Lambda collective flow in heavy ion reactions

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Abstract

Collective flow of Lambda hyperons in heavy ion reactions at SIS energies is investigated. It is found that a Λ mean field constructed on the basis of the quark model leads to a good description of the experimental data of the in-plane transverse flow of Λ’s. The attractive mean field can also give rise to an additional ”virtual” Λ radial flow directed inwards, which is reflected by a ”concave” structure of the transverse mass spectrum of the Λ hyperons emitted at midrapidity. The Λ radial flow is found to exhibit a strong mass dependence: The flow is visible in the Ni+Ni system, but is strongly reduced in the system of Au on Au.

Key words: Lambda hyperons, transverse flow, radial flow, QMD
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1 Introduction

Potentials of hyperons such as Λ, Σ, Ξ etc. in a nuclear environment have attracted interest not only in nuclear physics, but also in astrophysics. It has long been realized that hyperons will appear in the dense core of neutron stars where the conversion of nucleons to hyperons through the weak interaction is energetically favored because at the Fermi surface the total energy of the nucleons will otherwise exceed the mass of hyperons[1,2]. The presence of hyperons significantly softens the equation of state of dense hadronic matter. This leads to the prediction of a lower neutron star mass, which is closer to astrophysical measurements than previous predictions for hyperon-free neutron stars[2,3]. Other possible mechanisms to reduce neutron star masses include kaon condensation which was suggested by Kaplan and Nelson[4]. Hyperon-nucleus potentials can be extracted from hypernuclei[5]. Theoretical models have also been used to study hyperon-nucleus potentials. The approaches vary
from meson-exchange [6–8] to QCD (Quantum Chromodynamics)-based models[9,10]. According to the quark model, a hyperon interacts with nucleons predominately through its non-strange quark content[11]. Consequently, potentials of different hyperons in nuclear matter should satisfy a simple scaling in terms of the number of non-strange quarks in the hyperons[10]. This speculation should be confronted with precise experimental tests.

Heavy ion reactions can serve as an alternative way for the investigation of hyperon-nucleus potentials. In fact, heavy ion reactions provide the only way to study in laboratories hyperon properties in a nuclear environment which is much denser and hotter than nuclei in their ground states. On the other hand, collective flow analysis turns out to be powerful for the study of the in-medium particle dynamics in heavy ion reactions. Experimental data about the flow of nucleons have been shown to yield stringent constraints on the nuclear equation of state (EOS)[12]. Recent studies revealed that the flow of kaons provides valuable information on kaon properties in the nuclear medium[13–15]. In this paper we will study the flow of Lambda hyperons in heavy ion reactions.

We will explore in the present work two types of collective flows of Λ’s, namely the in-plane transverse flow and the radial flow. The transverse flow has been intensively studied for both nuclear fragments and for secondary particles, while the radial flow has been known conventionally as a collective expansion of the dense and hot fireball formed in colliding nuclei. In a recent work[15], we have shown that secondary particles such as \( K^+ \) and \( K^- \) mesons can also develop a collective motion in the same direction as the radial expansion of the fireball. This novel collective flow of the secondary particles is called ”radial flow” as well. The present work will investigate the possible formation of the Λ radial flow. We assume in the present study heavy ion beam energies between 1 and 2 GeV/nucleon. This energy region is near the Λ production threshold in free nucleon-nucleon collisions (1.58GeV), and is well studied experimentally at Berkeley and Darmstadt. This paper is organized as follows. In section 2, we describe the Λ dynamics in heavy ion reactions within the framework of Quantum Molecular Dynamics (QMD). Section 3 is devoted to the transverse flow of Λ’s. In section 4 we explore the radial flow of Λ’s. Section 5 is a summary of the paper.

