

Mesonic Decay of Charm Hypernuclei Λ_c^+

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Abstract. Λ_c^+ hypernuclei are expected to have binding energies and other properties similar to those of strange hypernuclei in view of the similarity between the quark structures of the strange and charmed hyperons, namely $\Lambda(uds)$ and $\Lambda_c^+(udc)$. One striking difference however occurs in their mesonic decays, as there is almost no Pauli blocking in the nucleonic decay of a charm hypernucleus because the final-state nucleons leave the nucleus at high energies. The nuclear medium nevertheless affects the mesonic decays of charm hypernucleus because the nuclear mean fields modify the masses of the charm hyperon. In the present communication we present results of a first investigation of the effects of finite baryon density on different weak mesonic decay channels of the Λ_c^+ baryon. We found a non-negligible reduction of the decay widths as compared to their vacuum values.

1 Introduction

The possible existence of charm hypernuclei has been suggested [1] right after the discovery of the charm quark and a first explicit calculation [2] of their binding energies was performed using a meson exchange model with coupling constants determined by SU(4) flavor symmetry. More recently, calculations were performed [3] using the quark meson coupling model at the Hartree level — the predicted binding energies per baryon in Λ_c^+ , Σ_c , Ξ_c hypernuclei ranging from O to Pb are quite substantial, on average of the order of 7.5 MeV. Such binding energies are of similar magnitude to those of J/Ψ binding in nuclear matter [4] and finite nuclei [5]. Vacuum effects [6] and Fock terms [7], although crucial for capturing pionic effects in matter [8], are not expected to have a great impact on the binding energies. Up to now there is no experimental evidence of the existence of a charm hypernucleus, apart from an emulsion experiment at Fermilab with 250 GeV protons that indicated that Λ_c^+ hypernuclei have been produced in the collisions [9]. New experimental possibilities were explored [10, 11] at the beginnings of the 1990's, but concrete hopes for the production of such hypernuclei comes with the completion of the FAIR facility (where Λ_c^\pm can be produced in $\bar{p}p$ annihilation processes [12]) and the installation of a 50 GeV high-intensity proton beam at the J-PARC complex.

The study of charm hypernuclei is interesting for several reasons; among the most interesting in our view are: (1) they bring the opportunity to learn about the poorly known interactions of charmed baryons with nucleons [13, 14]; (2) they offer also the opportunity to learn about medium effects on

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diquark correlations, as the masses of the light u and d quarks are affected by the medium while the mass of the heavy c quark is not affected; and (3) few-nucleon (typically one or two) charmed states have the potential of having a rich spectroscopy similar to the X,Y,Z mesons.

One particular observable that can be affected by the medium is the weak-decay lifetime of the charmed baryon because of the change in its mass. There are no Pauli blocking effects on the decaying baryon – for the case of Λ_c^+ , for instance, the decays $\Lambda\pi^+$ and $\Sigma^+\pi^0$ are not blocked, and in the decay $p\bar{K}^0$ the proton leaves the nucleus with a large momentum. In the present communication we present the results of a first investigation [15] of the effects of finite baryon density on different weak mesonic decay channels of the Λ_c^+ baryon.

2 In-medium mesonic decays of Λ_c^+

We evaluate the decay rate in infinite nuclear matter via the imaginary part of the self-energy diagram depicted in Fig. 1. To evaluate the diagram, we employ the effective weak-decay Lagrangian density

$$\mathcal{L}_{\Lambda_c BM} = ig_{\Lambda_c BM} \bar{\psi}_{\Lambda_c} (A_{BM} + B_{BM}\gamma^5) \phi_M \psi_B + \text{h.c.}, \quad (1)$$

where $g_{\Lambda_c BM} = 10^{-2} G_F V_{ud} V_{cs}$, with $G_F = 1.16 \times 10^{-5} \text{ GeV}^{-2}$ being the Fermi constant and $V_{ud} = 0.974$, $V_{cs} = 0.973$ relevant CKM matrix elements. For the density dependence of Λ_c^+ we use the results from the QMC model [3]. Finite nuclei can be treated in the local density approximation.

