We study $K^+$ and $\Lambda$ flow in heavy-ion collisions at beam energies of about 2A GeV. We present our results in both the 'traditional' (i.e., in terms of the average transverse momentum in the reaction plane) as well as 'modern' (i.e., in terms of coefficients of the Fourier analysis of azimuthal distributions) methods of flow analysis. We find significant differences between the $K^+$ and the $\Lambda$ flow: while the $\Lambda$ flow is basically similar to that of nucleons, the $K^+$ flow almost disappears. This difference is attributed chiefly to their different mean field potentials in dense matter. The comparisons with the experimental data, as well as theoretical results from independent calculations, indicate clearly the pivotal roles of both $K^+$ and $\Lambda$ medium effects. We emphasize that similar experimental data from independent collaborations are essential for the eventual verification of these medium effects.

25.75.Dw, 26.60.+c, 24.10.Lx

I. INTRODUCTION

Whether and how hadronic properties, such as their masses, widths, and dispersion relations, are modified in hot and dense medium is a topic of great current interest. Of particular importance are the medium modifications of kaon properties, as they are related to both spontaneous and explicit chiral symmetry breaking, and they are useful inputs for the study of kaon condensation and neutron star properties [14,15]. Since the pioneering work of Kaplan and Nelson [3] on the possibility of kaon condensation in nuclear matter, a huge amount of theoretical effort has been devoted to the study of kaon properties in dense matter, using such diversified approaches as chiral perturbation theory [1,2], the Nambu–Jona-Lasinio model [3], and SU(3) Walecka-type mean-field model [4,5]. These calculations indicate that $K^+$ feels a weak repulsive potential, arising from the near cancellation of attractive scalar and repulsive vector potentials. On the other hand, the $K^−$ feels a strong attractive potential, since its vector potential is attractive as well.

Closely related to this are the in-medium properties of hyperons, which, like kaons, also carry explicitly the strangeness. There also have been quite extensive theoretical studies for hyperon (in particular $\Lambda$) properties in nuclear matter. In Ref. [16], a potential was calculated in the Dirac-Brueckner approach using a boson-exchange model for the $\Lambda N$ interaction. In Refs. [17,18] the SU(3) Walecka-type model was used to study the hyperon properties. Generally, the results from these theoretical studies are in agreement with the empirical $\Lambda$ potential extracted from the analysis of hypernucleus properties [13,20], namely, an attractive potential of about −30 MeV.

The analysis of $K^+$-nucleus scattering [21] and hypernucleus structure probes the properties of $K^+$ and $\Lambda$ at densities below normal nuclear matter densities $\rho_0$. For the study of kaon condensation and the role of hyperons in neutron stars [22], much higher densities are involved. This can only be obtained by analysing heavy-ion collision data on various observables involving strangeness. Of particular interesting is a comparative and simultaneous study of $K^+\Lambda$ and $\Lambda$ observables, such as their collective flow which is the focus of this paper.

In heavy-ion collisions at a few AGeV beam energies, the $K^+$ and $\Lambda$ are mostly produced together in the so-called associated processes, such as $BB \rightarrow B\Lambda K$ and $\pi B \rightarrow \Lambda K$, where $B$ represents a baryon such as a nucleon or a delta resonance. Without final-state interactions, their momentum spectra are expected to be quite similar. Thus any observed difference in their flow patterns can mainly be attributed to the difference in their final-state interactions. This includes both the rescattering with the environment (the short-range correlation) and their propagation in mean-field potentials (the long-range correlation). In certain energy regions, the $K^+N$ and $\Lambda N$ cross sections are actually quite similar (see below), thus the difference in their flow patterns may eventually be traced back to the difference in their mean-field potentials.

The experimental and theoretical studies of collective flow of various types have been an important component of relativistic heavy-ion collisions [23]. Traditionally, in-plane directed flow is characterized by the average transverse momentum $\langle p_T \rangle$ as a function of the rapidity $y$, based on the Danielewicz-Odyniec method [24]. This kind of ‘traditional’ analysis has been carried out mainly for heavy-ion collisions up to Bevalac and SIS energies (1-2A GeV) [24]. Recently, there is a resurgence of the flow study in heavy-ion collisions at AGS (10A GeV) [25,26] and SPS (200A GeV) energies [29,30], using a method [31,32] based on the Fourier analysis of the azimuthal particle (energy) distributions. This ‘modern’ method of flow analysis is less affected by the uncertainties in the reaction plane determination [33].

