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Charm Production in Interactions of Antiproton with Proton and Nuclei at \( \bar{P} \text{ANDA} \) Energies

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Abstract We study the production of charmed baryons in the antiproton–proton and antiproton–nucleus interactions within a fully covariant model that is based on an effective Lagrangian approach. The baryon production proceeds via the \( t \)-channel \( D^0 \) and \( D^{*0} \) meson-exchange diagrams. We have also explored the production of the charm-baryon hypernucleus \( ^{16}\Lambda_c O \) in the antiproton-\( ^{16}O \) collisions. For antiproton beam momenta of interest to the \( \bar{P} \text{ANDA} \) experiment, the \( 0^\circ \) differential cross sections for the formation of \( ^{16}\Lambda_c O \) hypernuclear states with simple particle-hole configurations, have magnitudes in the range of a few \( \mu \text{b/sr} \).

1 Introduction

Several interesting and intriguing questions in hadron physics can be elucidated by experiments involving medium-energy antiproton (\( \bar{p} \)) beams on fixed-targets. The future \( \bar{P} \text{ANDA} \) (“antiproton annihilation at Darmstadt”) experiment at the under-construction antiproton and ion research facility (FAIR) in Darmstadt, Germany, will perform such studies at the beam momenta \( \leq 15 \text{ GeV/c} \) [1]. This includes measurements of the charm-meson and charm-baryon production in the antiproton (\( \bar{p} \)) collisions with protons and nuclei at the beam momenta \( \leq 15 \text{ GeV/c} \). The accurate knowledge of the charm-meson \( DD \) (\( \bar{D}^0 D^0 \) and \( D^- D^+ \)) production cross sections is important because the charmonium states above the open charm threshold will generally be identified by means of their decays to \( DD \) channels [2].

Studies of production and spectroscopy of charm-baryons (e.g. \( \Lambda_c^+ \)) are similarly interesting. In contrast to the mesons, there can be more states of these systems as there are more possibilities of orbital excitations (baryon resonances) due the presence of three quarks. At higher \( \bar{p} \) beam momenta at the \( P \text{ANDA} \) facility the yields of the channels with charm-baryons exceed those of the charm-meson channels by factors of 3-4, which is confirmed by calculations reported in Refs. [3–6].

The \( \Lambda_c^+ - N \) interaction has come in focus after discoveries of many exotic hadrons [e.g. \( X(3872) \), and \( Z(4430) \)] by the Belle experiments [7]. Because performing scattering experiments in this channel is not feasible for the time being, a viable alternative to determine this interaction is provided by the studies of the \( \Lambda_c^+ \) hypernuclei that can be done by the \( \bar{p} \) induced reactions on nuclei at the \( P \text{ANDA} \) facility. In the past the studies of the \( \Lambda - N \) and \( \Sigma - N \) interactions, respectively [8,9]. The existence of the \( \Lambda_c^+ \) hypernuclei was predicted already in 1975 [10]. More
recently, systematic studies have been reported of the $\Lambda_c^+$ hypernuclei with mass numbers ranging between 17 to 209 within the quark-meson coupling (QMC) model (see, e.g. [11]).

In this contribution, we present some results of our investigations of the production of charmed baryons in the antiproton-proton interactions and of the charm-baryon hypernucleus $^{16}_c\Lambda$ in the $\bar{p} + ^{16}_cO$ collisions, within a fully covariant model that is based on an effective Lagrangian approach.

2 Results and Discussion

2.1 Production of Charmed Baryons in $\bar{p}p$ Collisions

We have calculated the cross sections of the $\bar{\Lambda}_c^- \Lambda_c^+$, $\bar{\Lambda}_c^- \Sigma_c^+$, and $\bar{\Sigma}_c^- \Sigma_c^+$ production channels in $\bar{p}p$ collisions within a single-channel effective Lagrangian model [3,12,13], where this reaction is described as a sum of the $t$-channel $D^0$ and $D^{*0}$ meson-exchange diagrams (see, Fig. 1). The effective Lagrangians for the $D^0$ and $D^{*0}$ meson-exchange vertices were taken to be $\mathcal{L}_{D^0BN} = ig_{BD^0N}\bar{\psi}_B\gamma_5\psi_N\phi_{D^0} + H.c.$, and $\mathcal{L}_{D^{*0}BN} = g_{D^{*0}BN}\bar{\psi}_B\gamma_{\mu}\psi_N\sigma_{\mu\nu}G_{D^{*0}}^{\mu\nu} + H.c.$, respectively. In these expressions $\psi'_s$ represent the baryon fields, $\phi$ and $\theta$ depict the fields of $D^0$ and $D^{*0}$ mesons, respectively. The values of the coupling constants $g_{ND^0B}, g_{ND^{*0}B}$, and $f_{ND^{*0}B}$ were 13.98, 5.64 and 18.37, respectively, for vertices involving the $\Lambda_c^+$ baryon and 2.69, 3.25 and $-7.88$, respectively, for $\Sigma_c^+$ baryon vertices.

