PHYSICAL REVIEW C **74**, 064902 (2006)

Elliptic flow of ϕ mesons and strange quark collectivity

J. H. Chen,[1,2] Y. G. Ma,[1,*] G. L. Ma,[1,2] X. Z. Cai,[1] Z. J. He,[1] H. Z. Huang,[3] J. L. Long,[1] W. Q. Shen,[1] C. Zhong,[1] and J. X. Zuo[1,2]

[1]*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, People's Republic of China*

[2]*Graduate School of the Chinese Academy of Sciences, Beijing 100080, People's Republic of China*

[3]*University of California, Los Angeles, California 90095, USA*

(Received 8 March 2006; published 1 December 2006)

Based on a multiphase transport model, we have studied the elliptic flow v_2 of ϕ mesons from the reconstructed K^+K^- decay channel at the top Relativistic Heavy Ion Collider energy at Brookhaven National Laboratory. The dependences of v_2 on transverse momentum p_T and collision centrality are presented and the rescattering effect of ϕ mesons in the hadronic phase is also investigated. The results show that experimental measurement of v_2 for ϕ mesons can retain the early collision information before the ϕ decays and that the ϕ v_2 value obeys the constituent quark number scaling that has been observed for other mesons and baryons. Our study indicates that the ϕ v_2 mostly reflects partonic-level collectivity developed during the early stage of the nucleus-nucleus collision and the strange and light up/down quarks have developed similar angular anistropy properties at the hadronization.

DOI: 10.1103/PhysRevC.74.064902 PACS number(s): 24.10.Cn, 24.10.Pa, 25.75.Dw

I. INTRODUCTION

Elliptic flow in heavy-ion collisions is a measure of the azimuthal angular anisotropy of the particle distribution in momentum space with respect to the reaction plane [1]. The magnitude of the elliptic flow depends on both initial spatial asymmetry in noncentral collisions and the subsequent collective interactions. The elliptic flow is thus sensitive to the properties of the dense matter formed during the initial stage of heavy-ion collision [2–5] and parton dynamics [6] at Relativistic Heavy Ion Collider (RHIC) energies. Experimentally, elliptic flow has been measured as functions of collision centrality, transverse momentum, (pesudo)rapidity, and particle species [7–11] in ^{197}Au+^{197}Au collisions from RHIC at Brookhaven National Laboratory (BNL). The experimental results for the charged kaon, proton, and pion [8] show that the elliptic flow first increases with particle transverse momentum following the hydrodynamic behavior and then saturates in the intermediate transverse momentum region. More importantly, a number-of-constituent-quark (NCQ) scaling has been discovered for identified particle elliptic flow in the intermediate-p_T region for baryons and mesons. The pion elliptic flow v_2 data are somewhat higher than the NCQ scaling, which can be attributed to the large contribution to the pion yield from secondary decays [12,13]. The NCQ scaling at RHIC is an important indication for the effective constituent quark degree of freedom at hadronization and the formation of hadrons through the parton coalescence mechanism [14,15]. Similarly, Yan and Ma *et al.* [16] recently demonstrated a number-of-nucleon scaling for anisotropic flow of light nuclear clusters in nuclear collisions at Fermi energies, which is interpreted as a consequence of the nucleon coalescence mechanism.

Strange-quark dynamics is a useful probe of the dense matter created at RHIC. Enhanced strangeness production [17] has been proposed as an important signal for the formation of the quark-gluon plasma (QGP) in nuclear collisions. The dominant production of $s\bar{s}$ pairs via the gluon-gluon interaction may lead to a strangeness (chemical and flavor) equilibration time comparable to the lifetime of the QGP whereas the strangeness equilibration time in a hadronic fireball is much longer than the lifetime of the hadronic fireball. The subsequent hadronization of the QGP is then expected to result in an enhanced production of strange particles. In particular, it has been argued that with the formation of QGP the production of ϕ mesons is enhanced. Furthermore, ϕ mesons could retain information on the condition of the hot plasma at hadronization because ϕ mesons interact weakly in the hadronic matter [18]. The measurement of ϕ mesons has been of great interest in the study of collision dynamics and the properties of the dense matter created at RHIC [19–21].

