Productions of kaon and lambda by 50 GeV protons incident on nuclear targets*

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Abstract A Glauber multiple scattering theory in terms of partons and nucleons is applied to study productions of kaon, lambda and antilambda in 50 GeV proton-nucleus scatterings at JHF (the Japan Hadron Facility). The ratios of the differential cross sections of nucleon-tungsten to nucleon-beryllium are calculated versus the transverse momentum at central rapidity. The cancellation between the single and double scattering amplitudes leads to nuclear enhancement of strangeness production at central rapidity.

Keywords Double scattering, Nuclear enhancement, Strangeness production

1 Introduction

The Japan Hadron Facility (JHF) is to accelerate protons to the energy of 50 GeV with a very high intensity. The protons bombarding heavy nuclei create a large amounts of strange particles like kaon and lambda. The kaons are furthermore utilized to produce hypernuclei in the K-arena experimental hall. Something like how many hypernuclei may be produced by the kaon-nucleus interactions depends on the momentum spectrum of the kaons. It is therefore interesting to study the momentum distribution and intensity of the kaons produced by the 50GeV protons. While a nucleon collides with a very light nucleus, the cross section of nucleon-nucleus is almost the sum of all nucleon-nucleon cross sections. However, a heavy nucleus does not have this additivity property due to the nuclear effect.[1~3] Particle production spectra in nucleon-nucleus collisions may show such nuclear effect in comparison to free nucleon-nucleon collisions. While the projectile nucleon passes through the nucleus, it suffers a number of collisions. The bigger the nucleus radius is, the more the collisions is. To study the nuclear effect, the Glauber multiple scattering theory is generalized from baryon level to parton level. After an incident projectile nucleon suffers a collision, the resultant energetic baryon-like object can be treated loosely as the projectile object which continues to make further collisions along the direction of the projectile. In the Glauber model at baryon level[4], the basic baryon-baryon cross section, σ_{BB}, is taken to be the same throughout the passage of the baryon through the nucleus. If the $\sigma_{\mathrm{BB}}t(\vec{b})\mathrm{d}\vec{b}$ is the probability for having a baryon-baryon collision within the transverse area element $\mathrm{d}\vec{b}$ when one baryon is situated at an impact parameter $\vec{b}$ relative to another baryon, the function $t(\vec{b})$ is called as the baryon-baryon thickness function. If baryons are not polarized, $t(\vec{b}) = t(b)$. With the basic baryon-baryon cross section and thickness function, the amplitude for nucleon-nucleus collision is constructed.

While the Glauber model is generalized to a collision process in the parton model, the nucleon (baryon) passage in the nucleus is replaced by the parton passage in the nucleus. First, a parton in the projectile nucleon collides with a nucleon in the target to produce a parton. Second, this parton continues to collide with another target nucleon to produce another parton. In such parton-nucleus multiple collisions, the basic cross section is parton-nucleon inclusive cross section and the thickness function is kept as that defined at the baryon level. Theory formulation for single and double scatterings is presented in the next section.[5] Within this theory, productions of kaons, lambdas and antilambdas in proton-tungsten and

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proton-beryllium collisions are calculated at the center-of-mass energy of nucleon-nucleon collision, $\sqrt{s} = 9.7\,\mathrm{GeV}$, which corresponds to 50 GeV projectile protons in the laboratory frame. Transverse momentum distributions of produced strangeness particles, discussion and conclusions are given in the final section.

2 Formulation

A parton-nucleon cross section is calculated from parton-parton differential cross sections in perturbative QCD.[6,7] Let h^{ij} denote the differential cross section for a parton-nucleon scattering, $i + N \to j + X$. If the partons i and j have momenta p_i and p_j, respectively, then the parton-nucleon cross section can be written as following

$$\sigma_i(p_i) = \frac{1}{2}\sum_j \int \frac{\mathrm{d}^3 p_j}{E_j} h^{ij}(p_i, p_j) \qquad (1)$$

While the Glauber multiple scattering theory is applied to the parton-nucleus scatterings, thickness functions are defined by

$$T_A^{\pm}(b,z) = \pm\int_z^{\pm\infty} \mathrm{d}z' \rho(b,z')$$

and

$$T_A(b) = T_A^-(b,z) + T_A^+(b,z) \qquad (2)$$

The thickness function satisfies $\int \mathrm{d}^2 b T_A(b) = A$ with the number of nucleons in a nucleus, A. We take the nucleus to be a hard sphere of the radius $R_A = R_0 A^{1/3}$, where nucleons are uniformly distributed and $R_0 = 1.14\mathrm{fm}$. The probabilities for parton i not to interact with the nucleons up to z and j not to interact after z are, respectively,

$$e^{-\sigma_i(p_i)T_A^-(b,z)},\ e^{-\sigma_j(p_j)T_A^+(b,z)} \qquad (3)$$

The probability for one parton-nucleus scattering, $i + A \to j + X$, is

$$\frac{\mathrm{d}H_{(1)}^{ij}}{\mathrm{d}^2 b} = \int_{-\infty}^{+\infty} \mathrm{d}z e^{-\sigma_i T_A^-(b,z)} \rho(b,z) h^{ij} e^{-\sigma_j T_A^+(b,z)}$$

$$= \frac{h^{ij}}{\sigma_j - \sigma_i}(e^{-\sigma_i T_A(b)} - e^{\sigma_j T_A(b)}) = h^{ij} T_A(b)[1 - \frac{\sigma_i + \sigma_j}{2} T_A(b)] \qquad (4)$$

