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Angular Momentum and Magnetic Field in Relativistic Heavy-ion Collisions

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ABSTRACT

Recent relativistic heavy-ion collision experiments have found evidences for the generation of strong magnetic field and global angular momentum. This brief article aims to highlight the physics aspects of these observations.

INTRODUCTION

It is now well established that quantum chromodynamics (QCD) is the theory of strong interactions. Heavy-ion collisions at relativistic energies create strongly interacting QCD matter at extreme conditions which provides the opportunity to study the thermodynamic and transport properties of various exotic phases of QCD. It was predicted that non-central collisions produce an extremely strong magnetic field ($\sim 10^{18} - 10^{19}$ Gauss) [1] and large global angular momenta ($\sim 10^4 - 10^5\ \hbar$) [2]. In this article, various theoretical aspects of these features and their observable consequences will be outlined.

MAGNETIC FIELD AND ANGULAR MOMENTUM

In Fig. 1, the mechanism due to which magnetic field is produced in non-central relativistic heavy-ion collisions

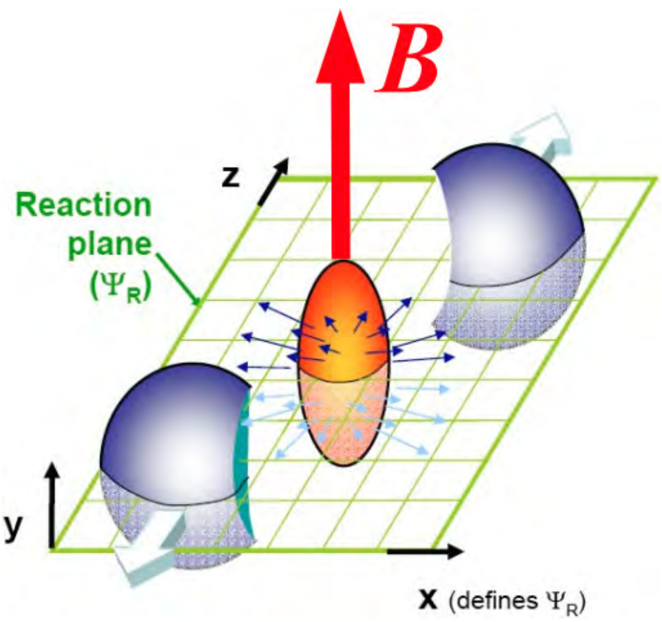

Fig.1: Generation of magnetic field in non-central relativistic heavy ion collisions [3].

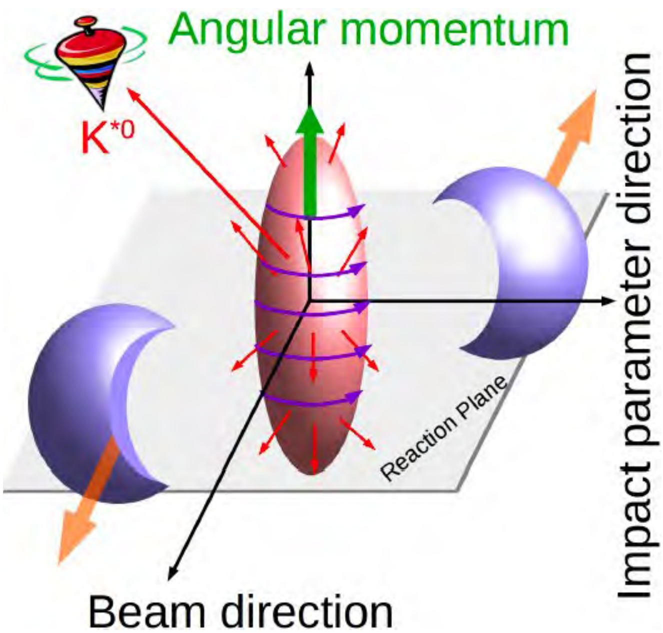

Fig. 2: Global angular momentum generation in non-central relativistic heavy ion collisions [4].

is depicted. The magnetic field is produced due to the fast moving charged nuclei before collisions and spectators (shown in purple) after collision. On the other hand, global angular momentum is generated due to non-central collisions of inhomogeneous nuclei as shown in Fig. 2. While the duration of the magnetic field is very short (typically 1 fm/c) due to fast receding spectators, angular momentum remains for a longer time in the central region owing to the conservation law.

Figure 3 shows the time evolution of magnetic field created by a point unit charge in units of squared pion mass [1]. The solid line corresponds to results obtained using finite conductivity of the medium and the dashed-dotted line corresponds to evolution in free space. One can see that the magnetic field in both cases drops very fast with time. However, for finite conductivity, this drop is relatively slow, which encourages theorists to apply relativistic magnetohydrodynamics in order to study the collective behavior of the QCD matter [5].

Figure 4 shows global angular momentum (in units of $\hbar$) of the interaction region as a function of the impact parameter for Au–Au collisions at a center-of-mass energy of 200 GeV per nucleon. The two curves correspond to nuclear density taken as a hard sphere (solid line) and from the Woods-Saxon potential (dashed line). It is interesting to note that the global angular momentum remaining in the system attains a maximum at a particular value of the impact parameter. This can be attributed to the fact that for central collisions, if the two nuclei collide head on no angular momentum is imparted to the system. On the other hand, for very peripheral collisions, the overlap region between the nuclei decreases leading to a decrease in the "moment of inertia" of the produced medium which eventually results in smaller global angular momentum.