We use a multiphase transport (AMPT) model to investigate the effect of parton dynamics related to ϕ mesons. The MPT consists of four main components [22]: initial conditions, partonic interactions, conversion from partonic matter into hadronic matter, and hadronic interactions in collision evolution. The initial conditions, which include the spatial distribution of participant matter, minijet parton production, and soft string excitations, are obtained from the HIJING model [23]. Scattering among partons are modeled by Zhang's parton cascade (ZPC) [24], which calculates two-body parton scatterings using cross sections from pQCD with screening masses. In the default MPT model [25] partons are recombined with their parent strings when they stop interacting, and the resulting strings fragment into hadrons according to the Lund string fragmentation model [26]. In the MPT model with the string melting scenario [27], a quark coalescence model is used to combine partons into hadrons. The evolution dynamics of the hadronic matter is described by a relativistic transport (RT) model [28]. Details of the MPT model can be found in [22].

In this article, we present a detailed study of the elliptic flow of ϕ mesons at the top RHIC energy based on the MPT model with the string melting scenario [22]. The string

*Corresponding author; E-mail: ygma@sinap.ac.cn

melting scenario is believed to be much more appropriate than the default MPT scenario since the energy density in these collisions is much higher than the critical density for the QCD phase transition. The MPT model with the string melting scenario has successfully described the elliptic flow of stable baryons and mesons [22,27]. It can also describe higher order anisotropic flow parameters v_n including the odd-n ones [29]. In this work, we focus on the ϕ mesons. We follow the method used in the experimental analysis by reconstructing ϕ mesons in the final state from fitting the invariance mass distribution of all K^+ and K^- pairs with a Breit-Wigner function including the intrinsic decay width of ϕ mesons [30]. The parton scattering cross section is chosen as 10 mb. The transverse momentum and collision centrality dependences of the ϕ-meson v_2 have been studied and the NCQ scaling has also been observed in the MPT model. In addition, the rescattering effect on the ϕ-meson v_2 has been investigated in the hadronic phase using the RT model where rescattering processes of ϕ mesons and their decay daughters are included [31]. We note that our study based on the MPT model for ϕ-meson elliptic flow differs from that of Ref. [32], where the dynamical quark coalescence model has been used for studies of ϕ-meson production and elliptic flow.

II. ANALYSIS METHOD

The reconstruction of ϕ mesons was accomplished by calculating the invariant mass ($m_{\rm inv}$), transverse momentum (p_T), and azimuthal angle (Φ) of pairs that formed from all permutations of candidate K^+ with K^- at a given ϕ rapidity range ($|y| < 1.0$). The resulting $m_{\rm inv}$ distributions consist of the ϕ signal superimposed on a large background that is predominantly combinatorial. The shape of the combinatorial background was calculated using the mixed-event method [33]. A Breit-Wigner function plus a linear function can describe the $m_{\rm inv}$ distribution well. The left panel of Fig. 1 shows the $m_{\rm inv}$ distribution for ϕ mesons from minimum bias collisions using ~1.8 M Au + Au Monte Carlo MPT events.

The elliptic flow v_2 is calculated by the STAR standard method [11] based on the distribution of particle raw yields as a function of azimuthal angle Φ with respect to the event plane angle Ψ. The raw yields of ϕ mesons are extracted from fits to $m_{\rm inv}$ distribution in each p_T and $\Phi - \Psi$ bin. The event plane angle Ψ is determined from the azimuthal distribution of charged tracks within a window of $0.2 < p_T < 2.0$ GeV/c and pseudo-rapidity $|\eta| < 1.0$, which is used as an estimate of the reaction plane angle [34,35]. To avoid autocorrelations, tracks associated with a ϕ candidate are explicitly excluded from the event plane calculation. The right panel of Fig. 1 shows the azimuthal angular distribution of raw ϕ yields with respect to the event plane from the minimum bias collisions in the $0.4 < p_T < 3.0$ GeV/c range. The dashed line is the result of a fit to the function $\frac{dN}{d(\Phi-\Psi)} = A[1 + 2v_2 \cos 2(\Phi - \Psi)]$, where A is a normalization constant. The finite resolution in the approximation of the event plane as the reaction plane smears out the azimuthal angular distribution and leads to a lower value in the apparent anisotropy parameters [35]. This event plane resolution is determined by dividing each event into random subevents and calculating the difference in event plane angles between subevents. We obtained an event plane resolution of 0.91, which is 20 % larger than the experimental resolution reported by STAR [11]. This is due to the fact that the number of tracks per event used in our simulation is larger than that from the data. To verify our resolution correction, we have also calculated the v_2 with respect to the real reaction plane ($\Psi = 0$), which is known a priori in our model calculation. From Fig. 2, the v_2 extracted from the true reaction plane is in good agreement with the one extracted from the event plane corrected for the resolution effect. Our result also illustrates that the experimental elliptic flow analysis method can faithfully describe the magnitude of the elliptic flow for ϕ mesons.

