Review of the Safety of LHC Collisions
Addendum on strangelets

LHC Safety Assessment Group

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Abstract

It is stated in section 5 of the LSAG report that there is no basis for any conceivable threat from strangelet production at the LHC. Our arguments follow closely the line of reasoning of previous reports [1, 2], but they put particular emphasis on two observations. First, on general grounds, the probability for strangelet production decreases with increasing center-of-mass energy. As a consequence, strangelet production at LHC is less likely than at RHIC, just as it was less likely at RHIC than in the heavy-ion programs at lower center-of-mass energies pursued in the 1980s and 1990s. Secondly, RHIC data strongly disfavour models of particle production which were advocated as production mechanisms for strangelets. On the contrary, RHIC data give strong support to a thermal model of particle production, which puts tight upper bounds on strangelet production. In this Addendum, we provide background information to support these statements and the main conclusions drawn from them. In particular, we recall the main arguments of the safety reports [1, 2], and we discuss how these arguments can be strengthened in the light of recent data from RHIC.

Strangelet Properties

Strange quark matter is a hypothetical state of matter consisting of roughly equal numbers of up, down and strange quarks. It has been speculated that strange quark matter might constitute the true ground state of baryonic matter, being more stable than ordinary nuclei [3, 4]. Hypothetical small lumps of strange quark matter, having atomic masses comparable to ordinary nuclei, are often referred to as 'strangelets'. Such strangelets might be either stable or metastable. At present, a first principle theory of strange quark matter is not within theoretical reach. It would require major theoretical breakthroughs in the application of QCD to finite density and to mesoscopic systems. As a consequence, theoretical studies on whether strangelets can exist for some parameter range depend on model-dependent assumptions. As reviewed in detail in [1, 2], theoretical speculations about the existence of strangelets may be summarized as follows:

1. *It is unclear whether bulk strange quark matter exists at all.*

2. *It is unclear whether bulk strange quark matter can be stable.*
   If it does exist, strange quark matter may be absolutely stable in bulk at zero external pressure, though the expected values for the relevant parameters tend to disfavour stability [2].

3. *Finite size effects make it very unlikely that small strangelets ($A < 10$) can be stable or long-lived.*
   Even if bulk strange quark matter is stable, finite-size effects (surface tension and curvature) significantly destablize strangelets with low baryon number. For typical parameters, it has been estimated that finite-size effects add, e.g., 50 MeV per baryon for A = 20 and 85 MeV per baryon for A=10 [2].

4. *Stable strangelets, if they exist, could be present only in states of low entropy (i.e., temperature).*
   Hot strangelets are much less stable than cold ones. The characteristic scale to decide what is hot or cold is set by the binding energy per baryon of the strangelet. On general thermodynamic grounds, the timescale for evaporation of hot strangelets is expected to be very small, though difficult to calculate. Assuming typical nuclear binding energies of O(1) MeV, one expects that stable strangelets are would need to be much colder than the matter produced in heavy-ion collisions [1, 2].

5. *If stable strangelets exist, they are most likely positively charged.*
   If strange matter contained equal numbers of u, d and s quarks, it

> would be electrically neutral. Since, s quarks are heavier, Fermi gas kinematics alone indicates that strange quarks are suppressed, giving strange matter a positive charge per unit baryon number. However, the effects of gluon exchange reactions are difficult to quantify. Perturbatively, gluon exchange is repulsive and increases the mass. But gluon interactions weaken as quark masses are increased, so the gluonic repulsion is smaller between $s-s$, $s-u$ or $s-d$ pairs than between u and d quarks. Hence, increasing the strength of gluon interactions tends to reduce the charge of quark matter negative, and also to unbind it. Unreasonably low values of the bag constant are necessary to compensate for a large repulsive gluonic interaction energy, which is why negatively-charged strangelets are regarded as extremely unlikely [1].

Hypothetical disaster scenarios based on strangelet production in heavy-ion collisions require that strangelets be stable or very long-lived, and hence that they are sufficiently cold. It has been argued in detail [1] that each of these conditions is unlikely. In the following, we discuss in particular how RHIC data allow us to strengthen the argument that sufficiently cold strangelets cannot be produced in the hot particle furnace created in a heavy ion collision. Moreover, most hypothetical disaster scenarios require that the produced strangelet be charged negatively, so that its fusion with positively charged nuclei could lead to a hypothetically disastrous chain of events. In contrast, in normal matter, positively-charged strangelets would capture electrons, which would shield any fusion with other nuclei. To trigger a run-away reaction in the latter case, one must invoke an ionizing mechanism (e.g., by transporting the strangelets to the interior of the Sun [8]), and this adds another layer of unlikely assumptions.

