Exploratory studies: searching for strong CP violation in heavy ion collisions

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The strong $\mathcal{CP}$ problem remains one of the most outstanding puzzles of the Standard Model. Even though several possible solutions have been put forward (for example, the axion scenario), at present it is still not clear why $\mathcal{P}$ and $\mathcal{CP}$ invariances are respected by strong interactions in spite of the possible presence of $\mathcal{CP}$–odd "θ–term" in the QCD lagrangian[1]. Moreover, it was proposed that in the vicinity of the deconfinement phase transition QCD vacuum can contain metastable domains possessing non-trivial topological Chern–Simons number and inducing $\mathcal{P}$ and $\mathcal{CP}$ violation [2]. It was also suggested that this phenomenon would manifest itself in specific correlations of pion momenta [2, 3]. Such "$\mathcal{P}$–odd bubbles" are a particular realization of an excited vacuum domain which may be produced in heavy ion collisions [4]. Several dynamical scenarios for the decay of $\mathcal{P}$–odd bubbles have been considered [5], and numerical lattice calculations of the fluctuations of Chern–Simons number in classical Yang–Mills fields have been performed [6, 7].

The studies of $\mathcal{P}$– and $\mathcal{CP}$–odd correlations of pion momenta [8, 9], including those proposed in ref[10], have shown that such measurements are feasible with large event samples. This also applies to the interesting idea [11] of using Λ–hyperon spin correlations. Recently, it has been proposed that $\mathcal{P}$– and $\mathcal{CP}$–breaking in a domain of a highly excited vacuum state can manifest itself in heavy ion collisions through the charge asymmetry of the produced hadrons with respect to the reaction plane [12]. In other words, a $\mathcal{CP}$–odd domain would induce an electric dipole moment (e.d.m.) of the quark–gluon plasma, much like a non–zero θ–term induces an e.d.m. of the neutron (it should be noted that the most stringent limits on $\mathcal{CP}$–odd effects in "cold" QCD vacuum result from the neutron e.d.m. measurements). The estimated magnitude of the expected charge asymmetry ($\sim 1\%$) makes the effect amenable to observation in the existing and/or future heavy ion experiments. A method of measuring the charge asymmetry based on the "mixed harmonics" technique has been proposed [13]. Very recently, the STAR Collaboration performed a preliminary analysis of the charge asymmetry in $Au-Au$ collisions at $\sqrt{s}/A = 62$ GeV [14]. The results look promising, even though the systematic uncertainties have still to be carefully analyzed. All of the experimental studies described above would benefit from the large event samples available at RHIC-II.

The problem of $\mathcal{CP}$ invariance in strong interactions is of fundamental importance. It has far–reaching implications for the cosmology of the Early Universe (for example, $\mathcal{CP}$–odd effects at the deconfinement phase transition could help to understand the origin of the strong magnetic fields in space [2]). The breaking of $\mathcal{CP}$ at the QCD phase transition and the associated generation of Chern-Simons number is analogous to the generation of baryon number at the electro–weak phase transition. It is clear that the experimental studies of $\mathcal{CP}$ violation at RHIC are important and would enrich our understanding of bulk non–equilibrium dynamics in QCD and related gauge theories.

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[1] At zero temperature and density, a theorem by Vafa and Witten [1] states that $\mathcal{P}$ and $\mathcal{CP}$ cannot be broken in the true ground state of QCD. However, this theorem does not apply to QCD matter at finite temperature and density.

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