III. RESULTS

The upper panel of Fig. 3 shows the elliptic flow v_2 of ϕ mesons from minimum-bias MPT ^{197}Au + ^{197}Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Experimental data [8] of $K^+ + K^-$ and $p + \overline{p}$ are also presented for comparison. We note that the ϕ-meson v_2, in comparison with v_2 of charged kaons and protons

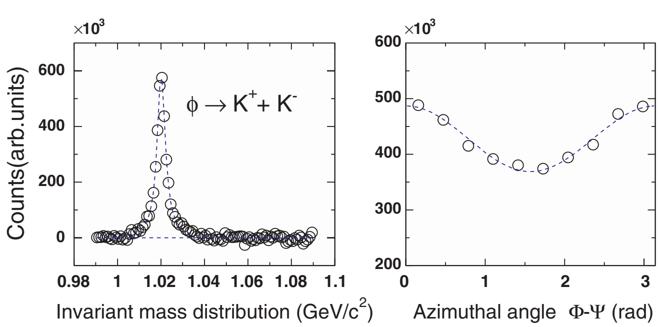

FIG. 1. (Color online) Left panel: $m_{\rm inv}$ distribution from minimum bias (0%–80%) Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Dashed line is a fit of the Breit-Wigner function plus a linear background. Right panel: Azimuthal angular distributions of raw ϕ yields with respect to the event plane. Dashed line represents the fit result. The transverse momentum range of the figure is $0.4 < p_T < 3.0$ GeV/c.

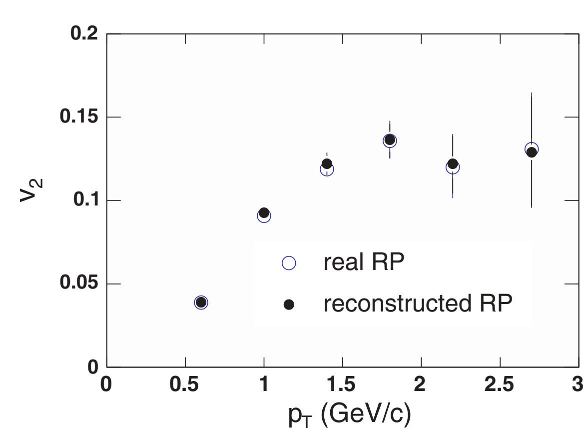

FIG. 2. (Color online) Comparison of elliptic flow values obtained from using the real reaction plane (RP) and the event plane angle corrected for the resolution effect.