Kaoon flow as a probe of the kaon potential in dense matter was first proposed by Li et al. [33,34]. Lambda flow was studied by Li and Ko in Ref. [37]. Indeed, quite different flow patterns were predicted for $K^+$ and $\Lambda$, because of their different mean-field potentials. This
has stimulated many experimental activities both at SIS [8] [11] and AGS [12] [14]. So far, the experimental data from the FOPI collaboration [15] [11] and the EOS collaboration [12] [13] seem to support the scenario that the \(K^+\) feels a weak repulsive potential, while the \(\Lambda\) feels an attractive potential, in nuclear matter.

This paper is an extension of Refs. [35–37]. We will first compare our results with existing experimental data from the FOPI collaboration, and with theoretical results from other independent calculations [42, 43]. We will then report our predictions for Ru + Ru collisions at 1.69 A GeV, currently under investigation by the FOPI collaboration. Here we shall concentrate on the centrality dependence of the \(K^+\) and \(\Lambda\) flow. We will also present our predictions for Au + Au collisions at 2A GeV, current under investigation by the E895 collaboration [48, 49] (and possible by the E866 collaboration [14]). Here we shall discuss our results in terms of the Fourier coefficients of the azimuthal distributions.

This paper is arranged as follows. In Section II, we review the relativistic transport model, the in-medium properties of \(K^+\) and \(\Lambda\), and their production cross sections. The results for Ni + Ni and Ru + Ru are presented in Section III, in terms of ‘traditional’ flow variables. The results for Au + Au collisions are presented in Section IV, in terms of ‘modern’ flow variables. The paper ends with a short summary in Section IV.

**II. THE RELATIVISTIC TRANSPORT MODEL AND STRANGENESS PRODUCTION**

Heavy-ion collisions involve very complicated nonequilibrium dynamics. One needs to use transport models in order to extract from experimental data the information about in-medium properties of hadrons. In this work we will use the relativistic transport model similar to that developed in Ref. [50]. Instead of the usual linear or nonlinear \(\sigma - \omega\) models, we base our model on the effective chiral Lagrangian recently developed by Furstahl, Tang, and Serot [51], which is derived using dimensional analysis, naturalness arguments, and provides a very good description of nuclear matter and finite nuclei. In the mean-field approximation, the energy density for the general case of asymmetric nuclear matter is given by

\[
\varepsilon_N = \frac{2}{(2\pi)^3} \int_0^{K_f} \frac{k^3}{d} \sqrt{k^2 + m_N^2} + \frac{2}{(2\pi)^3} \int_0^{K_f} \frac{k^3}{d} \sqrt{k^2 + m_N^2} + \frac{K_f}{2} k^2 + \frac{1}{2C_s^2} W^2 - \frac{1}{2C_s^2} R^2 + \frac{1}{2C_s^2} \Phi^2
\]

Here we shall discuss our results in terms of the Fourier coefficients of the azimuthal distributions.

This paper is an extension of Refs. [35–37]. We will first compare our results with existing experimental data from the FOPI collaboration, and with theoretical results from other independent calculations [42, 43]. We will then report our predictions for Ru + Ru collisions at 1.69 A GeV, currently under investigation by the FOPI collaboration. Here we shall concentrate on the centrality dependence of the \(K^+\) and \(\Lambda\) flow. We will also present our predictions for Au + Au collisions at 2A GeV, current under investigation by the E895 collaboration [48, 49] (and possible by the E866 collaboration [14]). Here we shall discuss our results in terms of the Fourier coefficients of the azimuthal distributions.

