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To cite this article: D. E. Kharzeev & J. Liao (2019) Isobar Collisions at RHIC to Test Local Parity Violation in Strong Interactions, Nuclear Physics News, 29:1, 26-31, DOI: [10.1080/10619127.2018.1495479](https://doi.org/10.1080/10619127.2018.1495479)

To link to this article: <https://doi.org/10.1080/10619127.2018.1495479>



Published online: 29 Mar 2019.



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Isobar Collisions at RHIC to Test Local Parity Violation in Strong Interactions

D. E. KHARZEEV^{1,2} AND J. LIAO³

¹*Department of Physics and Astronomy, Stony Brook University, NY, USA*

²*Department of Physics and RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY, USA*

³*Physics Department and Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN, USA*

Introduction

The discovery of the Higgs boson has completed the Standard Model of fundamental interactions. The Standard Model describes the strong and electroweak interactions by generalizing the concept of local gauge invariance that underlies the Maxwell theory of electromagnetism to non-Abelian gauge groups. A non-Abelian group has the elements that do not commute, such as the group of rotations in three dimensions, where a rotation around axis x followed by a rotation around axis y yields a different result from doing these rotations the other way around. The resulting theory is both elegant and powerful—it is believed to describe all known properties of the physical world, except gravity. In spite of their deceptively simple structure, non-Abelian gauge theories possess many surprising features that are still not understood.

A prime example of this puzzling behavior is provided by the theory of strong interactions: quantum chromodynamics (QCD). The fundamental building blocks of QCD—the quarks—have masses that within the Standard Model are determined by their couplings to the vacuum condensate of Higgs bosons. The lightest of the quark family—up (u) and down (d) quarks—have very small masses of a few MeV. For reasons that remain mysterious to this day, quarks do not appear in the physical spectrum. Instead, they are permanently bound inside hadrons. The protons and neutrons that compose the atomic nuclei are naively depicted as bound states of three light quarks. Nevertheless, the proton and neutron masses appear about a hundred times larger than the total mass of their constituents! The numerical simulations of QCD on the lattice faithfully reproduce the hadron spectrum, and show that the theory is correct. Nevertheless, the confinement of quarks and the origin of hadron masses in QCD remain at the top of the list of puzzles of modern physics; they also constitute one of the seven Millennium problems selected by the Clay Mathematics Institute.

There are good reasons to believe that the key to the puzzles of QCD is *chirality*—the property that distinguishes a quark from its mirror image. The (nearly) massless quark possesses chirality because its spin is either parallel or antiparallel to its momentum. Picturing the spin as rotation, we can thus imagine the quark propagating through space as either a right-handed or left-handed screw and call it right or left handed. Because the massless quarks propagate with the speed of light, the sign of the spin projection on momentum is the same in all reference frames—so the quark’s chirality is well defined. Moreover, the perturbative interactions of quarks with gluons (the gauge bosons of QCD, analogous to photons in Maxwell electrodynamics) are also not allowed to transform left-handed quarks into right handed and vice versa. The left-handed and right-handed quarks should thus behave as if they lived on two different sides of the mirror, without ever transforming into each other—QCD is thus expected to possess the *chiral symmetry*.

Surprisingly, the chiral symmetry appears completely absent in the spectrum of hadrons—the eigenstates of the QCD Hamiltonian. Moreover, the very existence of massive bound states of massless quarks implies that left- and right-handed quarks can transform into each other—a confined quark should change the direction of its momentum upon reflection from a confining potential that does not flip its spin. Understanding the fate of the chiral symmetry in QCD may thus be the key to solving the problem of confinement. The link between confinement and the breaking of chiral symmetry also suggests that in the deconfined quark-gluon phase of QCD, the chiral symmetry should be restored—and lattice QCD confirms this expectation.