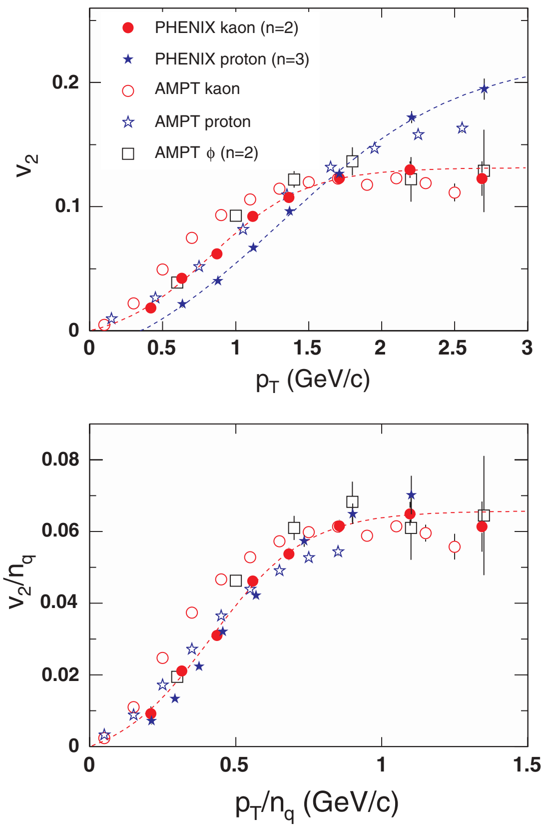

FIG. 3. (Color online) Top panel: p_T dependence of the v_2 for ϕ mesons compared with $K^+ + K^-$ and $p + \overline{p}$. Data are taken from Ref. [8]. Dot-dashed lines are the fitted results with function ($f_{v_2}(n) = \frac{an}{1+\exp[-(p_T/n-b)/c]} - dn$, where a, b, c and d are the fit parameters and n is the constituent-quark number). Bottom panel: NCQ-scaled v_2 as a function of NCQ-scaled transverse momentum. The error bars represent statistical errors only.

all from the MPT model, satisfies the mass-ordering behavior of v_2 predicted by the hydrodynamic model calculation [36] in the low-p_T region. However, the MPT calculation results of v_2 for charged kaons and protons are about 25% larger than the experimental data in the $p_T < 1.5$ GeV/c region. This may result from the large parton scattering cross section (10 mb) used in this Monte Carlo MPT calculation. To explore the intermediate-p_T ($1.5 < p_T < 4.0$ GeV/c) phenomenon, where the so-called NCQ scaling in elliptic flow for identified particles has been observed at RHIC [7] and the quark coalescence or recombination mechanism has been used to explain the scaling [14,15], the large parton scattering cross section is needed to produce the magnitude of the elliptic flow in the intermediate-p_T region matching the experimental measurement [27].

Our MPT calculation indicates that the v_2 of ϕ mesons at intermediate p_T seems to saturate and to follow the same behavior as that of $K^+ + K^-$. The lower panel of Fig. 3 shows elliptic flow v_2 normalized by the number of constituent quarks for charged kaons, protons, and ϕ mesons. In the intermediate-p_T region of $p_T/n_q > 0.6$ GeV/c the elliptic flow of charged kaons, protons, and ϕ mesons from the MPT calculation seems to satisfy the NCQ scaling. This result

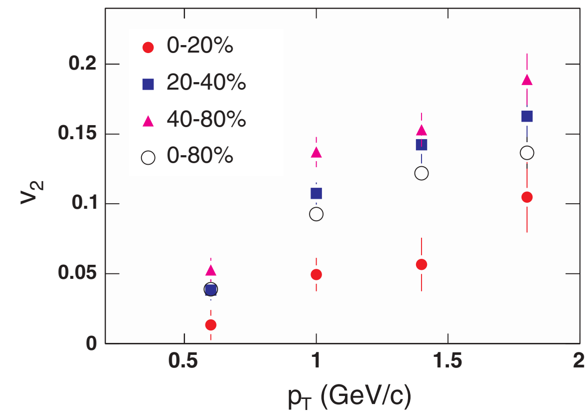

FIG. 4. (Color online) v_2 of ϕ mesons as a function of p_T in the centralities of 0%–20%, 20%–40%, 40–80%, and 0%–80%. The error bars represent statistical errors only.

implies that u, d, and s quarks in the initial partonic matter formed in relativistic heavy-ion collisions develop significant collectivity with strength characterized by v_2/n_q.

We have also studied the collision centrality dependence of ϕ-meson v_2 at several centrality intervals: 0%–20%, 20%–40%, 40%–80%, and 0%–80%. Figure 4 shows that, for each centrality bin, the $v_2(p_T)$ of ϕ mesons increases with their p_T. Among different centrality bins, the values of $v_2(p_T)$ increase from central to semiperipheral collisions, which can be understood as a result of increasing initial spatial eccentricity.

Because the $K^+ + K^-$ pair from the decay of a ϕ meson is likely to undergo rescatterings in the medium during the hadronic evolution, this might lead to a reconstructed K^+K^- invariant mass situated outside the original ϕ-meson mass peak. It is thus of interest to study the in-medium rescattering effect in details. This is carried out by turning on and off the RT process during the hadronic evolution in the MPT model. The elliptic flow v_2 of ϕ mesons without RT indicates the elliptic flow developed before the hardonic rescattering stage. In contrast, the v_2 of ϕ mesons after RT includes all contributions from both partonic and hadronic stages. In Fig. 5, the v_2 for

