第 33 卷 第 3 期 原 子 核 物 理 评 论 Vol. 33, No. 3
2016 年 9 月 Nuclear Physics Review Sep. , 2016

Article ID: 1007-4627(2016) 03-0281-05

K_s^0 and Λ Production in pp Collisions at Ultra-relativistic Energy

CAI Yanbing, LI Yunde

(*Department of Physics, Yunnan University, Kunming 650091, China*)

Abstract: The transverse momentum spectrum of K_s^0 and Λ in relativistic heavy-ion collisions is calculated based on perturbative quantum chromodynamics. It is found that the initial parton production processes are prominent and the contribution of photoproduction processes is evident at LHC energies. By taking into account the photoproduction processes, the theoretical simulations could give nice descriptions of experimental data. The numerical results indicate that the modification of photoproduction processes of K_s^0 and Λ cannot be negligible in relativistic heavy-ion collisions.

Key words: photoproduction process; strangeness; heavy ion collision

CLC number: O571.6 **Document code:** A **DOI:** 10.11804/NuclPhysRev.33.03.281

1 Introduction

In relativistic heavy-ion collisions the strange particle production is an important tool to investigate the properties of the hot and dense matter created in the collision, since there is no net strangeness content in the initially colliding nuclei[1]. In particular, neutral strange particles such as K_s^0 and Λ are of great interest because of their associated production and the fact that they are not influenced by the Coulomb interaction[2].

The transverse momentum spectra of K_s^0 and Λ have been measured in pp collisions at different energy range by the RHIC-STAR collaboration at $\sqrt{s} = 200$ GeV and by the LHC-ALICE collaboration at $\sqrt{s} =$ 2.76 TeV. These data call for theoretical efforts to overcome the challenges presented by the high-energy of nuclear collision. Perturbative quantum chromodynamics has proven to be successful in describing inclusive hadron production in elementary collisions. This calculation applies the factorization theorem to calculate hadron production[3–4]. The partonic cross sections are calculable in perturbative quantum chromodynamics at high energy to leading order using Feynman diagrams. The non-perturbative parton distribution functions and fragmentation functions are obtained by parameterizations of experimental data.

In this paper, we investigate the production of high-p_T K_s^0 and Λ induced by photoproduction processes in pp collisions at $\sqrt{s} = 200$ GeV and 2.76 TeV. High-p_T processes involve a large momentum transfer, so the running coupling may be small enough to justify the use of perturbative techniques. The photoproduction processes play a fundamental role in the ep deep inelastic scattering at Hadron Electron Ring Accelerator(HERA)[5–6]. At high energies, the nucleus or the charged partons can emit high-energy photons (and hadronlike photons) in relativistic nucleus-nucleus collisions[7–8]. These photons can interact with the parton of another incident nucleon, then the final partons fragment into K_s^0 and Λ.

The paper is organized as follows: In Sect. 2, we present the production of large-p_T K_s^0 and Λ in pp collisions. The direct and resolved photoproduction processes are presented. In Sect. 3, the numerical results of K_s^0 and Λ with three different scale at $\sqrt{s} = 200$ GeV and 2.76 TeV are presented. Finally, a conclusion is given in Sect. 4.

2 K_s^0 and Λ production

The high-p_T K_s^0 and Λ can be produced by initial parton collisions, which are illustrated in Fig. 1. Parton a of the incident nucleon A can interact with the parton b of another incident nucleon B, then the parton c(quark or gluon) produced by this interaction

Received date: 25 Sep. 2015; **Revised date:** 12 Jan. 2016

Foundation item: National Natural Science Foundation of China(11465021, 11065010)

Biography: CAI Yanbing(1989–), male, Malong, Yunnan, Student, working on the field of theory physics: particle physics and nuclear physics; E-mail: myparticle@163.com

Corresponding author: LI Yunde, E-mail: yndxlyd@163.com.