Chirality is also at the root of another puzzle in QCD—the so-called “strong CP problem.” The structure of QCD naturally allows for a violation of parity in strong interactions through a so-called “ θ -term,” with a non-zero “ θ -angle” inducing parity-odd effects. Yet experimentally P

and CP violations in strong interactions never have been observed. The ongoing experiments attempt to discover CP violation in strong interactions by increasing the precision in the measurement of the electric dipole moment of the neutron (that would violate CP invariance); however, so far they have been only providing an increasingly tight bound on it. It has been proposed that the strong CP problem can be solved by promoting the θ -angle to a dynamical field, and letting the expectation value of this field relax to zero in the ground state [1]. This would bring to life a new light parity-odd elementary particle—the axion [2, 3]. The axions are considered as likely candidates for Dark Matter in the Universe.

The dynamics of axions, as well as the chirality-violating interactions of quarks and the breaking of chiral symmetry, are governed by the effects that stem from the complicated vacuum structure of QCD as a non-Abelian gauge theory. The compact nature of non-Abelian groups opens the possibility to construct the ground state in these theories as a superposition of topological sectors that are degenerate in energy but possess different winding numbers. The transitions between these vacuum sectors change the chirality of the system, and, through the quantum *chiral anomaly* [4, 5], can change the chirality of quarks that is naively forbidden for massless fermions.

If this sounds too formal, imagine an ant on the left side of a vertically positioned paper strip. Let us call this ant left handed, and let us assume that the ant is forbidden to cross the edge of the strip, which would make it right handed. Let us now introduce a non-trivial topology of the ground state by twisting the strip and gluing its ends to form the Möbius strip. A famous illustration of this configuration by M. C. Escher can be seen at <http://www.mcescher.com/gallery/recognition-success/mobius-strip-ii/>. The ant can now easily move from the left side of the strip to the right one without disobeying the ban on crossing the edge. Similar chirality violation processes are believed to exist in the vacuum of QCD; they may be responsible for the breaking of chiral symmetry and the formation of hadron masses. In the electroweak sector of the Standard Model, such vacuum transitions induce the violation of the baryon number. Shortly after the Big Bang, these transitions produced the baryon asymmetry of the Universe. It is thus likely that we owe our existence to the vacuum structure of non-Abelian gauge theories.

While the chirality violation induced by the vacuum transitions is central to the present theoretical understanding of non-Abelian gauge theories, and thus to our picture of the Universe, such transitions have never been directly detected in an experiment. The change of chirality (say,

from left to right handed) induces a *local parity violation*; this is analogous to the effect that would be induced by a fluctuating axion field. Is there a way to detect this local parity violation in an experiment?

Recently it has been proposed [6] that the transitions between different vacuum sectors creating a local violation of parity can be observed in heavy ion collisions through the measurement of azimuthal distributions of the produced charged hadrons. This is because the chirality-changing transitions in a magnetic field induce an electric current—a so-called “chiral magnetic effect” [7] (see Refs. [8, 9] for reviews). The chiral magnetic effect requires the presence of both a topologically nontrivial configuration of the gauge field (such as the one responsible for the chirality-changing vacuum transitions), and of charged chiral fermions (such as the quarks in a chirally symmetric quark-gluon plasma).

Colliding heavy ions create a fireball of hot quark-gluon matter penetrated by magnetic field, of strength proportional to the electric charge of the ion. The chiral magnetic effect would manifest itself through the fluctuations in the electric charge asymmetry of the produced hadrons relative to the reaction plane of the heavy ion collision. This would amount to the fluctuations of the electric dipole moment of the produced fireball on the event-by-event level [6]. The experimental observable needed to detect this effect has been proposed in Ref. [10]. These electric charge fluctuations arise from the fluctuations in chirality, or the local violation of parity, in the background of the magnetic field. The propagation of the chiral magnetic current is enabled by the *chiral symmetry restoration* predicted by lattice QCD to occur in the deconfined quark-gluon matter.

The chiral magnetic effect appears to have implications beyond the nuclear and particle physics. The recent discovery of three-dimensional chiral materials (Dirac and Weyl semimetals) makes it possible to study this effect in well-controlled tabletop experiments. The study of electric conductivity of a Dirac semimetal ZrTe_5 in parallel electric and magnetic fields (a parity-breaking, topologically non-trivial configuration of the Abelian gauge field) led to the discovery of the chiral magnetic effect [11, 12]. This makes the chiral magnetic effect an appropriate and calibrated tool for detecting the local parity violation in QCD.

