PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 60, No. 5
May 2003
pp. 1005–1009

Observing *B*-violation in relativistic heavy-ion collisions

RAJARSHI RAY
Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, India

Abstract. Under certain situations, partons formed in heavy-ion collision experiments may expand out forming a shell-like structure. The partons in the outer shell subsequently hadronize, leaving a bubble of pure deconfined vacuum for a first-order quark–hadron phase transition. The bubble collapses and may eventually decay into particles which may thermalize to temperatures exceeding the electroweak transition temperature ($\sim$100 GeV) at LHC. This will lead to the possibility of unsuppressed electroweak baryon number violating processes.

Keywords. Baryon number violation; deconfinement; heavy-ion collision.

PACS Nos 25.75.-q; 12.38.Mh; 98.80.Cq

1. Introduction

In this talk we try to argue that under certain situations, partons formed in relativistic heavy-ion experiments may expand out forming a shell-like structure, leaving a supercooled ($T = 0$) deconfined vacuum bubble inside. As the partons in the outer shell hadronize, the bubble inside collapses down relativistically, with highly Lorentz contracted walls, concentrating the entire energy into extremely small regions. Eventually the bubble walls collide and may decay to a thermal ensemble of particles, leading to temperatures of the order of several GeV for RHIC energies, and may even exceed the electroweak transition temperature ($\sim$100 GeV) for LHC. This gives rise to the possibility of observing sphaleron transitions and resulting baryon number violation in heavy-ion collisions at LHC. At RHIC, such high temperatures will lead to clear signals like very large P_{T} partons, dileptons, and enhanced production of heavy quarks. Due to the concentration of large energy at these hot spots, possibility of Higgs and top quark production may also arise.

2. The physical picture

According to the conventional picture in a relativistic heavy-ion collision experiment, a system of dense partons is formed in between the two receding nuclei at some initial time τ_{i}. The transverse radius of the region equals the nuclear radius R_A. This parton system then expands and cools. The region outside the initial parton system being in the confining phase, there must be an interface separating the two regions (figure 1a). Initial expansion will be longitudinal for proper times $\tau < R_A$, and will become three-dimensional expansion

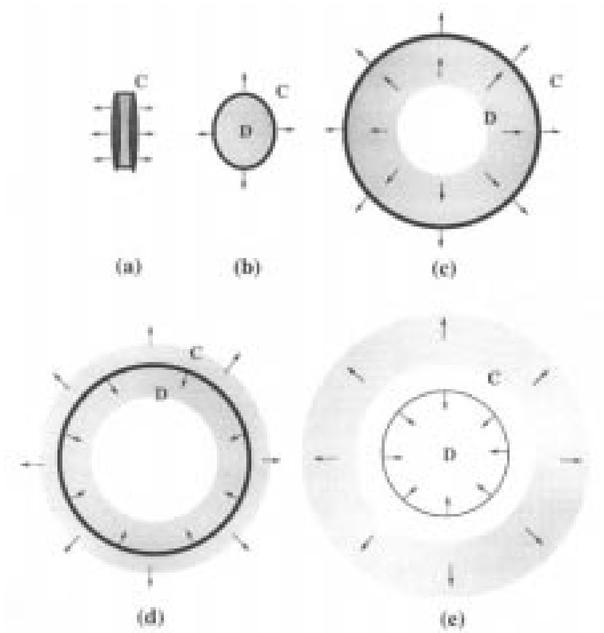

Figure 1. Cartoon of possible formation and evolution of fireball (see text for details).

for larger times. It is expected that energy density (or the temperature) still remains sufficiently high so that by the time expansion becomes three-dimensional, the parton system remains in the deconfining phase (figure 1b).

It is possible that due to the rapid three-dimensional expansion the parton system readily falls out of thermal equilibrium and move out as freely streaming relativistic particles. A shell-like distribution of partons will arise in such a situation [1]. This happens because, all partons having velocity $\simeq c$, will pile up in a shell of radius $\simeq c \times t$, with the thickness of the shell being of the order of the size of the initial region when the three-dimensional expansion began, i.e., about $2 \times R_A$ (figure 1c).

