Subthreshold cascade production in heavy ion collisions

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Abstract. Using a gauged flavor SU(3)-invariant hadronic Lagrangian, we have calculated the cross sections for the strangeness-exchange reactions \(Y Y \rightarrow N \Xi (Y = \Lambda, \Sigma)\) in the Born approximation. These cross sections are then used in the Relativistic Vlasov-Uehling-Uhlenbeck (RVUU) transport model to study \(\Xi^+\) production in Ar+KCl collisions at incident energy of 1.76\(A\) GeV and impact parameter \(b = 3.5\) fm. We find that including the contributions of hyperon-hyperon scattering channels strongly enhances the yield of \(\Xi^+\), leading to the abundance ratio 
\[
\frac{\Xi^-}{(\Lambda + \Sigma^0)} = 3.38 \times 10^{-3},
\]
which is essentially consistent with the recently measured value of 
\[
(5.6 \pm 1.2^{+1.8}_{-1.7}) \times 10^{-3}
\]
by the HADES collaboration at GSI.

1. Introduction

The study of particle production in heavy ion collisions at energies below their thresholds in nucleon-nucleon collisions was a topic of extensive studies during the 1990s [1, 2, 3, 4, 5]. The main motivation for such study is that it offers the possibility of extracting information on the nuclear equation of state (EOS) at densities above that of normal nuclear matter. In particular, the yield of strange hadrons, such as the kaon, has been shown to be sensitive to the stiffness of the nuclear equation of state up to three times normal nuclear matter density, with a softer EOS giving a larger yield than a stiff EOS. Indeed, experimental results obtained by the KaoS Collaboration [6] at the Society for Heavy Ion Research (GSI) in Germany on the yield of kaons in heavy ion collisions at subthreshold energies have led to the conclusion that the nuclear equation of state at high densities is soft, consistent with an incompressibility of about 200 MeV extracted from the collective flow studies by the Plastic Ball [7] and EOS [8] Collaborations from Lawrence Berkeley Laboratory (LBL) and the E877 [9] and E895 [10] Collaborations at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory (BNL). More recently, the doubly strange baryons \(\Xi\) from Ar+KCl collisions at 1.76\(A\) GeV, which is below the threshold energy of 3.74 GeV in a nucleon-nucleon collision, was measured by the HADES Collaboration at GSI [11]. The measured abundance ratio including the statistical and systematic errors is 
\[
\frac{\Xi^-}{(\Lambda + \Sigma^0)} = (5.6 \pm 1.2^{+1.8}_{-1.7}) \times 10^{-3}.
\]
This value is about 10-20 times larger than those given by the statistical model [12] and the relativistic transport model [13]. Because of the very low collision energy, secondary reactions other than the direct reaction \(NN \rightarrow N\XiKK\) are expected...
to contribute significantly to $\Xi$ production in these collisions. In Ref. [13], the strangeness-
exchange reaction $\bar{K}Y \rightarrow \pi \Xi$ ($Y = \Lambda, \Sigma$) between antikaon and hyperon was introduced in the
Vlasov-Uheling-Uhlenbeck (RVUU) transport model [14] to study $\Xi$ production in heavy ion
collisions. The cross sections used in Ref. [13] were taken from the coupled-channel calculation
of Ref. [15] based on a gauged flavor SU(3)-invariant hadronic Lagrangian. Since there are
more hyperons than antikaons in heavy ion collisions at this energy, the strangeness-exchange
reaction $YY \rightarrow N \Xi$ between two hyperons is expected to be important for $\Xi$ production in these
collisions. In a recent study [16], we have used the same hadronic Lagrangian as in Ref. [15]
to evaluate the cross sections for the reaction $YY \rightarrow N \Xi$. For an exploratory study, these
cross sections are calculated in the Born approximation with the cutoff parameter in the form
factors at interaction vertices fitted to the cross sections for the reactions $\bar{K}Y \rightarrow \pi \Xi$ obtained in
Ref. [15]. For completeness, we also include the reaction $\bar{K}N \rightarrow K \Xi$ with its cross section taken
from empirically available values. Our results show that the inclusion of the reaction $YY \rightarrow N \Xi$
significantly enhances the yield of $\Xi$ in heavy ion collisions at subthreshold energies, resulting in
the abundance ratio $\Xi^−/(\Lambda + \Sigma^0) = 3.38 \times 10^{-3}$ in Ar+KCl collisions at 1.76A GeV and impact
parameter $b = 3.5$ fm, which is essentially consistent with the recently measured experimental
value. We find, however, that the contribution of the reaction $\bar{K}N \rightarrow K \Xi$ to the $\Xi$ yield is
negligible.