2 Lambda dynamics in the QMD model

In heavy ion reactions at beam energies of 1-2 GeV/nucleon Lambda’s are produced mainly via the reactions \( B+B \rightarrow B+\Lambda+\bar{K}^+ \) and \( \pi+B \rightarrow \Lambda+K^+ \)[16].
Here B stands for a nucleon or a nucleonic resonance $\Delta$ or $N^*$. Due to strangeness conservation a $\Lambda$ hyperon is accompanied by a positive charged kaon in both reactions. So we treat the Lambda production in the QMD model in a similar way as we did for $K^+$ mesons in a previous work[14]. We have used for both reactions calculated cross sections which agree with the experimental data[17,18]. While the baryon-baryon (B-B) reaction is mainly isotropic, the $\pi$-baryon ($\pi$-B) reaction exhibits a strong asymmetric angular distribution due to the P-wave contribution. The anisotropy of the $\pi$B reaction has been taken into account with a parametrization of the experimental data. This enabled us to reproduce very well the experimental angular distribution of $K^+$'s in heavy ion reactions[19]. A Lambda hyperon can not be absorbed in nuclear matter. It, however, experiences strong elastic scatterings on nucleons. The $\Lambda N$ elastic cross section is about 100 mb at a $\Lambda$ laboratory momentum of 0.2 GeV/c, and becomes even larger with decreasing momenta[20]. We include Lambda-nucleon scatterings with use of a parametrization of the experimental cross section[21].

The $\Lambda$ mean field in nuclear matter is constructed on the basis of the quark model as usual[11,21]. The vector and scalar potentials acting on a $\Lambda$ hyperon are taken to be two thirds of that experienced by a nucleon, namely

$$\Sigma^\Lambda_S = \frac{2}{3} \Sigma^N_S$$

$$\Sigma^\Lambda_V = \frac{2}{3} \Sigma^N_V$$

(1)

(2)

where $\Sigma^N_S$ and $\Sigma^N_V$ are the nucleon scalar and vector potentials evaluated in the non-linear $\sigma$-$\omega$ model[22]. The mean-field potential of Lambda’s is then defined as the difference between the in-medium dispersion relation and the free one:

$$U^\Lambda = \sqrt{(m^\Lambda - \Sigma^\Lambda_S)^2 + \vec{p}^2} + \Sigma^\Lambda_V - \sqrt{m^2 + \vec{p}^2}$$

(3)

In Fig.1 we present the $\Lambda$ potential at zero momentum as a function of nuclear matter densities. This potential agrees at saturation density $\rho_0 = 0.16 fm^{-3}$ roughly with the value extracted from hypernuclei[23]. One can see from the figure that the $\Lambda$ potential is attractive at nuclear matter densities below three times the saturation density ($\rho < 3\rho_0$). The maximal density reached in heavy ion reactions at 1-2 GeV/nucleon is about $3\rho_0$. Therefore, one will see in these reactions mainly effects of an attractive potential. We notice that the $\Lambda$ potential (eq.3) is defined in a non-covariant way since the contribution of the spatial components of the nucleon current is neglected[24]. This approximation should be justified for the present study due to twofold reasons. First, the
velocity of Λ’s is quite limited in the center-of-mass frame of the colliding nuclei, since we consider in the present paper a beam energy close to the Λ production threshold for free NN collisions. Second, the Λ hyperons experience frequent scatterings with nucleons, which further reduce dramatically the Λ velocity relative to surrounding nucleons. Therefore, the flow of the Lambdas should not change by much as one changes from the non-covariant Λ dynamics to a fully covariant one.

The motion of Λ hyperons is determined with the Hamiltonian:

\[ H_\Lambda = \sum_{i_\Lambda} \left( \sqrt{m_{\Lambda}^2 + \vec{p}_{i_\Lambda}^2} + U_{i_\Lambda} \right). \]  

The Λ production probability in an in-medium hadron-hadron collision could be different from that of a collision in free space. The magnitude of this medium effect depends on the in-medium potentials of all the hadrons involved in the collision, i.e., nucleons, pions, kaons and Λ’s. The potentials of these hadrons have been not yet well determined both experimentally and theoretically.Uncertainties in evaluating the medium effect may also arise from the procedure to decompose the interactions of the hadrons with the nuclear medium into a long-range mean-field part and a short-range hard-scattering part. The magnitude of the medium modification of the Λ and \( K^+ \) production probability is still under current debates[17,25]. However, such an effect should not change the collective flow of the Λ’s, and therefore is neglected in the present work.