The angular momentum left in the overlap region remains for a longer time due to the conservation of total angular momentum. This has motivated theorists to formulate relativistic fluid dynamics with explicit angular momentum conservation [6]. These new formulations have also been applied in numerical modeling of the evolution; see Ref. [7] for a recent review.

EXPERIMENTAL SIGNATURES

The experimental observable which was suggested as the most effective probe of strong magnetic field was the charge separation in relativistic heavy ion collisions leading to signatures of CP violation [8]. It was proposed that magnetic field through the axial anomaly will induce a parallel electric field which will eventually lead to separation of different charges. Shortly after that, measurement of charge separation with respect to the reaction plane was proposed [9] and eventually measured by the STAR collaboration [10]. This so-called "chiral magnetic effect" is considered as one of the important observations in relativistic heavy-ion physics.

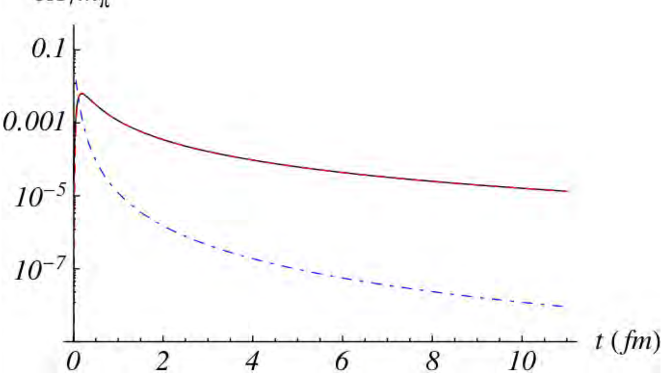

Fig.3: Time evolution of magnetic field created by a point unit charge with (solid line) and without (dashed-dotted line) conductivity [1].

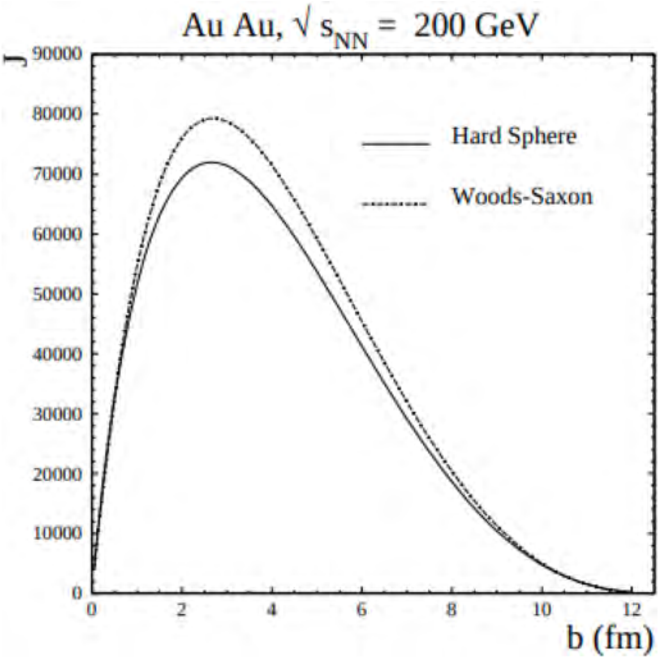

Fig.4: Angular momentum (in units of $\hbar$) of the interaction region as a function of the impact parameter for Au-Au collisions at center-of-mass energy of 200 GeV per nucleon [2].

For experimental signatures of the global angular momentum, polarization observables were proposed [2]. It was suggested that the global angular momentum will lead to creation of non-vanishing vorticity in the system and a distinctive signature of the vortices is the generation of an average polarization of the emitted hadrons. Once again STAR collaboration measured the global Λ hyperon polarization, which led to the evidence for discovery of "most vortical fluid" [11]. This measurement by the STAR collaboration was performed on the Λ hyperon which is a spin-1/2 particle. Recently, ALICE collaboration has also observed the effect of global angular momentum on polarization of vector mesons, K^{*0} and ϕ, which are spin-1 particles [12].

OUTLOOK

The physics of strong magnetic field and global angular momentum in relativistic heavy-ion collisions has attracted much attention from both theoretical and experimental communities. Several observables were proposed from theoretical calculations, which were also followed up by experimental measurements leading to the discovery of very interesting phenomena. While the qualitative features have been established, the quantitative agreement of theory with experiment still requires much effort on both the theoretical and experimental side. For instance, the numerical simulation of evolution of the QCD medium is based on either magnetohydrodynamics or so-called "spin-hydrodynamics" for calculation of observables pertaining to magnetic field or global angular momentum, respectively. However, these two effects are not entirely separatable and therefore a unified framework of "spin-magnetohydrodynamics" needs to be developed for precise calculation of experimental observables. On the experimental side, error bars on measurements also need to be reduced in order to separately quantify the effects from global angular momentum and magnetic field. This is indeed a fast developing area of research with exciting physics opportunities for both theoretical and experimental physicists.

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