Phenomenology of strangeness production at high energies

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received 14 December 2016; accepted 16 January 2017
published online 2 February 2017

PACS 25.75.-q – Relativistic heavy-ion collisions
PACS 25.75.Dw – Particle and resonance production
PACS 24.85.+p – Quarks, gluons, and QCD in nuclear reactions

Abstract – The strange-quark occupation factor (γs) is determined from the statistical fit of the multiplicity ratio K+/π+ in a wide range of nucleon-nucleon center-of-mass energies (\(\sqrt{\Delta NN}\)). From this single-strange-quark subsystem, \(\gamma_s(\sqrt{\Delta NN})\) was parametrized as a damped trigonometric functionality and successfully implemented into the hadron resonance gas model, at chemical semi-equilibrium. Various particle ratios including K−/π−, Λ/π−, and \(\bar{\Lambda}/\pi−\) are well reproduced. The phenomenology of \(\gamma_s(\sqrt{\Delta NN})\) suggests that the hadrons (\(\gamma_s\) rises) at \(\sqrt{\Delta NN} \approx 7\) GeV seem to undergo a phase transition to a mixed phase (\(\gamma_s\) decreases), which is then derived into partons (\(\gamma_s\) remains unchanged with increasing \(\sqrt{\Delta NN}\)), at \(\sqrt{\Delta NN} \approx 20\) GeV.

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Introduction. – The energy scan of the Super Protonsynchrotron (SPS) confirms continuation and completion of the set of excitation functions observed at the Alternating Gradient Synchrotron (AGS) — among others — the ratios of various particle multiplicities. Widely known examples include the so-called Marek’s horn-like structure of K+/π+ [1], which was confirmed in various heavy-ion collisions experiments [2–5], the kick, which is to be drawn through a rapid change in the slope of the produced pions per participating nucleon and the plateau of the averaged transverse momentum \(\langle p_T\rangle\) of kaons, known as step. The recent energy scan of the Relativistic Heavy Ion Collider (RHIC) confirms the horn-like structure and both kick and step observations [3] as well. These phenomena apparently indicate remarkable changes taking place in the strongly interacting system at relativistic energies. Various explanations were proposed so far [1, 6–12], including the onset of deconfinement, the manifestation of a critical endpoint, etc. That the thermal models do not seem to be able to reproduce such a remarkable structure represents one of the chronic puzzles faced by the particle scientists, to which a great number of experiments and theoretical and numerical studies were devoted.

When focusing on the discussion of the horn-like structure of K+/π+, we first observe an increase in K+/π+ with increasing nucleon-nucleon center-of-mass energy \(\sqrt{\Delta NN}\) up to a certain value (at projectile energy of \(\sim 30\) AGeV [2,13]), which is then followed by a rapid decrease. At higher \(\sqrt{\Delta NN}\), K+/π+ remains almost unchanged shaping a plateau at the top RHIC energies. This continues up to the Large Hadron Collider (LHC) energies, where another puzzle was recently reported, namely the proton anomaly or the discrepancy between calculated and measured p/π ratio [14]. It was conjectured that, this energy dependence can be generated by the hadronic kinematic model [15] and also when assuming a transition from a baryon-dominated system (at low collision energy) to a meson-dominated system (at high collision energy) [6]. Introducing heavy masses of unknown hadronic resonances (Hagedorn mass spectrum) [8] is believed to assure a release of additional color degrees of freedom (dof) [1] so that large numbers of pions even greater than that of the kaons can be guaranteed. The latter, in turn, can be achieved when including heavy-hadron resonances from the recent compilation of the Particle Data Group (PDG) [7] in the HRG model. All these proposals were implemented but
unfortunately not able to give an unambiguous clarification so far.

For the production and evolution of strange quarks (and strange hadrons) with varying collision energies, a microscopic model was alternatively utilized [16], where the momentum-integrated Boltzmann equation should be first evaluated. In the Bag model, the ratios of strangeness to entropy was studied in dependence of the collision energy $\sqrt{s_{NN}}$ [21]. Interestingly, a scaling behavior similar to the one from the hadronic nonequilibrium kinetic model, which considers the energy-dependent lifetime of the fireball [10] was obtained. Both are found similar to the observed $K^+/\pi^+$ ratio. The present letter introduces an energy-dependent strange-quark occupation factor ($\gamma_s$) deduced, phenomenologically, and assures the best reproduction of various particle ratios.

