 doi:10.20944/preprints202112.0498.v1

On the quantum nature of a fireball created in ultrarelativistic nuclear collisions

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Abstract. In the article, the fireball formed in the collision of relativistic nuclei is considered as a quantum object. Based on this, an attempt is made to explain the difference in the measurements of hyperon yields in the two experiments - NA49 and NA57. Using the basic principles of quantum mechanics, it was shown that a fireball can have two quantum states - with and without ignited Quark-Gluon Plasma (QGP). With an increase of the collision energy of heavy ions, the probability of QGP ignition increases. At the same time, the probability of the formation of a fireball without igniting the QGP also remains not zero.

Keywords: Hadronic matter, Quark-Gluon Plasma, heavy-ion collisions, hyperon production, mid-rapidity multiplicity, nuclear spin.

1 Introduction

The difference between the two experiments - NA49 and NA57 in the strange (hyperon) sector [1] has not yet been explained. This shows that we have missed something in understanding the nature of the fireball formed in collisions of relativistic nuclei.

A possible methodological reason for the difference in measurements between the two experiments is related to the different method for determining the centrality of the collision of two heavy ions [1], [2]. But so far this issue remains unaddressed. Moving away from this methodological issue, I consider another possible reason for the mismatch of measurements of NA49 and NA57.

The main goal of experiments on heavy ion collisions is to study the properties of Quark-Gluon Plasma (QGP). One of the main signals about the formation of QGP is an increase in the yield of hyperons, due to a decrease in the threshold energy for the formation of hyperons in comparison with that in the collision of protons [3], [4]. The almost twofold difference in the hyperon yields of the two experiments, NA49 and NA57, has not yet been discussed from the standpoint of the fundamental properties of the fireball and the processes occurring in the target when relativistic heavy ions pass through it.

The work is organized as follows. The second section shows the difference between measurements in two experiments in which a quantum object is observed. Section III shows the application of the formulas obtained in section II to the results of NA49 and NA57 in their strange sector. Section IV discusses possible methods for testing the idea discussed in the article. Section V contains conclusions.

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2 Theoretical reasoning

Let us consider a quantum system described by wave function $\Psi(x)$, where x is a complete set of variables from which the wave function depends. Let L be a physical quantity (observable) that characterizes a specific property of a given quantum system. Let L has discrete spectra of eigenvalues L_a, L_b and them correspond complet set of eigenfunctions $\Psi_a(x)$ and $\Psi_b(x)$, respectively. Then we can write $\Psi(x) = a \cdot \Psi_a(x) + b \cdot \Psi_b(x)$, where a and b are an amplitudes of partial states $\Psi_a(x)$ and $\Psi_b(x)$, respectively. The average value of the observable L, multiple repeated measurements of which must be processed, is

$$\langle L \rangle = \int \Psi^*(x) \hat{L} \Psi(x) dx. \tag{1}$$

Hermitian operator $\hat{L}$ is matched to a physical value L. Average value $\langle L \rangle$ coincides with average value, obtained by statistical processing of the results of experimental measurements. Further we can write:

$$\langle L \rangle = \int \Psi^*(x) \hat{L} \Psi(x) dx = L_a a^* a \int \Psi_a^*(x) \Psi_a(x) dx + L_b b^* b \int \Psi_b^*(x) \Psi_b(x) dx = L_a a^2 + L_b b^2, \tag{2}$$

for normalized and orthogonal eigenfunctions $\Psi_a(x)$ and $\Psi_b(x)$, respectively. And a^2 and b^2 are a square of modules of amplitudes of partial states $\Psi_a(x)$ and $\Psi_b(x)$, respectively.

Suppose the first experiment "1" measures L in an acceptance area Ω_1 (kinematic and hardware conditions of the experiment that limit the signal) from which the states Ψ_a and Ψ_b are visible without possibility of their separation. The second experiment "2" measures in an acceptance area Ω_2 from which only the state Ψ_a is visible. Let us not know in advance what state exists at the moment of measurement.

The result of measurement of L by experiment "1" : $\langle L \rangle_1 = L_a a^2 + L_b b^2$. The result of measurement of L by experiment "2": $\langle L \rangle_2 = L_a a^2$.