fragment into K_s^0 and Λ. The corresponding invariant cross section(LO) is described in the perturbative quantum chromodynamics parton model on the basis of the factorization theorem as convolution[9–11]

$$E_{\rm h}\frac{{\rm d}\sigma^{\rm LO}}{{\rm d}^3p_{\rm h}}({\rm A}+{\rm B}\to{\rm h}+{\rm X};\ s,p_{\rm T}) = \frac{1}{\pi}\int{\rm d}x_{\rm a}{\rm d}x_{\rm b}f_{\rm a/p}(x_{\rm a},Q^2)f_{\rm b/p}(x_{\rm b},Q^2)\times \frac{{\rm d}\hat{\sigma}}{{\rm d}\hat{t}}({\rm ab}\to{\rm cd};\hat{s},\hat{t})\frac{1}{z_{\rm c}}D_{\rm c}^{h}(z_{\rm c},\hat{Q}^2)\ , \quad (1)$$

where ${\rm d}\hat{\sigma}/{\rm d}\hat{t}$ is the hard scattering cross section of the subprocesses ab $\to$ cd. These subprocesses are $q\bar{q}\to q'\bar{q}'$, $qq'\to qq'$, $q\bar{q}\to q'\bar{q}'$, $qq\to qq$, $q\bar{q}\to q\bar{q}$, $qg\to qg$, $q\bar{q}\to gg$, $gg\to q\bar{q}$, $gg\to gg$.

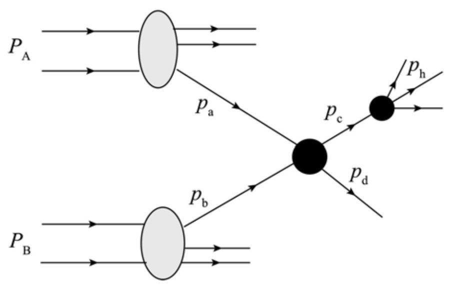

Fig. 1 The initial parton production processes of large-$p_{\rm T}$ K_s^0 and Λ via the fragmentation of quark or gluon. $p_{\rm a}=P_{\rm A}x_{\rm a}$, $p_{\rm b}=P_{\rm B}x_{\rm b}$, $p_{\rm h}=p_{\rm c}z_{\rm c}$.

$f_{\rm a/p}(x_{\rm a},Q^2)$ and $f_{\rm b/p}(x_{\rm b},Q^2)$ are the parton distribution functions for the colliding partons a and b carrying fractional momentum $x_{\rm a}$ and $x_{\rm b}$ in the interacting protons, respectively[12]. The function $D_{\rm c}^h(z_{\rm c},\ \hat{Q}^2)$ gives the probability for parton c to fragment into hadron h with momentum fraction $z_{\rm c}$ at scale $\hat{Q}$[13–14]. We use LO parton distribution functions from MSTW 2008[12] and a NLO set of fragmentation functions[14].

For pp collisions, the whole proton is a source of photons[15]. In these semielastic direct photoproduction processes, the high energy photon from the proton A can interact with the parton from proton B by the interaction of $\gamma q\to\gamma q$, $\gamma q\to qg$, $\gamma g\to q\bar{q}$, $\gamma g\to gg$(Fig. 2). The invariant cross section for semielastic direct photoproduction processes(semi.dir.) in pp collisions can be written as

$$E_{\rm h}\frac{{\rm d}\sigma^{\rm semi.dir.}}{{\rm d}^3p_{\rm h}}({\rm A}+{\rm B}\to{\rm h}+{\rm X};\ s,p_{\rm T}) = \frac{1}{\pi}\int{\rm d}x_{\rm a}{\rm d}x_{\rm b}f_{\gamma/p}(x_{\rm a})f_{\rm b/p}(x_{\rm b},Q^2)\times \frac{{\rm d}\hat{\sigma}}{{\rm d}\hat{t}}({\rm ab}\to{\rm cd};\hat{s},\hat{t})\frac{1}{z_{\rm c}}D_{\rm c}^{\rm h}(z_{\rm c},\hat{Q}^2)\ , \quad (2)$$

where $f_{\gamma/{\rm p}}(x_{\rm a})$ is the photon spectrum function from the charged proton, it can be obtained from the Weizsacker-Williams approximation[16–18].

$$f_{\gamma/{\rm p}}(x_{\rm a})=\frac{\alpha}{2\pi(x_{\rm a})}[1+(1-x_{\rm a})^2]\times \left[\ln A-\frac{11}{6}+\frac{3}{A}-\frac{3}{2A^2}+\frac{1}{3A^3}\right]\ , \quad (3)$$

where $A=1+(0.71/Q^2_{\min})$. At high energies $Q^2_{\min}$ is given by $m_{\rm p}^2x_{\rm a}^2/(1-x_{\rm a})$.

