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ϕ meson production in Au + Au and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract

We report the STAR measurement of ϕ meson production in Au + Au and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Using the event mixing technique, the ϕ spectra and yields are obtained at mid-rapidity for five centrality bins in Au + Au collisions and for non-singly-diffractive $p+p$ collisions. It is found that the ϕ transverse momentum distributions from Au + Au collisions are better fitted with a single-exponential while the $p+p$ spectrum is better described by a double-exponential distribution. The measured nuclear modification factors indicate that ϕ production in central Au + Au collisions is suppressed relative to peripheral collisions when scaled by the number of binary collisions ($\langle N_{\text{bin}}\rangle$). The systematics of $\langle p_t\rangle$ versus centrality and the constant ϕ/K^- ratio versus beam species, centrality, and collision energy rule out kaon coalescence as the dominant mechanism for ϕ production.

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In elementary collisions the production of the ϕ meson, the lightest bound state of strange quarks ($s\bar{s}$), is suppressed because of the OZI rule [1–3]. In heavy-ion collisions, however, strange quarks are produced copiously and ϕ enhancement is observed relative to expectations from $p+p$ collisions [4–6]. Theoretical calculations have tried to address the origins of this enhancement [7–9]. The ϕ meson is also thought to have a small hadronic cross-section [10] and may provide direct information about the dense matter at hadron formation without perturbations from co-moving hadrons. For these reasons, ϕ production in relativistic nuclear collisions has been of great interest.

The mechanism for ϕ production in high energy collisions has remained an open issue. A naive interpretation of the ϕ enhancement observed in heavy-ion collisions would be that the ϕ is produced hadronically via $K\bar{K} \to \phi$. Hadronic rescattering models such as RQMD and UrQMD [11,12], implementing such processes, predict an increase in the ϕ/K^- ratio as a function of the number of participants. Rescattering models also predict similar increases in the $\langle p_t\rangle$ of the proton and ϕ meson.

The nuclear modification factors (R_{AA} and R_{CP}) of the ϕ meson are important in differentiating between mass and particle species ordering. Current measurements of identified hadrons by STAR (Λ and K_S^0) and PHENIX (proton and π^0) show that R_{CP} for the Λ differs from that of the K_S^0 [13] and R_{CP} for the proton differs from that of the π^0 [14]. It is difficult, however, to determine whether this difference is related to the mass of the particle or the type of the particle (whether it is a baryon or a meson) since there is a significant mass difference between the Λ and the K_S^0 or the proton and π^0. The ϕ, however, has a mass that is similar to that of the Λ and proton, yet is a meson. A direct comparison of the ϕ R_{CP} and R_{AA} with these previous measurements will provide more insight into this mass vs. particle species dependence.

The STAR detector [15] consists of several subsystems in a large solenoidal analyzing magnet. For the data taken during the second RHIC run (2001–2002) presented here, the experimental setup consisted of a time projection chamber (TPC), a central trigger barrel (CTB), a pair of beam–beam counters (BBC), and two zero degree calorimeters (ZDC). The ZDCs are used as the experimental trigger for Au + Au collisions while the BBCs are used for the $p+p$ trigger.

The results presented here were obtained from about 2.1 million minimum-bias Au + Au events, 1.1 million central Au + Au events and 6.5 million non-singly-diffractive (NSD) $p+p$ events. Reconstruction of the ϕ was accomplished by calculating the invariant mass (m_{inv}), transverse momentum (p_t), and rapidity (y) of pairs that formed from all permutations of candidate K^+ with K^-. The resulting m_{inv} distribution consisted of the ϕ signal atop a large background that is predominantly combinatorial. The shape of the combinatorial background was calculated using the mixed-event technique [16,17].

For the centrality measurement, the raw hadron multiplicity distribution within a pseudo-rapidity window $|\eta| \leqslant 0.5$ is divided into five bins corresponding to 50–80%, 30–50%, 10–30%, top 10% and top 5% of the measured cross-section for Au + Au collisions. Events are selected with a primary vertex z position from the center of the TPC of $|z| < 25$ cm for Au + Au collisions and $|z| < 50$ cm for $p + p$ collisions, where z is along the beam axis. These events are further divided according to z to reduce acceptance-induced distortions in the mixed-event background. Correlations in the background due to elliptic flow were minimized by mixing events with similar reaction plane angles. Consistent results are obtained when we construct the background distribution using like-sign pairs from the same-event.