The occupation factors of light and strange quarks, $\gamma_l$ and $\gamma_s$, respectively, were first introduced by Letessier and Rafelski as a plausible explanation for the strangeness enhancement [17], which was proposed as a sensitive signature for the formation of quark-gluon plasma (QGP). It was argued that the energy threshold for $s\bar{s}$ pair production considerably differs due to the underlying QCD symmetries. In the QGP phase, $\epsilon_{\text{thr}} \approx 300$ MeV, while in the hadron phase, $\epsilon_{\text{thr}} \approx 700$ MeV, because the energy threshold corresponds to two times the rest mass of the partons and hadrons of interest. Thus, it was conjectured that the creation of QGP should be accompanied by an increase in the strangeness production. This was first confirmed experimentally [18] and also in the first-principle lattice QCD simulations [19]. Also, it was assumed that the nonequilibrium values, i.e., the ones differing from unity, assigned to $\gamma_s$ would be able to characterize the legend energy dependence of $K^+/\pi^+$ [11]. The present work is an extension and updating of ref. [11] with the most recent experimental results and more plausible phenomenological explanations.

From the experimental point of view, the relative production of strange and nonstrange quark numbers was analysed in elementary and in nucleus collisions [20]. Relatively to the light-quark pair production, it was concluded that $s\bar{s}$ pairs would be considerably suppressed. Through quark counting, one assumes that $\bar{u}u:d:d:s\bar{s} = 1:1:1$; $\lambda_s$, where $\lambda_s \equiv \gamma_s \ll 1$ apart from some factors characterizing the results from heavy-ion collisions. This observation was first confirmed in heavy-ion collisions at $\sqrt{s} \approx 60$ GeV [21]. It was reported that the experimental estimation for average multiplicities of $\langle N_{s\bar{s}} \rangle$ allowed the conclusion that $\lambda_s$ is not sensitive to the interacting system, e.g., quantam numbers of colliding nuclei, but apparently to the collision energies [21],

$$\lambda_s = \frac{\langle N_{s\bar{s}} \rangle}{\langle N_{q\bar{q}} \rangle - \langle N_{s\bar{s}} \rangle}, \quad (1)$$

where $\langle N_{q\bar{q}} \rangle = \langle N_{dd} \rangle + \langle N_{s\bar{s}} \rangle$, i.e., $\lambda_s$ can be determined from the detection of strange mesons and the total meson multiplicity.

**Approach.** – In the partition function of a grandcanonical ensemble describing a strongly interacting system, statistically, $\gamma_l$ and $\gamma_s$ can be integrated as pre-factors to the Boltzmann exponential,

$$\ln Z(T,\mu) = \pm \sum_{i} \frac{V \delta_{i}}{2\pi \sigma} \int_{0}^{\infty} k^2 dk \ln \left[ 1 \pm (\gamma_l^n)^i \left( \gamma_s^n \right)^i e^{\left( \frac{\mu_i - \epsilon_i (k)}{T} \right)} \right], \quad (2)$$

where $\pm$ stands for fermions and bosons, respectively, and $\epsilon_i(k) = (k^2 + m_i^2)^{1/2}$ is the energy-momentum relation of the i-th hadron. Implementing Hagedorn picture for which heavy resonances are composed of lighter ones which, in turn, consist of lighter ones and so on, the subscript i refers to a summation over fermions and bosons from a recent compilation of PDG. The chemical potential $\mu_i$ is composed of various contributions, for instance,

$$\mu_i = B_i \mu_B + S_i \mu_S + \cdots, \quad (3)$$

where $B_i$ and $S_i$ are baryon and strangeness quantum number of the i-th hadron resonance and $\mu_B$ and $\mu_S$ are the baryon and strangeness chemical potential, respectively. $V$ and $T$ are the fireball volume and temperature, respectively.

In eq. (2), $n_l$ and $n_s$ are the number of light and strange quarks, respectively, of which each fermion or boson is composed. When unity is assigned to $\gamma_l$ and $\gamma_s$, at full chemical equilibrium, as for the case in the equilibrium hadron resonance gas (HRG) model, the calculated $K^+/\pi^+$ poorly generates the horn-like structure measured at SPS energies, but greatly overestimates the results at high $\sqrt{s_{NN}}$. It is worth highlighting that at AGS energies, the equilibrium HRG calculations seem to describe well the production rates of strange hadrons [11,12,22]. In this energy limit, the HRG calculations do not seem to be sensitive to $\gamma_s$, as to the resonance masses and the excluded volume corrections, etc., see fig. 2. The statistical nature of strangeness production, in our case kaons, is conjectured to be maintained, when ad hoc nonequilibrium values are assigned to the strange-quark occupation factor ($\gamma_s \neq 1$) [17]. The present letter concludes a rapid strangeness enhancement at AGS energies at the equilibrium light-quark occupation factor ($\gamma_l = 1$), i.e., chemical semi-equilibrium.

