Production of K^-p and $K^+\bar{p}$ bound states in pp collisions and interpretation of the $\Lambda(1405)$ resonance

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We study the production of charged particles (K^+, K^-, p, and $\bar{p}$) in proton-proton (pp) collisions at $\sqrt{s} = 0.9$ TeV within the PACIAE model whose parameters we fix by comparing the yield of charged particles with experimental data from ALICE. We analyze the production of K^-p and $K^+\bar{p}$ bound states with the PACIAE+DCPC model. Results of our work indicate that in pp collisions at $\sqrt{s} = 0.9$ TeV the $\Lambda(1405)$ and its antiparticle may be produced at almost the same rate if the $\Lambda(1405)$ is a K^-p bound state formed during the hadron rescattering period. The combined yield of K^-p and $K^+\bar{p}$ bound states is found to be of the order of 10^{-3}, but the experimental results indicate that the combined yield of $\Lambda(1405) + \overline{\Lambda}(1405)$ is of the order of 10^{-2} if $\Lambda(1405)$ is a standard three-quark baryon. Since there are no experimental data available on this observable at present, our work may provide a guide for future experiments.

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I. INTRODUCTION

Exotic nuclei have been the subject of extensive theoretical and experimental research in recent years. It is believed that information about exotic nuclei in high density matter may play a key role in understanding neutron stars as well as the origin and abundance of elements in the universe. The phenomenological study of exotic nuclei with a $\overline{K}$ component is usually based on the assumption that the $\overline{K}N$ interaction supports the $\Lambda(1405)$ as a bound state of K^-p [1–3]. The $\overline{K}N$ potential is characterized by a strongly attractive $I = 0$ $\overline{K}N$ interaction which can been obtained from a meson-exchange model [4] or an SU(3) chiral Lagrangian [5].

In the quark model, the interpretation of the $\Lambda(1405)$ as the lower $l = 1$ excited state of the Λ ground state is problematic because of its relatively low mass compared to the heavier $l = 1$ excited state, $\Lambda(1520)$. Constituent quark models predict two approximately degenerate Λ states with $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$ and masses around 1520 MeV [6,7]. However, the discovery of the $l = 1$ Λ_c excited states $\Lambda_c(2595)$ ($J^P = \frac{1}{2}^-$) and $\Lambda_c(2625)$ ($J^P = \frac{3}{2}^-$) leads to the argument that the $\Lambda(1405)$ is in fact a uds system, a partner of $\Lambda_c(2595)$ [8]. In Ref. [8] the udQ $l = 1$ excited baryons, where Q stands for an s, c, or b quark, are treated as meson-like states in which the ud quark pair is treated as one compact state and the heavier quark Q is far from the center of mass of the ud cluster. In the heavy quark limit $m_Q \to \infty$ the spin-orbit force for the meson-like Λ_Q excited states becomes proportional to $1/m_Q$. If one goes further and uses $1/m_Q$ scaling down to m_s, the observed $\Lambda_c(2625)$–$\Lambda_c(2595)$ mass splitting leads to a difference in the masses of $\Lambda(1520)$ and $\Lambda(1405)$ of approximately 110 MeV [8].

The $\Lambda(1405)$ has been studied intensively in SU(3) chiral unitary theories and is expected to be generated as a resonance from the interaction of meson-baryon coupled channels [9–18]. In the framework of the chiral coupled-channel approach, one may single out the so-called Castillejo-Dalitz-Dyson (CDD) resonances which are not generated from the interaction of two-body coupled channels. In the framework of SU(3) chiral unitary models, the nucleon resonance $N(1535)$ is generated dynamically [19,20]. Results from [21], however, indicate that the $\Lambda(1405)$ can be mainly described as a dynamical state of meson-baryon scattering while the $N(1535)$ has a large three-quark ($3q$) component.

As discussed in Ref. [22] and a review by Dalitz in Ref. [23], the physical nature of the $\Lambda(1405)$ is still unclear. The interpretation of the $\Lambda(1405)$ as a $\overline{K}N$ bound state requires the observation of another state lying close to the $\Lambda(1520)$. However, this energy region has been well explored in $\overline{K}N$ scattering experiments and no such resonance has been found [24]. The most appropriate explanation for the low position of the $\Lambda(1405)$ in the energy spectrum appears to be a strong coupling of the bare $3q$ state at around 1500 MeV to meson-baryon channels. This conjuncture is supported by [25–27], where the meson-baryon scattering system has been investigated including the flavor-singlet $3q$ state Λ^1 as the unperturbed $\Lambda(1405)$.