Particle identification (PID) is achieved by correlating the ionization energy loss (dE/dx) of charged particles in the TPC gas with their measured momentum. The measured $\langle dE/dx \rangle$ is reasonably well described by the Bethe–Bloch function [10,18] smeared with a resolution of width σ. By measuring the $\langle dE/dx \rangle$, pions and kaons can be identified up to a momentum of about 0.6 GeV/c while protons ($\bar{p}$) can be separated from pions and kaons up to a momentum of about 1.1 GeV/c. Tracks within 2σ of the kaon Bethe–Bloch curve are selected for this analysis.

To obtain the ϕ spectra, same-event and mixed-event distributions are accumulated and background subtraction is done in each p_t, y and centrality bin. The mixed-event background m_{inv} distribution is normalized to the same-event m_{inv} distribution in the region above the ϕ mass ($1.04 < m_{\text{inv}} < 1.2$ GeV/c^2). A small, smooth residual background can remain near the ϕ peak in the subtracted m_{inv} distribution, because the mixed-event sample does not perfectly account for the production of background pairs (protons ($\bar{p}$) and/or pions from PID leak-through) that are correlated, either by Coulomb or other interactions or by such instrumental effects as track merging [19]. The raw yield in each bin is then determined by fitting the background subtracted m_{inv} distribution to a Breit–Wigner function plus a linear background in a limited invariant mass range. The measured mass and width of the ϕ are consistent with the value listed by the Particle Data Group [18] convoluted with detector resolution.

Using GEANT and detector response simulations, the data are corrected for acceptance, kaon decay and tracking efficiencies to obtain the final distributions presented here. The total corrections derived from the simulation are 4–40% and 5–50% in the covered p_t range of 0.4–3.5 GeV/c for the 0–5% and 50–80% centrality bins in Au + Au collisions, respectively. Fig. 1 shows the transverse mass distributions from

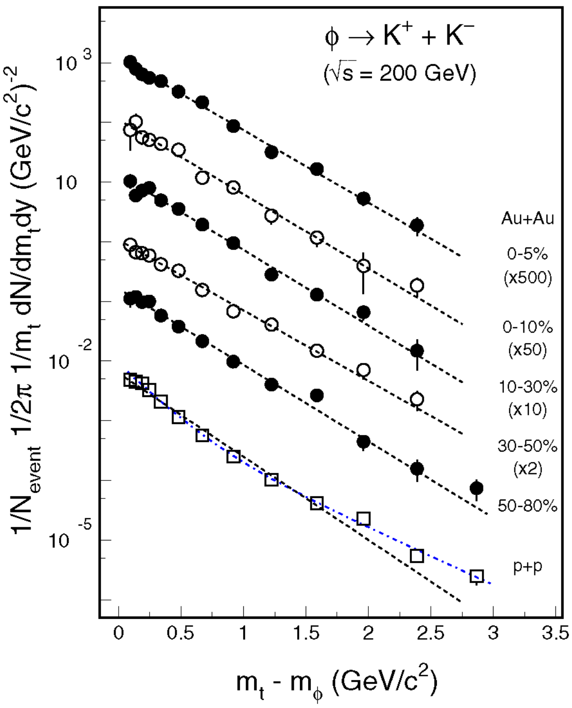

Fig. 1. The transverse mass distributions from Au + Au (circles) and $p + p$ (squares) collisions at 200 GeV. For clarity, some Au + Au distributions for different centralities are scaled by factors. The top 5% data are obtained from the central trigger data set. All other distributions are obtained from the minimum-bias data set. Dashed lines represent the exponential fits to the distributions and the dotted-dashed line is the result of a double-exponential fit to the distribution from $p + p$ collisions. Error bars are statistical errors only.

Au + Au (circles) and NSD $p + p$ (squares) collisions at 200 GeV. The spectra are obtained from the rapidity range $|y_\phi| < 0.5$. For clarity, some Au + Au distributions for different centralities are scaled by factors indicated in the figure. Dashed lines represent exponential fits to the distributions and the dotted-dashed line represents a double-exponential fit to the $p + p$ result.