A strangeness suppression factor, i.e. $\gamma_s < 1$, was explicitly assumed in ref. [23],

$$\gamma_s(\sqrt{s_{NN}}) = 1 - \alpha \exp \left( -\beta \sqrt{A \sqrt{s_{NN}}} \right), \quad (4)$$

where $\alpha = 0.606$, $\beta = 0.0209$, and $A$ stands for the atomic numbers of the colliding nuclei. This has the advantage to reduce the production rate of the strange hadrons [23].

In the present work, we also assume $\gamma_l = 1$. But for $\gamma_s$, we fit our HRG calculations, where the number density can be derived from eq. (2), on $K^+/\pi^+$ at varying $\sqrt{s_{NN}}$ with
which is given as a dashed curve. So far, both expressions compare our results with predictions deduced from eq. (4), illustrated as a solid curve. For the sake of completeness, we aim to parametrize the HRG calculations with $\gamma_s$ taken as a free parameter. The dashed curve represents eq. (4).

...the experimental results, see top panel of fig. 1. From the statistical fit to this single-strange-quark subsystem, we aim to parametrize $\gamma_s$ as functionality of $\sqrt{s_{NN}}$. Details about HRG can be taken from ref. [24], where $\sqrt{s_{NN}}$ is related to the baryon chemical potential ($\mu_B$) and thus directly enters the partition function, eq. (2). For specific particle species, their number densities are composed of the contributions coming from the corresponding hadrons and those stemming from heavy resonances decaying into the particles of interest. The latter should be weighted by the corresponding branching ratios.

Within the extensive statistics, it is conjectured that the colliding system reaches the stage of chemical freezeout, which is characterized by two thermodynamic quantities, $T$ and $\mu_B$, which can be deduced from statistical fits of the HRG calculations of various particle ratios and/or yields the experimental multiplicities. The resulting $T$ and $\mu_B$ are well described by various freezeout conditions [24–27]. Concretely, we implement $s/T^3 = 7$ [28,29], with $s$ being the entropy density. In fitting the experimental $K^+/\pi^+$ to the HRG calculations, we assume $\gamma_s$ as a free parameter, while the values of the parameters $T$ and $\mu_B$ are determined at $s/T^3 = 7$ and $\gamma_0$ is assigned a constant value. As mentioned, we concentrate the discussion on fitting with the single-strange-quark subsystem $K^+/\pi^+$ and assume that the resulting $\gamma_s(K^+/\pi^+)$ remains valid with the entire HRG thermal model.

**Results.** In fig. 1, the resulting $\gamma_s$ are depicted as a function of $\sqrt{s_{NN}}$ (symbols with errors). At the chemical freezeout, these are well described by a damped trigonometric functionality,

$$
\gamma_s(\sqrt{s_{NN}}) = a \exp(-b \sqrt{s_{NN}}) \sin(c \sqrt{s_{NN}} + d) + f
$$

(5)

with $a = 2.071\pm0.259$, $b = 0.282\pm0.062$, $c = 0.362\pm0.051$, $d = 4.78\pm0.21$, and $f = 0.764\pm0.249$. Expression (5) is illustrated as a solid curve. For the sake of completeness, we compare our results with predictions deduced from eq. (4), which is given as a dashed curve. So far, both expressions do not allow for any concrete conclusion. This might be only possible when they do (or do not) succeed in reproducing other particle ratios as illustrated in fig. 2.

When the energy dependence of $\gamma_s$, eq. (4) [23], is implemented, we first find that the resulting $\gamma_s$ is monotonically depending on $\sqrt{s_{NN}}$. At $\sqrt{s_{NN}} \lesssim 200$ GeV, we find that $\gamma_s$ exponentially increases, while at higher energies, $\sqrt{s_{NN}}$ likely approaches an asymptotic value, the chemical equilibrium. At $\gamma_l = 1$ and with eq. (4), four particle ratios are calculated and shown in fig. 2. This shall be elaborated shortly. For now, we merely highlight that the results are almost identical to the ones calculated at full...
chemical equilibrium. Accordingly, one can easily judge about the improvement made through eq. (4).

