{1}{2} r_e q^2$, a_s: scattering length, r_e: effective range → Direct information of interaction

Density Effect





- density dependent BBM interaction vertices → $g(\rho)$,$\alpha(\rho)$
- Medium effect on higher strangeness is enhanced → Channel dependent behavior.

Low Energy Parameters: Nuclear Structure information

$\lim_{q\to 0} q\cot\delta \approx -\frac{1}{a_s} + \frac{1}{2} r_e q^2$, a_s: scattering length, r_e: effective range → Direct information of interaction

Hypernuclear Mean Fields

- In-medium singlet and triplet scattering lengths determine the nuclear matter potential.
- Nuclear matter hyperon potential in leading order

$$U_\Lambda(\rho) = \frac{4\pi\hbar^2}{2\mu_{BB}} \left(\frac{1}{4} a^{SE}_{BB}(\rho) + \frac{3}{4} a^{TE}_{BB}(\rho) \right) \rho = U_{\Lambda 0}(\rho)$$

$$= \mathrm{U}_{\Lambda\omega}(\rho) + U_{\Lambda\sigma}(\rho_s)$$

for a total nuclear density ρ given by the isoscalar condensed omega and sigma meson mean-fields .

Other Hyperon Mean Fields

- Σ mean-field for $q = \pm 1, 0$ accordingly

$$U_{\Sigma^q}(\rho) = U_{\Sigma 0}(\rho) + \frac{3}{4} U_{\Sigma 1}(\rho)$$

- With the isovector mean-field given by the nuclear isovector density ρ_1

$$U_{\Sigma 1}(\rho) = \frac{4\pi\hbar^2}{2\mu_{\Sigma N}} \left(a_{\Sigma N}^{SE} - a_{\Sigma N}^{TE} \right) \rho_1 = U_{\Sigma\rho}(\rho_p, \rho_n) + U_{\Sigma\delta}(\rho_{sp}, \rho_{sn})$$

- Accordingly for the Cascade mean-fields $U_{\Xi 0}$ and $U_{\Xi 1}$
- Effective range item terms $\rightarrow$ momentum dependence of the baryon mean-fields
- caveat: lack of scattering data
- Solved by "extrapolation" using SU(3) relations between BB-meson coupling constants

Summary and Outlook

Summary

- Revised version OBE for hyperons
- Baryon scattering amplitudes and Low-energy parameters in nuclear matter
- Scattering lengths and effective ranges as functions of density
- Hyperon mean-fields from low-energy parameters

Outlook

- Talk by Horst Lenske, Tomorrow: Derive a covariant Baryon-EDF by using Dirac-Brueckner-Hartree-Fock (DBHF) vertex functional
- Applications to finite nuclei
- Hyper-matter to astrophysical studies

My heartfelt gratitude to the organizers for making it possible to attend the prestigious HYP2022 - virtually.

References

1.H. Lenske, M. Dhar et al., Progress in Particle and Nuclear Physics 98 (2018) 119–206,
2. M. Dhar, Hyperon Interaction in Free Space and Nuclear Matter Within a SU(3) Based Meson Exchange Model (Dissertation JLU Giessen), 2016,
3. H. Lenske, M. Dhar, Lect.Notes Phys. 948 (2018) 161

Back UP

Comparison of Different Meson Exchange Models

Model	Mesons	Channels	Para. (free:fit)	$SU(3)_f$	NN fit	Form Factor
GiBE	nonets	OBE	15:3	✓	×	Dipole
ESC	nonets +higher lying mesons +Pomeron	OBE + TME +MPE + Multi-P	20:20	✓ + Breaking	✓	Gaussian
Jülich04	nonets except σ, ρ, η	OBE +TME + MPE	27:27	SU(6)	✓	Dipole

TME: Two- Meson-Exchange, MPE: Meson-Pair-Exchange, Multi-P: Multi Pomeron Exchange

[Stoks et al.,PRC59(1999);Haidenbauer et al., PRC72(2005) 044005]

Low Energy Parameter Values

Channel	a_s^{free}	a_s^{sat}
$\Lambda n \rightarrow \Lambda n$	-1.50	-0.76
$\Sigma^+ p$	-1.44	-0.86
$\Sigma^+ \Sigma^+$	-5.75	-1.23

Channel	r_e^{free}	r_e^{sat}
$\Lambda n \rightarrow \Lambda n$	2.34	2.01
$\Sigma^+ p$	5.18	5.34
$\Sigma^+ \Sigma^+$	1.94	2.78