The detection of local parity violation requires a dedicated, high statistics study of charged hadron production in the collisions of relativistic heavy ions. Fortunately, at present in the world there are two operating accelerators that collide relativistic heavy ions—the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and at the Large Hadron Collider (LHC) at CERN. This makes it possible to search for the local parity violation through the

study of azimuthal asymmetry in the distributions of the produced charged hadrons.

The predicted fluctuations in the hadron electric charge asymmetry have been observed both at RHIC by the STAR Collaboration [13] and the LHC by the ALICE Collaboration. However, such fluctuations may also arise from backgrounds driven by the geometry of the colliding ions. Moreover, a recent measurement of the charge fluctuations in pA collisions [14] indicates a large contribution of background to the fluctuations in charge asymmetry. In pA collisions the correlation between the direction of magnetic field and the orientation of reaction plane is weaker than in AA collisions but is still sizeable [15]. A decisive discovery of the local parity violation thus requires a clear separation of the signal from the backgrounds. This separation requires varying the magnetic field without changing the geometry of the collision—the chiral magnetic current, and thus the electric charge asymmetry, would then change proportionally to a magnetic field, but the backgrounds would stay fixed. Such an experiment is possible in the collisions of different isobars—the nuclei with identical mass number (and size), but different electric charges. Because the magnetic field produced in the collision is proportional to the electric charge of the nucleus, isobar collisions allow varying of the magnetic field without changing the geometry of the produced fireball [15, 16].

A strong dedicated effort by STAR Collaboration at RHIC and accelerator scientists at BNL, with crucially important contributions by the researchers from Oak Ridge National Laboratory and RIKEN Institute in Japan, has made the isobar collision experiment a reality. The isobar run at RHIC will take place very soon, in the spring of 2018, and will use the zirconium Zr and ruthenium Ru isobars. These isobars have identical mass number $A = 96$ (and thus are very close in size) but different electric charge: $Z = 40$ for Zr and $Z = 44$ for Ru. Because of this, the backgrounds in ZrZr and RuRu collisions should be nearly identical, but the magnitude of the chiral magnetic effect driven by the magnetic field should significantly differ.

The calculations indicate [15, 16] that the ongoing 2018 dedicated isobar run can establish (or put a stringent limit on) the presence of the chiral magnetic effect in QCD at the level of five standard deviations. The conclusive observation of the chiral magnetic effect would directly establish, for the first time, the existence of chirality-violating transitions that stem from the vacuum structure of QCD, and the existence of a chirally symmetric phase of quark-gluon matter at high energy density. We now proceed to describing the pertinent experiment, and the underlying theory, in more detail.

Chiral Magnetic Effect in Heavy Ion Collisions

In a heavy ion collision, the two incident nuclei carry large positive charge (e.g., $Z = 79$ for Au nucleus) and move at nearly the speed of light. As a result, there exists a very strong magnetic field co-moving with the initial ions, with its extreme strength arising from the large Z value as well as an immense Lorentz boost factor (e.g., ~ 100 at RHIC top energy). If the collision is non-central (as is typically the case), the centers of the two nuclei are displaced from each other by the impact parameter b in the transverse plane that is perpendicular to the beam axis: see the illustration in panel (a) of Figure 1. Upon the collision impact, the magnetic fields of the colliding ions add coherently in the overlap zone. The peak value of the magnetic field is as large as a few times the pion mass squared, $eB \sim m_\pi^2$ [17]. In more conventional units, this value corresponds to about 10^{17} Gauss and exceeds the magnetic field on the surface of magnetars by about a hundred times—quite possibly this is the strongest magnetic field that can be created in the present day universe.

Furthermore, the temperature of the quark-gluon matter produced in the collision is expected to be sufficient for the restoration of chiral symmetry to take place—therefore the light (up and down) quarks behave as massless chiral fermions. The topological transitions (such as the “instantons” or “sphalerons”) creating an excess of left-handed and right-handed fermions is in general imbalanced in each event. As a result, heavy ion collisions produce a chirally imbalanced, locally P- and CP-odd, system of chiral fermions in a strong magnetic field, in which the Chiral Magnetic Effect (CME) should occur [6].