Strangelet Production mechanisms in heavy-ion collisions

Strangelets, if they exist at all, are hadronic systems made out of quarks. Any model for their production should be first tested against the existing data on the production of nuclei. This line of argument has been explored in [2]. Here, we sharpen its conclusions in the light of recent data from RHIC. There are three models of particle production, which have been considered in the context of strangelet production in heavy-ion collisions:

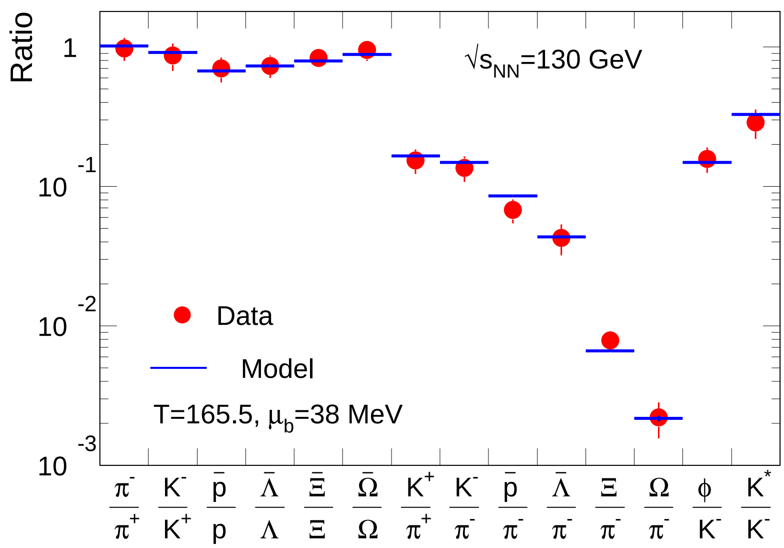

Figure 1: Comparison of the experimental data on different particle multiplicity ratios obtained at RHIC at $\sqrt{s_{\rm NN}}$ = 130 GeV with thermal model calculations [6]. The abundances of strange and multiple strange hadron species are well-described in terms of a chemical freeze-out temperature and baryon chemical potential. The dependences of these parameters on the center-of-mass energy is shown in Fig. 2.

1. **Thermal models** Hadron production in heavy-ion collisions is remarkably well described in terms of a statistical model. This model describes hadron yields in terms of the grand canonical ensemble of a hadron resonance gas at temperature T and baryon chemical potential μ_B [5], which characterizes the net baryon density. Figure 1 illustrates the success of this model for particle production in heavy-ion collisions at RHIC. The relative abundance of all particle species with n_s strange quarks (where experimental obseervations extend up to $n_s = 3$ only), are well described by the model. The temperature T and baryochemical potential m_B of this model show a characteristic dependence on