The deconfining vacuum region ($r < ct - 2R_A$) can turn into the confining vacuum via nucleation and subsequent coalescence of confining vacuum bubbles. But since we assume freeze-out preceeds hadronization, thermal bubble nucleation is not possible. Again, the probability of nucleation of a quantum bubble at $T = 0$ is proportional to e^{-S_0}, where S_0 is the bubble action. We find $S_0 = 100$ in natural units, and hence quantum bubble nucleation is also negligible. Eventually, due to expansion the partonic shell hadronizes as its energy density falls below a critical value. The interface now starts to shrink as the partons convert into hadrons (figure 1d).

Shrinking through the shell the interface will continue to move inward due to negative pressure of the metastable vacuum. Now we have a spherical bubble of pure false vacuum whose walls are collapsing down ultra-relativistically (figure 1e).

3. Estimates and results

We take the total energy $E_{\rm tot}$ of the initially produced partonic blob to be $E_{\rm tot} = \varepsilon_{\rm i}\pi R_A^2 \Delta z_{\rm i}$, where $\varepsilon_{\rm i}$ is the initial energy density expected in the collision and $\Delta z_{\rm i}$ is the initial thickness of the central region. In view of various uncertainties in the estimates of $\varepsilon_{\rm i}$, $\tau_{\rm i}$, $\Delta z_{\rm i}$ etc., we examined a range of values of $\Delta z_{\rm i}$. We will take $\Delta z_{\rm i} = 0.15$ fm for LHC, and equal to 0.22 fm for RHIC, and an optimistic value $\Delta z_{\rm i} = 1$ fm for both LHC and RHIC.

To make estimate of the bubble parameters, i.e., vacuum energy density ρ and surface tension σ, we first need to define an order parameter characterising the deconfinement and confinement phases along the interface separating them. It is perfectly sensible to believe that QCD admits a metastable vacuum even at zero temperature. The entire physics of Bag model is within this type of framework. The region inside the Bag is in the deconfining vacuum which is metastable with higher potential energy (the Bag constant). The region outside the Bag is in the confining vacuum with zero potential energy, with a wall separating the two regions. The physics of Bag model can be captured by postulating a color dielectric field χ with the following form of the effective potential [2,3]

$$V(\chi) = \frac{m_{\rm gb}^2}{2}\chi^2\left[1 - 2\left(1-\frac{2}{\alpha}\right)\frac{\chi}{\sigma_v} + \left(1-\frac{3}{\alpha}\right)\frac{\chi^2}{\sigma_v^2}\right] \tag{1}$$

with corresponding Lagrangian density being $L = \frac{1}{2}(\partial_\mu\chi)^2 - V(\chi)$. Here, $\sigma_v = \sqrt{2\alpha B/m_{\rm gb}^2}$ where $m_{\rm gb}$ is the glue ball mass, B is the Bag constant. Thus, $\chi = 0$ in the outside confining region, and non-zero inside the deconfining Bag. This feature is consistent with the picture of a first order deconfinement–confinement phase transition at finite temperature usually described by a finite temperature effective potential given as a function of the expectation value of the Polyakov line $\langle L\rangle$ [4]. Thus, we assume that the color dielectric field χ captures the physics of $\langle L\rangle$ at $T = 0$. Using the above potential, we first obtain the profile of the *true vacuum* bubble by solving for the instanton solution for the tunneling through the barrier from $\chi \neq 0$ metastable vacuum to the $\chi = 0$ true vacuum. (The action for this bubble is about 100 in natural units.) But we have a large bubble of deconfining vacuum which is embedded in the confining vacuum (figure 1e). We obtain its profile (approximately) by inverting the profile of the true vacuum bubble. For this profile the total energy E is obtained by numerically integrating $\frac{1}{2}(\bigtriangledown\chi)^2 + V(\chi)$ for two different bubble radii, and put in the following equation to solve for σ and ρ.

$$E = 4\pi r^2\sigma + \frac{4\pi}{3}r^3\rho. \tag{2}$$

For the parameter set of ref. [2], we find $\sigma = 64.8$ MeV/fm^3 and $\rho = 27.8$ MeV/fm^3 ($\simeq (122\ \text{MeV})^4$). So now, given the initial total energy $E_{\rm tot}$ and assuming energy conserving expansion, one can add up the volume, surface and shell energies when the shell has attained a critical energy density $\varepsilon_{\rm c}$ to get

$$\frac{4\pi}{3}r^3\rho + 4\pi r^2\sigma + \frac{4\pi}{3}(r^3 - (r-\Delta r)^3)\varepsilon_{\rm c} = E_{\rm tot}. \tag{3}$$