Let us apply a model that takes into account the existence of only the Ψ_b state for a quantum system: $L_b^{th} \approx L_b$. Difference between measurements of both experiments:

$$\langle L \rangle_1 - \langle L \rangle_2 = L_b b^2 \approx L_b^{th} b^2. \tag{3}$$

Therefore, the probability of the state Ψ_b

$$b^2 = \frac{\langle L \rangle_1 - \langle L \rangle_2}{L_b^{th}}. \tag{4}$$

Probability of Ψ_a state is $a^2 = 1 - b^2$.

Let us apply a model that takes into account the existence of only the Ψ_a state for a quantum system. Then:

$$\langle L \rangle_1 - \langle L \rangle_2 = L_b b^2 \neq L_a^{th} b^2, \tag{5}$$

$$b^2 \neq \frac{\langle L \rangle_1 - \langle L \rangle_2}{L_a^{th}}, \tag{6}$$

that is, even if a model is good, we get conflicting results.

Formulas (3-6) are used in the next section for explanation of differences between NA57 and NA49 in the hyperon sector.

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3 Application to experimental data

Let experiment 1 be NA57 and experiment 2 - NA49. Let the observed L be the multiplicity, $\frac{dN}{dy}|_{y=0}/N_{wound}$, of hyperons $\Lambda^0 + \Sigma^0$ at mid-rapidity for the central $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 17.3$ GeV. Or $L = \frac{dN}{dy}|_{y=0}/N_{wound} \equiv (\Lambda^0 + \Sigma^0)/N_{wound}$. And average value $\langle L \rangle \equiv \frac{1}{N_{ev}} \sum_{i=1}^{N_{ev}} \frac{(\Lambda^0+\Sigma^0)}{N_{wound}}(i)$, where N_{ev} is the number of central heavy-ion collisions selected by the trigger, i is an ith measurement. Let a time interval of the fireball existence, created in those collisions, is around $15\,fm/c$ [5], then: $\delta t \cdot \delta E = 15\,fm/c \cdot 6MeV = 3 \cdot 10^{-22} MeV \cdot s \simeq \hbar/2$, where an uncertainty of the energy was taken equal to an uncertainty of the chemical freeze-out temperature δT_{ch} from [6] (it is the same for all energy scan range and centralities) obtained from the wide range of the particle ratios [7] - [10], measured by STAR, which equal to an average uncertainty of the kinetic (thermal) freeze-out temperature δT_{kin} from [1] for central collisions, obtained from the spectra of hyperons measured by NA49 at $\sqrt{s_{NN}} = 17.3$ GeV. An uncertainty of the kinetic (thermal) freeze-out temperature obtained by NA57 from spectra of hyperons [2] for the most central collisions is 10 MeV at $\sqrt{s_{NN}} = 17.3$ GeV. We assume that a fireball has some probability to be created with an ignition QGP inside it ($p_{QGP} < 1$), and it has some probability to be created contsisting of only hadronic matter (Hadronic Fireball - HF), without QGP ignition ($p_{HF} < 1$). Probably, $p_{QGP} + p_{HF} = 1$.

We took data of the multiplicity of both experiments and of both the models - PHSD (QGP formation, the transport model of a fireball evolution with the partonic degrees of freedom) and HSD (HF formation, the transport model of a fireball evolution without the partonic degrees of freedom) from Fig.21 of [5] (Table 1) and we substituted them in (3) (b is QGP state here, and b^2 is p_{QGP}):

$$p_{QGP} = \frac{((\Lambda^0 + \Sigma^0)/N_{wound})_{NA57} - ((\Lambda^0 + \Sigma^0)/N_{wound})_{NA49}}{((\Lambda^0 + \Sigma^0)/N_{wound})_{PHSD}}. \quad (7)$$

We have assumed that NA57 sees both the states (Hadronic Fireball and QGP Fireball), and NA49 preferentially sees the Hadronic Fireball through Λ^0-hyperon probe without QGP formation. Substituting values from Table 1 (2nd column), we have the probability of creation of QGP state of matter in the central heavy-ion collisions at $\sqrt{s_{NN}} = 17.3$ GeV is $p_{QGP} = 0.45 \pm 0.15$.