In a double scattering, a parton k produced first in the scattering, $i + N \to k + X$, continues to collide with another nucleon to produce the outgoing parton j, i.e. $k + N \to j + X$. The parton k produced at the space point z propagates without any interaction until the space point z' with the probability $e^{-\sigma_k \int_z^{z'} \mathrm{d}z'' \rho(b,z'')}$. Integrating over the z' as did in the derivation of $\frac{\mathrm{d}H_{(1)}^{ij}}{\mathrm{d}^2 b}$, we can write the contribution to $i + A \to j + X$ from two parton-nucleon scatterings as

$$\frac{\mathrm{d}H_{(2)}^{ij}}{\mathrm{d}^2 b} = \sum_k \int_{-\infty}^{+\infty} \mathrm{d}z e^{-\sigma_i T_A^-(b,z)} \rho(b,z) \frac{h^{ik}h^{kj}}{\sigma_j - \sigma_k}[e^{-\sigma_k T_A^+(b,z)} - e^{-\sigma_j T_A^+(b,z)}] \frac{\mathrm{d}^3 p_k}{E_k}$$

$$= \sum_k \frac{\mathrm{d}^3 p_k}{E_k} \frac{h^{ik}h^{kj}}{\sigma_j - \sigma_k}[\frac{e^{-\sigma_i T_A(b)} - e^{-\sigma_k T_A(b)}}{\sigma_k - \sigma_i} - \frac{e^{-\sigma_i T_A(b)} - e^{-\sigma_j T_A(b)}}{\sigma_j - \sigma_i}]$$

$$= \frac{1}{2} T_A^2(b) \sum_k \frac{\mathrm{d}^3 p_k}{E_k} h^{ik} h^{kj} \qquad (5)$$

Therefore, up to second order in $\sigma T_A(b)$, we have the differential cross section for $i + A \to j + X$,

$$\frac{\mathrm{d}H^{ij}}{\mathrm{d}^2 b} \approx h^{ij} T_A(b) + \frac{1}{2} T_A^2(b)[\sum_k \frac{\mathrm{d}^3 p_k}{E_k} h^{ik} h^{kj} - \frac{\sigma_i + \sigma_j}{2} h^{ij}] \qquad (6)$$

The positive first term and the negative second term in the brackets are cancelled each other. This indicates that the interference between double and single scatterings comes into play. With the parton distributions $f_{i/N}(p_i)$, the differential cross section for $N+N \to j+X$ is given by

$$\sigma^j_{NN} = \sum_i \int \frac{\mathrm{d}^3 p_i}{E_i} f_{i/N}(p_i) h^{ij} \tag{7}$$

In order to show nuclear effects, we compare the differential cross sections of $N+A \to j+X$ to $N+N \to j+X$,

$$R_A = \frac{\sigma^j_{NA}}{A\sigma^j_{NN}} = 1 + \frac{9A^{1/3}}{16\pi R_0^2 \sigma^j_{NN}} \sum_i \int \frac{\mathrm{d}^3 p_i}{E_i} f_{i/N}(p_i) [\sum_k \frac{\mathrm{d}^3 p_k}{E_k} h^{ik} h^{kj} - \frac{\sigma_i + \sigma_j}{2} h^{ij}] \tag{8}$$

For the production of a hadron h, jet fragmentation function is employed. The ratio between the differential cross sections of $N+A \to h+X'$ and $N+N \to h+X$ is

$$R^h_A(p_\mathrm{T}) = \frac{\int \mathrm{d}z f^h_j(z, p^j_\mathrm{T}) \sigma^j_{NA}(p^j_\mathrm{T})}{A \int \mathrm{d}z f^h_j(z, p^j_\mathrm{T}) \sigma^j_{NN}(p^j_\mathrm{T})} \tag{9}$$

with $z = p_\mathrm{T}/p^j_\mathrm{T}$. To compare with experimental data, we calculate hadron productions in target nuclei of tungsten and beryllium, and define a ratio by

$$R^h_{\mathrm{W/Be}}(p_\mathrm{T}) = \frac{R^h_\mathrm{W}(p_\mathrm{T})}{R^h_\mathrm{Be}(p_\mathrm{T})} \tag{10}$$

