On isotopic symmetry breaking in Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV in the NA61/SHINE experiment at SPS

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Recently, the NA61/SHINE collaboration at CERN reported the isospin symmetry breaking in Ar+Sc nuclear collisions at an energy of $\sqrt{s_{NN}} = 11.9$ GeV [1]. The ratio of averaged charged to neutral kaon yields was measured revealing a statistically significant deviation of $(18.4 \pm 6.1)\%$ from unity —- a value expected under isospin symmetry conservation. In this report, we describe briefly the experimental techniques used by the NA61/SHINE in registration of charged and neutral kaons and we are focusing on some of existing modern phenomenological models that could be projected – in a consistent way, to the additional experimental studies of isospin symmetry breaking.

I. INTRODUCTION

The ratio $R_K = \frac{\langle K^+ \rangle + \langle K^- \rangle}{2\langle K^0_s \rangle}$ of averaged charged to neutral kaon mean yields was measured recently in Ar+Sc nuclear collisions at $\sqrt{s_{NN}} = 11.9$ GeV at the SPS at CERN [1]. A statistically significant deviation of (18.4±6.1)% from the value of unity was found meaning the vilotaionisospin symmetry. The exact isospin symmetry conservation ($R_K = 1$) is traditionally expected to hold for strong interactions, in collisions of nuclei with Z=N, under the assumption of virtually identical u and d quark masses and their zero electric charge. New data on asymmetric charged-over-neutral kaons yields were recently obtained in Ar+Sc nuclear collisions at $\sqrt{s_{NN}} = 8.8 GeV$ [2]. The excess of charged-over-neutral kaon production was also observed in $\pi^- + C$ collisions $158 GeV/c$ [3] and in DIS scattering of 10 GeV electrons on deutrons [4]. By combinig the results of measurements, the 5.3 σ level of significance of the isospin-symmetry violation beyond the known effects is currently obtained [5]. Possible

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sources of this statistically significant isospin symmetry violation, observed by NA61/SHINE and supporting the previously measured world data, have been intensively discussed in a number of theoretical papers, including [6], [7], [8], [9], [10], [11], [12], [13], [14]. However, the problem is rather deep and requires more of both theoretical and experimental efforts.

In the given report, we intend to try to highlight some of the existing tensions between the model approaches and suggest experimental possible verifications.

This paper is organized as follows. In Section II we describe briefly the experimental techniques used by the NA61/SHINE and some additional results in the isospin-symmetry breaking studies. Some phenomenological models and the attempts to describe the Violation of charge-symmetry invariance by the known effects are discussed .

We present in Section 3 the results of our studies using the Modified UrQMD model ("UrQMD(3:1)") that follows the idea of the different probabilities in u and d quarks production rate as introduced in [14]. Prediction by the 'UrQMD(3:1)" of noticeable isospin-symmetry breaking in symmetric 12C+12C collisions at $\sqrt{s_{NN}} = 34GeV$ are alo presented, as an example that might be checked at the available future facilities.

II. NA61/SHINE EXPERIMENT AT CERN AND ISOSPIN-SYMMETRY BREAKING STUDIES

A very efficient successor of NA49 experiment, the NA61/SHINE facility [15] is continuing studies at CERN SPS of properties of strong interaction, of the phase diagram of strongly interacting matter and search for the critical point, on the onset of deconfinement, the detection of the open charm and measurements of hadron yields for neutrino programs and cosmic ray physics. The available hadron beams include protons (400 GeV/c), secondary π, K, p (13–350 GeV/c) and ion beams of Ar,Xe,Pb (13–150 AGeV/c), Be (13–150 AGeV/c, from Pb fragmentation).

The facility provides charged particle tracking efficiency at the level $> 95\%$, a large acceptance in full forward c.m. hemisphere for charged and neutral (decaying to charged) hadrons, particle identification dE/dx down to p_t=0 – in the Time Projection Chambers (TPCs) and Time-of-flight , collision centrality determination with Projectile Spectator Detectors, the various targets including liquid H_2 and water, the Vertex detector for open charm measurements and the Double wall He- beam pipe inside the TPCs (that provides a

possibility of 10-fold increase of the beam intensity).