This paper is arranged as follows. In Section II, we review the relativistic transport model, the in-medium properties of \(K^+\) and \(\Lambda\), and their production cross sections. The results for Ni + Ni and Ru + Ru are presented in Section III, in terms of ‘traditional’ flow variables. The results for Au + Au collisions are presented in Section IV, in terms of ‘modern’ flow variables. The paper ends with a short summary in Section IV.
Particles produced in elementary hadron-hadron interactions in heavy-ion collisions cannot escape the environment freely. Instead, they are subjected to strong final-state interactions. For the kaon, because of strangeness conservation, its scattering with nucleons at low energies is dominated by elastic and pion production processes, which do not affect its final yield but changes its momentum spectra. Similarly, at low-energies, the $\Lambda$ is dominated by elastic and pion production processes, conservation, its scattering with nucleons at low energies state interactions. For the kaon, because of strangeness, the nuclear medium, one with and one without medium interactions in heavy-ion collisions cannot escape the environment. Since the exact value of $\Sigma_{KN}$ there is also the range term which reduces the scalar potential for the kaon. If one considers only the Kaplan-Nelson term, then

$$U_{\Lambda}(k, \rho) = \frac{1}{2} \left( (m_{\Lambda} - \Phi_{\Lambda})^2 + k^2 \right)^{1/2}.$$

where $b_K = 3/(8 f_\pi^2) \approx 0.333$ GeV fm$^3$, $a_K$ is the parameter that determines the strength of the attractive scalar potential for the kaon. If one considers only the Kaplan-Nelson term, then $a_K = \Sigma_{KN}/f_\pi^2$. In the same order, there is also the range term which reduces the scalar attraction. Since the exact value of $\Sigma_{KN}$ and the size of the higher-order corrections are still under intensive debate, we take the point of view that $a_K$ can be treated as free parameter and try to constrain it from the experimental observables in heavy-ion collisions. In Ref. [55,56] it was found that $a_K \approx 0.22$ GeV$^2$ fm$^3$ provide a good description of $K^+$ spectra in Ni+Ni collisions. This value will be used in this work as well. Actually, since $K^+$ interaction is relatively weak, the kaon potential in nuclear matter, at least at low densities, can also be obtained from the $KN$ scattering length in free space using the impulse approximation. In Fig. 2 we show the kaon potential as a function of density, which is defined as

$$U_K(k, \rho) = \omega_K - (m_K^2 + k^2)^{1/2}.$$

The open circle in the figure is the kaon potential at $\rho_0$ obtained in the impulse approximation. It is well-known that the quark counting rule applies approximately to the $\Lambda$ potential. Thus the $\Lambda$ potential is about 2/3 of that of nucleon:

$$\Phi_\Lambda = 2/3 \Phi, \quad W_\Lambda = 2/3 W.$$

The $\Lambda$ optical model potential can then be defined as

$$U_\Lambda(k, \rho) = \left( (m_{\Lambda} - \Phi_{\Lambda})^2 + k^2 \right)^{1/2} + W_\Lambda - \left( m_{\Lambda}^2 + k^2 \right)^{1/2}.$$
our results include this cut are in good agreement with the data. This is important, as all the following discussions about $K^+$ and $\Lambda$ flow are presented with respect to the nucleon flow.

While the nucleon flow parameter is about 150 MeV/c, the flow parameters of the primordial $K^+$ and $\Lambda$ are 20 and 40 MeV/c, respectively.

![Figure 3](image3.png)

**FIG. 3.** Comparison of proton flow with experimental data from the FOPI collaboration [38]. The role of the transverse momentum cut is highlighted.

**A. Ni+Ni collisions**

As mentioned in the Introduction, since the $K^+$ and $\Lambda$ are produced together in associated processes, their flow pattern should be very similar, if there were no any final-state interactions for these particles. The flow of primodial kaons and lambda hyperons should reflect the collective flow of baryon-baryon and pion-baryon pairs from which they are produced. The results are shown in Fig. 4. As can be seen, both $K^+$ and $\Lambda$ show positive flow, in the same direction as that of nucleons. In terms of the average transverse momentum, the $\Lambda$ flow is stronger than that of $K^+$, because it is heavier. Actually, their transverse velocities are quite similar, as shown in the lower window of the figure. This velocity is acquired from the Lorentz boost in the direct of nucleon flow. Both the $K^+$ and $\Lambda$ flow, without any final-state interactions, are much weaker than that of nucleon (see the dotted line in Fig. 3). This statement can be quantified by introducing the so-called flow parameter $F$, defined as the slope parameter of the transverse momentum curve at the mid-rapidity,

$$F = \frac{d\langle p_x \rangle}{dy} |_{y=0}. \quad (9)$$

![Figure 4](image4.png)

**FIG. 4.** $K^+$ and $\Lambda$ flow in central Ni+Ni collisions at 1.93A GeV. The upper window shows the average transverse momentum, while the lower window shows the velocity (normalized by their respective masses). The results shown are for the case without any final-state interactions.