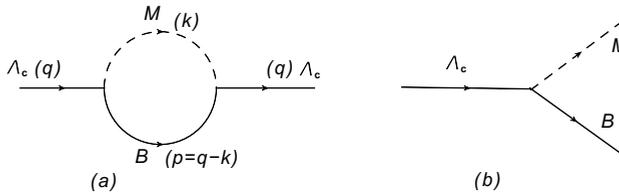


Figure 1. (a) One loop baryon-meson BM self-energy of Λ_c^+ : $B = \Lambda, \Sigma^+, p$; $M = \pi^+, \pi^0, \bar{K}^0$. (b) decay diagram, the imaginary part of (a).

We start examining the role of the Pauli principle in the $\Lambda_c^+ \rightarrow p\bar{K}^0$ decay, neglecting all other possible medium effects. The in-medium decay width $\Gamma_T(q)$ for a generic baryon-meson (BM) decay $\Lambda_c^+ \rightarrow BM$, where $q = |\mathbf{q}|$ with \mathbf{q} the momentum of the Λ_c^+ , can be written as the difference $\Gamma_T(q) = \Gamma_V(q) - \Gamma_D(q)$, where $\Gamma_V(q)$ is vacuum decay width and $\Gamma_D(q)$ is a density dependent width due to Pauli-blocking:

$$\begin{aligned} \begin{pmatrix} \Gamma_V(q) \\ \Gamma_D(q) \end{pmatrix} &= \frac{g_{\Lambda_c BM}^2}{16\pi q m_{\Lambda_c}} \left[(m_{\Lambda_c} + m_B)^2 - m_M^2 \right] \left[|A_{BM}|^2 + \left(\frac{(m_{\Lambda_c} - m_B)^2 - m_M^2}{(m_{\Lambda_c} + m_B)^2 - m_M^2} \right) |B_{BM}|^2 \right] \\ &\times \int_{\omega^-(q)}^{\omega^+(q)} \left(\frac{1}{\theta(\omega - \omega^{\text{th}}(q))} \right) d\omega, \end{aligned} \quad (2)$$

where m_{Λ_c} , m_B and m_M are the masses of Λ_c^+ , baryon B and meson M , respectively, and θ is the step function with

$$\omega^\pm(q) = \frac{R^2}{2m_{\Lambda_c}^2} \left[(q^2 + m_{\Lambda_c}^2)^{1/2} \pm qW \right], \quad \omega^{\text{th}}(q) = (q^2 + m_{\Lambda_c}^2)^{1/2} - (k_F^2 + m_B^2)^{1/2}, \quad (3)$$

where $R^2 = m_{\Lambda_c}^2 + m_M^2 - m_B^2$, $W = (1 - 4m_M^2 m_{\Lambda_c}^2 / R^4)^{1/2}$, and k_F is the nuclear matter Fermi momentum given in terms of the baryon density ρ as $k_F = (3\pi^2/2\rho)^{1/3}$.

There is no Pauli blocking in the $\Lambda_c^+ \rightarrow \Lambda\pi^+$ and $\Lambda_c^+ \rightarrow \Sigma^+\pi^0$ decays and $\Gamma_D(q)$ is nonzero only in the nucleonic decay $\Lambda_c^+ \rightarrow p\bar{K}^0$. Notice that $\Gamma_D(q)$ vanishes for $\rho_B = 0$ as $\omega^{\text{th}}(q) > \omega^+(q)$ in this case and the step function in Eq. (2) gives zero for the integral. The dot-dashed line in Fig. 2 presents the momentum dependence of the ratio $\Gamma_T/\Gamma_V = 1 - \Gamma_D/\Gamma_V$ for the $\Lambda_c^+ \rightarrow p\bar{K}^0$ decay channel in nuclear matter ($\rho = \rho_0 = 0.16 \text{ fm}^{-3}$). Clearly, the effect of the Pauli principle is negligible. Physically, this is due to the fact that the momentum of the outgoing proton is of the order of, or larger than the Fermi momentum — this is transparent in the plot of $\omega^{\text{th}}(q)$ that shows that it barely takes values within the region delimited by the curves of $\omega^+(q)$ and $\omega^-(q)$ as demanded by the theta function in Eq. (2) for a $\Gamma_D(q) \neq 0$.

