The big questions in small systems

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The early universe, very briefly after the Big Bang, was in a state of high temperature and high density. In order to recreate such a state of matter like the strongly coupled Quark–Gluon Plasma (sQGP) in the laboratory, mini bangs are produced by colliding heavy ions at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory and subsequently at the Large Hadron Collider (LHC) at CERN. When the interesting results started pouring in from the LHC in high-energy p + p and p + A (small systems), the efforts to characterize the transition from these small systems to heavy ions (A + A) faced big questions, since the small system results have striking similarities to heavy ions in the higher multiplicity domains. The sQGP is a very good liquid with astonishingly low viscosity, and the recent observations of QGP-like phenomena in small collision systems have led to new implications. We briefly discuss these exciting new observations and their implications, including the questions that have emerged during such studies using heavy quarks.

Free coloured particles do not exist in nature, and quarks[1] and gluons[2] are confined inside colourless particles called hadrons. The governing interaction in the subatomic world is the strong interaction, which is explained by quantum chromodynamics (QCD)[3]. The refinements of the quark model of hadrons and the progress of QCD eventually led to expectations that matter at very high densities may have been as quasi-free quarks and gluons, the quark–gluon plasma (QGP)[4–8]. The 'Big Bang' or early universe properties can be explored experimentally by relativistic nucleus–nucleus collisions ('little bangs') at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) in the laboratory[8].

The term 'strongly coupled QGP (sQGP)' was conceived when it was noticed that QGP formed in relativistic heavy-ion collisions was not a weakly coupled gas but on a strongly coupled liquid[4,8,9]. The study of QGP generally includes analyses of soft (low, transverse momentum, p_T) particles whose behaviour can be described by hydrodynamical models, along with the hard partons that can interact with QGP[10]. We cannot portray the $A + A$ systems (or nucleus–nucleus collisions) successfully unless we understand the small systems like proton–proton ($p + p$) and proton–nucleus ($p + A$) collisions[7,8,10]. Recent observations regarding QGP-like behaviour in $p + p$ and $p + A$ collisions (small systems) have been contrary to our conventional understanding of high-energy, heavy-ion physics.

Small systems

Demarcating the initial-state effects from the final-state interactions in QGP requires control measurements like $p + A$ collisions[6,11,12]. The system size evolution at freeze-out can be further understood from small systems (like $p + p$ and $p + A$), along with the rescattering effects[10,13]. Testing and understanding these assumptions with LHC and RHIC datasets are underway, with further possibilities at the Electron-Ion Collider (EIC)[14].

The heavy quarks, which are pivotal experimental probes, interact via the strong interaction while passing through QGP[12,15]. They are expected to lose an important part of their energy and can retrieve the initial anisotropy of the medium produced through high-energy nucleus–nucleus collisions[15]. Measurements of quarkonium yield and its modification are sensitive to the temperature of QGP[10,12,15]. The nuclear modification factor (R_{AB}), considering the collisions between two nuclei A and B, is formulated as the ratio of particle yield in AB collisions to those in $p + p$ collisions scaled by the average number of binary nucleon–nucleon collisions, $\langle N_{\text{coll}}\rangle$, in AB collisions. It is expressed as:

$$R_{AB}(p_T) = \frac{\mathrm{d}^2 N_{AB}/\mathrm{d}p_T\mathrm{d}y_{c.m}}{\langle N_{\text{coll}}\rangle \mathrm{d}^2 N_{pp}/\mathrm{d}p_T\mathrm{d}y_{c.m}}$$

$$= \frac{\mathrm{d}^2 N_{AB}/\mathrm{d}p_T\mathrm{d}y_{c.m}}{\langle T_{AB}\rangle \mathrm{d}^2 \sigma_{pp}/\mathrm{d}p_T\mathrm{d}y_{c.m}}, \qquad (1)$$

where $y_{c.m}$ is the rapidity calculated in the centre-of-mass frame of the colliding nucleons and $\langle T_{AB}\rangle$ is the nuclear overlap function (calculated using the Glauber model) which takes into account the nuclear collision geometry[10]. The much-needed reference measurements for QGP studies are furnished by the small system ($p + p$ and $p + A$) collisions[7,8,10]. QGP formation is not assumed in small systems, as the transverse size of the overlap region is comparable to that of a single proton[10].

Do the heavy quark production rates in high-multiplicity $p + p$ collisions at LHC energies show experimental results similar to the J/ψ suppression? Since the heavy quark yields in heavy-ion collisions are expected to be modified relative to minimum bias $p + p$ collisions[8], such a prominent question is likely to arise. The relative production of J/ψ, as a function of multiplicity, shows a linear rise for p_T-integrated yields. This increase is prominent for high-p_T J/ψ mesons, which we observe for $p + p$ collisions at $\sqrt{s}$ = 13 TeV (ref. 16). An escalation of the relative J/ψ and Υ yields[17–19] with the relative charged-particle multiplicity was observed in p + Pb collisions at 8.16 TeV (ref. 20). The $p + p$ collisions also showed similarity with the $p + A$ measurements[18,19,21].

The initial state effects in nuclear collisions can be understood via small systems[8,10]. The cold nuclear matter (CNM) effects (such as nuclear modification of the parton distribution functions or break-up of the quarkonium state in CNM) are unclear at RHIC energies[10]. The nuclear modification factor R_{pA} is the ratio of $p + A$ to $p + p$ cross-sections normalized to the average number of binary nucleon collisions[8]. Several novel, unexpected phenomena have been observed in $p + p$ and $p + A$ collisions, which produce striking similarities to the heavy-ion phenomenology[7,8,10]. The rise of the J/ψ (quarkonia) normalized yields, when found comparable to the increase seen for the D-mesons (open charm)[22,23], hints towards a common mechanism.