If the ratio $R^h_{\mathrm{W/Be}}$ at some transverse momentum p_T is greater than 1, then the nucleus tungsten gives rise to nuclear enhancement. This was so-called Cronin effect. At present, there are very few experimental data. First, the hadron productions of π^+, π^-, K^+, K^-, proton and antiproton are calculated at the center-of-mass energy per nucleon-nucleon collision $\sqrt{s} = 38.8GeV$. Compared to the experimental data[8], a low cutoff of transverse momentum is determined, $p_0 = 1.75\,\mathrm{GeV}$. This cutoff separates contributions from the hard processes calculated in perturbative QCD and soft processes. This low cutoff of the transverse momentum is assumed to be independent of the center-of-mass energy $\sqrt{s}$. It is thus employed to study strangeness productions like K^+, K^-, Λ and $\bar{\Lambda}$, in proton-nucleus collisions at the center-of-mass energy $\sqrt{s} = 9.7\,\mathrm{GeV}$, that is the situation of 50 GeV protons incident on a target nucleus at the JHF.

The $R^h_{\mathrm{W/Be}}(p_\mathrm{T})$ is calculated at central rapidity $y = 0$ and results are shown in Fig.1. The central rapidity is defined by

$$y = \frac{1}{2} \ln \frac{E + p_\mathrm{L}}{E - p_\mathrm{L}}$$

where the E and p_L are energy and longitudinal momentum of the produced particle.

3 Discussions and conclusions

In the parton-nucleus scattering, only single and double scatterings are taken into account. The triple scattering and higher scatterings are neglected since their amplitudes are small. We have seen the cancellation between the double scattering and single scattering from Eq.(8). This manifests that there is a nuclear enhancement of $R^h_{\mathrm{W/Be}}(p_\mathrm{T})$ around the transverse momentum $p_T = 2GeV$ as shown in Fig.1. For different hadron production, the ratio $R^h_{W/Be}(p_T)$ is not identical due to different fragmentation functions. The nuclear enhancement is proportional to $A^{1/3}$, which is the average number of nucleons inside a nucleus along the beam direction. For the beryllium, $A^{1/3}$ is close to 1, and there is very small nuclear enhancement. For the heavy nucleus tungsten, the nuclear enhancement is strong. We conclude that nuclear enhancement can be observed when heavy nuclei are bombarded with 50 GeV protons. Such enhancement increases the intensity of produced strange particles.

This work establishes the scattering mechanism between the intermediate partons produced in previous parton-parton scattering and partons in another target nucleon. The mechanism contains three aspects: (1) The intermediate parton must be less absorbed by the medium before collision with another target nucleon. (2) The intermediate partons have positive rapidity and favor colliding with a parton carrying big longitudinal momentum fraction of the nucleon. (3) Produced partons concentrate in the region around the central rapidity in the center-of-mass frame where nuclear enhancement can be observed.

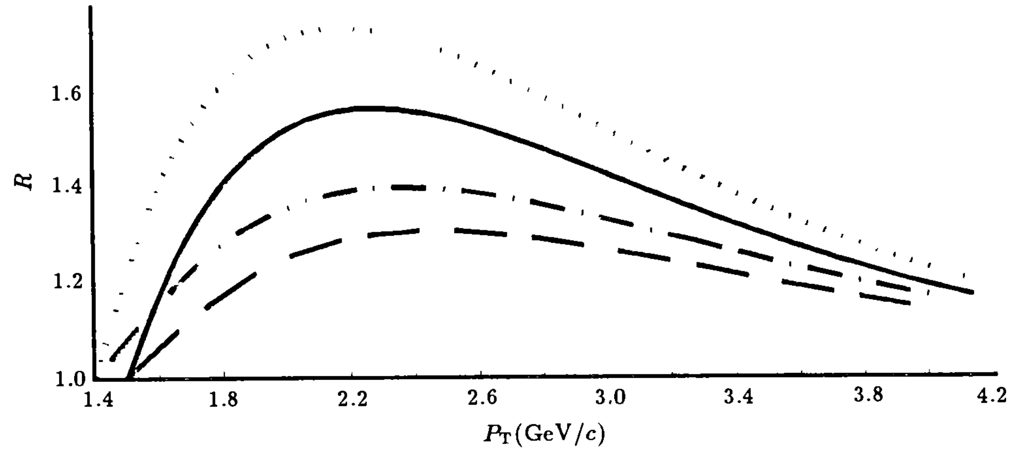

Fig.1 Calculated relative productions ($R_{W/Be}$) of kaon and lambda produced by 50 keV protons incident on nucleus tungsten and beryllium versus the transverse momentum at central rapidity. Solid, dashed, dotted and dot-dashed lines represent productions of K^+, K^-, Λ and $\overline{\Lambda}$, respectively

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