2. The hadronic model and the cross sections for $YY \rightarrow N \Xi$

Possible reactions for $\Xi$ production from hyperon-hyperon collisions are $\Lambda\Lambda \rightarrow N \Xi$, $\Lambda\Sigma \rightarrow N \Xi$, and $\Sigma\Sigma \rightarrow N \Xi$. We have evaluated the cross sections for these reactions in the Born
approximation using the same gauged SU(3) flavor symmetric Lagrangian as introduced in
Ref. [15] for studying $\Xi$ production from the reactions $\bar{K}\Lambda \rightarrow \pi \Xi$ and $\bar{K}\Sigma \rightarrow \pi \Xi$. Specifically,
the interaction Lagrangian is given by

$$L = i \text{Tr}(\bar{B}\partial\bar{B}) + \text{Tr}[(D_{\mu}P^1D^\mu P)] + g' \left\{ \text{Tr} \left[ (2\alpha - 1) \bar{B}\gamma^5\gamma^\mu BD_{\mu}P + \bar{B}\gamma^5\gamma^\mu (D_{\mu}P) B \right] \right\} + \frac{g}{2m} \text{Tr} \left[ (2\alpha - 1) \bar{B}\sigma^{\mu\nu}BD_{\mu}V_{\nu} + \bar{B}\sigma^{\mu\nu} (D_{\mu}V_{\nu}) B \right],$$

where $D_{\mu} = \partial_{\mu} - ig[V_{\mu}; \cdot]; B, P$ and $V$ denote, respectively, the baryon, pseudoscalar meson
and vector meson octets; and $g', g^1$ and $g$ are coupling constants.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Born diagrams for the reactions $\Lambda\Lambda \rightarrow N \Xi$, $\Lambda\Sigma \rightarrow N \Xi$, and $\Sigma\Sigma \rightarrow N \Xi$.

In the Born approximation, the reactions $\Lambda\Lambda \rightarrow N \Xi$, $\Lambda\Sigma \rightarrow N \Xi$, and $\Sigma\Sigma \rightarrow N \Xi$ are described
by the tree-level $t$-channel and $u$-channel diagrams with $K$ and $K^*$ exchanges shown in Fig. 1. To evaluate their cross sections, we have used coupling constants, shown in Table 1, that are
taken from empirical information if available or determined from the SU(3) relations. We have
also introduced a monopole form factor $F(q, \Lambda) = \Lambda^2/(\Lambda^2 + q^2)$, where $q$ is the three-momentum
transfer, at each interaction vertex to take into account the finite size of hardrons. As shown in Fig. 2, with the same value \( \Lambda = 0.7 \) GeV at all vertices, we have been able to reproduce the cross sections for the reactions \( \bar{K}\Lambda \to \pi\Xi \) and \( \bar{K}\Sigma \to \pi\Xi \) that are obtained from the coupled-channel calculation based on the same hadronic Lagrangian [15].

Table 1. Coupling constants.

| Vertex \( f \) | Vertex \( g \) | \( g^t \) |
|----------------|----------------|----------|
| \( K\Lambda \) -3.52 | \( K^*N\Lambda \) -5.63 | -21.5 |
| \( KN\Sigma \) 0.992 | \( K^*N\Sigma \) -3.25 | 6.31 |
| \( K\Lambda\Xi \) 0.900 | \( K^*\Lambda\Xi \) 5.63 | 6.52 |
| \( KS\Xi \) -3.54 | \( K^*S\Xi \) -3.25 | -26.4 |

Figure 2. (Color online) Isospin-averaged cross sections for (a) \( \bar{K}\Lambda \to \pi\Xi \) and (b) \( \bar{K}\Sigma \to \pi\Xi \). Solid lines are from the Born approximation with the cutoff parameter \( \Lambda = 0.7 \) GeV in the form factor, and dashed lines are those based on the coupled-channel calculation [15, 13].