Summary

Are there any better alternatives than the nuclear modification factor? The nuclear modification factor (eq. (1)) is based on normalising such small systems; we have assumed them to be elementary and simple. However, these recent experimental observations in $p+p$ collisions have challenged such formulations, and we need better alternatives. The central-to-peripheral modification factor[10]:

$$R_{\mathrm{CP}} = \langle N_{\mathrm{coll}}^{\mathrm{peripheral}} \rangle \mathrm{Yield}_{\mathrm{Pb-Pb}}^{\mathrm{central}} / \langle N_{\mathrm{coll}}^{\mathrm{central}} \rangle \mathrm{Yield}_{\mathrm{Pb-Pb}}^{\mathrm{peripheral}}, \tag{2}$$

is hence defined to understand the differences between the central and peripheral collisions. For R_{CP}, the yields are calculated in the different centrality classes and are divided by the corresponding average number of binary collisions. The most peripheral bin is used as a reference for R_{CP}, since hot and dense medium formation is not expected in the peripheral $A+A$ collisions. If collective expansion occurs in peripheral $A+A$ collisions, whether R_{CP} will still evolve as a better alternative is a pertinent question[10].

Do small systems like $p+p$ collisions have flow effects? Results from CMS show that within experimental uncertainties, the multi-particle cumulant $v_2\{4\}$ and $v_2\{6\}$ values in $p+p$ collisions at high multiplicity are in agreement with each other and comparable to $p+\mathrm{Pb}$ and $\mathrm{Pb}+\mathrm{Pb}$ collisions[15,24,25]. The ATLAS experiment at 13 TeV has explored the elliptic flow (v_2) coefficients for heavy-flavour decay muons in $p+p$ collisions, along with a separation between charm and bottom contributions[26]. The v_2 coefficient for bottomonia measurements in heavy ions is compatible with zero, as published by ALICE[27] and CMS[28] experiments.

The $p+p$ collisions at higher multiplicities in Run-3 and Run-4 at LHC can facilitate connecting the differences between the $p+p$ and heavy-ion collisions[29]. The quarkonium measurements from ALICE in $p+A$ collisions will improve our understanding of small systems[20]. The larger datasets will help in studying the rare probes with better precision[29].

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1. Riordan, E. M., *Science*, 1992, **256**, 1287–1293.
2. Ellis, J., *Int. J. Mod. Phys. A*, 2014, **29**(31), 1430072.
3. Marciano, W. J. and Pagels, H., *Phys. Rep.*, 1978, **36**, 137.
4. Shuryak, E. V., *Phys. Rep.*, 1980, **61**, 71.
5. Shuryak, E. V., *Rev. Mod. Phys.*, 2017, **89**, 035001.
6. Kisslinger, L. S. and Das, D., *Int. J. Mod. Phys. A*, 2016, **31**(7), 1630010.
7. Das, D., *Int. J. Mod. Phys. A*, 2022, **37**(23), 2230012.
8. Das, D., *Int. J. Mod. Phys. A*, 2021, **36**(24), 2130014.
9. Shuryak, E. V., *Prog. Part. Nucl. Phys.*, 2009, **62**, 48.
10. Das, D., *Nucl. Phys. A*, 2021, **1007**, 122132.
11. Das, D. (ALICE collaboration), *Nucl. Phys. A*, 2011, **862–863**, 223.
12. Kisslinger, L. S. and Das, D., *JHEP*, 2017, **1709**, 105.
13. Das, D., *Adv. High Energy Phys.*, 2018, **2018**, 3794242.
14. Abdul Khalek, R. *et al.*, *Nucl. Phys. A*, 2022, **1026**, 122447.
15. Das, D. and Dutta, N., *Int. J. Mod. Phys. A*, 2018, **33**(16), 1850092.
16. Acharya, S. *et al.* (ALICE collaboration), *Phys. Lett. B*, 2020, **810**, 135758.
17. Adamová, D. *et al.* (ALICE collaboration), *Phys. Lett. B*, 2018, **776**, 91–104.
18. Chatrchyan, S. *et al.* (CMS collaboration), *JHEP*, 2014, **4**, 103.
19. Aaboud, M. *et al.* (ATLAS collaboration), *Eur. Phys. J. C*, 2018, **78**(3), 171.
20. Acharya, S. *et al.* (ALICE collaboration), *JHEP*, 2020, **9**, 162.
21. Abelev, B. *et al.* (ALICE collaboration), *Phys. Lett. B*, 2012, **712**, 165–175.
22. Adam, J. *et al.* (ALICE collaboration), *JHEP*, 2015, **9**, 148.
23. Adam, J. *et al.* (ALICE collaboration), *JHEP*, 2016, **8**, 078.
24. Khachatryan, V. *et al.* (CMS collaboration), *Phys. Lett. B*, 2017, **765**, 193.
25. Khachatryan, V. *et al.* (CMS collaboration), *Phys. Rev. Lett.*, 2015, **115**(1), 012301.
26. Aad, G. *et al.* (ATLAS collaboration), *Phys. Rev. Lett.*, 2020, **124**(8), 082301.
27. Acharya, S. *et al.* (ALICE collaboration), *Phys. Rev. Lett.*, 2019, **123**(19), 192301.
28. Sirunyan, A. M. *et al.* (CMS collaboration), *Phys. Lett. B*, 2021, **819**, 136385.
29. Citron, Z. *et al.*, *CERN Yellow Rep. Monogr.*, 2019, 1159–1410.

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