Recently, the extensive measurements of $\pi^{\pm}, K^{\pm}, pand\bar{p}$ spectra were performed by the NA61/SHINE collaboration in 40Ar+45Sc collisions at 13 to 150AGeV/c [16]. Detailed studies of neutral K_s^0 meson production were also performed [17]. K_s^0 mesons were registered via reconstruction of verticies of their decay to $\pi+, \pi-$. It were these studies [17] that the statistically significant observation of the isotopic symmetry violation was observed. Additional results were also obtained at $\sqrt{NN} = 8.8GeV$ [2]. Indications on the violation of isospin symmetry beyond the known effects were observed in other experiments of hadron collisions in a broad energy range. This includes π^-+C results [3] at 156 Gev/c, $e + e-$ collisions at CM energies from 2.000 to 3.671 GeV [18], in the deep inelastic scattering of 10 GeV electrons on deuterons [4]. and in pp scattering at $\sqrt{s_{NN}} = 7.7$, 8.8 and 12.3 GeV [19], [20].

Isospin-symmetry breaking effects due to the well known difference of masses of u and d quarks ($m_u = 2.16 \pm 0.07$MeV and $m_d = 4.70 \pm 0.07$MeV [21]) and, accordingly, due to the relative magnitude of the differences in the mass ratios of kaons (~ -0.004), were found to be small.The difference leads to an increase of R_K resulting from direct kaon production by about 0.02 [1].The influence of this mass difference on R_K was also quantified using the statistical Hadron Resonance Gas (HRG) model [10] –by removing resonances from the particle list of HRG. It was numerically verified that HRG for collisions of nuclei with equal numbers of neutrons and protons ($Q/B = 1/2$), and with the exact isospin symmetry, gives $R_K = 1$, as expected [1].The results were also cross-checked with the the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) model [9]. We may conclude here that neither UrQMD nor HRG – widely used models, were found not to be able to describe the observed the isospin-symmetry violation.

The role of decays of resonances was also estimated in [1]. Including the kaon production from resonance decay ϕ (1020) meson increases R_K by about 0.03 and in case of decay of resonances $a0(980)$ and $f0(980)$ - one gets an increase of R_K by about 0.5%.

The electromagnetic interactions due to different electric charges of u and d quarks lead to a different phase space for their production, favoring $u\bar{u}$ pairs and thus the charged kaons, so that the account of electromagnetic interaction between K^+ and K may increase the R_K by at most 3% at the highest collision energy [1].

The problems and the current status of the isospin-symmetry breaking discovered by

NA61/SHINE in nucleus–nucleus collisions at the CERN SPS were recently addressed at "ISO-BREAK 25" Workshop "Isospin symmetry violation: kaons and beyond". The summary of discussions was published in [22].

In particular, it includes the references on the predictions for the isospin symmetry possible violation in nucleus–nucleus collisions done by several MC well-known event generators of considerably different physics assumptions (HRG, UrQMD,SMASK, EPOS, PHSD and QC). All results of these model, mentioned above, are lying around value of $R_K = 1$ well below the experimental mean value of 1.18.

In the present Section we mention below two controversial approaches to describe the observed isotopic symmetry violation: the similarity approach is keeping the isospin-symmetry conservation at the quark level while another one is based on the purely phenomenological introduction of different probabilities $(3 : 1)$ of $u\bar{u}$ and $d\bar{d}$ quark pairs production in the color fields.