In the work presented in this paper, the PACIAE model (a parton and hadron cascade model) [28–30] is used to simulate the production of charged particles (K^+, K^-, p, and $\bar{p}$) in pp collisions at a center-of-mass energy of $\sqrt{s} = 0.9$ TeV, and

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to analyze their yield at mid-rapidity ($|y| < 0.5$). This yield is then compared with experimental data from ALICE [31] to fix the model parameters. In a next step, the DCPC model (a dynamically constrained phase space coalescence model) [32–36] is used to study the production of K^-p and $K^+\bar{p}$ clusters and to predict their yield as bound states. We expect that their yield in pp collisions may provide some information about the nature of the $\Lambda(1405)$.

II. THE PACIAE MODEL AND PRODUCTION OF CHARGED PARTICLES

PACIAE, which is based on the earlier PYTHIA model [37], is able to simulate both proton-proton (pp) and nucleus-nucleus (NN) collisions. For pp collisions, the extensions included in PACIAE comprise the parton initiation stage, the parton rescattering before hadronization, and the hadron rescattering after hadronization. Thus, this model consists of the following four stages:

(1) The parton initialization stage for a pp collision. Here, the string fragmentation is switched off temporarily in PACIAE and diquarks and antidiquarks are broken up. In this way, a partonic initial state is obtained which represents quark-gluon matter (QGM) formed in the parton initialization stage of a pp collision.
(2) The parton evolution stage (rescattering). In this stage, the rescattering among partons in the QGM is taken into account by the $2 \to 2$LO-pQCD (leading order perturbative QCD) parton-parton cross sections [38]. The total and differential cross sections in the parton evolution are then simulated by Monte Carlo methods.
(3) The hadronization. Here, the partonic matter formed after parton rescattering is hadronized either by the Lund string fragmentation [39] after string reconstruction or by the Monte Carlo coalescence model [28].
(4) The hadron evolution (rescattering) stage. In this final stage, the hadronic matter produced in the previous stage evolves and rescatters. This is done as usual by considering two-body elastic and inelastic collisions, until the hadronic freeze-out is reached. In particular, rescatterings among π, K, p, n, $\rho(\omega)$, Δ, Λ, Σ, Ξ, Ω, J/Ψ, and their antiparticles are taken into account.

We simulate pp collisions within PACIAE at a center-of-mass energy of $\sqrt{s} = 0.9$ TeV. The capability of PACIAE to describe the production of charged particles in pp collisions as well as the production of hypertriton has been detailed in Refs. [29,30,32–36,40,41]. To obtain a suitable set of model parameters, we show results on the yield of (K^+, K^-, p, and $\bar{p}$) at mid-rapidity ($|y| < 0.5$) within a p_T range of 0.2–6 GeV/c for kaons and 0.3–6 GeV/c for protons. The PACIAE results, as shown in Table I, are found to be in line with the experimental data.

III. K^-p AND $K^+\bar{p}$ PRODUCTIONS

In this work, the $\Lambda(1405)$ is produced during the hadron evolution period, based on the assumption that the $\Lambda(1405)$ resonance is a K^-p bound state with a binding energy of $B_K = 27$ MeV and a width of $\Gamma = 40$ MeV [1–3]. The root mean square (rms) distance D_0 between K^- and p is taken to be $D_0 = 1.36$ fm, as mentioned in Refs. [3,42] and illustrated in Fig. 1.

TABLE I. Yield of charged particles at mid-rapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 0.9$ TeV. ALICE experimental data are taken from [31].

Particle type	ALICE data	PACIAE
K^+	0.183 ± 0.004	0.176
K^-	0.182 ± 0.004	0.171
p	0.083 ± 0.002	0.078
$\bar{p}$	0.079 ± 0.002	0.076

To construct the clusters of K^-p and $K^+\bar{p}$, the kaons and protons produced within PACIAE are used as input of the DCPC (dynamically constrained phase space coalescence) model. The DCPC model has been used earlier to study the production of light nuclei, light antinuclei, hypertritons and antihypertritons in pp and Au + Au collisions [32–36].

