# The Prediction of Exotic Nuclei (anti-) $K^-pp$ Production in Proton and Proton Collisions at $\sqrt{s}$ = 13 TeV

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## Abstract

The production of $K^-pp$ and $K^-pp$ are predicted by using the Dynamically Constrained Phase space Coalescence (DCPC) model based on the final state of the hadron ($K^{\pm}, p, \overline{p}$) from the PACIAE model at scaled mid-rapidity | y | < 1 and the transverse momentum ($p_T$) range of 0.1 - 1.7 GeV/c in proton-proton collisions at $\sqrt{s}$ = 13 TeV. The results of charge particles $K^{\pm}, p$ and $\overline{p}$ are consistent with CMS experimental data. The result of simulation presented that the yield of the $K^-pp$ is about $8.76\times10^{-4}$ and bigger than their anti ($K^+\overline{pp}$) according to the hypothesis that these exotic nuclei clusters are constructed in the way that (anti-)kaon directly traps two (anti-)protons, without going through process of the $\Lambda^* p$ doorway state.

**Keywords:** Exotic nuclei, Kaonic Nuclei, Kaon, Proton, Heavy ion

## Introduction

To understand the structure of nuclear matter and its interaction including, the fundamental forces and the evolution of the universe, the nuclear and particle physicists have to use the exotic nuclei as key topics. The kaonic nucleus is an important issue due to the exotic properties are expected such the information of dense states as a result of strong attractive $\overline{K}N$ interaction (Akaishi Y et al,2002; Dote A et al,1953; Yamazaki T & Akaishi Y, 2002). The theoretical information of $K^-pp$, T. Yamazaki et al. (2007) studied about the $K^-pp$ bound state which is expected to be formed as the $\Lambda^* - p$ system by the $\Lambda^*$ is the bound state of $K^-p$ and the mass and width of $K^-pp$ are 2322 MeV and 60 MeV

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respectively. Moreover, In the experimental informations of kaonic nuclei $K^{-}pp$ have reported by Angnello et al. (2005) observed a kaon bound state of $K^{-}pp$ in $e^{+}e^{-}$ collisions. They achieve in discovering kaon bound state of $K^{-}pp$ by the way of two body decay into $\Lambda$ hyperon and proton with binding energy of 115 MeV and decay width of 67 MeV. Additionally, the report from the DISTO collaboration (Yamazaki T et al, 2010) presented that the strong bound compact $K^{-}pp$ state which formed in $pp \rightarrow K^{-} + X$ reaction by the rate of $X$ is found nearly the $\Lambda(1405) \equiv \Lambda^{*}$ production rate. The mass of $X$ is about 2267 MeV/c$^2$ and width of 118 MeV. Furthermore, Ichikawa Y. et al. (2015) from the J-PARC E27 collaboration reported that the $\Lambda$(1405) resonance is estimated to be produced the $K^{-}pp$ from the process of $\Lambda^{*}p \rightarrow K^{-}pp$ by the binding energy and width are 95 MeV and 162 MeV, respectively. As well, J-PARC E15 collaboration Sada Y. et al. (2016) presented about the distribution of the $\Lambda p$ invariant mass in $^{3}He(K^{-}, \Lambda p)x$ reaction at 1.0 GeV/c. The distribution show that the pole has mass of $X$ = 2355 MeV and decay width of 110 MeV.