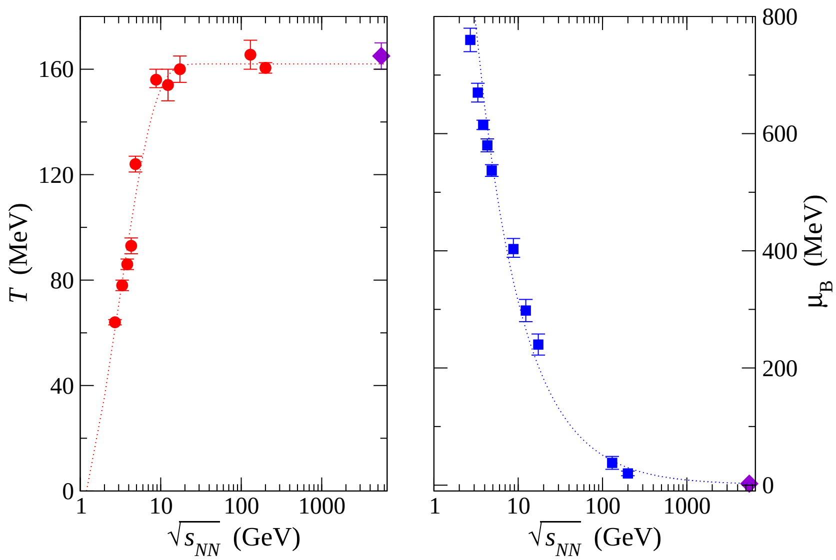

Figure 2: Thermal model fits at mid-rapidity of the freeze-out temperature T and the baryon chemical potential μ_B as functions of the center-of-mass energy $\sqrt{s_{NN}}$. The data points up to RHIC energies are taken from [6]. The points at $\sqrt{s_{NN}} = 5.5$ TeV are based extrapolations of the measured trend [7]. The decrease of baryon chemical potential with center-of-mass energy makes strangelet production less likely at higher center-of-mass energies.

the center-of-mass energy of the heavy-ion collision, as seen in Fig. 2. The temperature increases with increasing collision energy, saturating at $T \sim 165$ MeV, whereas the baryon chemical potential decreases. The reason for the decrease of μ_B is that, at higher collision energies, the same net baryon number is distributed over a wider longitudinal kinematic range, resulting in a lower net baryon density and hence a lower value of μ_B.

The statistical approach can also be applied to the production of complex nuclei. The penalty factor for the yield Y_A of a nucleus A compared to $A-1$ is the ratio of Boltzmann weights [2]

$$P_F = \frac{Y_A}{Y_{A-1}} \simeq \exp\left[-\frac{(m_N - \mu_B)}{T}\right] , \qquad (1)$$

where m_N is the nucleon mass. For the relevant temperature of $T = 165$

MeV, a small baryon chemical potential $\mu_B \ll m_N$ as shown in Fig. 2, and $A = 10$, this gives a relative suppression factor 3×10^{-25} compared to the production of nucleons. We note that this would be the suppression factor for the production of normal nuclei. The production of any strangelet of $A = 10$ may be expected to be suppressed significantly more than the production of a normal $A = 10$ nucleus. Moreover, the grand canonical ensemble, on which the above estimates are based, is expected to be modified by an additional canonical suppression factor, as soon as the constraint from the finite total baryon number in the collision becomes relevant at sufficiently large A. Taking these considerations into account, the suppression factor 3×10^{-25} is an extremely conservative upper bound. If one repeats the exercise with $A = 20$, one is led to a suppression factor 10^{-49}.
We note that the production of light nuclei with $A \ll 10$ has been measured in central heavy-ion collisions at AGS, SPS and RHIC. It is well accounted for by the penalty factor (1): see, e.g., [18] for a comparison of thermal model calculations to data. The measured penalty factors for light nuclei range from 1/50 at AGS, to $\sim 1/300$ at the SPS, and for antinuclei they range from $1/(2 \times 10^5)$ at the AGS and 1/3000 at the SPS to 1/1500 at RHIC [2]. As functions of center-of-mass energy, the penalty factors increase for nuclei, but - due to the decrease of the baryon chemical potential with $\sqrt{s_{\rm NN}}$, they decrease for antinuclei. In a system with postive net baryon number, the total yield of nuclei is always larger than the yield of antinuclei. For this reason, the above estimate is based on the thermal production of nuclei.

2. **Coalescence models** The basic physics idea of coalescence models is that a nucleus A forms when A nucleons occupy the same 'interaction volume'. In these models, the yield Y_A of nuclei A is related to the initial yield Y_N of nucleons as

$$Y_A = B_A \left(Y_N\right)^A , \tag{2}$$

where B_A is the so-called coalescence parameter. The penalty factor P_F for coalescing an additional nucleon onto an existing cluster is then [2]

$$P_F = \frac{Y_A}{Y_{A-1}} = \left(\frac{B_A}{B_{A-1}}\right)_0 \frac{V_0}{V} Y_N \, . \tag{3}$$

Here, V denotes the interaction volume over which coalescence is effective, and the subscript '0' refers to a reference scale set, e.g., by determining the coalescence parameter and the interaction volume at a specific collision energy.

It has been emphasized previously in [2] that predictions from the coalescence models are in qualitative and even reasonable quantitative agreement with thermal models. For instance, in [2] it was estimated on the basis of coalescence models that the suppression factor for production of an $A = 20$ nuclei in a central heavy ion collision is $10^{-50^{-3}_{+4}}$. This compares very well with the suppression factor of order 10^{-49} obtained in the above discussion of thermal models.