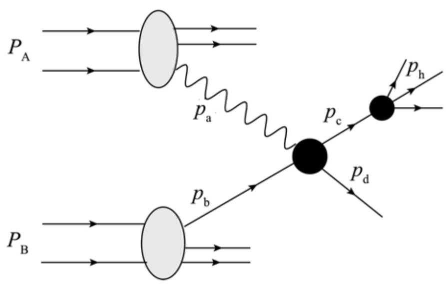

Fig. 2 The semielastic direct photoproduction processes of large-$p_{\rm T}$ K_s^0 and Λ. $p_{\rm a}=P_{\rm A}x_{\rm a}$, $p_{\rm b}=P_{\rm B}x_{\rm b}$, $p_{\rm h}=p_{\rm c}z_{\rm c}$.

In ultrarelativistic condition, a hadron can also be regarded as a beam of freely moving elementary constituents, which is same as the quark-parton model[19–20]. Therefore, the ultrarelativistic fermion also can emit photons, then the high energy photon interacts with the parton b of another incident proton B by the interaction of $\gamma q\to\gamma q$, $\gamma q\to qg$, $\gamma g\to q\bar{q}$, $\gamma g\to gg$(Fig. 3). The invariant cross section for inelastic direct photoproduction processes(inel.dir.) can be written as

$$E_{\rm h}\frac{{\rm d}\sigma^{\rm inel.dir.}}{{\rm d}^3p_{\rm h}}({\rm A}+{\rm B}\to{\rm h}+{\rm X};\ s,p_{\rm T}) = \frac{1}{\pi}\int{\rm d}x_{\rm a}{\rm d}x_{\rm b}{\rm d}z_{\rm a}f_{\rm a/p}(x_{\rm a},Q^2)f_{\rm b/p}(x_{\rm b},Q^2)\times f_{\gamma/{\rm q_a}}(z_{\rm a})\frac{{\rm d}\hat{\sigma}}{{\rm d}\hat{t}}({\rm a'b}\to{\rm cd};\hat{s},\hat{t})\frac{1}{z_{\rm c}}D_{\rm c}^{h}(z_{\rm c},\hat{Q}^2)\ , \quad (4)$$

where $f_{\gamma/{\rm q_a}}(z_{\rm a})$ is the photon spectrum from the quark of the incident nucleon in relativistic hadron-hadron collisions. The probability of finding a photon in an ultrarelativistic fermion f is given by[19, 21]

$$f_{\gamma/{\rm f}}(x)=\frac{\alpha}{\pi}Q^2\left\{\frac{1+(1-x)^2}{x}\left(\ln\frac{E}{m}-\frac{1}{2}\right)+ \frac{x}{2}\left[\ln(\frac{2}{x}-2)+1\right]+\frac{(2-x)^2}{2x}\ln\left(\frac{2-2x}{2-x}\right)\right\}\ , \quad (5)$$

where x is the photon's momentum fraction, Q, m, E and are the charge, mass[22], and energy of the parton, respectively.

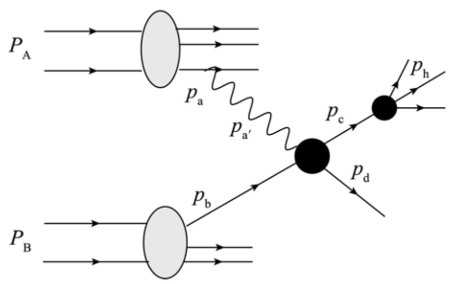

Fig. 3　The inelastic direct photoproduction processes of large-p_T K_s^0 and Λ. $p_a = P_A x_a$, $p_b = P_B x_b$, $p_{a'} = p_a z_a$, $p_h = p_c z_c$.

Besides, the uncertainty principle allows the high energy photon for a short time to fluctuate into a quark-antiquark pair which then interacts with the partons of the proton(Fig. 4). In such interactions the resolved photon can be regarded as an extended object consisting of quarks and also gluons. The interactions are the so-called resolved photoproduction processes[23]. The invariant cross section for inelastic resolved photoproduction processes(inel.res.) can be written as

$$E_h \frac{d\sigma^{\text{inel.res.}}}{d^3 p_h}(A+B \to h+X;\ s, p_T)$$
$$= \frac{1}{\pi}\int dx_a dx_b dz_a dz_{a'} f_{a/p}(x_a, Q^2) f_{b/p}(x_b, Q^2) f_{\gamma/q_a} \times$$
$$(z_a) f_{q_{a''}/\gamma}(z_{a'}, Q^2) \frac{d\hat{\sigma}}{d\hat{t}}(a''b \to cd; \hat{s}, \hat{t}) \frac{1}{z_c} D_c^h(z_c, \hat{Q}^2)\ , \tag{6}$$

where $f_{q_{a''}/\gamma}(z_{a'}, Q^2)$ is the parton distribution of the resolved photon[24]. The elementary cross sections are similar to the cases of the initial parton processes.