In the left panels of Fig. 3, we show by solid lines the isospin-averaged cross sections for the reactions \( \Lambda\Lambda \to N\Xi \) (panel (a)), \( \Lambda\Sigma \to N\Xi \) (panel (b)), and \( \Sigma\Sigma \to N\Xi \) (panel (c)) as functions of the center-of-mass energy \( \sqrt{s} \), obtained with \( \Lambda = 0.7 \) GeV. The magnitude of our cross section for the reaction \( \Xi N \to \Lambda\Lambda \) is similar to that of Ref. [17] obtained from the SU\(_6\) quark model formulated in the resonance group method, but is smaller than that extracted from the \( (K^-, K^+)\Xi^- \) reactions in a nucleus [18], and larger than that from a coupled-channel calculation based a chiral effective lagrangian [19]. For comparisons, we also show in the left panels of Fig. 3 the cross sections for the reaction \( YY \to N\Xi \) for the cutoff parameters \( \Lambda = 0.5 \) GeV (dashed lines) and \( \Lambda = 1 \) GeV (dotted lines). As expected, the cross sections are larger for a larger \( \Lambda \). Further shown in the right panels of Fig. 3 are the cross sections for the inverse reactions \( \sigma_{N\Xi \to \Lambda\Lambda} \), \( \sigma_{N\Xi \to \Lambda\Sigma} \), and \( \sigma_{N\Xi \to \Sigma\Sigma} \) obtained from above cross sections by the detailed balance relations. We note that the cross sections for the reactions \( N\Xi \to \Lambda\Lambda \), \( \Lambda\Sigma \to N\Xi \), and \( \Sigma\Sigma \to N\Xi \) diverge near their threshold energies, since these reactions are exothermic, i.e., the total mass is larger in the initial state than in the final state.
Figure 3. (Color online) Cross sections for (a) $\Lambda\Lambda \rightarrow N\Xi$, (b) $\Lambda\Sigma \rightarrow N\Xi$, (c) $\Sigma\Sigma \rightarrow N\Xi$, (d) $N\Xi \rightarrow \Lambda\Lambda$, (e) $N\Xi \rightarrow \Lambda\Sigma$, and (f) $N\Xi \rightarrow \Sigma\Sigma$ as functions of the center-of-mass energy $\sqrt{s}$ from the Born approximation with cutoff parameters $\Lambda = 0.5$ GeV (dashed lines), $\Lambda = 0.7$ GeV (solid lines), and $\Lambda = 1$ GeV (dotted lines).

3. The relativistic Vlasov-Uhling-Ulenbeck transport model
To study $\Xi$ production in heavy ion collisions at subthreshold energies, we have generalized the RVUU transport model [14] to include the reactions $Y Y \leftrightarrow N\Xi$ besides the reaction $\bar{K}Y \leftrightarrow \pi\Xi$ that were already included in Ref. [13]. For completeness, we have also included the reactions $\bar{K}N \leftrightarrow K\Xi$ using the empirical cross sections [20]. In addition to these reactions and other reactions involving nucleons, Delta resonances, hyperons, pions, kaons, and antikaons, the VUU model also includes the mean-field effect on the propagation of baryons, kaons, and antikaons. For nucleons and Delta resonances, their mean-field potentials are taken from the relativistic mean-field model via the scalar and vector potentials, so their motions are given by the following equations of motion:

$$\begin{align*}
\dot{x} &= \frac{p^*}{E^*} \\
\dot{p} &= -\nabla_x (E^* + W_0)
\end{align*}$$

where $m^* = m - \Phi$, $p^* = p - W$, $E^* = \sqrt{p^{*2} + m^{*2}}$ with $\Phi$ and $W = (W_0, W)$ being the scalar and vector mean fields, respectively. These mean fields are calculated from the effective chiral Lagrangian of Ref. [21] with parameters determined from fitting the nuclear matter
incompressibility $K_0 = 194 \text{MeV}$ and the nucleon effective mass $m'/m = 0.6$ at normal nuclear matter density $\rho_0 = 0.15 \text{fm}^3$. For $\Lambda$ and $\Sigma$ hyperons, their mean-field potentials are taken to be $2/3$ of the nucleon mean-field potential according to their light quark content. Similarly, the mean-field potential for $\Xi$ is $1/3$ of that of the nucleon.