3 Lambda transverse flow

Transverse flow is a collective emission of particles sidewards in the reaction plane of colliding nuclei. This type of collective flow can be quantitatively described with the particle momentum projected onto the reaction plane as a function of rapidity[26]. A flow results in a non-zero in-plane momentum at projectile and target rapidity. The existence of the transverse flow was originally predicted for nuclear matter by the hydrodynamic model[27,28], and was later verified by experiments[29]. It has been found that the transverse flow of nucleons or composite particles such as deuterons, helions etc. exhibits interesting dependence on the bombarding energy. At low energies where the attractive mean field dominates the interaction, the projectile fragments are deflected towards the target[30]. If the bombarding energy is high so that the overlapping matter is strongly compressed, positive pressure will develop in
the interaction zone. Consequently, the projectile fragments will be deflected away from the target (so-called "bounce-off")[29]. Between the two extreme cases, one finds a certain incident energy where the attractive component and repulsive component of the nuclear mean field counterbalance each other, and therefore the transverse flow disappears[31–33]. This special energy, called in literature "balance energy", is about $E_{bal} = 10-25$ MeV/nucleon as found experimentally[31,32]. The beam energies considered in the present work (1-2 GeV/nucleon) are much higher than $E_{bal}$. We therefore will see a bounce-off of nucleons for the reactions under consideration[14].

The studies of the transverse flow of nuclear fragments have motivated a lot of recent studies which analyzed the in-plane momentum of secondary particles such as pions, kaons, antiprotons etc. at varying rapidity[13,14,34,35]. In analogue to the nucleon flow, one usually says that a transverse flow of the secondary particles happens as a non-zero in-plane momentum of the particles is observed at projectile or target rapidity. The transverse flow of the secondary particles turns out to provide information on the in-medium dynamics of these particles. The pion transverse flow was found to be anticorrelated to the nucleon flow[34,35]. This behavior of the pion flow can be attributed to rescatterings and reabsorptions of the pions in the nuclear medium. The kaon transverse flow was shown to be sensitive to in-medium modifications of kaon properties[13,14]. In this section we explore the transverse flow of $\Lambda$’s, and its possible sensitivity to the Lambda-nucleus potential.

We present in Fig.2 the $\Lambda$ in-plane momentum as a function of rapidity calculated from the QMD model for the reaction Ni+Ni at an incident energy of 1.93 GeV/nucleon and within an impact parameter region of $b = 0-4$ fm. Also shown in the figure are the experimental data of the FOPI Collaboration[36]. A transverse momentum cut of $P_t/m_\Lambda > 0.5$ has been used in obtaining both the experimental and the theoretical spectrum. $\Lambda$ rapidity is calculated in the center-of-mass frame of the reaction system and normalized to the projectile rapidity. We have performed the QMD calculations in two cases: with and without the in-medium $\Lambda$ potential. One can see from the figure that the calculation without the potential deviates from the experimental data at high rapidity, while the full calculation reproduces well the data. The FOPI experiment has found that the $\Lambda$ flow essentially follows the proton flow in the same reaction, while the positive charged kaon flow is very weak (The kaon in-plane momenta are nearly zero.). In a previous study with the same QMD model as used in the current work, we have got a very good agreement with the FOPI data for both proton and kaon flow[14]. As can be seen in Fig.2 the $\Lambda$ flow obtained without the potential is weaker than the one from the full calculation. One can understand the effect of the potential on the $\Lambda$ flow in a similar way as one did for the kaon flow. Provided that the Lambda’s
and kaons would experience neither rescattering nor an in-medium potential, they should have a same flow pattern, since a Λ hyperon and a $K^+$ meson are created simultaneously from a BB or πB collision. The $K^+$ mesons feel in the nuclear medium a repulsive potential which repels the kaons away from their sources and by that leads to a near-vanishing $K^+$ transverse flow. Λ hyperons, on the contrary, experience an attractive mean field at the beam energies under consideration. Thus the Λ flow changes to be more pronounced due to the potential.