In the DCPC model, the yield of a single particle is given by the integral

$$Y_1 = \int_{H \leqslant E} \frac{d\vec{q}\,d\vec{p}}{h^3}, \tag{1}$$

where H and E denote the Hamiltonian and the energy of the particle, respectively. The yield of a cluster consisting of N particles is then calculated by the equation

$$Y_N = \int \cdots \int_{H \leqslant E} \frac{d\vec{q}_1 d\vec{p}_1 \cdots d\vec{q}_N d\vec{p}_N}{h^{3N}}. \tag{2}$$

Therefore, the yield of a K^-p cluster in the DCPC model is obtained by

$$Y_{K^-p} = \int \cdots \int \delta_{12} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2}{h^6}, \tag{3}$$

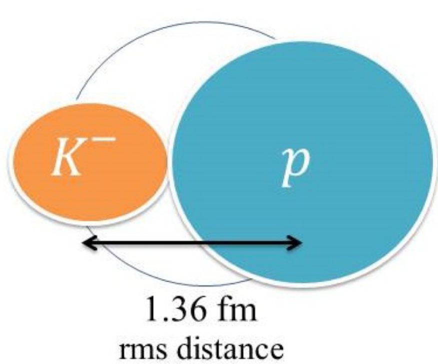

FIG. 1. The rms distance between K^- and p [42].

TABLE II. The effective masses of kaons and protons in a nuclear medium.

Particle type	m_0 (GeV)	m (GeV)
K^+	0.493	0.513
K^-	0.493	0.393
p	0.983	0.750
$\bar{p}$	0.983	0.850

with

$$\delta_{12} = \begin{cases} 1 & \text{if } 1 \equiv K^-, 2 \equiv p, \\ & m_\Lambda - \Delta m \leqslant m_{\text{inv}} \leqslant m_\Lambda + \Delta m, \\ & q_{12} \leqslant D_0, \\ 0 & \text{otherwise,} \end{cases}$$

where q_{12} is the distance between the two particles, m_Λ denotes the mass of $\Lambda(1405)$, and Δm refers to its mass uncertainty (assumed to be half of its decay width: $\Delta m = \Gamma/2$). Since the calculated decay width of $K^- p$ is 0.04 GeV [43], a reasonable value for Δm is 0.02 GeV. The invariant mass m_{inv} of the $K^- p$ state is readily calculated to be

$$m_{\text{inv}} = [(E_{K^-} + E_p)^2 - (\vec{p}_{K^-} + \vec{p}_p)^2]^{1/2}, \tag{4}$$

with the kaon and proton energies

$$E_{K^-} = \sqrt{\vec{p}_{K^-}^{\,2} + m_{K^-}^2}, \tag{5}$$

$$E_p = \sqrt{\vec{p}_p^{\,2} + m_p^2}. \tag{6}$$

Here, m_{K^-} and m_p are the effective masses of K^- and p in nuclear matter. By replacing K^- with K^+ and p with $\bar{p}$, the yield of $K^+\bar{p}$ can be calculated in the same way. Constructing the $K^- p$ bound state in the setup of a high energy pp collision, the effective masses of K^- and p are required. From studies of in-medium meson and baryon masses in pp collisions at $\sqrt{s} = 0.9$ TeV, we know that p and $\bar{p}$ are mostly produced with kinetic energies around 140 and 180 MeV, respectively [44–46]. With these kinetic energies, the effective masses of p and $\bar{p}$ are estimated to be $0.8m_{p,0}$ and $0.9m_{p,0}$, respectively, where $m_{p,0}$ is the mass of the free proton [44].

We assume the effective masses of K^- and K^+ to be $(m_{K^-,0} + 0.02)$ GeV and $(m_{K^-,0} - 0.1)$ GeV as calculated from an SU(3) chiral Lagrangian in Ref. [45]. Here, $m_{K^-,0}$ denotes the mass of the free K^-. The effective masses of K^+, K^-, p, and $\bar{p}$ are then inserted into Eq. (4) to calculate the invariant masses m_{inv} listed in Table II.