This research concerns about the study of the production of exotic nuclei in heavy ion collision. By the aim of the research is to form the cluster of $K^{-}pp$ and their anti-cluster and to calculate the yield of $K^{-}pp$ by using the PACIAE+DCPC model and analyze the charged particles ($K^{\pm}$, $p$, $\bar{p}$) than compare to the CMS experimental data (Sirunyan AM et al, 2017)

## Methods

### PACIAE and Dynamically Constrained Phase Space Coalescence (DCPC) Model

The PACIAE model is developed from the PYTHIA 6.4 model (Sjostrand T, Mrenna S and Skands PZ, 2006). It is consisted of four stages of the parton initialization, parton evolution, hadronization and hadron evolution. The PACIAE is a model for the ultra-relativistic nuclear collisions which is a parton and hadron cascade model. In the PACIAE model, the stage of parton initialization, a nucleus-nucleus collision is broken up into a sequence of nucleon-nucleon collision. This stage the string fragmentations are temporarily break down and di-(anti)quarks are decomposed into (anti)quarks. The second stage parton evolution or parton rescattering ,the $2 \rightarrow 2$LO – pQCD differential cross section consider the partons in quark-qluon matter by obtained the total cross section (Combridge B. L., Kripfganz J., and Ranft J., 1977). Then the simulation of parton re-scattering is simulated by using the Monte Carlo method (Y. L. Yan et al, 2010). In the of hadronization, the string fragmentation was built up. Then the (anti)quark – pairs are generated in the LUND string fragmentation regime (T. Sjostrand, 1994). The final stage, by using the same way with parton rescattering, the hadron evolution is the process of hadronic freeze – out of the particles such as $K, p, n, \pi, \Lambda$ etc.

In This work, the DCPC model is applied to create the cluster of exotic nuclei $K^-pp$ by its yield calculations are following the (anti)kaon and (anti)proton from PACIAE model simulations. From the research on the basic anti-K nuclear cluster $K^-pp$ and its enhanced formation in the $p + p \rightarrow K^+ + X$ reaction explained about the channel of $K^-pp$ production may be produced by the following processes (Yamazaki T & Akaishi Y, 2007).

$$p + p \rightarrow K^+ + \Lambda^* + p \,, \quad (1)$$

$$\Lambda^* + p \rightarrow K^-pp \,, \quad (2)$$

As mentioned in Ref. (Yamazaki T & Akaishi Y, 2007; Yamazaki T & Akaishi Y, 2007), the $K^-pp$ bound state is formed through the $\Lambda^* p$ doorway state and the structure of $K^-pp$ is displayed in the figure 1. The formation of the $K^-pp$ bound state is produced by the strong attractive interaction between $K^-$ and proton. From this information can be described that the $K^-pp$ bound state possibly formed in the process that a $K^-$ directly traps two protons. The DCPC model is analyzing the cluster of $K^-pp$ by following the uncertainty principle in quantum statistical mechanics. From the uncertainty principle describe about both of position ($\Delta q$) and momentum ($\Delta p$) cannot define in the six-dimension phase space, so we can estimate the production of a particle by the integral as follows

$$Y_1 = \int_{H \le E} \frac{d\vec{q}\,d\vec{p}}{h^3} \quad (3)$$

Where E and H stand for the energy and Hamiltonian of particle. For $K^{-}pp$ the equation (3) can be calculated as in equation (4),

$$Y_{Kpp} = \int \ldots \int \delta_{123} \frac{d\vec{q}_1 d\vec{p}_1 d\vec{q}_2 d\vec{p}_2 d\vec{q}_3 d\vec{p}_3}{h^9}, \tag{4}$$

where

$$\delta_{123} = \begin{cases} 1 & \text{if } 1 \equiv \text{K},\ 2 \equiv \text{p},\ 3 \equiv \text{p} \\ & \text{m}_0 - \Delta m \leq \text{m}_{inv} \leq \text{m}_0 + \Delta m \\ & \text{q}_{12} \leq D_0, \text{q}_{13} \leq D_0, \text{q}_{23} \leq D_0, \\ 0 & \text{otherwise} \end{cases}$$

The $\text{m}_0$, $\Delta m$, $\text{m}_{inv}$, $D_0$ are rest mass, mass uncertainty, invariant mass and diameter of kaonic nucleus respectively. The invariant mass can be calculated as

$$M_{inv} = \sqrt{(E_K + E_p + E_p)^2 - (\vec{p}_K + \vec{p}_p + \vec{p}_p)^2} \tag{5}$$