Our parametrization for $\gamma_s$, eq. (5), contrarily shows a nonmonotonic energy dependence. At $\sqrt{s_{NN}} \lesssim 7$ GeV, $\gamma_s$ exponentially increases with increasing $\sqrt{s_{NN}}$. Then, within the energy range $7 \lesssim \sqrt{s_{NN}} \lesssim 20$ GeV, $\gamma_s$ rapidly decreases. At higher energies, $\gamma_s$ becomes energy independent, especially at the top RHIC and LHC energies. Its asymptotic value is given by the parameter $f$ in eq. (5).

The top panel of fig. 2 shows $K^+/\pi^+$ (symbols) as a function of $\sqrt{s_{NN}}$, which, in turn, is related to $\mu_B$. The dashed curve gives HRG calculations, at equilibrium occupation parameters, namely full chemical equilibrium $\gamma_1 = \gamma_3 = 1$. The double-dotted curve illustrates results at $\gamma_1 = 1$, while $\gamma_3$ is determined from eq. (4) [17]. The earlier estimations excellently reproduce the $K^+/\pi^+$ results at $\sqrt{s_{NN}} \lesssim 10$ GeV. At higher energies, although they overestimate the experimental results, a horn-like structure remains guessable. The latter calculations do not possess any horn-like structure. At high energies, they fit well with the results from equilibrium HRG, i.e., they overestimate the measurements as well.

Our results are presented as a solid curve. They are deduced from ideal HRG calculations, i.e., point-like constituents, PDG compilation, etc. In these calculations, chemical semi-equilibrium, namely $\gamma_i(\sqrt{s_{NN}}) = 1$ but $\gamma_3(\sqrt{s_{NN}})$ is to be determined from eq. (5), is assumed. From the fact that eq. (5) stems from the statistical fit of the HRG calculations to the measured $K^+/\pi^+$, the excellent agreement between the solid curve and $K^+/\pi^+$ results is obvious. To judge the validity of our parametrization, eq. (5), we still need to utilize it in calculating other quantities and we might also need to run further checks, such as lattice QCD thermodynamics and examine the thermodynamic consistency, etc. The latter shall be subjects of future studies. For the phenomenological focus of the present letter, we concentrate on calculating various particle ratios.

Panels (b), (c), and (d) of fig. 2 depict $K^-/\pi^-$, $\Lambda/\pi^-$, and $\bar{\Lambda}/\pi^-$, respectively, as functions of $\sqrt{s_{NN}}$. These experimental results are confronted to the HRG calculations at full chemical equilibrium, i.e., $\gamma_i(\sqrt{s_{NN}}) = 1$ (dashed curves) and quasi-equilibrium, i.e., $\gamma_i(\sqrt{s_{NN}}) = 1$ and $\gamma_3(\sqrt{s_{NN}}) = 1$. The latter is given by eq. (4) [17] (double-dotted curves). We find that they are almost compatible with the HRG calculations at full chemical equilibrium.

Our HRG calculations with eq. (5) are presented as solid curves. Here, we find that the agreement with the experimental results is remarkably improved. Thus, we conclude that our parametrization for $\gamma_s(\sqrt{s_{NN}})$ enables the thermal models, the HRG, for instance, to reproduce various particle ratios. Relatively to eq. (4), eq. (5) agrees very well with the experimental results.

Discussion and conclusions. – As discussed in the Introduction, various interpretations for the horn-like structure measured in $K^+/\pi^+$ have been proposed, for example, parametrization for the evolution of the fireball and the produced-particle densities [10]. It was noticed that, for beam energies $> 30$ AGeV, the fireball lifetime decreases, whose interplay with the initial energy density determines the final-state density. The hadronic kinetic model based on these assumptions, besides full chemical equilibrium, is conjectured to describe well different particle ratios including $K^+/\pi^+$.

Also, to interpret the energy dependence of the kaon production, a microscopic approach and full chemical equilibrium have been proposed [16]. Here, the evolution of strangeness production was modelled by the momentum-integrated Boltzmann equation. This approach was borrowed from the freezout processes in the thermal expansion of the early universe [30]. When an initial partonic phase is assumed at collision energies greater than a certain threshold, a nonmonotonic energy dependence of $K^+/\pi^+$ was obtained.