We have to check this result for other observables and should obtain the same result because the formulas (3)-(6) should remain the same for any observables for which we see an inexplicable difference between the measurements of the two experiments. From Fig.21-22 of [5], the multiplicities for $\bar{\Lambda}^0 + \bar{\Sigma}^0$, Ξ^- and $\bar{\Xi}^+$ were taken for the central collisions and they are shown in Table 1 (3d-5th columns). Repeating (3) for the new observables we have:

$\bar{\Lambda}^0 + \bar{\Sigma}^0$: $p_{QGP} = 0.513 \pm 0.16$;
Ξ^-: $p_{QGP} = 0.34 \pm 0.4$;
$\bar{\Xi}^+$: $p_{QGP} = 0.57 \pm 0.2$.

We see that all four probabilities coincide in the limits of errors. This is an indirect confirmation of the hypothesis that the fireball has two quantum states. Averaging over

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Table 1: Multiplicities of hyperons created in $Pb + Pb$ central collisions at $\sqrt{s_{NN}} = 17.3$ GeV at mid-rapidity measured by NA57 and NA49 Collaborations and calculated by PHSD/HSD models (are taken from Fig.21-22 of [5]).

	$(\Lambda^0 + \Sigma^0)/N_{wound}$	$(\bar{\Lambda}^0 + \bar{\Sigma}^0)/N_{wound}$	$(\Xi^-)/N_{wound}$	$(\bar{\Xi}^+)/N_{wound}$
NA49	$(36.6 \pm 4.35) \cdot 10^{-3}$	$(3.97 \pm 0.85) \cdot 10^{-3}$	$(4.616 \pm 1.6) \cdot 10^{-3}$	$(9.27 \pm 1.79) \cdot 10^{-4}$
NA57	$(53 \pm 3.22) \cdot 10^{-3}$	$(6.97 \pm 0.412) \cdot 10^{-3}$	$(6 \pm 0.2) \cdot 10^{-3}$	$(1.46 \pm 0.1) \cdot 10^{-3}$
PHSD	0.03645	$5.85 \cdot 10^{-3}$	$3.98 \cdot 10^{-3}$	$9.27 \cdot 10^{-4}$
HSD	0.03585	$2.67 \cdot 10^{-3}$	$3.16 \cdot 10^{-3}$	$2.78 \cdot 10^{-4}$

these four values gives $< p_{QGP} >= 0.47 \pm 0.23$. Thus, only half of the events in central collisions of heavy ions at the considered energy ignite the QGP state, the other half create a fireball only with only hadronic states of freedoms: $< p_{HF} >= 1- < p_{QGP} >= 0.53 \pm 0.23$.

Now we assume that NA49 sees only the QGP Fireball through hyperon probes. Repetition of calculations for this case with use of (6) where we now take HSD data for the denominator (Table 1) gives the next probabilities of a Hadronic Fireball creation:

$\Lambda^0 + \Sigma^0$: $p_{HF} = 0.46 \pm 0.15$;
$\bar{\Lambda}^0 + \bar{\Sigma}^0$: $p_{HF} = 1.12 \pm 0.35$;
Ξ^-: $p_{HF} = 0.43 \pm 0.5$;
$\bar{\Xi}^+$: $p_{HF} = 1.9 \pm 0.72$.

We see useless values of probabilities greater than one and their large differences among themselves. Average probability $< p_{HF} >= 0.98 \pm 0.43$.

It can be assumed that the probability of creating a QGP Fireball increases with an increase in the energy $\sqrt{s_{NN}}$, which is evident from the calculations made for peripheral ($N_{wound} < 100$) collisions of heavy ions with the formation of hyperons, which were taken from the source Fig.21-22 from [5]: $< p_{QGP} >= 0.23 \pm 0.26$ (calculation not shown here). Less energy pumped into a fireball created in peripheral collisions of heavy ions is equivalent to a decrease in collision energy. This means an increase in the probability of creating a QGP fireball as increases in energy $\sqrt{s_{NN}}$.