As illustrated in panel (a) of Figure 1, the CME-induced electric current, along the magnetic field direction, will transport positive charges toward one side of the reaction plane while negative charges toward the other side, thus leading to a charge separation signal across the reaction plane.

In heavy ion experiments the CME-induced charge separation signal can be measured via the azimuthal correlations between pairs of charged hadrons. Consider the illustration in panel (a) of Figure 1: a same-charge pair of hadrons (particles 1 and 2) will be preferably emitted into the near-side directions with respect to the reaction plane, thus contributing negatively to the correlation $\langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle$; an opposite-charge pair of hadrons (particles 1 and 2') will be preferably emitted into the back-to-back directions with respect to the reaction plane, thus contributing positively to the correlation $\langle \cos(\phi_1 + \phi_{2'} - 2\Psi_{RP}) \rangle$. The first measurement of such azimuthal charge-dependent correlations of hadrons was reported by the STAR collaboration in 2009 [13], and is

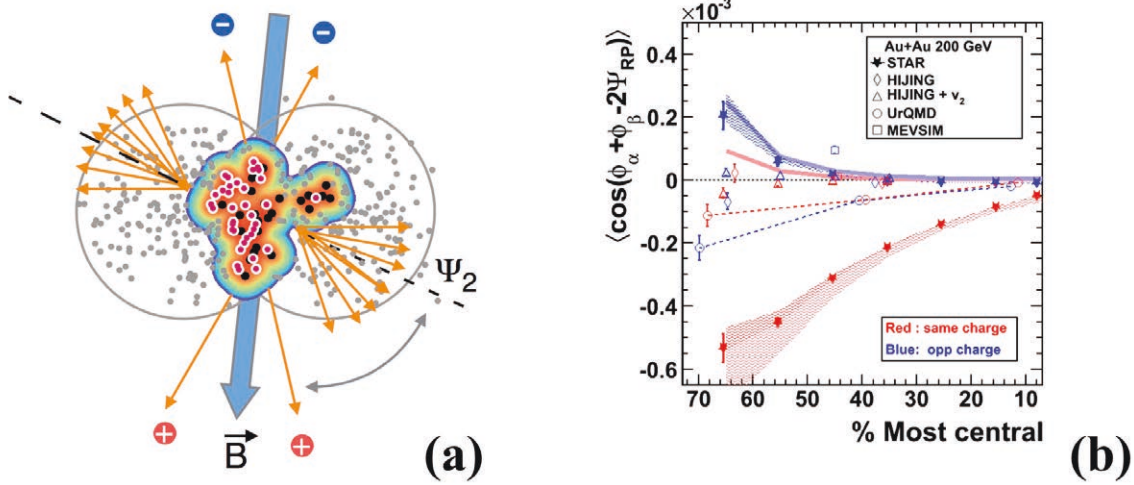


Figure 1. (a) An illustration of the Chiral Magnetic Effect (CME) in a non-central heavy ion collision event. (Image credit: BNL and P. Tribedy.) The CME-induced current flows along the magnetic field direction and transports the positive and negative charges in opposite directions, thus leading to a charge separation with respect to the reaction plane. This charge separation can be measured through the azimuthal correlation of charged hadron pairs. (b) The azimuthal correlation between same-charge and opposite-charge hadron pairs measured by the STAR collaboration. The same-charge pair correlator is negative while the opposite-charge pair correlator is positive, as expected from CME. The centrality dependence is also in line with CME expectation since the magnetic field produced by the ions vanishes in central collisions. The observed charge asymmetry cannot be fully explained by conventional collision event simulations without the CME. Panel (b) is adapted from Ref. [13].

shown in panel (b) of Figure 1. A strong charge asymmetry is indeed observed in this correlation, which is negative for same-charge pairs while positive for opposite-charge pairs, as expected from CME. The splitting between these correlators increases significantly from central to peripheral collisions, as also expected from CME due to the centrality dependence of the magnetic field. A series of subsequent measurements were carried out across a wide beam energy span by STAR, PHENIX, ALICE, and CMS collaborations at RHIC and the LHC. Furthermore, a signature of a CME-induced collective excitation called the Chiral Magnetic Wave [18] was also observed later by the STAR Collaboration [19]. Over the past several years, the evidence for the CME, in particular at RHIC energies, has been accumulating. At the same time, the backgrounds to the effect have also been identified. The physicists in the heavy ion community have thus appropriately exercised a great caution, working hard on analyzing the possible backgrounds prior to claiming this potentially important discovery.