Similarity approach. It was recently obtained [11], [12], in the assumption of the similarity of inclusive spectra of the hadrons produced with small p_t in the mid-rapidity region in nucleus–nucleus collisions, and with the account of the quark-gluon dynamics, that the ratio R_K of the averaged yields of charged kaons to neutral ones could be above 1 even in the case of isospin-symmetry conservation at the quark level. An accurate description of p_t spectrum of K^0_sat midrapidity was obtained in [11] for Ar+Sc collisions for $\sqrt{s_{NN}} = 11.9$ GeV. Satisfactory descriptions of inclusive spectra of charged $K^{\pm}$ mesons produced at midrapidity (y=0) for Ar+Sc collisions were obtained earlier [13]. The model [11] includes the gluon transverse momentum dependence at low QCD scales and the Lund model of hadronization of strings. The calculations do not contradict to the world data at $\sqrt{s_{NN}}$= 6-40 GeV and $\sqrt{s_{NN}} = 3TeV$ [11]. However, we may note that this nice approach is currently limited to midrapidity region of particle production where usually strings formed with sea-quarks are dominating. The prediction of this similarity approach of considerable rise of R_K value with the decreasing energy of collisions – below $\sqrt{s_{NN}} \sim 6$ GeV, also requires to be checked in the future high statistics experimental studies in this region.

Modified UrQMD. Quite recently, the novel explanation of the observed violation of isospin symmetry in relativistic nucleus-nucleus reactions was proposed in the modified UrQMD approach[14] that describes the hadronic interactions at low and intermediate energies in terms of interactions between known hadrons and their resonances. At higher

energies, $> 5GeV$, the excitation of color strings and their subsequent fragmentation into hadrons dominates the multiple production of particles [9].The model has been modified by including the violation of isospin symmetry by the parametrized string breaking: it brings as three times more probable to produce $u\bar{u}$ pair than a $d\bar{d}$ one.

Remarkably, it is important to note, that the parameters of the model were defined and fixed in fitting the isospin symmetry violation observed in e^+e annihilation at center-of-mass energies from 2.000 to 3.671 GeV [18]. In this way, the ratio R_K also was corretly described in paper [14] with the previously fixed string hadronization parameters, the data on kaon productions in pp scattering at $\sqrt{s_{NN}} = 7.7$, 8.8 and 12.3 GeV for ratios of yields K^+, K^- [19] and K_s^0 [20]. This purely phenomenological approach of the modified UrQMD with fixed parameters [14] has demonstrated its consistence when applied further successfully to Ar+Sc data on isotopic symmetry breaking. Therefore, it was tempting to consider some projections of this modified approach to the collisions of different nuclei, in particular, to test isotopic symmetry violation in case symmetric 12C+12C collisions.

III. OUR RESULTS ON VIOLATION OF ISOSPIN SYMMETRY IN THE MODIFIED URQMD CODE

We have modified the UrQMD code following the ideas of [14] to allow for a relative increase (3:1) in the production probability of up-quarks as compared to down-quarks instead of the standard assumption (1:1). This 3:1 ratio was fixed [14] using the refitted string fragmentation parameters to describe the $e + e-$ collision data. Our modified code is denoted below as "UrQMD(3;1)". First of all, we show in Figure 1, Left, the results of our calculations for charged (neutral) kaons using the "UrQMD(3:1)" code with the string parameters fixed following the ideas of [14] – which allow for an 3:1 asymmetry between up- and down-quark production. Results are compared to the rapidity distributions of the averaged sum of charged (K^+ and K^-) and of K_s^0 mesons in 0-10% central Ar+Sc collisions at $\sqrt{s_{NN}} =$ 11.9 GeV. Our new "UrQMD(3:1)" code calculations of the p_t spectra are demonstrating a satisfactory agreement with the experiment.

We compare also in Figure 2 Right, bottom panel, the experimental and "UrQMD(3:1)" calculations and $R_K(p_t)$ ratio . It is interesting to note that the main deviation of R_K from unit is concentrated in the "soft" region, i.e.below 1.5 $GeV/c.$, in a quantitative agreement

with the experiment.

Finally, we show in Figure 2 Left, predictions for rapidity distributions of charged (K^+ and K^-) and of K_s^0 mesons in central (0-2 fm impact parameter class) collisions 12C+12C at $\sqrt{s_{NN}} = 34$ GeV , calculated as an example, in modified"UrQMD(3:1)". The last on gives at the midrapidity the value of $R_K = 1.1$, and it is reaching the values of ~ 1.2 at the forward/bacward rapidities.

