Baryon Interactions in Nuclear and Hypernuclear Matter

H. Lenske, C. Keil, R. Shyam
†

Institut für Theoretische Physik, Universität Giessen, D-35392 Giessen
†Saha Institute of Nuclear Physics, Calcutta, India

Abstract.
The production and structure of $\Lambda$ hypernuclei are investigated in field theoretical models. The production in coherent p+A reactions is investigated by means of a resonance model. Results of exploratory calculations for associated strangeness production are presented for proton reactions on $^{40}$Ca. The target single particle wave functions are obtained from DDRH theory with density dependent Dirac-Brueckner meson-baryon vertices. The dependence of the in-medium vertices on density is discussed.

INTRODUCTION

A major goal of hadron physics is to understand the interactions among the various members of the baryonic and mesonic flavor multiplets. For that aim an important class of processes is the implementation of a strange hadron into a nuclear environment by means of an appropriate reaction and investigations of the subsequent evolution of that system. Here we consider interaction within the lowest baryon flavor octet. We are especially interested in associated $K^+\Lambda$ strangeness production in hadronic reactions. As an interesting alternative to more common approaches using pion and kaon reactions $[1]$ we consider strangeness production in exclusive $p+A \rightarrow \Lambda (A+1) + K^+$ reactions at incident kinetic energies in the COSY energy regime. A field theoretical model is used describing associated strangeness production by the excitation of intermediate nucleon resonances decaying into the $K^+\Lambda$ channel. Since we are aiming at hypernuclei only those processes in which the hyperon in captured in a bound orbit are considered. Clearly, since these are highly selective reactions at large momentum transfer, a high sensitivity on nuclear wave functions has to be expected. We use DDRH theory $[2]$ as a state-of-the-art relativistic field theory for the nuclear structure calculations, known to describe both normal nuclei $[3]$ and hypernuclei $[4]$ very accurately. This allows us to investigate the production cross sections for various nuclear states thus establishing the link from the production to the spectroscopy of the final hypernuclei and sampling their wave function at momenta which otherwise are not accessible.
ASSOCIATED STRANGENESS PRODUCTION IN PROTON-NUCLEUS REACTIONS

The production of Λ-hypernuclei with high intensity proton beams is an interesting alternative to more common pion and antikaon induced production scenarios [1]. In principle, the production process can proceed in a variety of reactions like p + A(N,Z) → ΛB(N − 1,Z) + n + K+, p + A(N,Z) → ΛB(N,Z − 1) + p′ + K+, and p + A(N,Z) → ΛB(N,Z) + K+ where N and Z are the neutron and proton numbers, respectively, in the target nucleus. Here, we study the last reaction [to be referred to as A(p,K+)ΛB] which is exclusive in the sense that the final channel is a two body system. In this reaction the momentum transfer to the nucleus is much larger than in (π+,K+) reaction, about 1.0 GeV/c as compared to about 0.330 GeV/c in forward direction.

The elementary production process is a two-nucleon mechanism (TNM) [3,4,7] where the kaon production proceeds via a collision of the projectile nucleon with one of its target counterparts, thereby exciting intermediate baryonic resonances decaying in turn into a kaon and a Λ hyperon. The N*(1650), N*(1710), and N*(1720) states are especially important [6]. The nucleon and the hyperon are captured into nuclear orbitals while the kaon is rescattered onto its mass shell. Three active bound state baryon wave functions are taking part in the reaction process allowing the large momentum transfer to be shared among the participants.

We use a field theoretical approach with effective Lagrangians for the nucleon-nucleon-pion (NNπ) and N*-nucleon-pion (N*π) vertices [6]. They are given by

\[
\mathcal{L}_{NN\pi} = -\frac{g_{NN\pi}}{2m_N} \Psi \gamma_\mu \gamma_5 \tau \cdot (\partial^\mu \Phi_\pi) \Psi.
\]

(1)

\[
\mathcal{L}_{N^{1/2}_{1/2}\pi} = -\frac{g_{N^{1/2}_{1/2}\pi}}{m_N} \Psi N^{1/2}_{1/2} \Gamma \tau \Phi_\pi \Psi + h.c.,
\]

(2)

\[
\mathcal{L}_{N^{3/2}_{1/2}\pi} = \frac{g_{N^{3/2}_{1/2}\pi}}{m_N} \Psi N^{3/2}_{1/2} \Gamma \tau \cdot \partial^\mu \Phi_\pi \Psi + h.c..
\]

(3)

where \( m_N \) denotes the nucleon mass. The operator \( \Gamma_\pi \) is either \( \gamma_5 \) (unity) or unity (\( \gamma_5 \)) depending upon the parity of the resonance being even or odd, respectively. Following Ref. [7] we use a pseudovector (PV) coupling for the NNπ vertex and a pseudoscalar (PS) one for the \( N^{1/2}_{1/2}\pi \) vertex. The effective Lagrangians for the resonance-hyperon-kaon vertices are written as

\[
\mathcal{L}_{N^{1/2}_{1/2}\Lambda K^+} = -g_{N^{1/2}_{1/2}\Lambda K^+} \bar{\Psi} N^{1/2}_{1/2} \Gamma \tau \Phi_{K^+} \Psi + h.c.,
\]

(4)

\[
\mathcal{L}_{N^{3/2}_{1/2}\Lambda K^+} = \frac{g_{N^{3/2}_{1/2}\Lambda K^+}}{m_{K^+}} \bar{\Psi} N^{3/2}_{1/2} \Gamma \tau \cdot \partial^\mu \Phi_{K^+} \Psi + h.c..
\]