The most pressing challenge for this search is the contamination from backgrounds resulting from a combination of mundane effects. Indeed, the charge asymmetry correlation measurement, while sensitive to the existence of the CME signal, is at the same time significantly affected

by certain correlation effects that have nothing to do with CME. For example, the late stage of a heavy ion collision is dominated by scatterings among produced hadrons and hadronic decays, which could result in nontrivial correlations among charged particles. Consider, for example, a neutral ρ meson decaying into two charged pions. The “daughter” pions, one being positively charged while the other being negatively charged, both have their momentum direction preferably aligned with the “parent” ρ meson’s original momentum. The produced pair of pions thus acquire a correlation between the azimuthal directions of their momenta. In addition, the strength of this correlation would differ for the pions emitted along the in-plane direction and those emitted along the out-of-plane direction, simply because there are more parent ρ mesons moving in-plane. Such a difference is controlled by an anisotropy coefficient of the bulk particle production called elliptic flow v_2 and it is precisely this difference that would be picked up by the charge asymmetry correlation measurement designed to measure the CME signal. To make it worse, the dependence of v_2 on the collision centrality turns out to be very similar to that of magnetic field that drives the CME. As a result, it is extremely difficult to reliably separate such background correlations from the sought-after CME.

Isobar Collisions at RHIC

Over the past several years, a few proposals for extracting the true signal were put forward; however, all of them were subject to a number of drawbacks. The theoretical uncertainties and experimental limitations made it very difficult to quantitatively separate the possible signal from the backgrounds. The situation cried out for new approaches. Such a novel idea emerged and matured in the last two years, based on contrasting collisions of the isobaric nuclei. In one sentence, this idea could be summarized as follows:

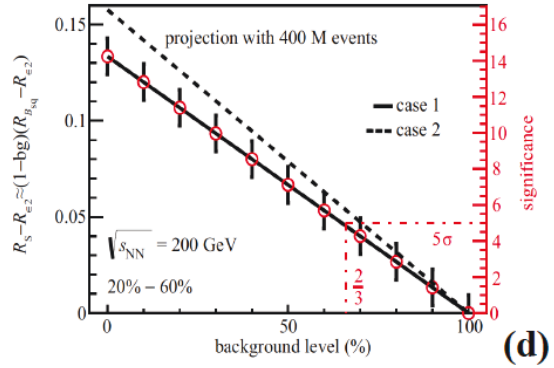
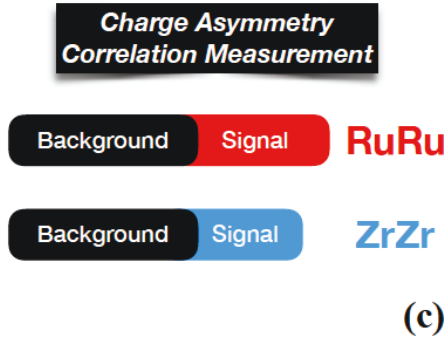
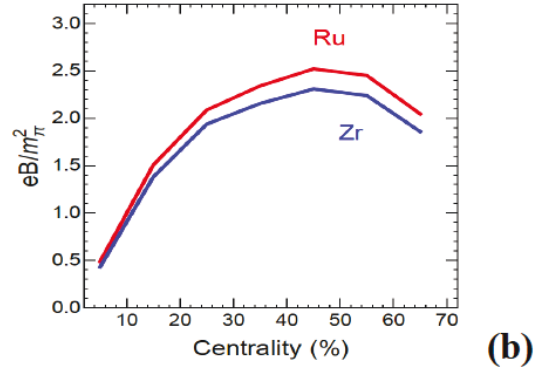
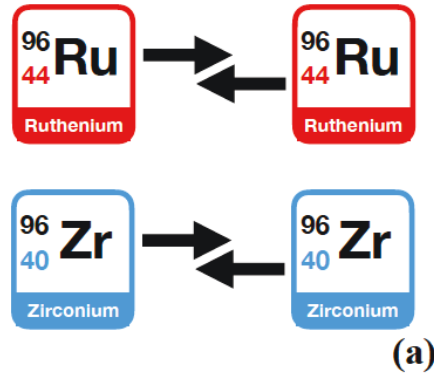