Since coalescence models do not differ qualitatively from thermal models, the same safety arguments apply. For this reason, we emphasize in the main LSAG report that in the detailed study of heavy-ion collisions at RHIC and lower energies, no evidence for an anomalous coalescence mechanism has been found. The basis of the 2003 report has been fully vindicated by further RHIC running.

3. **Distillation mechanism**

Strangeness distillation has been proposed specifically as a mechanism for strangelet production. This mechanism assumes that a baryon-rich quark-gluon plasma is produced in a heavy-ion collision, which cools by evaporation from its surface. Due to the large baryon chemical potential in this plasma, an $\bar{s}$ quark would be more likely to pair with an u or d quark, than an s quark with an $\bar{u}$ or $\bar{d}$. As a consequence, the cooling of the plasma would lead to an excess of s quarks in a baryon-rich lump, which may finally become a strangelet.

We note that this production process would be more likely for large baryon chemical potential, and thus would be less likely for heavy-ion collisions at the LHC than at lower center-of-mass energies. Moreover, there is by now significant empirical evidence against a dynamical picture of heavy-ion collisions in which strangeness distillation could be operational. In particular, empirical evidence from RHIC strongly supports explosive production scenarios, in which, for instance, collective-flow gradients increase with center-of-mass energy [17]. The short lifetime of the produced systems (of the order of 10 fm/c) is not expected to allow for an evaporation process. Moreover, the explosive collective dynamics is expected to favor bulk emission rather than surface emission [17]. So, there is no evidence for a distillation mechanism capable of strangelet production at RHIC, and this suggestion for strange particle production has been abandoned for the LHC.

Direct experimental searches for strangelets

Strangelets have been searched for in ordinary matter on Earth [9] and in heavy-ion collisions over a wide range of center-of-mass energies. In particular, searches for stranglets have been reported by several experiments at the Brookhaven Alternating Gradient Synchrotron [10, 11, 12, 13], by the NA52 Collaboration at the SPS [14, 15], and by the STAR Collaboration at RHIC [16]. All of these searches yielded negative results and reported complementary upper limits. In particular, STAR reported an upper limit of less than 10^{-6} strangelets per central Au-Au collision for strangelets with lifetimes > 0.1 ns and mass larger than 30 GeV/c^2.

More details about the experimental situation can be found in the previous reports [1, 2].

Summary of the safety argument

Quantitative considerations

The maximal luminosity of lead-lead (Pb+Pb) collisions at the LHC is $\mathcal{L} = 10^{27}\,/\mathrm{cm}^2\,\mathrm{s}$. With a hadronic Pb+Pb cross section of 8 barn, this implies a rate of up to 8000 Pb+Pb collisions per second. With a foreseen running time of 1 month per year (10^6 seconds) times a duration of the program of, say, 10 years, we arrive at a conservative upper bound on the total number of ion-ion collisions at the LHC of $\mathcal{O}(10^{11})$. However, a large fraction of the hadronic Pb+Pb cross section is diffractive or very peripheral. Only 10 percent of the entire rate can be considered as being sufficiently central for creating a collision system characteristic of a heavy-ion collision with a number of participants $N_{\mathrm{part}} > 20$ say. As a consequence, a conservative bound on the number of heavy ion collisions relevant for production of an $A = 10$ nucleus is $\mathcal{O}(10^{10})$.

Our conservative estimate for the thermal production of a *normal* $A = 10$ nucleus at the LHC was 3×10^{-25} times the rate of nucleon production. Taking the latter rate to lie in the hundreds, we arrive at a probability of $\sim 10^{-13}$ that a single normal nucleus of size $A = 10$ is produced during the entire LHC program as a result of the essentially thermal dynamics in a heavy ion collision. So, if LHC would run for the entire lifetime of the Universe, the probability of producing such a single nucleus via thermal production would be 1/1000 [1].

We note that the above is an estimate for the thermal production of a *normal* $A = 10$ nucleus from a hadron gas of temperature $T = 165$ MeV. The production of normal nuclear matter provides an extremely conservative upper bound on the production of strange quark matter. For this reason, we find that the significant empirical support for thermal particle production in heavy ion collisions, which was substantiated further by RHIC data in recent years, strengthens the main conclusion of the 2003 report [2]. There is no basis for any conceivable threat from strangelet production at the LHC.

Qualitative considerations

The above estimate of an upper limit to the probability of $A = 10$ nuclei can be further strengthened by the following qualitative argument, which is based on general principles of thermodynamics alone.