IV. CONCLUSIONS

Possible sources of the isospin symmetry breaking, measured by the $NA61/SHINE$ in charged-to -neutral kaon yields $R_K = (K^+ + K^-)/2K_s^0$, were discussed in a number of theoretical papers and are still a subject of debates [6], [14] and [11]). The consistent fundamental explanation of the observed violation of the isospin symmetry, of its dependence on energy and type of colliding systems, of different manifestations of effect at central and forward rapidities is needed.

We demonstrate on the base of "UrQMD(3:1)" model, with the parameters fixed in $e+e-$ data, that the violation of the isospin symmetry is also expected in collisions of nuclei with equal number of neutrons and protons, in particular, the effect should be studied in details in 12C+12C high energy collisions.

The modified "UrQMD(3:1)" model shows also that the effect of the isospin symmetry breaking has a certain rapidity dependence – the values of R_k have a tendency to noticably increase at higher rapidities. Besides, the "UrQMD(3:1)" model confirms the experimental observation that the effect of the isospin symmetry breaking is concentrated mostly in the "soft" region of transverse momenta ($p_t < 1,5GeV/c$ of kaons production.

The projection of the "UrQMD(3:1)" model with the fixed ratio of 3:1 of up- to down-quarks production, as defined in $e + e-$ collision data on kaon yields at $\sqrt{s} = 3GeV$ [18] and further successfully applied to *pp* collisions data [19], [20] and to Ar+Sc data, could be considered as reasonable one for the consistent predictions of the isospin symmetry breaking in symmetric collisions of 12C+12C nuclei.

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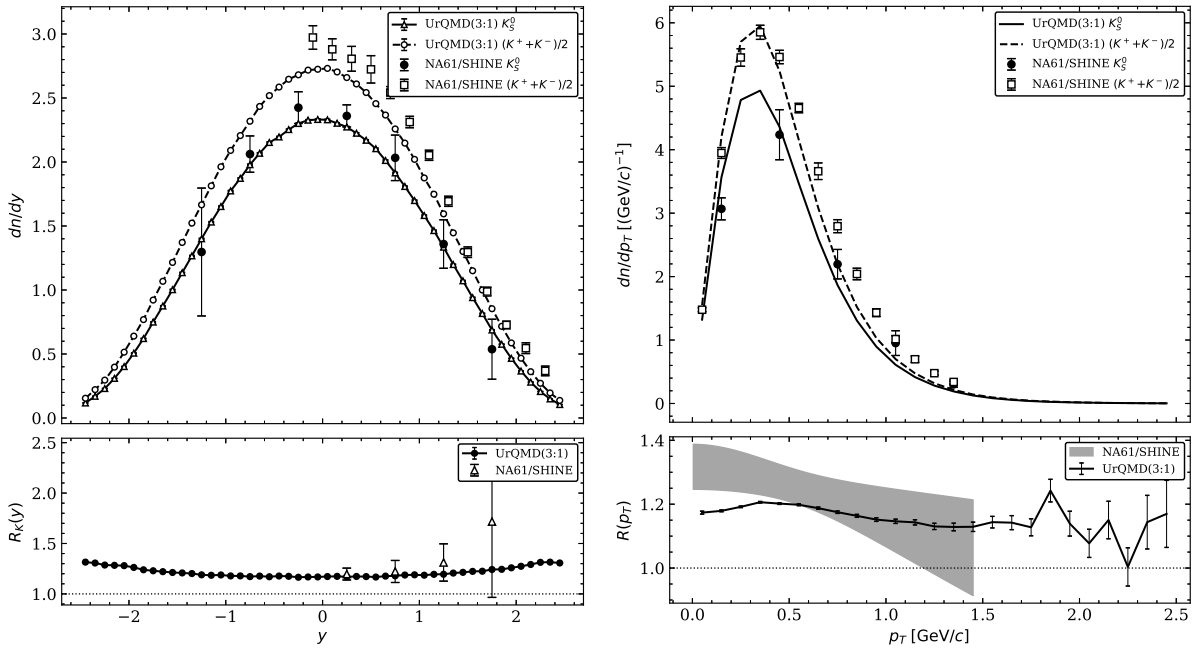
FIGURE CAPTIONS:

Figure 1. Left: Rapidity distributions of averaged sum of charged (K^+ and K^-) and of K_s^0 mesons in 0-10% central Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV. Dots - experimental data [1]. The dotted (solid) lines show results of calculations for charged (neutral) kaons using our modified UrQMD ("UrQMD(3:1)" code with the string parameters fixed in [14] – which allow for an 3:1 asymmetry in probability of up- and down- quark production in the elementary color field. Results are calculated for 0–2 fm centrality class. Right: Rapidity distributions of "UrQMD(3:1)" ratios $R_k = (1/2\,(K^+ + K^-))\,/K_s^0$ (see text). The bottom panel shows results for $R_K(p_t)$ in Ar+Sc Collisions.

Figure 2. Left: Rapidity distributions of $R_K = (1/2\,(K^+ + K^-))\,/K_s^0$ calculated in "UrQMD(3:1)" for 0–2 fm centrality class data on 12C+12C collisions at $\sqrt{s_{NN}} = 34$ GeV for rapidity distributions of charged (K^+ and K^-) and of K_s^0 mesons. String parameters are fixed following the ideas of [14] which allow for an 3:1 asymmetry between up- and down- quark "UrQMD(3:1)" Right: results for p_t spectra of charged (K^+ and K^-) and of K_s^0 mesons in central (0-2 fm impact parameter class, 0¡y¡2 rapidity range) C+C collisions at $\sqrt{s_{NN}} = 34$ GeV. Bottom panel shows predictions for $R_K(p_t)$ in 12C+12 Collisions.



(a) (b)

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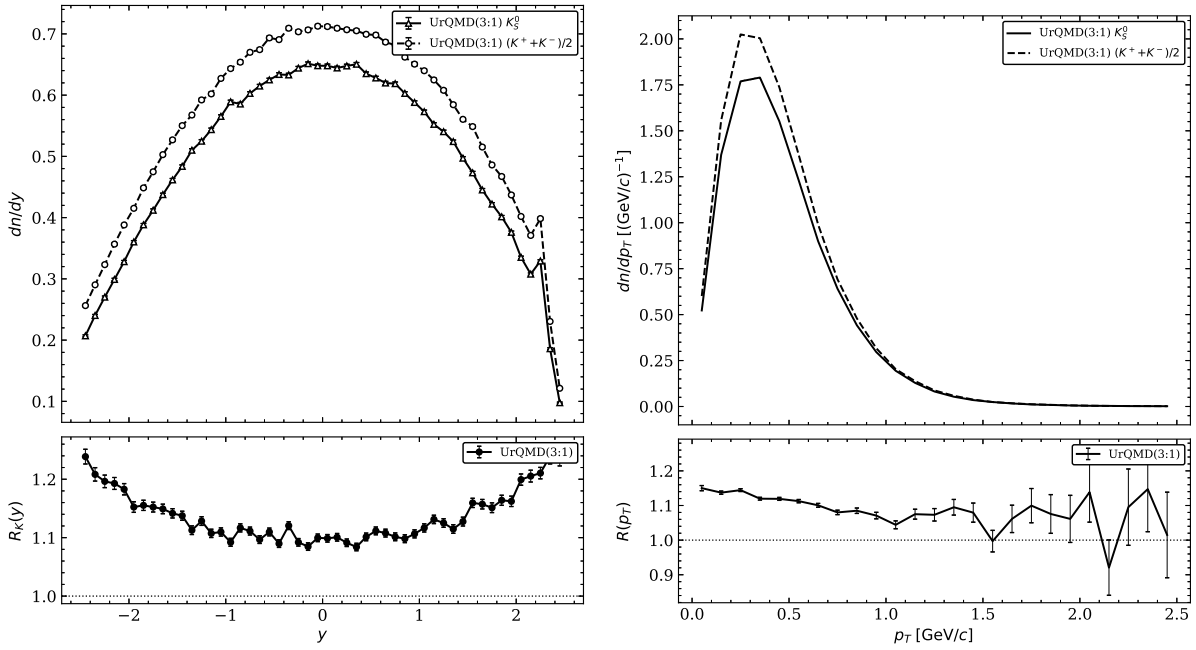

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