Figure 2 displays the total cross sections of the reactions $\bar{p}p \rightarrow \bar{\Lambda}_c^- \Lambda_c^+$ [upper panel], and $\bar{p}p \rightarrow \bar{\Lambda}_c^- \Sigma_c^+$ [lower panel] as a function of $\bar{p}$ beam momenta that vary in the range of threshold to 18 GeV/c, which is of
interest to the \( \bar{p} ANDA \) experiment. The threshold beam momenta for \( \Lambda^- \Lambda^+_c \) and \( \Lambda^- \Sigma^+_c \) production channels are 10.162 and 10.99 GeV/c, respectively. For \( \bar{p}_{lab} \) around 15 GeV/c, \( \sigma_{tot} \) for the \( \Lambda^- \Lambda^+_c \) channel is about one order of magnitude larger than that for the \( \Lambda^- \Sigma^+_c \) channel. The likely reasons for this difference are the smaller coupling constants at the \( ND^* \Sigma^+_c \) vertices and the destructive interference between the \( D^{*0} \) and \( D^0 \) exchange terms in case of the \( \Lambda^- \Sigma^+_c \) final state.

For both production channels, we note that the \( D^{*0} \) exchange process dominates the cross sections. The \( D^0 \) exchange contributions are nearly two orders of magnitude smaller than those of the \( D^{*0} \) exchange in case of the \( \Lambda^- \Lambda^+_c \) final state and nearly an order of magnitude for the \( \Lambda^- \Sigma^+_c \) final state in the region of higher beam momenta. Interestingly, we notice in the lower panel that, even though for \( \bar{p}_{lab} \) beyond 14 GeV/c the individual contributions of the \( D^0 \) exchange terms are at least one order of magnitude smaller, they still influence the total cross sections significantly through the interference terms that are destructive in this case.

2.2 Production of Charm-Baryon Hypernucleus \( ^{16}_{ \Lambda^c} O \) in \( \bar{p}_{16}O \) Collisions

We describe this reaction within an effective Lagrangian model presented above. As discussed earlier, \( \Lambda^- \Lambda^+_c \) production takes place via \( t \)-channel exchanges of \( D^0 \) and \( D^{*0} \) mesons in collisions of \( \bar{p} \) with one of the protons of the target nucleus in the initial state [see, Fig. 1]. The \( \Lambda^+_c \) is captured into one of the orbits of the residual nucleus to make the hypernucleus, while \( \Lambda^- \) rescatters onto its mass shell. At the upper vertices of Fig. 1, the amplitudes involve free-space spinors of the antiparticles, while at the lower vertices, they have spinors for the bound proton in the initial state and bound \( \Lambda^+_c \) in the final state. These are the solutions of the Dirac equation for a bound state problem in the presence of external potential fields. They are calculated within the QMC model. In this model [14], quarks within the non-overlapping nucleon bags (modeled using the MIT bag), interact self-consistently with the isoscalar-scalar (\( \sigma \)) and isoscalar-vector (\( \omega \)) mesons in the mean field approximation. The self-consistent response of bound quarks to the mean \( \sigma \) field leads to a new saturation mechanism for nuclear matter. For a comprehensive review of this model and its applications, we refer to Ref. [15].

The QMC model predicts three bound states for the charm-baryon hypernucleus \( ^{16}_{ \Lambda^c} O \). The predicted quantum numbers and binding energies of these states are: \( ^{16}_{ \Lambda^c} O(\Lambda^+_c 0p_{1/2}, \text{BE} = 7.17 \text{ MeV}) \), \( ^{16}_{ \Lambda^c} O(\Lambda^+_c 0p_{3/2}, \text{BE} = 7.20 \text{ MeV}) \), and \( ^{16}_{ \Lambda^c} O(\Lambda^+_c 0s_{1/2}, \text{BE} = 12.78 \text{ MeV}) \). We assume the initial bound proton state to have quantum numbers of the outermost \( 0p_{1/2} \) proton orbit of the target nucleus. The predicted binding energy of this state within the QMC model is 11.87 MeV.