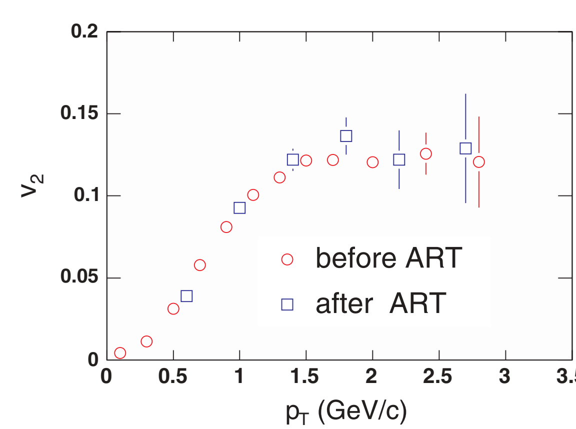

FIG. 5. (Color online) The hadronic rescattering effect on elliptic flow v_2 of ϕ mesons from the MPT model with the string melting scenario.

ϕ mesons before RT are directly extracted from the MPT model without the RT processes. In that case, ϕ mesons are explicitly present and do not need to be reconstructed from $K^+ + K^-$ decay channels. The v_2 after the RT processes is reconstructed from $K^+ + K^-$ pairs and the hadronic rescatterings are mostly due to kaon rescatterings in the hadronic stage. Error bars are statistical errors only. An interesting feature in Fig. 5 is that the two scenarios are in good agreement with each other after $p_T > 0.4$ GeV/c. In this case, the final hadronic rescattering effect on the ϕ-meson elliptic flow can be ignored within the errors. Our study of ϕ-meson v_2 confirms that ϕ mesons can retain useful information from the early stage of the nuclear collisions.

IV. SUMMARY

In summary, we have presented a study of elliptic flow of ϕ mesons using reconstucted K^+K^- pairs from minimum-bias ^{197}Au+^{197}Au collisions at $\sqrt{s_{NN}} = 200$ GeV in a multi-phase transport model with a string melting scenario. The v_2 of ϕ mesons seems to exhibit a behavior similar to that of other mesons. A number-of-constituent-quark scaling phenomenon of elliptic flow has been observed for ϕ mesons from the reconstruction of K^+K^- pairs. The coefficient $v_2(p_T/n_q)$ of ϕ mesons represents essentially the momentum-space anisotropy of constituent strange quarks that have arisen from the partonic collectivity developed in the initial stage of heavy-ion collisions. The collision centrality dependence of elliptic flow for ϕ mesons has also been studied. It is found that the ϕ-meson elliptic flow increases from central to semiperipheral collisions as a result of increasing initial spatial eccentricity. We have also studied the in-medium hadronic rescattering effect on elliptic flow of ϕ mesons. The results confirm that, within error bars, our reconstructed ϕ-meson v_2 can retain the early information before it decays. Comparing our predictions with the RHIC data for the elliptic flow of ϕ mesons is expected to shed light on these issues.

ACKNOWLEDGMENTS

We would like to acknowledge Drs. C. M. Ko, Z. W. Lin, B. Zhang, and B. A. Li for use of their MPT model. We also appreciate discussions and communications with Drs. C. M. Ko, N. Xu, and J. G. Ma. This work was supported in part by the Shanghai Development Foundation for Science and Technology under Grant Nos. 05XD14021 and 06JC14082 and by the National Natural Science Foundation of China under Grant Nos. 10535010, 10328259, and 10135030.

[1] J. Y. Ollitrault, Phys. Rev. D **46**, 229 (1992); W. Reisdorf and H. G. Ritter, Annu. Rev. Nucl. Part. Sci. **47**, 663 (1997); Y. G. Ma, W. Q. Shen, J. Feng, and Y. Q. Ma, Phys. Rev. C **48**, R1492 (1993); R. Lacey *et al.*, Phys. Rev. Lett. **70**, 1224 (1993); Y. Zheng, C. M. Ko, B. A. Li, and B. Zhang, *ibid.* **83**, 2534 (1999).

[2] H. Sorge, Phys. Lett. **B402**, 251 (1997); Phys. Rev. Lett. **78**, 2309 (1997); **82**, 2048 (1999).

[3] P. Danielewicz, R. A. Lacey, P.-B. Gossiaux, C. Pinkenburg, P. Chung, J. M. Alexander, and R. L. McGrath, Phys. Rev. Lett. **81**, 2438 (1998).