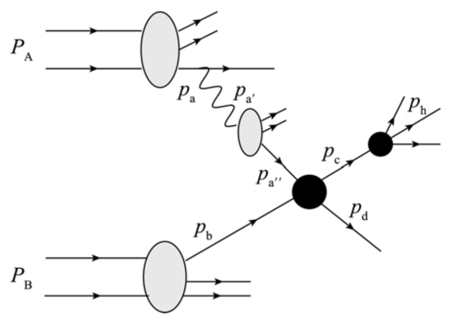

Fig. 4　The inelastic resolved photoproduction processes of large-p_T K_s^0 and Λ. $p_a = P_A x_a$, $p_b = P_B x_b$, $p_{a'} = p_a z_a$, $p_{a''} = p_{a'} z_{a'}$, $p_h = p_c z_c$.

3　Numerical results and discussions

The choice of the factorization scale $Q((p_T/3) < Q \leqslant 2p_T)$ will influence the cross section[25]. In this paper, we choose the momentum scales as $Q = p_T$ and $\hat{Q} = Q/z_c$. The total contribution is shown with the uncertainty band from the different choice of the factorization scale ($Q = p_T/2$ and $2p_T$). To compare with experimental results we need treat the production rate by scaling the results for proton proton collisions in the form $(1/2\pi p_T)(d^2N/dp_T dy) = (1/\sigma_{\text{total}})E(d\sigma/d^3p)$. y is the rapidity of the produced hadron. $\sigma_{\text{total}} = 30$ mb is the measured non-singly diffractive cross section[26]. The numerical results of our calculation for K_s^0 and Λ production in relativistic heavy ion collisions at $\sqrt{s} = 200$ GeV and 2.76 TeV are plotted in Figs. 5～8. For better visibility, the initial parton hard scattering spectrum is multiplied by 0.5 at $\sqrt{s} = 200$ GeV.

In Figs. 5 and 6, we present the transverse momentum distribution of K_s^0 and Λ in pp collisions at

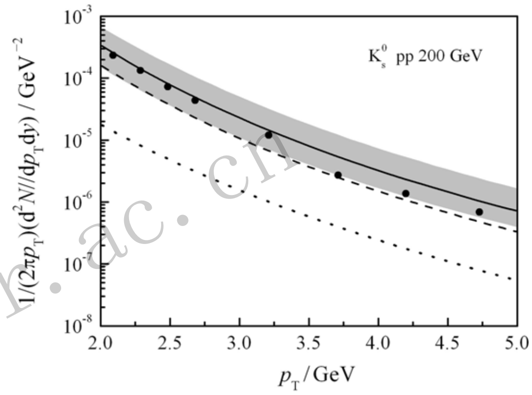

Fig. 5　The transverse momentum spectrum of K_s^0 for $y = 0$ in pp collisions at $\sqrt{s} = 200$ GeV.
The dashed line is for the initial parton hard scattering processes(LO), the dotted line is for the photoproduction processes(semi.dir.+inel.dir.+inel.res.), the solid line is for the total contribution, the band is the uncertainty from the different choice of the factorization scale. The data(filled circles) are taken from STAR[27].

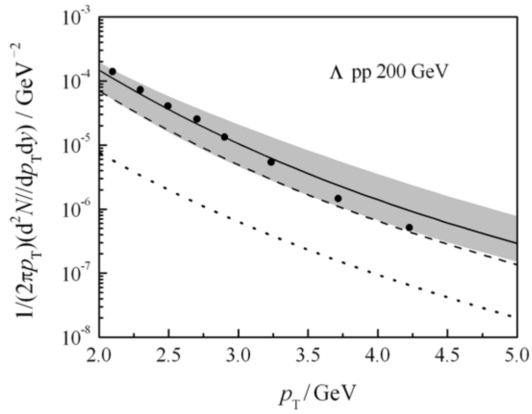

Fig. 6　The transverse momentum spectrum of Λ for $y = 0$ in pp collisions at $\sqrt{s} = 200$ GeV.
The dashed line is for the initial parton hard scattering processes(LO), the dotted line is for the photoproduction processes(semi.dir.+inel.dir.+inel.res.), the solid line is for the total contribution, the band is the uncertainty from the different choice of the factorization scale. The data(filled circles) are taken from STAR[27].