Whereas the energy of kaon and proton is defined as

$$E_K = \sqrt{\vec{p}_K^{\,2} + m_K^{\,2}}, \tag{6}$$

$$E_p = \sqrt{\vec{p}_p^{\,2} + m_p^{\,2}} \quad . \tag{7}$$

## Analysis Results

### The results of charged particles and (Anti-) $K^{-}pp$ production

The results of charged particle $K^{-}$, $K^{+}$, $p$, and $\bar{p}$ in $pp$ collisions at $\sqrt{s}$ = 13 TeV, From the calculation we found that the production of $K^{-}$, $K^{+}$, $p$, and $\bar{p}$ are corresponding to CMS data as shown in Table 1. For the results in the Table 2 are the prediction of kaonic nuclei $K^{-}pp$ and $K^{+}\overline{pp}$ with the uncertainty mass ranging from 0.02 to 0.05 GeV and the five value of $\text{m}_0$ 2.267, 2.269, 2.275, 2.322, and 2.355 GeV are taken from (Yamazaki T, Akaishi Y, 2007; Kezerashvili RY & Tsiklauri SM, 2014; Dote A, Hyodo T and Weise W, 2009; Nishikawa T & Kondo Y, 2008; Agnello M et al, 2005).

**Table 1** Charged particles $K^-$, $K^+$, $p$, and $\bar{p}$ production at scaled mid-rapidity $|y|<1$ in $pp$ collisions at $\sqrt{s}$ = 13 TeV.

| Particle | CMS data | PACIAE |
|---|---|---|
| $K^+$ | $0.318 \pm 0.007$ | 0.329 |
| $K^-$ | $0.331 \pm 0.011$ | 0.330 |
| $p$ | $0.169 \pm 0.004$ | 0.167 |
| $\bar{p}$ | $0.169 \pm 0.004$ | 0.167 |

The Table 1 present the production of charge particles $K^-$, $K^+$, $p$, and $\bar{p}$ at mid-rapidity $|y|<1$ in $pp$ collisions at $\sqrt{s}$ = 13 TeV. We found that the production of charge particles are consistent with the results of CMS experiment. This indicate that the PACIAE model are accurate and reliable for use to simulate the $K^-pp$ cluster. In the Figure 1 is the data plot which take the result from Table 1 to illustrate the comparison between the CMS data and PACIAE model. From the Figure 1 we can see clearly that CMS data are good described by PACIAE model. These implied that the charge particles from PACIAE model can be used to construct the cluster of kaonic nuclei $K^-pp$ by DCPC model in next step.

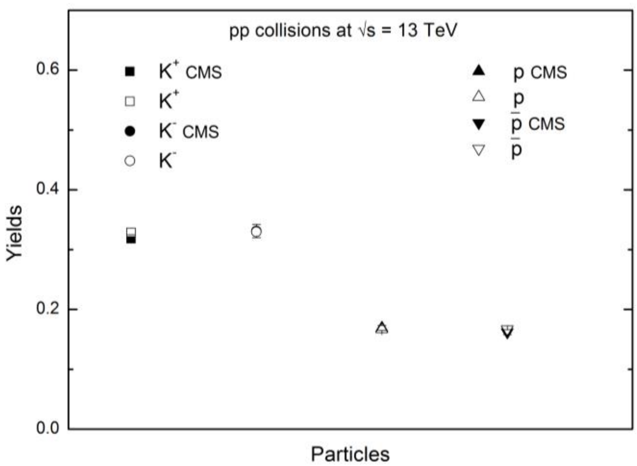


**Figure 1** Charged particles $K^-$, $K^+$, $p$, and $\bar{p}$ production at scaled mid-rapidity $|y|<1$ in $pp$ collisions at $\sqrt{s}$ = 13 TeV compare to the CMS data. Results are taken from Table1.