Figure 2. (a) The isobar pairs, RuRu and ZrZr, for the 2018 Run of RHIC collision experiment. While they have the same number of nucleons ($A = 96$), their electric charge ($Z = 44$ for Ruthenium and $Z = 40$ for Zirconium) differ by about 10%. (b) The magnetic field strength from the colliding isobar pairs. Due to the difference in the electric charges of the nuclei, the magnetic field in a RuRu collision is about 10% stronger than that in a ZrZr collision from the mid-central to peripheral collision centrality, as shown from event-by-event simulations. (c) An illustration of the contrast measurement between the isobar pairs. The signal of the CME is measured via the charge asymmetry correlation, which is contaminated by considerable background effects. The precise ratio of signal versus background is currently unknown. The isobar pairs have the same nucleon number and thus the same bulk collision dynamics, resulting in about the same background contributions. The CME signal is driven by the magnetic field, and the correlator scales as the square of its strength; therefore the correlator differs by about 20% between the isobar pairs. Therefore a sizeable CME signal would lead to a measurable difference between the isobar pairs. (d) Projected differentiation capability (vertical axis) of the contrast measurement versus the background level (horizontal axis) in the charge asymmetry correlation. The lower the background level is, the more definitively one could detect the CME signal by contrasting the isobar pairs. With the currently planned number of events to be collected during the RHIC's 2018 Run, one could expect a 5-sigma conclusion if the background may not exceed two thirds of the measured correlation. Panels (b) and (d) are adapted from Refs. [15, 16].

charge: $Z=44$ for Ru and $Z = 40$ for Zr (see panel (a) of Figure 2). One can then perform experiments with RuRu collisions and with ZrZr collisions at the same energy, and look for the difference of desired observables between the two colliding systems. The 10% difference in the electric charge implies about the same 10% difference in the magnetic field produced in RuRu and ZrZr collisions. Indeed, state-of-the-art computations of the magnetic field values based on event-by-event simulations have quantitatively demonstrated this to be the case (see panel (b) of Figure 2). This has profound consequence for the CME signal in the charge asymmetry correlator, which scales as the square of magnetic field strength. Since the two isobars have the same number of nucleons, one expects the produced bulk matter to behave in about the same way. In particular, the bulk expansion and the associated elliptic flow coefficient are expected to be very close. Therefore, for the charge asymmetry correlation measurement made in the RuRu system and that made in the ZrZr system, the background contribution would be identical between the two, while the CME signal contribution should differ by about 20%, as illustrated in panel (c) of Figure 2. Clearly, the measured difference in the correlation measurement between the two systems will depend on the ratio of the signal to background, which is currently poorly constrained. The lower the background level is, the more definitively one could detect the CME signal by contrasting the isobar pairs. By accumulating the collision events, one would gain higher and higher statistics and thus resolving power in spotting even a small shift in the observable. In panel (d) of Figure 2, we show the projected differentiation capability (vertical axis) of the contrast measurement of the charge correlation versus the background level (horizontal axis). One expects that a 5σ observation of the local parity violation will be possible if the background contributes less than two thirds of the measured correlation.

This decisive experiment for the search of CME had just begun in the spring 2018 RHIC run. If a conclusive observation of CME is achieved, it would amount to the experimental discovery of the restoration of chiral symmetry in hot QCD matter and to the first direct experimental observation of the topological fluctuations in QCD. We will be holding our breath awaiting the outcome of this groundbreaking experiment.

Funding

The work of DK was supported in part by the U.S. Department of Energy under contracts DE-FG-88ER40388, DE-SC-0017662, and DE-AC02-98CH10886. The work of JL was supported by the U.S. National Science Foundation under grant number PHY-1352368. This work was also supported by the Beam Energy Scan Theory (BEST) Topical Collaboration.

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D. E. KHARZEEV



J. LIAO