For kaons and antikaons, their mean-field potentials are derived, on the other hand, from the dispersion relation obtained in the chiral Lagrangian [22]

$$\omega_{K,K} = \left[ m_{K,K}^2 + p^2 - \frac{\Sigma_{NK}}{f^2} \rho_s + \left( \frac{3 \rho_N}{8} \right)^2 \right]^{1/2} \pm \frac{3 \rho_N}{8} \frac{f}{f^2}, \quad (3)$$

where $\rho_s = \langle \bar{N}N \rangle$ is the scalar density, $f = 103 \text{ MeV}$ is the pion decay constant, and the $\pm$ is taken as “+” for kaons and “-” for antikaons. The $KN$ and $\bar{K}N$ sigma term $\Sigma_{NK}$ in the above equation can in principle be calculated from the $SU(3)_L \times SU(3)_R$ chiral Lagrangian but are taken to have the values $\Sigma_{NK}/f^2 = 0.22 \text{ GeV}^2\text{fm}^3$ and $\Sigma_{\bar{K}N}/f^2 = 0.35 \text{ GeV}^2\text{fm}^3$ as in Ref. [13] from fitting the kaon and antikaon yields in heavy ion collisions.

Besides affecting the propagation of particles, the mean-field potential also has effect on the threshold energy for particle production as a result of the potential difference between the initial and final states of a reaction. As a result, the contribution of the reaction $\bar{K}Y \rightarrow \pi \Xi$ to $\Xi$ production in heavy ion collisions at subthreshold energies was found in Ref. [13] to be further enhanced. We note that in the RVUU model, kaons, antikaons, hyperons (lambdas and sigmas), and cascade particles are treated perturbatively by neglecting the effect of their production and annihilation on the collision dynamics, which is dominated by the more abundant nucleons, Delta resonances, and pions. In this approach, kaons, antikaons, and hyperon are produced from nucleon (Delta)-nucleon (Delta) and pion-nucleon (Delta) collisions whenever it is energetically allowed, and they are given probabilities that are determined by the ratios of their respective production cross sections to the total cross sections of the colliding particles. For $\Xi$ production from antikaon collisions with nucleons or hyperons and from hyperon-hyperon collisions, it is similarly treated but the probability of the produced $\Xi$ is reduced by the probabilities of colliding particles. The annihilation of these rare particles is treated in a similar way and leads to reductions of their probabilities. This approach thus takes into account the small probability associated with the production of two rare particles in a subthreshold heavy ion collision that are involved in the production of a $\Xi$.

4. Results

We have calculated the $\Xi$ yield in $^{40}\text{Ar} + ^{39}\text{KCl}$ collisions at incident energy $1.76 \text{ AGeV}$ and impact parameter $b = 3.5 \text{ fm}$, taking as an average of $^{40}\text{Ar} + ^{39}\text{K}$ collisions and $^{40}\text{Ar} + ^{35}\text{Cl}$ collisions, and compare it with the data from the HADES Collaboration at SIS.