[4] P. F. Kolb, P. Huovinen, U. Heinz, and H. Heiselberg, Phys. Lett. **B500**, 232 (2001).

[5] R. Raniwala, S. Raniwala, and Y. Viyogi, Phys. Lett. **B489**, 9 (2000).

[6] B. Zhang, M. Gyulassy, and C.-M. Ko, Phys. Lett. **B455**, 45 (1999).

[7] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92**, 052302 (2004).

[8] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 182301 (2003).

[9] B. B. Back *et al.* (PHOBOS Collaboration), Phys. Rev. C **72**, 051901 (2005).

[10] J. Adams *et al.* (STAR Collaboration), Phys. Rev. C **72**, 014904 (2005).

[11] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **95**, 122301 (2005).

[12] V. Greco and C. M. Ko, Phys. Rev. C **70**, 024901 (2004).

[13] X. Dong, S. Esumi, P. Sorensen, N. Xu, and Z. Xu, Phys. Lett. **B597**, 328 (2004).

[14] Z. W. Lin and C. M. Ko, Phys. Rev. Lett. **89**, 202302 (2002); V. Greco, C. M. Ko, P. Lévai, *ibid.* **90**, 202302 (2003); Phys. Rev. C **68**, 034904 (2003).

[15] R. J. Fries, B. Müller, C. Nonaka, and S. A. Bass, Phys. Rev. Lett. **90**, 202303 (2003).

[16] T. Z. Yan, Y. G. Ma, X. Z. Cai, J. G. Chen, D. Q. Fang, W. Guo, C. W. Ma, E. J. Ma, W. Q. Shen, W. D. Tian, and K. Wang, Phys. Lett. **B638**, 50 (2006).

[17] J. Rafelski and B. Müller, Phys. Lett. **B111**, 101 (1982); P. Koch, B. Müller, and J. Rafelski, Phys. Rep. **142**, 167 (1985).

[18] A. Shor, Phys. Rev. Lett. **54**, 1122 (1985).

[19] J. Adams *et al.* (STAR Collaboration), Phys. Lett. **B612**, 181 (2005).

[20] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. C **72**, 014903 (2005).

[21] C. Nonaka, R. J. Fries, and S. A. Bass, Phys. Lett. **B583**, 73 (2004).

[22] Z. W. Lin, C. M. Ko, B. A. Li, B. Zhang, and S. Pal, Phys. Rev. C **72**, 064901 (2005).

[23] X. N. Wang and M. Gyulassy, Phys. Rev. D **44**, 3501 (1991); M. Gyulassy and X. N. Wang, Comput. Phys. Commun. **83**, 307 (1994).

[24] B. Zhang, Comput. Phys. Commun. **109**, 193 (1998).

[25] Z.-W. Lin, S. Pal, C. M. Ko, B.-A. Li, and B. Zhang, Phys. Rev. C **64**, 011902(R) (2001).

[26] B. Andersson *et al.* Phys. Rep. **97**, 31 (1983).

[27] Z. W. Lin and C. M. Ko, Phys. Rev. C **65**, 034904 (2002); Z. W. Lin, C. M. Ko, and S. Pal, Phys. Rev. Lett. **89**, 152301 (2002).

[28] B. A. Li and C. M. Ko, Phys. Rev. C **52**, 2037 (1995).
[29] L. W. Chen, C. M. Ko, and Z. W. Lin, Phys. Rev. C **69**, 031901(R) (2004); Phys. Lett. **B605**, 95 (2005).
[30] T. Sjöstrand, arXiv:hep-ph/9508391.
[31] S. Pal, C. M. Ko, and Z. W. Lin, Nucl. Phys. **A707**, 525 (2002).
[32] L. W. Chen and C. M. Ko, Phys. Rev. C **73**, 044903 (2006).
[33] D. L'Hote, Nucl. Instrum. Methods Phys. Res. A **337**, 544 (1994).
[34] P. Danielewicz and G. Odyniec, Phys. Lett. **B157**, 146 (1985).
[35] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671 (1998).
[36] P. Huovinen, P. F. Kolb, U. Heinz, P. V. Ruuskanen, and S. A. Voloshin, Phys. Lett. **B503**, 58 (2001).