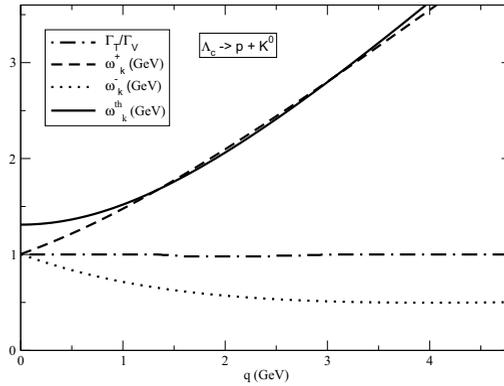


Figure 2. Momentum dependence of the ratio of the total to vacuum decay widths (dash-dotted line) for the $\Lambda_c \rightarrow p\bar{K}^0$ decay channel in nuclear matter at the saturation density ($\rho = \rho_0 = 0.16 \text{ fm}^{-3}$). Also shown are the quantities $\omega^+(q)$ (dashed line), $\omega^-(q)$ (dotted line), and $\omega^{\text{th}}(q)$ (solid line).

Next, we consider the effect of the in-medium mass shift of Λ_c^+ on the decay widths of the different channels — as the proton leaves the nucleus with high momentum, its mass shift is negligible. The density dependence on the mass is taken from the QMC model [3], which can be parametrized as

$$m_{\Lambda_c}^*(\rho)/m_{\Lambda_c} = a_0 e^{-a_1 \rho/\rho_0} + a_2, \quad (4)$$

with $a_0 = 0.121$, $a_1 = 0.565$ and $a_2 = 0.878$. The in-medium decay width is denoted by Γ_ρ and is given by the same expression as Γ_V in Eq. (2) but with m_{Λ_c} replaced by $m_{\Lambda_c}^*$. In Fig. 3 we present the ratio Γ_ρ/Γ_V as function of the baryon density, where Γ_ρ is evaluated at $q = m_{\Lambda_c}^*$ and Γ_V is evaluated at $q = m_{\Lambda_c}$. At the nuclear matter saturation density, $m_{\Lambda_c}^* = 2.146 \text{ GeV}$. The in-medium reduction of the decay widths is not small. Specifically, at the normal nuclear matter density, the reductions are 14.5%, 12% and 6.5% for $\Lambda_c \rightarrow \Lambda\pi^+$, $\Sigma^+\pi^0$, and $p\bar{K}^0$ decay channels, respectively. A local density approximation leads to similar reductions for medium to heavy nuclei [15].

Several issues need careful examination before definite conclusions can be drawn. Specifically, SU(4) flavor symmetry breaking in meson-baryon couplings have been shown to be significant [16] and its impact on the results needs to be assessed — the subject is also of crucial importance for the DN interaction [14] in connection to D -mesic nuclei. The consequences of medium modifications on the mass of Λ_c^+ on non-mesonic weak decays of charmed hypernuclei is under investigation [17].

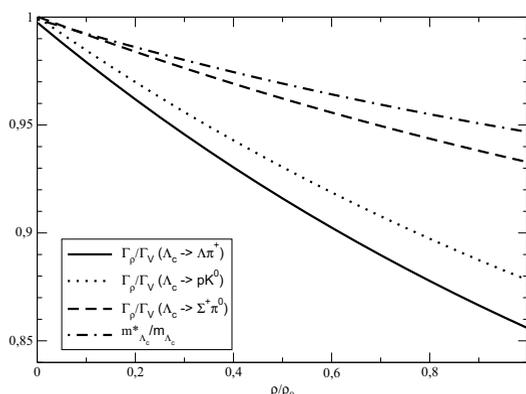


Figure 3. Γ_ρ/Γ_V for $\Lambda_c \rightarrow \Lambda\pi^+$ (solid line), $\Lambda_c \rightarrow \Sigma^+\pi^0$ (dashed line), $\Lambda_c \rightarrow p\bar{K}^0$ (dotted line) decay channels with ρ/ρ_0 . Also shown is $m_{\Lambda_c}^*/m_{\Lambda_c}$ (dot-dashed line).

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