![Figure 5](image5.png)

**FIG. 5.** Same as Fig. 4, including rescattering.
Including the $KN$ and $\Lambda N$ rescattering increases their flow in the direction of nucleons, as shown in Fig. 3. This enhancement is mainly due to the thermalization effects, which increase the average momenta of kaons and lambda hyperons. At the beam energies considered here, which are only slightly above the production threshold, the produced kaons and lambda hyperons usually have small momenta. By rescattering with energetic nucleons, their momenta increase, as does their flow strength. The $K^+$ flow parameter increases from 20 to 40 MeV, while the $\Lambda$ flow parameter increases from 40 to 75 MeV. Their flow velocities are still about the same, since their rescattering cross sections are not very different.

Their flow parameters are shown in Fig. 6. The $K^+$ flow parameter increases from 20 to 40 MeV, while the $\Lambda$ flow parameter increases from 40 to 75 MeV. Their flow velocities are still about the same, since their rescattering cross sections are not very different. To see more clearly the effects of final-state interactions, these results are summarized in Fig. 7, where the upper window shows those for $K^+$ and the lower window for $\Lambda$.

Finally the results for $K^+$ and $\Lambda$ flow including both rescattering and propagation in mean-field potentials are shown in Fig. 8. Since the $K^+$ potential is repulsive, kaons are pushed away from nucleons, leading to the near disappearance of the flow signal. The flow parameter turns from positive into negative, and is about -15 MeV. On the other hand, the $\Lambda$ potential is attractive, and lambda hyperons are pulled towards nucleons, leading to the further enhancement of its flow in the direction of nucleon flow. The $\Lambda$ flow parameter increases to about 130 MeV, close to that of nucleons. Therefore, the difference in their mean-field potentials lead to substantially different flow pattern for $K^+$ and $\Lambda$, although they are produced together in the same processes, and

Since the proposal of kaon flow as a signal of kaon potential in Ref. [35], the FOPI collaboration measured both $K^+$ and $\Lambda$ flow in Ni+Ni collisions at 1.93A GeV [38–41], while the EOS collaboration measured $\Lambda$ flow in Ni+Cu collisions at 2A GeV [42,43]. The comparison of our results with the FOPI data for $K^+$ flow are shown in Fig. 9. As in the experimental data, our results include a transverse momentum cut of $p_t/m_K > 0.5$, which increases the flow signal in the direction of the nucleon flow. Clearly, without the kaon medium effects, namely, the propagation in the repulsive mean-field potential, the $K^+$ flow is positive, and is in complete disagreement with the experimental data, which show a small antiflow in the mid-rapidity region. Including the effects of the repulsive potential, the kaons are pushed away from the nucleon, and our results are now in very good agreement with data. This indicates that the kaon potential as determined by Eq. (3) is reasonable.
The comparison of our results for Λ flow in the same system are shown in Fig. 8. Experimental data [38], though with quite large statistical uncertainties, clearly show that the Λ flow is in the same direction as nucleons, with a strength quite similar to that of nucleons. A similar observation has also been made by the EOS collaboration [42,43]. Such a strong positive flow can be achieved only after the inclusion of the Λ final-state interaction. An accurate determination of the role of the mean-field potentials, however, requires much improved data, especially near the mid-rapidity.