Fig. 4(a) shows the time evolution of $\pi$ and $\Delta$ abundances (left scale) and the central baryon density (right scale). It is seen that the colliding system reaches its highest density of about $1.87 \rho_0$ at about $7 \text{ fm}/c$ when most particles are produced. The $\pi$ abundance saturates at 10.3. Assuming isospin symmetry, the $\pi^-$ number is then 3.43 which is very close to the measured number of $3.9 \pm 0.1 \pm 0.1$ by the HADES Collaboration [23, 24]. The time evolution for the abundances of $K$, $\bar{K}$, $\Lambda$, and $\Sigma$ are shown in Fig. 4(b), and they saturate at the values of $5.32 \times 10^{-2}$, $1.15 \times 10^{-3}$, $2.60 \times 10^{-2}$, and $2.60 \times 10^{-2}$, respectively. Assuming isospin symmetry gives $2.61 \times 10^{-2}$ for the $K^+$ number, $5.75 \times 10^{-4}$ for the $K^-$ number, and $3.47 \times 10^{-2}$ for the $\Lambda + \Sigma^0$ number. These numbers are again close to corresponding measured numbers of $(2.8 \pm 0.2 \pm 0.1 \pm 0.1) \times 10^{-2}$, $(7.1 \pm 1.5 \pm 0.3 \pm 0.1) \times 10^{-4}$, and $(4.09 \pm 0.1 \pm 0.17) \times 10^{-2}$ by the HADES Collaboration [25]. For the time evolution of the $\Xi$ abundance, it is shown by the solid curve in Fig.4(c) and is seen to saturate at the value $2.34 \times 10^{-4}$. Taking $\Xi^-$ as half of $\Xi$ by assuming isospin symmetry, we obtained a $\Xi^-$ number of $1.17 \times 10^{-4}$ which is about half of
Figure 4. (Color online) Time evolutions of (a) central baryon density (right scale) and the abundances (left scales) of $\pi$, $\Delta$; (b) $K$, $\Lambda$, $\Sigma$, and $\bar{K}$; and (c) $\Xi$ produced from different reactions.

The measured number of $(2.3 \pm 0.9) \times 10^{-4}$ by the HADES Collaboration [26]. Our results thus lead to an abundance ratio $\Xi^-/(\Lambda + \Sigma^0) = 3.38 \times 10^{-3}$, which is essentially consistent with the measured value of $(5.6 \pm 1.2_{-1.7}^{+1.8}) \times 10^{-3}$ by the HADES collaboration.

The contributions to $\Xi$ production from different reaction channels are also shown in Fig.4(c). Dotted, dashed-dotted, and dash lines denote, respectively, the abundance of the $\Xi$ particles from the reactions $YY \rightarrow N\Xi$, $\bar{K}Y \rightarrow \pi\Xi$, and $\bar{K}N \rightarrow K\Xi$. Compared to the total $\Xi$ abundance, shown by the solid line in Fig.4, the contributions are 97.5%, 2.40%, and 0.1% from the reactions $YY \rightarrow N\Xi$, $\bar{K}Y \rightarrow \pi\Xi$, and $\bar{K}N \rightarrow K\Xi$, respectively. So the $YY \rightarrow N\Xi$ channel dominates $\Xi$ production in heavy ion collisions at subthreshold energies. This can be explained by the fact that the cross section for $YY \rightarrow N\Xi$ is almost 3-4 times the cross section for $\bar{K}Y \rightarrow \pi\Xi$, and almost hundred times the cross section for $\bar{K}N \rightarrow K\Xi$. Also, the hyperon abundance in the system is almost 20 times the anti-kaon abundance. We note that the relative contributions to the $\Xi$ yield from the reactions $\Lambda\Lambda \rightarrow N\Xi$, $\Lambda\Sigma \rightarrow N\Xi$ and $\Sigma\Sigma \rightarrow N\Xi$ are about 1, 4 and 1.

5. Discussions

Our results are obtained without the consideration of the isospin asymmetry effect due to different proton and neutron numbers in the colliding nuclei, which is expected to increase the final abundance ratio $\Xi^-/(\Lambda + \Sigma^0)$. If we assume that the abundance of $\Xi$ has reached chemical
equilibrium in heavy ion collisions, which is certainly questionable in view of the failure of the statistical model in describing the experimental data, this enhancement can be estimated using

\[ \frac{\Xi^-}{\Sigma^0} = e^{-\mu_c/T} = \frac{\Sigma^-}{\Sigma^0} = \frac{\Sigma^0}{\Sigma^+} = N/Z, \]

where \( \mu_c \) is the charge chemical potential and \( T \) is the temperature of the system. With the value \( N/Z \sim 1.14 \) for Ar\(^{40} + K^{30} \) or Ar\(^{40} + Cl^{35} \), we have \( \Xi^- = 0.533 \Xi \) and \( \Sigma^0 = 0.3314 \Sigma \), leading to the ratio \( \Xi^-/(\Lambda + \Sigma^0) = 3.60 \times 10^{-3} \) that is 6.5% larger than that for an isospin symmetric system.