Statistical uncertainties are shown in the figure and the results of the fits are listed in Table 1. The main contributions to the systematic uncertainty come from fitting to the K^+K^- invariant-mass distribution, tracking and the PID efficiency calculation. Different background functions and normalization factors for the mixed-event background were used to determine the uncertainty in the fitting to the invariant-mass distribution and is estimated to be about 5%. The uncer-

Table 1
Results of ϕ meson inverse slope parameter, $\langle p_t \rangle$, and dN/dy from NSD $p+p$ and Au + Au collisions at RHIC. An exponential fit is used for the Au + Au data while a double-exponential fit is used for the $p+p$ data. All values are for $|y| < 0.5$. In Au + Au collisions, the systematical uncertainties on the inverse slope, $\langle p_t \rangle$ and dN/dy are 11%. In $p+p$ collisions, the systematical uncertainties are 5% on $\langle p_t \rangle$ and 15% on dN/dy

Centrality	Slope (MeV)	$\langle p_t \rangle$ (GeV/c)	dN/dy
0–5%	363 ± 8	0.97 ± 0.02	7.70 ± 0.30
0–10%	357 ± 14	0.95 ± 0.03	6.65 ± 0.35
10–30%	353 ± 8	0.97 ± 0.02	3.82 ± 0.19
30–50%	383 ± 10	1.02 ± 0.03	1.72 ± 0.06
50–80%	344 ± 9	0.94 ± 0.02	0.48 ± 0.02
$p+p$ minbias	–	0.82 ± 0.03	0.018 ± 0.001

tainty from tracking and PID efficiency is estimated, by varying the tracking and PID cuts on the daughter tracks, to be 8%. The overall systematic uncertainty in the yield, dN/dy and $\langle p_t \rangle$ is estimated to be 11%, and includes an additional contribution from fitting the transverse momentum distributions. For Au + Au collisions, the inverse slope parameters and yields are extracted from a single exponential function fit. For $p+p$ collisions, however, there is an additional component beyond a single exponential, see dashed-line in Fig. 1. The power-law shape provides a better fit at the higher p_t region but failed at low p_t. Double-exponential function provided a better fit so it was used to extract the values of dN/dy and $\langle p_t \rangle$ for the $p+p$ collisions. For the heavy ion results, a Boltzmann distribution and a thermal + flow model [20] are also used to fit the data as a check of the systematic uncertainty in the extrapolated yield and $\langle p_t \rangle$. The systematic uncertainty is ∼15% in the overall normalization and $\leqslant 5\%$ in mean p_t for the $p+p$ data, including uncertainties in the vertex efficiency for very low multiplicity events.

The system-size and beam-energy dependence of $\langle p_t \rangle$, ϕ/K^- and ϕ/h^- are shown in Fig. 2. For comparison, the $\langle p_t \rangle$ of the $\bar{p}$, K^- and π^- are also shown [21]. At $\sqrt{s_{NN}} = 200$ GeV the ϕ/h^- ratio shows no significant dependence on centrality for Au + Au collisions (open circles in plot (b)). For $p+p$ collisions this ratio is lower by about 30% (open triangle in plot (b)). As a function of energy, see plots (c) and open circles in plot (d), both values of $\langle p_t \rangle$ and ϕ/h^- ratio increase. This indicates that the production of ϕ mesons is sensitive to the initial conditions of the collision.

The general trend for $\bar{p}$, K^- and π^- is an increase in $\langle p_t \rangle$ as a function of centrality, which is indicative of an increased transverse radial flow velocity component to these particles' momentum distributions. The ϕ $\langle p_t \rangle$, however, shows no significant centrality dependence. This is consistent with the conjecture that the ϕ does not participate in the transverse radial flow as does the $\bar{p}$, K^- and π^-. This is expected if the ϕ decouples early on in the collision before transverse radial flow is completely built up. If the ϕ hadronic scattering cross-section is much smaller than that of other particles, one would not expect the ϕ $\langle p_t \rangle$ distribution to be appreciably affected by any final state hadronic rescatterings. In contrast to these observations, the RQMD predictions of $\langle p_t \rangle$ for kaon, proton and ϕ all increase as functions of centrality [11,22].