Solving for r, we approximate the initial size of the false vacuum bubble by $r_{\rm f} \simeq r - R_A$. Then the total energy of the bubble is $E_{\rm f} = 4\pi r_{\rm f}^2\sigma + (4\pi/3)r_{\rm f}^3\rho$. All this energy is deposited

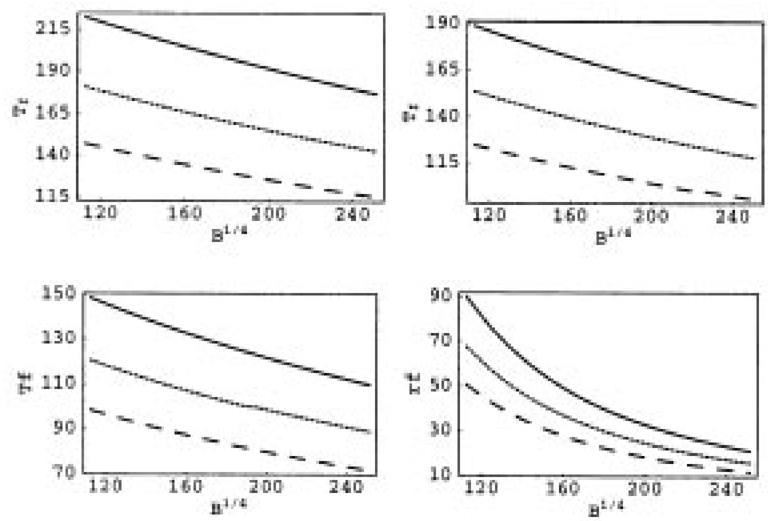

Figure 2. Final temperature (T_f) of the tiny hot spot formed due to collapse of a deconfined empty blob of radius r_f for different parameter values (see text).

by the shrinking bubble in a very tiny region, when quantum effects take over. The total energy of a plasma thus produced should equal E_f.

$$\frac{g_* \pi^2}{30} T_f^4 \frac{4\pi}{3} r'^3 + 4\pi r'^2 \sigma' + \frac{4\pi}{3} r'^3 \rho' \; = \; E_f, \tag{4}$$

where r' and T_f are the plasma size and temperatures respectively, with appropriate ρ' and σ' for given plasma constituents. For consistency of thermodynamic equilibrium, we choose the size of the region r' to be of the order of T_f^{-1}. We solve for T_f over a range of values of ρ and σ. Even for quite a large variation of σ, changes are negligible. We show results for varying ρ and for $A = 50, 100$ and 200 with $\triangle z_i = 1$ in figure 2. The top two figures are with $\sqrt{s} = 30$ TeV and 15 TeV respectively, and the bottom figures are for $\sqrt{s} = 5.5$ TeV (LHC c.m. energy). We find that even at the lowest $\sqrt{s} = 5.5$ TeV, and for $A = 50$ it may be possible to attain temperatures around 100 GeV. We repeated this estimation for $\triangle z_i = 0.15$ and found that only for higher $\sqrt{s}$ and A, such high temperatures can be attained. For RHIC $\sqrt{s} = 130$ GeV, maximum temperatures that can be obtained is about 30 GeV for $\triangle z_i = 1$, while it ranges about a couple of GeV for $\triangle z_i = 0.15$.

4. Conclusion

It will certainly be remarkable if baryon violation could be observed in relativistic heavy-ion collisions. As we discussed, given certain conditions, this might turn out to be a possibility in the upcoming LHC experiments. Among other signals for the creation of hot spots described here, are increased production of heavy quarks (e.g. top quark), anomalous production of very large P_T partons, dileptons, and photons. These are important because if the bubble collapse does not proceed to sizes much smaller than 1 fm due to possible fluctuations etc., these other signals can be used for detecting such a hot spot.

Acknowlegement

This talk is based on the work reported in *Nucl. Phys.* **A712**, 329 (2002).

References

[1] C Greiner and D H Rischke, *Phys. Rev.* **C54**, 1360 (1996)
A Abada and J Aichelin, *Phys. Rev. Lett.* **74**, 3130 (1995)
[2] S C Phatak, *Phys. Rev.* **C58**, 2383 (1998)
[3] H B Nielsen and A Patkos, *Nucl. Phys.* **B195**, 137 (1982)
[4] L D McLerran and B Svetitsky, *Phys. Rev.* **D24**, 1981 (1981)