Theoretically, kaon flow in Ni+Ni collisions has also been studied by several independent groups, using different dynamical models such as the Hadron-String Dynamics [45], the Quantum-Molecular Dynamics (QMD) [46], and the Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) [58]. The results from these calculations are qualitatively similar to ours, as summarized in Fig. 10. Without kaon medium effects, all the calculations predict a positive flow signal for kaons, and thus in disagreement with the experimental data (see upper window of the figure). Including the repulsive kaon potential, the kaon flow turns into a small antiflow, and all the three results are in good agreement with the data, as shown in the lower window of the figure.
We expect that the $K^+$ and $\Lambda$ flow in Ru+Ru collisions at 1.69A GeV to be very similar to that in Ni+Ni collisions at 1.93A GeV. To study the centrality dependence of the these flow patterns, we choose two impact parameters $b=1$ and 5 fm, corresponding to central and semi-central collisions. As a reference, we show in Fig. 11 the proton flow with and without the transverse momentum cut of $p_t/m > 0.5$. This cut is included to facilitate comparisons with future FOPI data. As expected, the proton flow is larger in semi-central collisions than in central ones.

The results for the primodial $K^+$ and $\Lambda$ flow are shown in Fig. 12. The results in the right panel include a transverse momentum cut of $p_t/m > 0.5$. In this case both the kaons and lambda hyperons flow in the same direction as the nucleons, but with a substantially smaller flow velocity. Just like nucleons, the flow of primodial kaons and hyperons is stronger in semicentral collisions than in central collisions. The results including the $KN$ and $\Lambda N$ rescattering are shown in Fig. 13. Again, the rescattering increases both the $K^+$ and $\Lambda$ flow in the direction of nucleon flow, and the rescattering effects are about the same for the central and semicentral collisions.

Finally, the results including both the rescattering and propagation in the mean-field potentials are shown in Fig.
Kaons are pushed away from nucleons by their repulsive potential, and lambda hyperons are pulled towards nucleon by their attractive potential, enhancing further its flow strength. The mean-field effects are seen to be stronger in semi-central collisions than in central ones. Although compression might be larger in central collisions, the density gradients, which determine the forces entering Eqs. (7) and (8), is larger in semi-central collisions, because of the existence of the spectator matter. This might explain why kaons in the semi-central collisions are pushed even further away from nucleons than those in central collisions, although the kaons in the former case have a larger positive flow than in the latter case (see Fig. 13) before the propagation in the mean-field potential sets in. After including the transverse momentum cut, the kaons are clearly anticorrelated with nucleons in semicentral collisions, with a flow parameter of about -20 MeV. On the other hand, at least near mid-rapidity, the kaons in the central collisions are seen to be correlated with nucleons, with a flow parameter of about 10 MeV.

The study of the centrality dependence of the kaon flow by the FOPI collaboration [47] will shed further light on the question of kaon medium effects in heavy-ion collisions.

\[
E \frac{d^3N}{d^3p} = \frac{d^2N}{p_t dp_t dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi) \right), \quad (10)
\]

where an expansion in terms of the azimuthal angle \( \phi \) is introduced. In practice, this expansion can be truncated at \( n = 2 \), so that

\[
E \frac{d^3N}{d^3p} \approx \frac{d^2N}{p_t dp_t dy} \frac{1}{2\pi} (1 + 2v_1 \cos\phi + 2v_2 \cos(2\phi)). \quad (11)
\]

Here \( v_1 \) reflects the relative abundance of particles in the positive \( x \)-axis versus that in the negative direction (directed flow), whereas \( v_2 \) measures the relative abundance of particles in the reaction plane versus that of out-of the reaction plane. Generally, both \( v_1 \) and \( v_2 \) depend on the transverse momentum \( p_t \) and rapidity \( y \). Integrating over transverse momentum, they can then be presented as a function of the rapidity, in the same way as the average transverse momentum is plotted as a function of the rapidity in the ‘traditional’ analysis. In this section we shall concentrate on the the directed flow of \( K^+ \) and \( \Lambda \), as measured by the first Fourier moment \( v_1 \), in Au+Au collisions at 2A GeV.

Recently, the study of collective flow has been quite active at higher AGS [24, 25] and SPS [24, 30] energies.
We first show in Fig. 15 the proton and pion flow for impact parameter $b < 6$ fm, which corresponds approximately to the centrality selection of the E895 collaboration [48]. We see a very strong positive flow for protons, which reaches about 0.3 nearly the projectile (target) rapidity. On the other hand, the pions show a very weak antiflow with respect to nucleons. This anticorrelation arises from the strong absorption of pions by spectator nucleons.