The yield ratio ϕ/K^- from this analysis is constant as a function of centrality and species ($p+p$ or Au + Au). In fact, for collisions above the threshold for ϕ production, the ϕ/K^- ratio is essentially independent of system size, e^+e^- to nucleus–nucleus, and energy from a few GeV up to 200 GeV (Fig. 2(d)) [4–6,18,23–25]. This is remarkable, considering that the initial conditions of an e^+e^- collision are so drastically different from Au + Au collisions. This observation may indicate that the ratio is dominated by the hadronization process.

Rescattering models (RQMD [11], UrQMD [12]) predict that about 2/3 of ϕ mesons come from kaon coalescence in the final state. The centrality dependence of the ϕ/K^- ratio alone provides a serious test of the current rescattering models. In these models, such as UrQMD, rescattering channels for ϕ production includes $K\bar{K}$ and K-hyperon modes and predicts an increasing ϕ/K^- ratio vs. centrality. These models also predict an increase in $\langle p_t \rangle$ for the proton, kaon, and ϕ of 40 to 50% from peripheral to central collisions. A comparison of the data to these models does not support the kaon coalescence production mechanism for ϕ mesons.

The particle-type dependence of the nuclear modification factors R_{AA} and R_{CP} [13,26] should be sensitive to the production dynamics and the hadronization process [27–31]. R_{AA} is the ratio of the differential yield in a centrality class of Au + Au collisions to the inelastic differential cross-section in $p+p$ collisions,

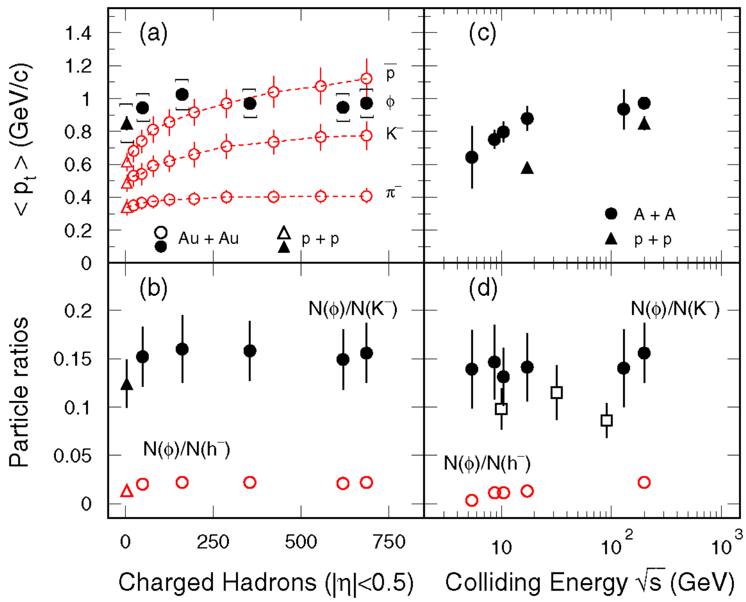

Fig. 2. (a) ϕ $\langle p_t \rangle$ (filled symbols) vs. measured number of charged hadrons ($N_{\rm ch}$) within $|\eta| \leqslant 0.5$ at 200 GeV. For comparison, the values of $\langle p_t \rangle$ for negative pions, kaons, and anti-protons (open symbols) are also shown; (b) ratios of $N(\phi)/N(K^-)$, filled symbols, and $N(\phi)/N(h^-)$, open symbols, vs. $N_{\rm ch}$; (c) $\langle p_t \rangle$ vs. center-of-mass beam energy from central nucleus–nucleus (filled circles) and $p+p$ collisions (filled triangles); (d) ratios of $N(\phi)/N(K^-)$ from central nucleus–nucleus collisions, filled circles, and $N(\phi)/N(h^-)$, open circles, vs. center-of-mass beam energy. $N(\phi)/N(K^-)$ ratio from e^+e^- collisions (open squares) are also shown. Note: all plots are from mid-rapidity. Both the statistical and systematic errors are shown for the 200 GeV STAR data, while only statistical errors are shown for the energy dependence of the particle ratios.