Strangelets are cold, dense systems. Like nuclei, they are bound by O(1–10) of MeV (if they are bound at all). Heavy-ion collisions produce hot systems. At LHC, the temperatures reached are in excess of 100 MeV. The second law of thermodynamics fights against the condensation of a system an order of magnitude colder than the surrounding medium. The hypothetical production of a cold strangelet from a hot hadron gas has been compared to producing an ice cube in a furnace [1].

The LSAG report has aimed at communicating this central qualitative idea. In the present addendum, we have provided the quantitative background, to which the notion of 'particle furnace' corresponds. As seen from Fig. 2, measurements show that heavy-ion collisions reach temperatures of

[1] One may add that in semi-peripheral collisions, nuclei with $A = 10$ may appear amongst the break-up products of the spectators of the nuclear projectile. However, such fragment production of nuclear remnants is not a mechanism that could give rise to strangelets. For this reason, we focus solely on thermal production rates of normal nuclei.

$T = 160$ MeV in the last stage of the collision. Moreover, the baryon chemical potential, which characterizes the net quark density, decreases as the center-of-mass energy increases, further decreasing the likelihood of producing any system with large atomic number. The particle abundances measured at RHIC and in lower-energy experiments are consistent with expectations from the thermal model of statistical hadronization (see Fig. 1). This model is also known to apply to the production of light nuclei, as far as they have been identified experimentally, and it provides a very large suppression factor for the production of $A = 10$ nuclei. On these grounds, we conclude that the experimental evidence from RHIC for the thermal model of particle production significantly strengthens the conclusions of the 2003 report of the LHC Safety Study Group.

References

[1] W. Busza, R. L. Jaffe, J. Sandweiss and F. Wilczek, "Review of speculative 'disaster scenarios' at RHIC," Rev. Mod. Phys. **72** (2000) 1125 [arXiv:hep-ph/9910333].

[2] J.-P. Blaizot, J. Iliopoulos, J. Madsen, G.G. Ross, P. Sonderegger and H.-J. Specht, "Study of potentially dangerous events during heavy-ion collisions at the LHC: report of the LHC safety study group", CERN 2003-001.

[3] A. R. Bodmer, Phys. Rev. D **4** (1971) 1601.

[4] E. Witten, Phys. Rev. D **30**, 272 (1984).

[5] P. Braun-Munzinger, K. Redlich and J. Stachel, arXiv:nucl-th/0304013.

[6] A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **772** (2006) 167 [arXiv:nucl-th/0511071].

[7] N. Borghini and U. A. Wiedemann, arXiv:0707.0564 [hep-ph].

[8] A. Kent, arXiv:hep-ph/0009130.

[9] R. Klingenberg, J. Phys. G **27** (2001) 475. P. Mueller, L. B. Wang, R. J. Holt, Z. T. Lu, T. P. O'Connor and J. P. Schiffer, Phys. Rev. Lett. **92** (2004) 022501 [arXiv:nucl-ex/0302025]. Z. T. Lu, R. J. Holt,

P. Mueller, T. P. O'Connor, J. P. Schiffer and L. B. Wang, Nucl. Phys. A **754** (2005) 361 [arXiv:nucl-ex/0402015].

[10] T. A. Armstrong *et al.* [E864 Collaboration], Phys. Rev. C **63** (2001) 054903 [arXiv:nucl-ex/0010017].

[11] A. Rusek *et al.* [E886 Collaboration], Phys. Rev. C **54** (1996) 15.

[12] D. Beavis *et al.* [E878 Collaboration], Phys. Rev. Lett. **75** (1995) 3078.

[13] H. Caines *et al.* [E896 Collaboration], J. Phys. G **27** (2001) 311.

[14] G. Appelquist *et al.* [NA52 (NEWMASS) Collaboration], Phys. Rev. Lett. **76** (1996) 3907.

[15] R. Arsenescu *et al.* [NA52 Collaboration], New J. Phys. **4** (2002) 96.

[16] V. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **76** (2007) 011901 [arXiv:nucl-ex/0511047].

[17] M. A. Lisa, S. Pratt, R. Soltz and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. **55** (2005) 357 [arXiv:nucl-ex/0505014].

[18] V. I. Kolesnikov [NA49 Collaboration], arXiv:0710.5118 [nucl-ex].