4 Check of the idea

We need to first consider the possible reasons for the differences in measurements between the two detectors of NA57 and NA49. We are dealing with the average multiplicity of hyperons corresponding to $y_{CM} = 0$. Thus, we are dealing with hyperons produced in the azimuthal plane. Suppose experiment 1 sees some type of hyperons in the interval of azimuthal angles $\Delta\Phi^1$, and experiment 2 - in the $\Delta\Phi^2$, and let be $\Delta\Phi^1 > \Delta\Phi^2$. If exist different azimuthal dependences of hyperon production for each of the quantum state of fireball then we might admit that experiment 2 is missing some peculiarity in hyperon production - an extremum (for example, the local maximum) in dead area of azimuthal angles, $\Delta\Phi^1 - \Delta\Phi^2$, thereby decreasing of yield of hyperons. But this is possible only if both experiments are measuring the hyperon production in the collisions of polarized nuclei, otherwise such azimuthal dependence cannot be measured. Nucleus $^{208}_{82}Pb$ has zeroth magnetic moment and spin in the ground state.

A beam of $^{208}_{82}Pb$ lead nuclei passes through two RF resonators of the SPS [11], 216 quadrupoles (max. gradient $22\,T/m$ at a length of 3 m [12], [13]) and 744 dipole magnets (max. induction on the beam axis $2.02\,T$ with a length of 6.5 m [12], [13] and an inevitable gradients at the edges of the magnets) of the ring of SPS before being ejected through the baffled magnets (magnetic induction $0.35 \div 1.5\,T$ with length $8 \div 10$ m [13] and inevitable gradients at the edges of the magnets) towards the target. Charged relativistic heavy ion $^{208}_{82}Pb\,(Z = +82)$ interacts with the electromagnetic fields of the magnets. In result, it can be excited and can obtain an electromagnetic moment (dipole, quadrupole, octupole, etc.). We can assume the preferencial orientation of the nuclear moments of nuclei of beam relative to the moving direction of the beam (no information in the literature). Thus, heavy ions of beam can be preferencially oriented along some direction (polarized) before heavy ions interact with target.

If we assume an excitation of heavy ion with maximal lifetime around 300 psec [14] and we have taken into account relativistic time delay then ion can pass only several meters after passing of the septum magnet before de-excitation what is not enough to reach the target which is situated at around hundred meters from the septum magnet [15]. Thereby, we have only spherically symmetric nuclei of beam without nuclear spins.

Heavy ions of a thin lead foil $^{208}_{82}Pb$ (the foil which is used in both experiments) are located in the nodes of the crystal lattice where these nuclei interact with the electric fields of the electronic system of solid. The foil is located at the room temperature - the temperature of the experimental hall. It can be assumed that lead nuclei in the crystal lattice (at the nodes of the crystal lattice) of a thin target foil can be excited into a state with spin and can be oriented due to electromagnetic interaction with the electric field of the crystal lattice. This interaction depends on the temperature, structure, defects of the lead foil, and on changes in the electronic and crystal structure of solid as a relativistic heavy ion of the beam moves through the crystal. In the literature considers the influence of only the first three factors on the states of nuclei with moments, for example, [16], where it is shown that the influence of the electronic structure on the state of the nucleus is very small. Therefore, we must exclude the first three influences. The ultrarelativistic heavy ion $^{208}_{82}Pb\,(Z = +82)$ loses about $7\,MeV$, passing through a lead foil about $100\,\mu m$ thick (calculated by the Bethe-Bloch formula). This energy loss is sufficient to excite the dipole or quadrupole moments of the $^{208}_{82}Pb$ nucleus [14]. The area of the beam spot on the foil varies within $1\,mm^2$ [17]. Data on the thickness of the lead foil in the NA49 and NA57 experiments were not found in the literature.

Then we can assume that the excitation of the lead nucleus (into a state with a nonzero spin) of the target occurs due to the energy lost by the heavy ion which is striking the target. Another heavy ion of the beam interacts with this excited heavy ion of the target before de-excitation. We can only assume that the polarization of an excited nucleus with spin in some direction is determined by the structure of the crystal and the defects of the sample ([16]) used for the target (I did not find these data for the target in the literature). The interaction of polarized nuclei of the target with spherically symmetric nuclei of the beam can create an azimuthal dependence of the production of hyperons.