scaled by the overlap integral $T_{AA} = \langle N_{\rm bin} \rangle / \sigma_{\rm inel}$ from a Glauber calculation [32]. The Glauber calculation was performed with $\sigma_{\rm inel} = 42 \pm 1$ mb. The inelastic differential cross-section in $p+p$ is estimated as the NSD yield times $\sigma_{\rm NSD}$, measured as 30.0 ± 3.5 mb, with a small correction, determined from Pythia calculations, of 1.05 at $p_t = 0.4$ GeV$/c$ and unity above 1.2 GeV$/c$ [26]. R_{CP} is the ratio of the yields between two Au + Au centrality classes, scaled by $\langle N_{\rm bin} \rangle$. The R_{CP} (Fig. 3(a)) for the ϕ meson at moderate p_t ($1.5 < p_t < 4$ GeV$/c$) is suppressed relative to the binary collision scaling (dashed horizontal line at unity).

A comparison of the R_{CP} for the ϕ, K_S^0 and Λ is shown in Fig. 3(a). Both statistical and systematic errors are included in the figure. The ratio R_{AA} for central (top 5%) and peripheral (60–80%) Au + Au data are shown in Fig. 3(b) and (c), respectively. R_{AA} for charged hadrons [26] is also shown as a reference. The charged hadron and ϕ peripheral R_{AA} both go above the binary scaling limit, but are consistent with unity within the systematic uncertainties. The ϕ central R_{AA} approaches unity and point to point is higher than R_{CP}. With the systematic uncertainty on the normalization of the ratio, however, both R_{AA} and R_{CP} are consistent. Note that a R_{AA} ratio that is higher than the R_{CP} ratio would be consistent with OZI suppression of ϕ production in $p+p$ [1–3] and/or strangeness enhancement in Au + Au collisions. A measurement of R_{AA} vs. system size may be sensitive to the system size at which OZI becomes irrelevant to ϕ production.

The ϕ R_{CP} result is consistent with a partonic recombination scenario [31,33,34]. In these models, the centrality dependence of the yield at intermediate p_t depends more strongly on the number of constituent quarks than on the particle mass. Further higher statistical data for the ϕ are needed to draw a conclusion.

In summary, STAR has measured ϕ meson production in $\sqrt{s_{NN}} = 200$ GeV Au + Au and NSD $p+p$ collisions at RHIC. The ϕ/K^- yield ratios from e^+e^-, $p+p$ and $A+A$ collisions over a broad range of collision energy above the ϕ production threshold are remarkably close to each other. ϕ production, when scaled by the number of binary collisions, is suppressed with respect to peripheral collisions in central

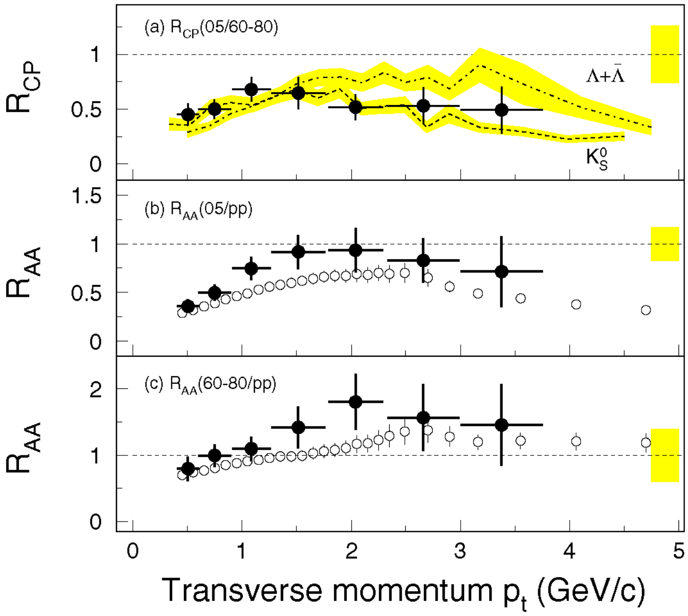

Fig. 3. R_{CP} (a): The ratio of central (top 5%) over peripheral (60–80%) (R_{CP}) normalized by $\langle N_{\text{bin}}\rangle$. The ratios for the Λ and K_S^0, shown by dotted-dashed and dashed lines, are taken from [13]; R_{AA} (b) and (c) are the ratios of central Au + Au (top 5%) to $p+p$ and peripheral Au + Au (60–80%) to $p+p$, respectively. The values of R_{AA} for charged hadrons are shown as open circles [26]. The width of the gray bands represent the uncertainties in the estimation of $\langle N_{\text{bin}}\rangle$ summed in quadrature with the normalization uncertainties of the spectra. Errors on the ϕ data points are the statistical plus 15% systematic errors.