Aside from the Λ mean field, Λ-nucleon scatterings also affect the Λ flow. At the beam energy under consideration the projectile-like and the target-like remnants are deflected away from each other as mentioned above. The transverse motion of these remnants can transfer to the Lambda’s through the Λ-nucleon scatterings. Consequently, the Λ flow is enhanced due to the Λ-nucleon scatterings.

The Λ transverse flow of the same reaction has also been studied in Ref.[21] with a different transport model, i.e. the Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) model. Authors of Ref.[21] used a non-covariant description of the Lambda dynamics which is quite similar to the one adopted by the present paper. Good agreement is found between Ref.[21] and the present study concerning the transverse flow of $K^+$’s and Λ’s. As far as the proton flow is concerned, small discrepancies exist between the two theoretical studies. Our QMD model turns out to reproduce very well the proton flow data up to $y_{cm}/y_{proj} = 1.5$, while the RBUU model of Ref.[21] slightly underpredicts the data at $y_{cm}/y_{proj} > 1$.

4 Lambda radial flow

Radial flow conventionally means a subsequent expansion of the dense and hot fireball formed in heavy ion reactions[37,38]. The fireball expansion has similar origin as the bounce-off: both are driven by the positive pressure in the overlap region of colliding nuclei. The threshold beam energy for onset of the expansion is found experimentally to be about 35 GeV/nucleon[39], slightly higher than the threshold energy for the occurrence of the bounce-off phenomenon, $E_{bat}$. The fireball expansion gives rise to some non-thermal behavior of nucleons[37], composite particles such as deuterons, tritons etc.[40]. It can also implement non-thermal features to secondary particles, provided that the beam energies are so high that hadron-hadron collisions in the late expansion phase of the reaction are still energetic enough to produce these particles. This condition is fulfilled at AGS and SPS energies (about 10 GeV/nucleon...
and 150 GeV/nucleon, respectively) for pions, kaons, Lambda’s etc.. Therefore, one can find information on the fireball expansion not only from nucleon observables but also from observables of these secondary particles[41–44]. At a subthreshold beam energy, one will hardly find effects of the fireball expansion on secondary particles, since the particles are produced mainly in the compression stage prior to the subsequent fireball expansion. In a recent study, we demonstrated that $K^+$ and $K^-$ mesons produced at a subthreshold beam energy (1.58 GeV/nucleon for $K^+$’s and 2.5 GeV/nucleon for $K^-$’s) can exhibit non-thermal features, however, due to their in-medium potentials instead of the fireball expansion[15]. $K^+$ ($K^-$) mesons feel a repulsive (attractive) potential in nuclear matter, which mutually accelerates (decelerates) the $K^+$ ($K^-$) mesons as they escape from the dense fireball. This results in a ”shoulder-arm” (”concave”) structure in the transverse mass spectrum of the $K^+$ ($K^-$) mesons emitted at midrapidity, which obviously deviates from a Boltzmann distribution. We called kaon radial flow the common acceleration or deceleration by the in-medium potentials.