**Table 2** The prediction of kaonic nuclei $K^{-}pp$ and $K^{+}\overline{pp}$ production at scaled mid-rapidity $|y|<1$ in $pp$ collisions at $\sqrt{s}$ = 13 TeV with $\Delta m$ ranging from 0.02 to 0.05 GeV

| $m_0$ | Kaonic nuclei | $\Delta m$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **0.020** | **0.025** | **0.030** | **0.035** | **0.040** | **0.045** | **0.050** |
| 2.267 | $K^{-}pp$ | 3.96 | 4.93 | 5.87 | 6.76 | 7.64 | 8.53 | 9.41 |
| 2.267 | $K^{+}\overline{pp}$ | 0.22 | 0.30 | 0.38 | 0.44 | 0.49 | 0.59 | 0.68 |
| 2.269 | $K^{-}pp$ | 4.04 | 4.93 | 5.93 | 7.02 | 7.98 | 8.81 | 9.76 |
| 2.269 | $K^{+}\overline{pp}$ | 0.35 | 0.42 | 0.46 | 0.52 | 0.62 | 074 | 0.82 |
| 2.275 | $K^{-}pp$ | 4.06 | 5.03 | 6.07 | 6.92 | 7.84 | 8.74 | 9.58 |
| 2.275 | $K^{+}\overline{pp}$ | 0.40 | 0.44 | 0.50 | 0.62 | 0.75 | 0.83 | 0.89 |
| 2.322 | $K^{-}pp$ | 8.51 | 10.49 | 12.51 | 14.42 | 16.30 | 18.16 | 20.00 |
| 2.322 | $K^{+}\overline{pp}$ | 0.67 | 0.80 | 0.96 | 1.11 | 1.27 | 1.46 | 1.61 |
| 2.355 | $K^{-}pp$ | 9.38 | 11.59 | 13.86 | 15.89 | 18.00 | 19.98 | 22.03 |
| 2.355 | $K^{+}\overline{pp}$ | 1.11 | 1.35 | 1.55 | 1.77 | 2.01 | 2.29 | 2.50 |

The results as shown in the Table 2 are the production of $K^{-}pp$ and $K^{+}\overline{pp}$ production at scaled mid-rapidity $|y|<1$ in $pp$ collisions at $\sqrt{s}$ = 13 TeV with $\Delta m$ ranging from 0.02 to 0.05 GeV. The $\Delta m$ estimated from width ($\Gamma$) of $K^{-}pp$ which found in the theory and experiment (Yamazaki T & Akaishi Y, 2007; Agnello M et al, 2005; Yamazaki T et al, 2010; Ichikawa Y et al, 2015; Sada Y et al, 2016) by the $\Delta m$ is considered as half of particle decay width ($\Delta m = \frac{\Gamma}{2}$). Therefore to cover the value of decay width, we set the $\Delta m$ is varying from 0.02 to 0.05 GeV. In this simulation is using the diameter of kaonic nucleus ($D_0$) about 2 fm which estimated from the molecular structure of $K^{-}pp$ ( Yamazaki T & Akaishi Y, 2007).