Also, the nuclear EOS used in the transport model can affect the final \( \Xi \) abundance in heavy ion collisions. The results presented in the previous Section are based on a soft EOS. Using a stiff EOS, we find that the \( \Lambda, \Sigma, \) and \( \Xi \) abundances are reduced to 1.74 \( \times 10^{-2} \), 1.77 \( \times 10^{-2} \), and 1.46 \( \times 10^{-4} \), respectively. The reason for this reduction in the hyperon abundances is that the energy density of the colliding system increases faster for a stiff EOS, thus making its expansion faster and reaction time short. However, the abundance ratio \( \Xi^-/(\Lambda + \Sigma^0) = 3.13 \times 10^{-3} \) for the stiff EOS is essentially the same as that for a soft EOS.

Furthermore, the results presented here are for the impact parameter \( b = 3.5 \) fm. A more realistic comparison with experimental data should include a distribution of impact parameters. We have checked that using different impact parameters, the ratio \( \Xi^-/(\Lambda + \Sigma^0) \) remains, however, essentially unchanged, since both hyperons and cascade abundances change by almost the same factor.

Finally, because of the very large \( \Xi \) production cross sections and the small size of the colliding system, the geometrical treatment of \( \Xi \) production from hyperon-hyperon scattering in terms of their scattering cross section as used in the RVU transport model may become inaccurate. This can be seen from the dependence of final \( \Xi \) abundance on the value of the cutoff parameter \( \Lambda \) in the form factor used in evaluating the cross sections of the reactions \( YY \rightarrow N\Xi \). As shown in Fig. 3, these cross sections increase with increasing value of \( \Lambda \). Results from our transport model study show, on the other hand, that the \( \Xi \) abundance decreases with increasing value of \( \Lambda \), that is, 3.17 \( \times 10^{-4} \) for \( \Lambda = 0.5 \) GeV, 2.34 \( \times 10^{-4} \) for \( \Lambda = 0.7 \) GeV, and 1.95 \( \times 10^{-4} \) for \( \Lambda = 1.0 \) GeV. Since the \( \Xi \) abundance changes only by about 30% when the \( \Xi \) production cross sections are varied by more than a factor of 4, our conclusion is expected to remain unchanged. Although our results seem to indicate that the \( \Xi \) abundance in these collisions is close to chemical equilibrium with respect to that of \( \Lambda + \Sigma \), the abundance ratio \( \Xi^-/(\Lambda + \Sigma) \) would decrease to the much smaller value expected from the statistical model if we stop the expansion of the system when this ratio reaches its maximum value, which according to Fig. 4 happens at about 10 fm/c after the initial contact of the two colliding nuclei when the density drops to about the normal nuclear matter density, and let the reactions \( YY \rightarrow N\Xi \) to continue. The observed large \( \Xi^-/(\Lambda + \Sigma) \) ratio is thus due to the early non-equilibrium effect in heavy ion collisions.

6. Summary
We have calculated the cross sections for the reaction \( YY \rightarrow N\Xi \) \( (Y = \Lambda, \Sigma) \) based on a gauged SU(3)-invariant hadronic Lagrangian in the Born approximation and found that these cross sections are almost 4 times the cross sections for the reaction \( KY \rightarrow \pi\Xi \) that was considered in previous studies. We then used these cross sections to study \( \Xi \) production in \( ^{40}\text{Ar} + \text{KCl} \) collisions at the subthreshold energy of 1.76 AGeV within the frame work of a relativistic transport model that includes explicitly the nucleon, \( \Delta \), pion, and perturbatively the kaon, antikaon, hyperons and \( \Xi \). We found that the reaction \( YY \rightarrow N\Xi \) would enhance the \( \Xi \) abundance by a factor of about 16 compared to that from the reaction \( KY \rightarrow \pi\Xi \), resulting in abundance ratio \( \Xi^-/(\Lambda + \Sigma^0) = 3.38 \times 10^{-3} \) that is essentially consistent with that measured by the HADES Collaboration at GSI. Our study has thus helped in resolving one of the puzzles in particle production from heavy ion collisions at subthreshold energies.
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