In Fig. 3, we show the \( 0^\circ \) differential cross sections \([d\sigma/d\Omega]_0\) for the reaction \( \bar{p}^{16}O \rightarrow \Lambda^-_{ \Lambda^c}^{16}O \) obtained by using the proton-hole and \( \Lambda^+_c \) bound state spinors calculated within the QMC model. Cross sections are shown for \( \bar{p} \) beam momenta in the range of threshold to 20 GeV/c. The charm-baryon hypernuclear states populated are \( 1^- \) and \( 0^- \), \( 1^+ \) and \( 0^+ \), and \( 2^+ \) and \( 1^+ \) corresponding to the particle-hole configurations \((0p_{1/2}^p, 0s_{1/2}^p), (0p_{1/2}^p, 0p_{1/2}^A), \) and \((0p_{1/2}^p, 0p_{3/2}^A), \) respectively. Cross sections to the higher \( J \) state of each configuration are shown in the upper panel while those to lower \( J \) in the lower panel. We see that for each particle-hole configuration, the state with higher \( J \) has larger cross section. For \( \bar{p} \) beam momenta of interest to the \( \bar{p} ANDA \) experiment (between 8 - 15 GeV/c), the magnitudes of \( 0^\circ \) differential cross sections vary between 1.5–3.8 \( \mu b/\text{sr} \), and 5.0–11.0 \( \mu b/\text{sr} \) for states \( 0^- \) and \( 1^- \), respectively, of the configuration \((0p_{1/2}^p, 0s_{1/2}^p), \). On the other hand, for states \( 1^+ \) and \( 2^+ \) of the configuration \((0p_{1/2}^p, 0p_{3/2}^A), \) it varies between 0.9–2.8, and 1.6–6.0 \( \mu b/\text{sr} \), respectively. These are relatively substantial values.

3 Conclusion

We investigated the production of charmed baryons, \( \Lambda^- \Lambda^+_c, \Lambda^- \Sigma^+_c \), in the \( \bar{p} p \) collisions within an effective Lagrangian model that involves the meson-baryon degrees of freedom. The production mechanism is described by the \( t \)-channel \( D^0 \) and \( D^{*0} \) meson-exchange diagrams, while largely phenomenological initial- and final-state interactions have been used to account for the distortion effects. In the range of beam momenta of interest to the \( \bar{p} ANDA \) experiment, the total cross sections for the \( \bar{p} \Lambda^- \Lambda^+_c \) production channel are about one order
Fig. 3 (Upper panel) Differential cross sections at 0° of the $\bar{p}^{16}\text{O} \rightarrow \Lambda_{c}^{-16}\text{O}$ reaction leading to the $^{16}\text{O}$ hypernuclear states of larger $J$ value of each particle-hole configuration as indicated. (Lower panel) The same as in (a) but for states of lower $J$ value of each configuration as indicated. In the legends $\Lambda_{c}$ corresponds to $\Lambda_{c}^{+}$.

magnitude larger than those of the $\Lambda_{c}^{-}\Sigma_{c}^{+}$ channel. The reasons for this is large destructive interference between the vector and tensor parts of the $D^{*0}$ meson-exchange term and relatively smaller coupling constants of the $ND^{*0}\Sigma_{c}^{+}$ vertices.

We have also studied the production of charm-baryon hypernucleus $^{16}\Lambda_{c}^{+}\text{O}$ in $\bar{p}^{16}\text{O}$ collisions within a similar model. At beam momenta of interest to the $\bar{P}ANDA$ experiment, the 0° differential cross section for the $\bar{p}^{16}\text{O} \rightarrow \Lambda_{c}^{-16}\text{O}$ reaction varies between 0.9 and 11 $\mu$b/sr depending on the final $\Lambda_{c}^{+}$ state excited in the reaction. This together with the low threshold beam momentum (3.953 GeV/c) for the production of the $^{16}\Lambda_{c}^{+}\text{O}$ hypernuclear states in the $\bar{p}^{16}\text{O}$ reaction, could make it possible to perform such experiments at the $\bar{P}ANDA$ facility even in the beginning stages of the FAIR.

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