The excitation functions in the particle multiplicities $K^+/\pi^+$ observed at SPS energies and confirmed in the RHIC energy scan, especially the horn-like structure, are analysed in the HRG statistical thermal model, in which point-like constituents and chemical semi-equilibrium are considered. The strange-quark occupation factor is assumed to vary with the collision energy. This idea was introduced and worked out by many authors, including Abdel Nasser Tawfik. Additionally to the best reproduction of various particle ratios, the present work introduces an updating with the most recent experimental results and presents a novel parametrization of the dependence of $\gamma_s$ on the collision energies. The resulting functionality describing $\gamma_s$ with varying $\sqrt{s_{NN}}$ is proposed as damped trigonometric functionality. Accordingly, such a nonmonotonic energy dependence of $\gamma_s$ was successfully implemented into the HRG model at chemical semi-equilibrium. As discussed, the particle ratios $K^-/\pi^-$, $\Lambda/\pi^-$, and $\bar{\Lambda}/\pi^-$ are well reproduced.

In the light of this phenomenologic good description and of the assumption that the light-quark occupation factor is assigned to the equilibrium value, we can conclude that $\gamma_s \lesssim 1$, i.e., chemical semi-equilibrium at all collision energies. Only at low SPS energy one obtains that $\gamma_s \approx 1$ and even slightly exceeds this characteristic value deriving the colliding system to full chemical equilibrium. Accordingly, we expect that such a state could possess maximum entropy. Although, other aspects of thermodynamic consistency shall be analysed in future works, we merely highlight that an old paper of Abdel Nasser Tawfik [11] reported on the energy dependence of $s/n$, where $n$ and $s$ are the number and entropy densities, respectively. It was concluded that the horn-like structure of $K^-/\pi^-$ is positioned where the maximum $s/n$ takes place.

So far, we conclude that at $\sqrt{s_{NN}} \lesssim 7$ GeV, the strongly interacting system is characterized by strangeness enhancement, i.e., $\gamma_s$ exponentially increases. Within this energy region, symmetry and dof seem to characterize
hadron matter. After reaching a maximum value, $\gamma_s \to 1$, another symmetry and other effective dof come to play an increasing role. This leads to a rapid decrease in $\gamma_s$. Within $7 \lesssim \sqrt{SN_N} \lesssim 20$ GeV, the value of $\gamma_s$ decreases from $\sim 1$ to $\sim 0.76$. It is believed that the hadron system is derived into a mixed phase, where both hadronic and partonic phase transition into a partonic phase. At higher energies, $\gamma_s$ reaches its asymptotic value, $f \simeq 0.76$. The interacting system is conjectured to undergo another phase transition into a partonic phase.

With this phenomenological description, we emphasize how $\gamma_s$ varies with the collision energy and implement this in calculating various particle ratios. We do not argue that $\gamma_s$ plays the role of an order parameter. Additionally, it is a quantity manifesting imprints of the QCD phase transition. Apparently, its value considerably changes with changing the underlying dof and symmetries. The latter could be utilized as order parameters. Although its energy dependence points to a first-order one going through an inhomogeneous phase composed of two states in a chemical quasi-equilibrium, the order of the phase transition itself would not be conveyed though $\gamma_s$ merely.

As introduced, we propose the functionality $\gamma_s(\sqrt{SN_N})$ derived from the statistical fit to the single-strange-quark subsystem $K^+/\pi^+$ and assume it to be applicable to the entire HRG model. This raises the question as to whether multi-strange-quark subsystems such as $\phi/\pi$ or $\Xi/\pi$ and $\Omega/\pi$ would revise this phenomenological picture. Another future work shall be devoted to formulate answers to this interesting question.