$\sqrt{s}=200$ GeV. Also, we compare the results of our calculation to the existing data. The experimental results are taken from Ref. [27]. We can see that, when $Q=p_{\rm T}$, there is fine coincidence between the transverse momentum distribution and the experimental data. When $Q=p_{\rm T}/2$, the transverse momentum distribution is larger than the experimental data. When $Q=2p_{\rm T}$, the transverse momentum distribution is smaller than the experimental data.

In Figs. 7 and 8, we present the transverse momentum distribution of $\rm K_s^0$ and Λ in pp collisions at $\sqrt{s}=2.76$ TeV. The data are taken from ALICE[28]. Similar trend could be seen at the RHIC energy and LHC energy. However, the contribution of photoproduction processes is different. At high energies, the proton equivalent photon spectrum obtained from Weizsacker-Williams approximation is $f_{\gamma/\rm p}\propto\ln(s/m_{\rm p}^2)$, where $m_{\rm p}$ is the proton mass. For the resolved photoproduction processes, the equivalent photon spectrum for the charged parton is $f_{\gamma/\rm q}\propto\ln(E/m_{\rm q})=\ln(\sqrt{s}/2m_{\rm q})+\ln(x)$, where $m_{\rm q}$ is the charged parton mass. Hence the photon spectrum becomes prominent at higher energies. Since the collision energy at LHC is larger than that energy at RHIC, the photon spectrum becomes important at LHC energies. Therefore the contribution of photoproduction processes is evident at LHC. Indeed, the contribution of photoproduction processes at LHC is larger than RHIC.

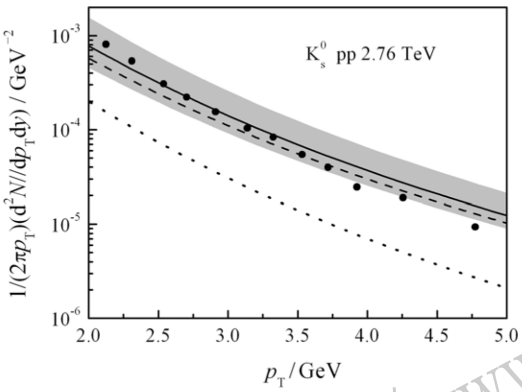

Fig. 7 The transverse momentum spectrum of $\rm K_s^0$ for $y=0$ in pp collisions at $\sqrt{s}=2.76$ TeV.
The dashed line is for the initial parton hard scattering processes(LO), the dotted line is for the photoproduction processes(semi.dir.+inel.dir.+inel.res.), the solid line is for the total contribution, the band is the uncertainty from the different choice of the factorization scale. The data(filled circles) are taken from ALICE[28].

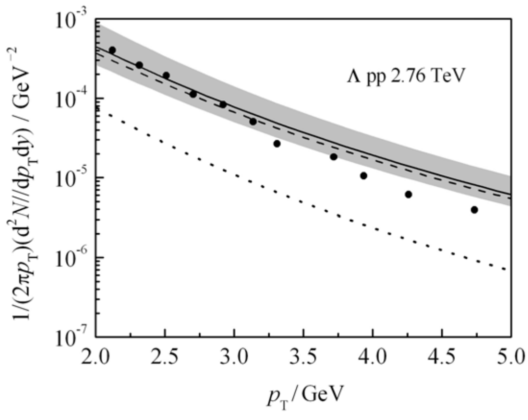

Fig. 8 The transverse momentum spectrum of Λ for $y=0$ in pp collisions at $\sqrt{s}=2.76$ TeV.
The dashed line is for the initial parton hard scattering processes(LO), the dotted line is for the photoproduction processes(semi.dir.+inel.dir.+inel.res.), the solid line is for the total contribution, the band is the uncertainty from the different choice of the factorization scale. The data(filled circles) are taken from ALICE[28].

4 Conclusions

We investigate the production of large-$p_{\rm T}$ $\rm K_s^0$ and Λ production in relativistic pp collisions by initial parton production processes and photoproduction processes. There are two kinds of photoproduction processes which should be considered. For the direct photoproduction process, the high energy photons, emitted from the whole proton or quarks inside the proton, interact with partons in the target proton directly. For the resolved photoproduction process, the high energy photon interacts with the partons in the target proton like a hadron. It is shown that with the increase of energy the contribution of photoproduction processes becomes important. Indeed, the photoproduction processes have contributed to over 10% of the total $\rm K_s^0$ and Λ production at $\sqrt{s}=2.76$ TeV. With the consideration of photoproduction processes, the factorization theorem with scale $Q=p_{\rm T}$ could give nice descriptions of $\rm K_s^0$ and Λ transverse momentum spectrum. The numerical results indicate that the photoproduction processes can improve the perturbative quantum chromodynamics calculations.