Figure 2 shows the average yield per event of $K^- p$ and $K^+\bar{p}$ as a function of the number of events in pp collisions at $\sqrt{s} = 0.9$ TeV using $\Delta m = 0.02$ GeV. It can be seen here that the average yield converges to a stable value if the number of events is larger than 1×10^6.

In this work, we have therefore analyzed a set of 1×10^7 events to ensure sufficient statistics. Table III shows the yields per event of $K^- p$ and $K^+\bar{p}$ in pp collisions at $\sqrt{s} = 0.9$ TeV with Δm varying from 0.005 to 0.050 GeV. To see the relation between the yield per event and Δm, the data in Table III are plotted in Fig. 3. We find that the yields of $K^- p$ and $K^+\bar{p}$ increase linearly with Δm. Furthermore, for a given Δm, the yields of $K^- p$ and $K^+\bar{p}$ are nearly equal due to the similar multiplicities of K^- and K^+ in pp collisions. For $\Delta m = 0.02$ GeV, i.e., equal to the aforementioned mass uncertainty of the $\Lambda(1405)$, the yields per event of $K^- p$ and $K^+\bar{p}$ are predicted to be $(1.656 \pm 0.018) \times 10^{-3}$ and $(1.727 \pm 0.030) \times 10^{-3}$, respectively.

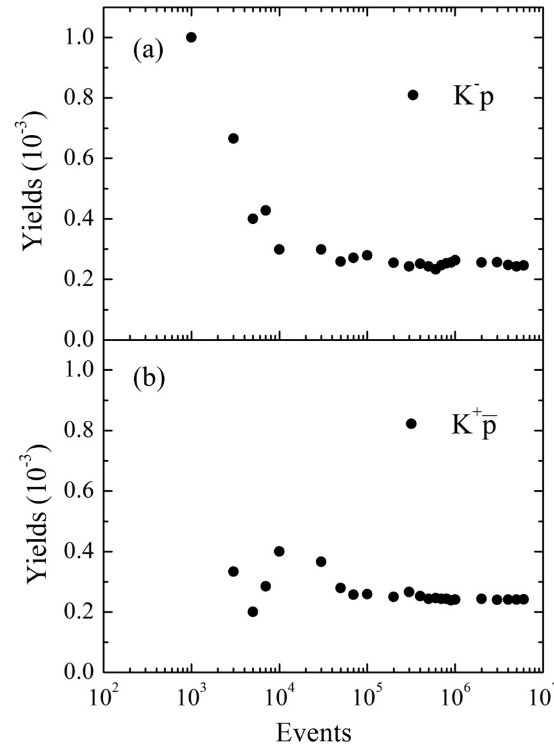

FIG. 2. The average yield per event of $K^- p$ (a) and $K^+\bar{p}$ (b) as a function of the number of events in pp collisions at $\sqrt{s} = 0.9$ TeV.

IV. DISCUSSION AND CONCLUSIONS

In the work presented here, we have used the PACIAE model to simulate pp collisions at a center-of-mass energy of $\sqrt{s} = 0.9$ TeV. The obtained yields of charged particles K^+,

TABLE III. Yield per event of $K^- p$ and $K^+\bar{p}$ in pp collisions at $\sqrt{s} = 0.9$ TeV with Δm varying from 0.005 to 0.050 GeV. The results are analyzed at mid-rapidity ($|y| < 0.5$) and transverse momenta of 0.2–6 GeV/c for kaons and 0.3–6 GeV/c for protons.

Δm	$K^- p$ (10^{-3})	$K^+\bar{p}$ (10^{-3})
0.005	0.409 ± 0.005	0.464 ± 0.013
0.010	0.830 ± 0.008	0.887 ± 0.016
0.015	1.242 ± 0.013	1.312 ± 0.022
0.020	1.656 ± 0.018	1.727 ± 0.030
0.025	2.088 ± 0.013	2.147 ± 0.060
0.030	2.476 ± 0.016	2.530 ± 0.071
0.035	2.892 ± 0.022	2.911 ± 0.088
0.040	3.295 ± 0.030	3.236 ± 0.083
0.045	3.701 ± 0.024	3.519 ± 0.083
0.050	4.084 ± 0.029	3.784 ± 0.091