In this section we investigate if Λ hyperons can also develop a radial flow similar to kaons. Fig.3 shows the transverse mass spectrum of the Λ hyperons emitted at midrapidity (-0.4 < $y_{cm}/y_{proj}$ < 0.4 ) calculated for the same reaction as in Fig.2. A ”concave” structure can be clearly observed in the spectrum at small values of the transverse mass ($m_T - M_\Lambda = \sqrt{m_\Lambda^2 + p_T^2} - m_\Lambda < 0.2$ GeV). This feature obviously distinguishes the Λ spectrum from a Boltzmann distribution (see a Boltzmann fit to the high-energy part of the Λ spectrum which is also shown in Fig.3). The ”concave” structure of the Λ spectrum arises from the attractive Λ mean field. If the Λ potential is neglected, the ”concave” shape disappears. This can be seen in Fig.4 where the Λ transverse mass spectrum from the QMD calculation without the potential is presented. The Λ spectrum is now exactly a Boltzmann distribution.

In order to extract information on the in-medium potentials from the transverse mass spectrum, we suggested in Ref.[15] an equation to fit the spectrum. The fit function has been derived by boosting a thermal Boltzmann distribution with a common radial velocity due to the in-medium potential.

\[
\frac{d^3N}{d\phi dy m_t dm_t} \sim e^{-(\frac{\alpha}{\gamma E} + \alpha)} \{ \gamma^2 E + \gamma \alpha T \left( \frac{E^2}{p^2} + 1 \right) + (\alpha T)^2 \frac{E^2}{p^2} \} \frac{\sqrt{(\gamma E + \alpha T)^2 - m^2}}{p} (5)
\]

where $E = m_t \cosh y$, $p = \sqrt{p_t^2 + m_t^2 \sinh^2 y}$, $\alpha = \gamma \beta p/T$, $\gamma = (1 - \beta^2)^{-1/2}$. There are two free parameters appearing in the fit equation (eq.5). Both of them have clear physical meanings: T is the average temperature of Λ sources, while the parameter $\beta = v/c$ is a common radial velocity of the Lambda’s
caused by the potential. An attractive potential leads to a reduction of \( \Lambda \) radial velocities. We thus should use in the fit equation a \( \beta \) directed towards the center of the fireball. One can extract the \( T \) value from the \( \Lambda \) spectrum which comes from the QMD calculation without the \( \Lambda \) potential. This yields a value of \( T = 115 \text{ MeV} \). The \( \beta \) value can be evaluated by comparing the simplified QMD calculation with the full one including the potential. We found from the calculations that the average mass of the midrapidity Lambda’s is reduced by the attractive potential from \( <m_T>-m_\Lambda = 127 \text{ MeV} \) to \( <m_T>-m_\Lambda = 115 \text{ MeV} \). This reduction accounts for a \( \beta \) value of \( \beta = 0.025 \) in the fit procedure. In Fig.3 we plot the result of the fit by using eq.5 with \( T \) and \( \beta \) parameters determined as above. A satisfactory agreement can be found from the figure between the full QMD calculation and the fit procedure. This demonstrates that a \( \Lambda \) radial flow forms in the reaction due to the attractive potential. However, the energy reduction caused by the potential is rather small compared to the thermal energy: the former is only about 10% of the latter. Therefore, experimental data of high accuracy are required in order to identify the \( \Lambda \) radial flow. We have noticed that the EOS Collaboration reported a measurement of the transverse mass spectrum of midrapidity Lambda’s in the reaction Ni + Cu at 2 GeV/nucleon[45]. However, the error bars of the EOS data are too large (in particular in the region of 0.2 GeV < \( m_T-m_\Lambda < 0.5 \) GeV) to enable us to draw any conclusion about the \( \Lambda \) radial flow.

It is interesting to study the influence of the size of the reaction system on the \( \Lambda \) radial flow. In order to do this, we also study with the QMD model reactions induced by massive nuclei, i.e. Au+Au. Fig.5 shows the calculated transverse mass spectrum of midrapidity Lambda’s for this reaction at an incident energy of 1 GeV/nucleon and at an impact parameter of \( b = 3 \text{ fm} \). This spectrum can be described very well by a pure Boltzmann distribution as can be seen in the figure. In Fig.6 we present the \( \Lambda \) spectrum of the same reaction as in Fig.5 from a calculation where the \( \Lambda \) mean field is neglected. One finds again that the QMD result without the \( \Lambda \) potential agrees well with a thermal distribution. The \( \Lambda \) spectrum from the simplified calculation is very similar to the one from the full calculation (Fig.5). The average transverse mass \( <m_t> \) is only reduced by about 1 MeV due to the potential. Thus, no effect of the \( \Lambda \) mean field can be observed and the radial flow is invisible in the Au+Au reaction.