References:

[1] ELIA D. J Phys Conf Ser, 2013, **455**: 012005.
[2] MERSCHMEYER M, LOPEZ X, BASTID N, *et al.* Phys Rev C, 2007, **76**: 024906.
[3] OWENS J F. Rev Mod Phys, 1987, **76**: 465.
[4] FU Y P, LI Y D. Nucl Phys Rev, 2010, **27**: 16.
[5] NISIUS R. Phys Rep, 2000, **332**: 165.
[6] KRAWCZYK M, ZEMBRZUSKI A, STASZEL M. Phys Rep, 2001, **345**: 265.
[7] YU G M, LI Y D. Phys Rev C, 2015, **91**: 044908.
[8] FU Y P, LI Y D. Phys Rev C, 2011, **84**: 044906.
[9] FEILD R D. Applications of Perturbative QCD[M]. Redwoodcity: Addison-Wesley Publishing Company, 1989: 270.

[10] ZHANG Y. ArXiv: hep-ph/0401198, 2004.
[11] ZHANG Y, FAI G, PAPP G, *et al.* Phys Rev C, 2002, **65**: 034903.
[12] MARTIN A D, STIRLING W J, THORNE R S, *et al.* Eu Phys J C, 2009, **63**: 189.
[13] PAPP G, LEVAI P, FAI G. Phys Rev C, 1999, **61**: 021902.
[14] ALBINO S, KNIEHL B A, KRAMER G. Nucl Phys B, 2008, **803**: 42.
[15] YU G M, LI Y D. Nucl Phys Rev, 2014, **31**: 142.
[16] DREES M, GODBOLE R M, NOWAKOWSKI M, *et al.* Phys Rev D, 1994, **50**: 2335.
[17] DREES M, ZOPPENFELD D. Phys Rev D, 1989, **39**: 2536.
[18] CAI Y B, YU G M, LI Y D. Nucl Phys Rev, 2014, **31**: 14.
[19] KNIEEHL B A. Phys Lett B, 1991, **254**: 267.
[20] ZHU J Q, LI Y D. Nucl Phys Rev, 2012, **29**: 336.
[21] BAUR G, HENCKEN K, TRAUTMANN D. J Phys G, 1998, **24**: 1657.
[22] OLIVE K A, AGASHE K, AMSLER C, *et al.* Chin Phys C, 2014, **38**: 090001.
[23] YIN R T, FU Y P, LI Y D. Nucl Phys Rev, 2011, **28**: 168.
[24] GLUCK M, REYA E, SCHIENBEIN I. Phys Rev D, 1999, **60**: 054019.
[25] BARNAFOLDI G G, FAI G, LEVAI P, *et al.* J Phys G, 2001, **27**: 1767.
[26] ALBINO S, KNIEHL B A, KRAMER G. Nucl Phys B, 2005, **725**: 181.
[27] HEINZ M. J Phys G, 2005, **31**: S1011.
[28] HANRATTY L D. Λ and K_S^0 production in Pb-Pb and pp collisions with ALICE at the LHC[M]. Birmingham: University of Birmingham, 2014(6): 113.

极端相对论能量的质子质子碰撞中的 $\mathbf{K_s^0}$ 和 $\boldsymbol{\Lambda}$ 产生

蔡燕兵，李云德

(云南大学物理系，云南 昆明 650091)

摘要： 基于微扰量子色动力学计算了相对论重离子碰撞中的 K_s^0 和 Λ 的横向动量谱。发现初态部分子产生过程是主要的，光生过程的贡献在 LHC 能量是明显的。通过考虑光生过程，理论计算能够较好描述实验数据。数值计算结果表明，在相对论重离子碰撞中光生过程对 K_s^0 和 Λ 的修正是不可忽略的。

关键词： 光生过程；奇异性；重离子碰撞

收稿日期： 2015-09-25；　**修改日期：** 2016-01-12
基金项目： 国家自然科学基金资助项目(11465021, 11065010)
通信作者： 李云德，E-mail: yndxlyd@163.com。