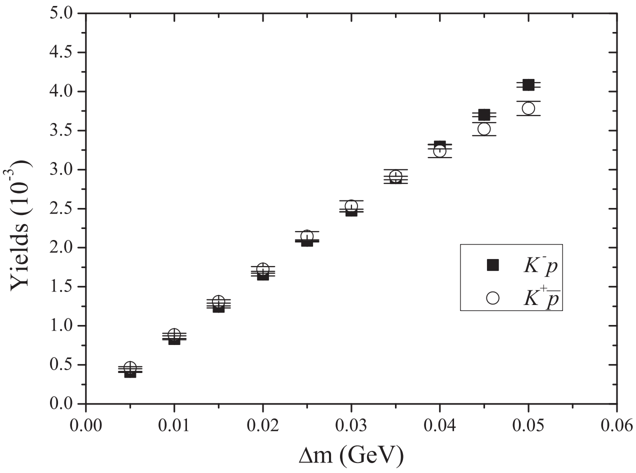

FIG. 3. Yields per event of K^-p and $K^+\bar{p}$. Results taken from Table III.

K^-, p, and $\bar{p}$ within PACIAE are in very good agreement with experimental data from ALICE. We have used the simulated kaons and protons as input to the DCPC model to construct K^-p and $K^+\bar{p}$ clusters through coalescence. Using a realistic invariant mass of 1.405 ± 0.02 GeV, we are able to predict the yields per event of K^-p and $K^+\bar{p}$ to be $(1.656 \pm 0.018) \times 10^{-3}$ and $(1.727 \pm 0.030) \times 10^{-3}$, respectively.

Our results indicate that the $\Lambda(1405)$ and its antiparticle may be produced at almost the same rate in pp collisions at $\sqrt{s} = 0.9$ TeV if the $\Lambda(1405)$ is a K^-p bound state formed during the hadron rescattering period. The combined yield of K^-p and $K^+\bar{p}$ is then estimated to be 3.38×10^{-3}.

The production rates of Λ and $\overline{\Lambda}$ have been measured at central rapidity in pp collisions at $\sqrt{s} = 0.9$ TeV by ALICE [47] and at $\sqrt{s} = 200$ GeV by STAR [48]. The ALICE and STAR results of the combined yields of Λ and $\overline{\Lambda}$ are $0.095 \pm 0.002 \pm 0.003$ and 0.074 ± 0.005, respectively. Measurements from STAR of the heavier strange baryons $\Sigma(1385)$ and $\Lambda(1520)$ produced in pp collisions at $\sqrt{s} = 200$ GeV have found the yields of $\Sigma(1385)$, $\overline{\Sigma}(1385)$, and $\Lambda(1520) + \overline{\Lambda}(1520)$ at values of $(10.7 \pm 0.4 \pm 1.4) \times 10^{-3}$, $(8.9 \pm 0.4 \pm 1.2) \times 10^{-3}$, and $(6.9 \pm 0.5 \pm 1.0) \times 10^{-3}$ [49]. That is, the yields of $\Lambda + \overline{\Lambda}$, $\Sigma(1385) + \overline{\Sigma}(1385)$, and $\Lambda(1520) + \overline{\Lambda}(1520)$ are around $9.5(7.4) \times 10^{-2}$, 1.96×10^{-2}, and 6.9×10^{-3}, respectively. It is believed that Λ, $\Sigma(1385)$, and $\Lambda(1520)$ are single strange baryons consisting of three quarks. Therefore, based on the yields of $\Lambda + \overline{\Lambda}$, $\Sigma(1385) + \overline{\Sigma}(1385)$, and $\Lambda(1520) + \overline{\Lambda}(1520)$, one may estimate a combined yield of $\Lambda(1405) + \overline{\Lambda}(1405)$ in pp collisions at $\sqrt{s} = 0.9$ TeV to be of the order of 10^{-2} at central rapidity if $\Lambda(1405)$ is a standard three-quark baryon.

To obtain further insight and understanding of the nature of the $\Lambda(1405)$ and $\overline{\Lambda}(1405)$ resonances, we therefore suggest measurements of their production rates in pp and heavy-ion collisions by the ALICE and STAR experiments.

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