That \( \Lambda \) radial flow forms in the Ni+Ni reaction but disappears in the Au+Au reaction can be attributed to \( \Lambda \)-nucleon scatterings. It is clear from Fig.4 and Fig.6 that \( \Lambda \)-nucleon scatterings alone cannot induce any two-temperature structure of the \( \Lambda \) spectrum. However, as soon as a \( \Lambda \) radial flow develops as a consequence of the attractive potential, \( \Lambda \)-nucleon scatterings begin to play a role in canceling the effect of the potential, since the scatterings bring the \( \Lambda \)’s
from the low energy region of $m_T - m_\Lambda < 0.2$ GeV to higher energies. As we have mentioned, a $\Lambda$ hyperon has a short mean free path in nuclear matter, especially for low-energy Lambda’s. One expects more $\Lambda$-nucleon scatterings in a larger system, and thus less low-$m_T$ Lambda’s. Consequently, one finds no "concave" structure in the $\Lambda$ spectrum in the reaction Au+Au, while this structure survives in the Ni+Ni reaction as a result of reduced $\Lambda$-nucleon scatterings. The density dependence of the $\Lambda$ potential could also play a role in the $\Lambda$ radial flow. As can be seen in Fig.1, the $\Lambda$ potential changes to be shallower as the density increases beyond the normal nuclear matter density $\rho_0$. A larger system has a larger stopping power, and thus a longer lifetime of the dense fireball. Consequently, the $\Lambda$ hyperons experience a less attractive potential in a larger system. This also leads to a weaker radial flow in the Au+Au reaction than in Ni+Ni reaction.

It is worthwhile to indicate that the $\Lambda$ radial flow is very sensitive to incident energies. The conclusions of the present work are drawn for the incident energies close to the $\Lambda$ production threshold for free NN collisions. These relatively low beam energies, i.e. 1-2 GeV/nucleon, lead to a negligible effect of the fireball expansion on the $\Lambda$'s as we have mentioned. However, as one goes to AGS energies or even SPS energies, the fireball expansion will play a non trivial role in determining the $\Lambda$ spectrum. The fireball expansion can reduce the multiplicity of low-$m_T$ $\Lambda$'s by pushing them to a finite $m_T$ corresponding to the common expansion velocity of the fireball. Consequently, the transverse mass spectrum of the $\Lambda$'s will show a "shoulder-arm" shape rather than a "concave" shape. Such "Shoulder-arm" structure has been observed by the E891 Collaboration for the incident energy of 11.6 GeV/nucleon[43]. This observation does not contradict with the present study.

5 Summary

In this paper we have studied the collective flow of $\Lambda$ hyperons in heavy ion reactions at SIS energies with the QMD model. It is shown that the FOPI data of the $\Lambda$ transverse flow, which is quantitatively described with the $\Lambda$ in-plane momentum as a function of rapidity, can be well reproduced by using a $\Lambda$ potential constructed based on the quark model. The QMD model used in the present paper can also describe very well the measured proton and kaon flow as shown in our previous work. A radial flow of $\Lambda$ hyperons is found to arise from the attractive $\Lambda$ potential in the Ni+Ni reaction. The flow results in a "concave" structure of the transverse mass spectrum of the $\Lambda$ hyperons emitted at midrapidity. However, as one changes to the reaction Au+Au, the $\Lambda$ radial flow vanishes. The size dependence of the $\Lambda$ radial flow can be attributed to frequent $\Lambda$-nucleon scatterings and reduced attraction of the $\Lambda$ potential in
a large system.