For a preliminary assessment of the above hypothesis, it is necessary to compare the azimuthal distributions of hyperons measured by two experiments - NA49 and NA57. These distributions are not presented in the published results of these experiments.

5 Conclusion

Consideration of a fireball created in central collisions of heavy ions $Pb+Pb$ at $\sqrt{s_{NN}} = 17.3$ GeV, as having a quantum nature, gives the probability of creating a Quark-Gluon Plasma (QGP) state of about 50% (rough estimate). This gives the next important conclusion that the phase trajectory of the fireball on the QCD phase diagram should be split into two, reflecting two possibilities of the fireball evolution (with and without ignition of the QGP). With an increase in the collision energy of heavy ions, the probability of QGP formation also increases.

References

[1] Alt, C., *et al.* (NA49 Collaboration) (2008) Energy dependence of Lambda and Xi production in central Pb+Pb collisions at 20A, 30A, 40A, 80A, and 158A GeV measured at the CERN Super Proton Synchrotron. Phys. Rev. C, 78, 034918.

[2] Bruno, G.E. (for the NA57 Collaboration) (2008) NA57 main results. J.Phys.G: Nucl.Part.Phys., 35, 044005.

[3] Curtis Patrick Leon Lansdell (2002) Charged Ξ Production in 130 GeV Au+Au Collisions at the Relativistic Heavy Ion Collider. Ph.D. Dissertation, the University of Texas, Austin.

[4] Matthew Allan Charles Lamont (2002) Neutral Strange Particle Production in Ultra-Relativistic Heavy Ion Collisions at $\sqrt{s_{NN}} = 130$ GeV. Ph.D. Dissertation, the University of Birmingham.

[5] Cassing, W., Bratkovskaya, E.L. (2009) Parton-Hadron-String Dynamics: an off-shell transport approach for relativistic energies. Nucl. Phys. A, 831, 215-242.

[6] Sabita Das (for the STAR collaboration) (2015) Chemical freeze-out parameters in Beam Energy Scan Program of STAR at RHIC. EPJ Web of Conf., 90, 10003.

[7] Sabita Das (for the STAR collaboration) (2013) Centrality dependence of freeze-out parameters from the beam energy scan at STAR. Nucl.Phys.A, 904-905, 891c-894c.

[8] Sabita Das (for the STAR collaboration) (2014) Study of freeze-out dynamics in STAR at RHIC Beam Energy Scan Program. J.Phys.: Conference Series, 509, 012066.

[9] Kumar, L. (for the STAR collaboration) (2011) Identified hadron production from the RHIC beam energy scan. J.Phys.G Nucl. Part. Phys., 38, 124145.

[10] Zhu, X. (for the STAR collaboration) (2012) Measurements of K^0_S, Λ and Ξ from $Au + Au$ collisions at $\sqrt{s_{NN}} = 7.7, 11$ and 39 GeV in STAR. Acta Phys.Polon. B, Proc. Supp., 5, 213-218.

[11] Kissler, K.H. (1998) SPS and LEP status report. CERNSL-98-053DI.
`https://cds.cern.ch/record/366023/files/sl-98-053.pdf`

 doi:10.20944/preprints202112.0498.v1

[12] Davide Tommasini (2010) The PS Booster , PS and SPS Magnets for the next 25 years. CERN TE-Note-2010-003.

https://cds.cern.ch/record/1233948

[13] Middelkoop, W.C. Magnetic and electrostatic deflecting devices.

http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/06/173/6173286.pdf

[14] Stone, N.J. (2014) Table of Nuclear Magnetic Dipole and Electric Quadrupole Moments. INDC International Nuclear Data Committee.

https://www-nds.iaea.org/publications/indc/indc-nds-0658/

[15] Antinori, F., *et al.* (NA57 Collaboration) (2006) Enhancement of hyperon production at central rapidity in 158 A GeV/c Pb-Pb collisions. J.Phys. G, 32, 427-442.

[16] Grechishkin, V.S. (1973) Nuclear quadrupole interactions in solids. Nauka, Moscow.

[17] The HiRadMat (High-Radiation to Materials) Facility at CERN SPS.

https://espace.cern.ch/hiradmat-sps/Wiki%20Pages/Beam%20Parameters.aspx