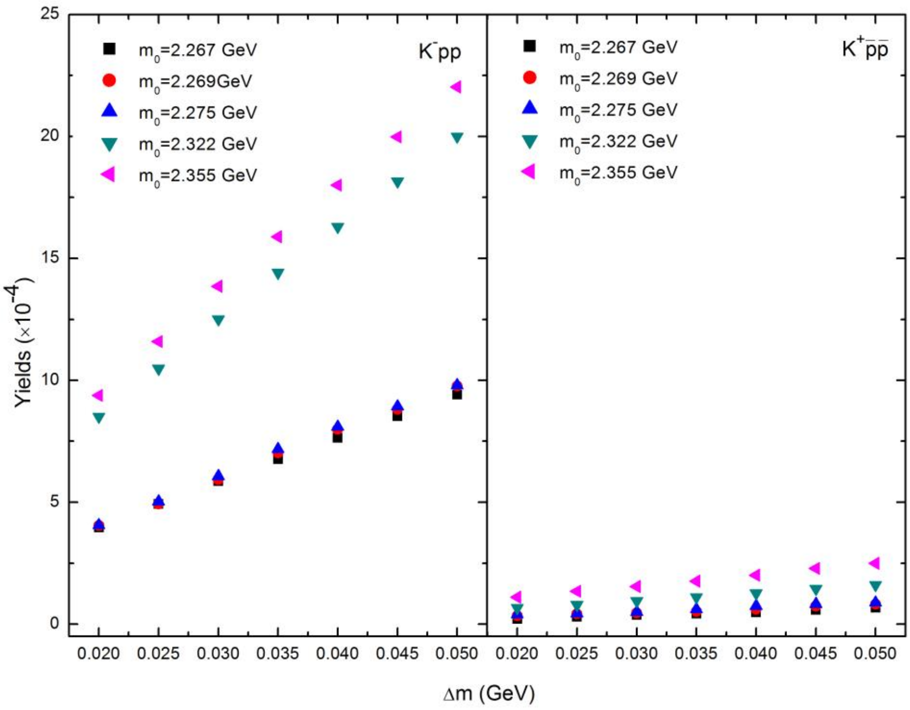


**Figure 2** The production per event of $K^{-}pp$ and $K^{+}\overline{pp}$ as a function of $\Delta m$ ranging from 0.02 to 0.05 GeV at scaled mid-rapidity $|y|<1$ in $pp$ collisions at $\sqrt{s}$ = 13 TeV. Results are taken from Table 2.

The Figure 2 show the results of $K^{-}pp$ and $K^{+}\overline{pp}$ yields which are plotted from the results in Table 2. It is seen from the graph in figure 2 about the production of kaonic nuclei $K^{-}pp$ and $K^{+}\overline{pp}$ with different $m_0$. The yields of $K^{-}pp$ and $K^{+}\overline{pp}$ are increased with $\Delta m$ and $m_0$. In this work we considered at $\Delta m$ = 0.03 GeV owning to the width from the experiment (Agnello M et al, 2005) around 0.067 GeV. So the average of the $K^{-}pp$ yields at $\Delta m$ = 0.03 GeV are equal to $8.76\times10^{-4}$.

## Discussion and Conclusions

In this research, we studied the production of charged particles by using the PACIAE model and $K^{-}pp$ and $K^{+}\overline{pp}$ production by the DCPC model at scaled mid-rapidity $|y|<1$ in $pp$ collisions at $\sqrt{s}$ = 13 TeV. The reults of $K^{-}$, $K^{+}$, $p$, and $\overline{p}$ by PACIAE are consistent with CMS experimental data. The prediction of $K^{-}pp$ and $K^{+}\overline{pp}$ production are seen clearly in the Figure 1 which the production of $K^{-}pp$ and $K^{+}\overline{pp}$ increase with $\Delta m$ and $m_0$. The yield $K^{+}\overline{pp}$ is smaller than the $K^{-}pp$ at each $m_0$ and $K^{-}pp$ is not very sensitive to either $\Delta m$ and $m_0$. From the result of the averaged yield of $K^{-}pp$ at $\Delta m$ = 0.03 GeV is about $8.76\times10^{-4}$ much larger than the yield of $K^{+}\overline{pp}$ as a result of charged particle $p$ is larger than $\overline{p}$, so we can describe that the kaonic nuclei $K^{-}pp$ and $K^{+}\overline{pp}$ are constructed in the process that $K^{-}$ and $K^{+}$ trap two proton and anti-proton directly without going through the $\Lambda^{*}p$ doorway state. Furthermore, the prediction of kaonic nuclei in our work by PACIAE+DCPC model can be using as the data base and the briefly review both in theory and experiment for future experimental setup can be used to confirm the exist of the kaonic nuclei in future.

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