REFERENCES

[1] Gazdzicki M. and Gorenstein M., Acta Phys. Pol. B, 30 (1999) 2705.
[2] NA49 Collaboration (Afanasiev S. V. et al.), Phys. Rev. C, 66 (2002) 054902.
[3] NA49 Collaboration (Alt C. et al.), Phys. Rev. C, 77 (2008) 024903.
[4] BRAHMS Collaboration (Arsene I. et al.), Nucl. Phys. A, 757 (2005) 1; BRAHMS Collaboration (Bearden I. G. et al.), Phys. Rev. Lett., 94 (2005) 162301; PHOBOS Collaboration (Back B. B. et al.), Nucl. Phys. A, 757 (2005) 28; STAR Collaboration (Adams J. et al.), Nucl. Phys. A, 757 (2005) 102; PHENIX Collaboration (Adcox K. et al.), Nucl. Phys. A, 757 (2005) 184; STAR Collaboration (Abelev B. I. et al.), Phys. Rev. C, 81 (2010) 024911.
[5] ALICE Collaboration (Fabian C. W.), J. Phys. G, 35 (2008) 104038; CMS Collaboration (d’Enterria D.), J. Phys. G, 35 (2008) 104039; ATLAS Collaboration (Grau N.), J. Phys. G, 35 (2008) 104040; ALICE Collaboration (Abelev B. et al.), Phys. Rev. Lett., 109 (2012) 252301.
[6] Cleymans J., Oeschler H., Redlich K. and Wheaton S., Eur. Phys. J. A, 29 (2006) 119.
[7] Andronic A., Braun-Munzinger P. and Stachel J., Nucl. Phys. A, 772 (2006) 167.
[8] Chatterjee S., Godbole R. M. and Gupta S., Phys. Rev. C, 81 (2010) 044907.
[9] Gazdzicki M., J. Phys. G, 30 (2004) S701; Tomask B., talk at the 15th Conference of Slovak and Czech Physicists, Kosice, Slovakia, 5–8 September 2005; Navak J. K., Alam J., Mohanty B., Roy P. and Dutt-Mazumder A. K., Acta Phys. Slov., 56 (2006) 27; Letessier J. and Rafelski J., Eur. Phys. J. A, 35 (2008) 221.
[10] Tomask B. and Kolomeitsev E. E., Eur. Phys. J. C, 49 (2007) 115.
[11] Tawfik A., Fizika B, 18 (2009) 141.
[12] Tawfik A., Prog. Theor. Phys., 126 (2011) 279.
[13] NA49 Collaboration (Lungwitz B. et al.), AIP Conf. Proc., 828 (2006) 321.
[14] ALICE Collaboration (Abelev B. et al.), Phys. Rev. Lett., 109 (2012) 252301.
[15] Tomask B. and Kolomeitsev E. E., Eur. Phys. J. C, 49 (2007) 115.
[16] Navak Jajati K., Banki Samrittha and Alam Jan-e, Phys. Rev. C, 82 (2010) 024914.
[17] Letessier J., Rafelski J. and Tounsi A., Phys. Rev. C, 50 (1994) 406.
[18] Koch P., Muller B. and Rafelski J., Phys. Rep., 142 (1986) 167.
[19] Kogut J. and Sinclair D., Phys. Rev. Lett., 60 (1988) 1250.
[20] Hoffmann W., Nucl. Phys. A, 479 (1988) 337c.
[21] Wroblewski A., Acta Phys. Pol. B, 16 (1985) 279.
[22] Castorina P., Plumari S. and Satz H., Int. J. Mod. Phys. E, 25 (2016) 1650058.
[23] Becattini F., Manninen J. and Gazdzicki M., Phys. Rev. C, 73 (2006) 044905; Becattini F. et al., Eur. Phys. J. C, 66 (2010) 377; Becattini F. and Manninen J., Phys. Rev. C, 78 (2008) 054901; Floris M. et al., Nucl. Phys. A, 931 (2014) 103; Becattini F., talk at the 33rd Workshop: Universality Features in Multihadron Production and the Leading Effect, Erice, Italy, 19–25 October 1996; Becattini F. et al., Phys. Rev. Lett., 111 (2013) 082302.
[24] Tawfik Abdel Nasser, Int. J. Mod. Phys. A, 29 (2014) 1430021.
[25] Tawfik Abdel Nasser, Int. J. Mod. Phys. A, 30 (2015) 1550027.
[26] Tawfik A., El-Bakry M. Y., Habashy D. M., Mohamed M. T. and Abbas E., Int. J. Mod. Phys. E, 25 (2016) 1650018.
[27] Tawfik A., El-Bakry M. Y., Habashy D. M., Mohamed M. T. and Abbas E., Int. J. Mod. Phys. E, 24 (2015) 1550067.
[28] Tawfik A., Nucl. Phys. A, 764 (2006) 387.
[29] Tawfik A., Europhys. Lett., 75 (2006) 420.
[30] Kolb E. and Turner M. S., Early Universe (Westview Press, New York, USA) 1994.