![Figure 15](image1.png)

**FIG. 15.** The rapidity dependence of the first moment ($v_1$) of $K^+$ and $\Lambda$ in Au+Au collisions at 2A GeV. The results shown are for the case without any final-state interactions.

The results for $K^+$ and $\Lambda$ flow in these collisions are shown in Figs. 16, 17, and 18, the the scenarios without final-state interaction, with rescattering, and with rescattering and propagation in mean-field potential, respectively. No transverse momentum acceptance has been applied.

Without any final-state interactions, both $K^+$ and $\Lambda$ show positive flow, in the same direction as nucleon, but with a much smaller $v_1$. Also, if we normalize these moments by their respective masses, we find that the normalized first moments of $K^+$ and $\Lambda$ are about the same, reflecting the fact that their flow velocities are similar, since they are produced from the same sources. The rescattering with nucleons is seen to increase the first moments of $K^+$ and $\Lambda$ in the direction of nucleon flow, just as it enhances their average transverse momenta. The flow patterns of the kaons and lambda hyperons are still quite similar after the inclusion of their rescattering with nucleons.

![Figure 16](image2.png)

**FIG. 16.** The rapidity dependence of the first moment ($v_1$) of $K^+$ and $\Lambda$ in Au+Au collisions at 2A GeV. The results shown are for the case without any final-state interactions.

![Figure 17](image3.png)

**FIG. 17.** Same as Fig. 16, with rescattering.

![Figure 18](image4.png)

**FIG. 18.** Same as Fig. 16, with rescattering and propagation in the mean-field potentials.

Finally, after the inclusion of the propagations in their mean-field potentials, the flow patterns of $K^+$ and $\Lambda$ become significantly different. Kaons are pushed away from nucleons, leading to an anticorrelation with nucleons. From the $v_1 - y$ plot, we can also define a so-called
flow parameter, $F_{\nu_1}$, as the slope of this plot at mid-rapidity. Clearly, the nucleons have a positive flow parameter, while the kaons show a negative flow parameter, after the inclusion of the mean-field effects. On the other hand, the lambda hyperons are pulled towards nucleons, leading to an enhancement of its flow in the same direction as nucleons. Its flow parameter after including these final-state interaction is quite similar to that of nucleons. Basically the $\nu_1$ versus $y$ plot provides quite similar information as the $\langle p_x \rangle$ versus $y$ plot. The advantage of working with $\nu_1$ is that one can obtain further information by analysing its transverse momentum (mass) dependence \[28\].

V. SUMMARY

We studied $K^+$ and $\Lambda$ flow in heavy-ion collisions at beam energies of about 2A GeV, using the relativistic transport model that includes the strangeness degrees of freedom explicitly. We find that, without any final-state interactions, both the $K^+$ and $\Lambda$ flow in the same direction as nucleons, but with much smaller flow velocities, which are quite similar for kaons and lambda hyperons. This small flow velocity reflects the collective flow of the baryon-baryon and pion-baryon pairs from which kaons and lambda hyperons are produced. The inclusion of their rescattering with nucleons enhances the flow of $K^+$ and $\Lambda$ in the direction of nucleons, as a result of thermalization effects. The flow velocities of kaons and lambda hyperons in this case are still quite similar, and smaller than that of nucleons. We find, furthermore, that the propagation in their mean-field potentials leads to quite different flow patterns for $K^+$ and $\Lambda$. Kaons are pushed away from nucleons by their repulsive potential, and lambda hyperons are pulled towards nucleons by their attractive potentials. This leads to the small antiflow of kaons with respect to nucleons, and the flow of lambda hyperons that is very close to that of nucleons. The comparison of our results with experimental data from the FOPI collaboration for Ni+Ni collisions, and with independent theoretical calculations, indicate clearly the important role of mean-field potentials. We also presented predictions for Ru+Ru collisions in terms of average transverse momentum $\langle p_x \rangle$, and for Au+Au collisions in terms of the first moment $\nu_1$ of the Fourier analysis of azimuthal particle distributions.

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