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Figure Captions

Fig. 1. The Λ mean-field potential in nuclear matter used in this work (at zero momentum). The circle denotes the potential at normal nuclear matter density $\rho_0$ extracted from hypernuclei experiments[23].

Fig. 2. The in-plane Λ momentum as a function of rapidity from the Ni+Ni reaction at 1.93 GeV/nucleon and within an impact parameter region of b=0-4 fm. The solid line denotes the QMD calculation including the full in-medium Lambda dynamics, while the dashed line is the QMD calculation without the Λ potential. The experimental data from the FOPI Collaboration are also presented.

Fig. 3. The transverse mass spectrum of the Λ hyperons emitted at midrapidity ( -0.4 < $y_{c.m.}/y_{proj}$ < 0.4 ) from the same reaction as in Fig.2. The histogram presents the result of the QMD calculation which is performed including the full in-medium Lambda dynamics. The dashed line presents the result of a pure thermal Boltzmann fit to the high energy part of the spectrum ( $m_t$-$m_0$ > 0.2 GeV ), while the dotted line is the fit according to eq.(5) where one assumes a Λ radial flow in addition to the thermal motion.

Fig. 4. The transverse mass spectrum of the Λ hyperons emitted at midrapidity ( -0.4 < $y_{c.m.}/y_{proj}$ < 0.4 ) from the same reactions as in Fig. 2. The histogram presents the result of the QMD calculation without the Λ mean field. Now a pure thermal fit (lines ) is sufficient to reproduce the spectrum.

Fig. 5. The transverse mass spectrum of the Λ hyperons emitted at midrapidity ( -0.4 < $y_{c.m.}/y_{proj}$ < 0.4 ) from the reaction Au+ Au at 1 GeV/nucleon and b=3 fm. The histogram presents the result of the QMD calculation with the Λ mean field, while the line is a Boltzmann fit to the QMD result.

Fig. 6. The transverse mass spectrum of the Λ hyperons emitted at midrapidity ( -0.4 < $y_{c.m.}/y_{proj}$ < 0.4 ) from the same reaction as in Fig.5. The histogram presents the result of the QMD calculation without the Λ mean field, while the line is a Boltzmann fit to the QMD result.
Fig. 1.
Fig. 2.

QMD, with mean field
QMD, no mean field
FOPI data

Ni+Ni 1.93 GeV/nucleon
b = 0–4 fm

\[ <P_x> \text{ [MeV/c]} \]

\( Y_{\text{cm}} / Y_{\text{proj}} \)
Fig. 3.

Ni+Ni 1.93 GeV/nucleon b=0−4 fm

\[ \Lambda -0.4 < y_{cm}/y_{proj} < 0.4 \]

\[ \frac{1}{2\pi m_t} \frac{dN}{dm_t dy} \text{ (GeV)}^{-2} \]

- QMD with potential
- Boltzmann fit
- fit with $\beta = 0.025$ and $T = 115$ MeV
Fig. 4.

Ni+Ni 1.93 GeV/nucleon b=0−4 fm

\[ \Lambda, \ -0.4 < \frac{y_{cm}}{y_{proj}} < 0.4 \]

\[ \frac{1}{2\pi m_t} \frac{dN}{dm_t dy} \text{ (GeV)}^{-2} \]

- QMD, no potential
- Boltzmann fit \( T = 115 \) MeV
\[ \frac{1}{2\pi m_t} \frac{dN}{d m_t} dy (\text{GeV})^2 \]

\[
\Lambda, \quad -0.4 < y_{cm}/y_{proj} < 0.4
\]

Fig. 5.
Fig. 6.

Au+Au 1GeV/nucleon b =3 fm

$\Lambda, \ -0.4 \prec y_{cm}/y_{proj} \prec 0.4$

$\frac{1}{2\pi m_t} \frac{dN}{dm_t dy}$ (GeV)$^{-2}$