Au + Au collisions. The lack of a significant centrality dependence of the ϕ/K^- ratio and the values of ϕ $\langle p_t\rangle$ effectively rule out kaon coalescence as a dominant production channel for the ϕ at this energy.

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References

[1] S. Okubo, Phys. Lett. 5 (1963) 165.
[2] G. Zweig, CERN Report No. 8419/TH412, 1964.
[3] J. Iizuka, et al., Prog. Theor. Phys. 35 (1966) 1061.
[4] B.B. Back, et al., Phys. Rev. C 69 (2004) 054901.
[5] S.V. Afanasiev, et al., Phys. Lett. B 491 (2000) 59.
[6] C. Adler, et al., Phys. Rev. C 65 (2002) 041901(R).
[7] A.J. Baltz, C. Dover, Phys. Rev. C 53 (1996) 362.
[8] A. Shor, Phys. Rev. Lett. 54 (1985) 1122.
[9] H. Sorge, et al., Phys. Lett. B 289 (1992) 6.
[10] D.H. Perkins, Introduction to High Energy Physics, fourth ed., Cambridge Univ. Press, Cambridge, 2000.
[11] H. Sorge, Phys. Rev. C 52 (1995) 3291.
[12] M. Bleicher, et al., J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859;
S.A. Bass, et al., Phys. Rev. C 60 (1999) 021902.
[13] STAR Collaboration, J. Adams, et al., Phys. Rev. Lett. 92 (2004) 052302.
[14] S.S. Adler, et al., Phys. Rev. C 69 (2004) 034909.
[15] K.H. Ackerman, et al., Nucl. Instrum. Methods Phys. Res. A 499 (2003) 624.
[16] D. L'Hote, Nucl. Instrum. Methods Phys. Res. A 337 (1994) 544.
[17] D. Drijard, H.G. Fischer, T. Nakada, Nucl. Instrum. Methods Phys. Res. A 225 (1984) 367.
[18] K. Hagiwara, et al., Phys. Rev. D 66 (2002) 010001, and references within.
[19] E. Yamamoto, PhD thesis, University of California, Los Angeles, 2001, unpublished.

[20] E. Schnedermann, J. Sollfrank, U. Heinz, Phys. Rev. C 48 (1993) 2462.
[21] J. Adams, et al., Phys. Rev. Lett. 92 (2004) 112301.
[22] Y. Cheng, et al., Phys. Rev. C 68 (2003) 034910.
[23] L. Ahle, et al., Phys. Rev. C 58 (1998) 3523.
[24] S.V. Afanasiev, et al., Phys. Rev. C 66 (2002) 054902.
[25] C. Adler, et al., Phys. Lett. B 595 (2004) 143.
[26] J. Adams, et al., Phys. Rev. Lett. 91 (2003) 172302.
[27] Z. Lin, C.M. Ko, Phys. Rev. Lett. 89 (2002) 202302.
[28] S.A. Voloshin, Nucl. Phys A 715 (2003) 379c.
[29] D. Molnar, S.A. Voloshin, Phys. Rev. Lett. 91 (2003) 092301.
[30] V. Greco, C.M. Ko, P. Levai, Phys. Rev. Lett. 90 (2003) 202302.
[31] R.J. Fries, B. Müller, C. Nonaka, S.A. Bass, Phys. Rev. Lett. 90 (2003) 202303;
R.J. Fries, B. Müller, C. Nonaka, S.A. Bass, Phys. Rev. C 68 (2003) 044902.
[32] J. Adams, et al., nucl-ex/0311017, Phys. Rev. C, submitted for publication.
[33] K.P. Das, R.C. Hwa, Phys. Lett. 68B (1977) 459.
[34] R.C. Hwa, C.B. Yang, Phys. Rev. C 67 (2003) 064902.