(5)

Here, \( \Psi_\mu^{N^*} \) is the vector spinor for the spin\( \frac{3}{2} \) particle. Further discussions about the vertices and coupling constants involving such particles are found in Refs. [6,7,8]. The amplitude for graph 1b with spin\( \frac{1}{2} \) baryonic resonance, for example, is given by,

\[
M_{1b}(N^{1/2}_{1/2}) = C^{1b}_{iso} \left( \frac{g_{NN\pi}}{2m_N} \right) \left( g_{N^{1/2}_{1/2}\pi} \right) \left( g_{N^{1/2}_{1/2}\Lambda K^+} \right) \bar{\Psi}(p_2) \gamma_5 \gamma_\mu q^\mu
\]


Angular distributions for production into various final $\Lambda$ single particle orbitals.

\[
\times \psi(p_1)D_\pi(q)\bar{\psi}(p_\Lambda)\gamma_5D_{N^*_1/2}(p_{N^*})\gamma_5
\times \phi^{(-)}_K(p'_K,p_K)\psi^{(+)}_{i}(p'_i,p_i),
\]

where various momenta are as defined in Fig. 1b. For a more detailed discussion we refer to ref. [6].

Angular distributions for associated strangeness production in a ($p,K^+$) reaction at $E_p = 2$ GeV on a $^{40}$Ca target are shown in fig. Although initial and final state interactions are at present not included the magnitude of the cross sections in the nano- to picobarn range can be expected to be realistic, ranging at the lower end of the experimental feasibility. The shapes of the angular distributions are depending sensitively on the quantum numbers of the orbits into which the $\Lambda$ is captured.

**INTERACTIONS IN HYPERMATTER AND HYPERNUCLEI**

The nuclear wave functions entering into the cross section calculation have been obtained by DDRH theory. This is a field theoretical approach accounting for the modifications of baryon-baryon interactions in matter with density dependent meson-baryon vertices. In [2] it was shown that a properly defined field theory, preserving covariance of
the field equations and thermodynamical consistency, is obtained when vertex functionals depending on the field operators are used. The medium dependence of the vertices is derived from Dirac-Brueckner (DB) calculations and applied in relativistic mean-field calculations to nuclei \[2, 3\] and hypernuclei \[4, 5\]. Hence, we obtain an ab initio description once the free space baryon-baryon interaction is specified. In the strangeness sector, however, the information is sparse making it necessary to introduce the ratio of the scalar to the vector meson coupling constant as a free parameter which is determined from hypernuclear spectra \[4\]. Interestingly, we find significant deviations from the expectations of the naive quark model: While the latter predicts a reduction of the meson-Λ vertices by \(\frac{1}{3}\) \[1\] the analysis of the existing data on Λ hypernuclei imply a reduction factors of about 50-60\% \[4\]. The single Λ separation energies are well described by our calculations, especially for the heavier mass region, \(A > 40\). Discrepancies for low masses, \(A < 16\), seem to be related to additional dynamical self-energies coming from core polarization, thus supporting a conjecture of Polls et al. \[9\].

It is worthwhile to consider more closely the general properties of in-medium interactions for the \(SU(3)_f\) flavor octet baryons. Denoting the in-medium vertices for meson \(\alpha = \sigma, \omega\) by \(\Gamma_{\alpha B}(\rho)\) the ratio of Λ to nucleon coupling constants is found to behave as \[4\]

\[
R_{\alpha} = \frac{\Gamma_{\alpha \Lambda}}{\Gamma_{\alpha N}} = \frac{g_{\alpha \Lambda}}{g_{\alpha N}} + O\left(\left(\frac{k_F^\Lambda}{k_F^N}\right)^2\right) \tag{7}
\]

showing that the in-medium vertices indeed reflect in leading order the free space properties of the couplings. The above relation indicates that the density dependence of baryons is most likely given by a common form factor depending on the Fermi momentum \(k_F^q\) of the flavor species \(q\). In fact, inspection of the in-medium Bethe-Salpeter equation shows that medium dependencies are introduced primarily through Pauli-blocking which obviously is related to particles of the same flavor \[10\]. As an overall effect, the intrinsic density dependence of the meson-baryon vertices leads to a considerable variation of the coupling strength over the nuclear volume \[4, 5\], suppressing the coupling with increasing density. In fact, the in-medium interactions can be represented in terms of a susceptibility tensor and the free space interaction, at least in the ladder approximation \[10\]. In the DB vertices \(\Gamma_{\alpha q}(k_F^q) = G_{\alpha q}F_{\alpha q}(k_F^q)\), obtained by solving the BS equation in ladder approximation, we may express the density dependence by form factors \(F_{\alpha q}(k_F^q)\) and an overall strength \(G_{\alpha q}\). From fig. 2 it is seen that the shape of the form factor is almost independent of the meson channel thus indicating universality.

**SUMMARY AND OUTLOOK**

The formation of hypernuclei in exclusive proton-nucleus reactions by associate \((K^+\Lambda)\) strangeness production has been discussed. The elementary vertices are described in a field theoretical model assuming a two-step type process where initially a nucleon is excited into a resonant state which subsequently decays into the \(K^+\Lambda\) final state and the hyperon is captured by the target nucleus. Angular distributions for the outgoing \(K^+\) were found to depend rather sensitively on the orbit occupied by the \(\Lambda\). Hypernuclear
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