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Recent development and prospect on heavy-ion collisions in colliders

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Abstract. Heavy ion collisions play a key role in advancing our understanding of the universe. These are collisions in which two atomic nuclei collide at high energy, releasing large amounts of energy and creating new elements. One of the fundamental theories of heavy-ion collisions is the quark-gluon plasma (QGP) theory. It suggests that in collisions at sufficiently high energies, the quarks and gluons of the colliding nuclei are no longer confined to individual particles, but form a new state of matter. In some heavy-ion collisions, the QGP may exhibit properties similar to those found in the early universe. In addition, studying heavy ion collisions could help answer some fundamental questions, such as the origin of mass and the nature of dark matter. This article focuses on the experimental setups related to Heavy-ion collisions and the results obtained by the researchers so far. The focus is on the more cutting-edge research built on Relativistic Heavy-ion Colliders. This article provides a partial summary of these results and an outlook on their future development.

Keywords: heavy-ion collisions, RHIC, quark-gluon plasma state

1. Introduction

1.1. Contextual knowledge

The Big Bang theory is widely accepted by modern physics as the universe's origin. In the early universe, matter was in a high temperature and density state. The temperature drops to a few hundred MeV after about a few microseconds. A quark-gluon plasma is generated. At this time, quarks and gluons break through quark confinement and are in a state of largely scale-free activity. As the temperature decreases, quarks and gluons are imprisoned inside the nucleus by the strong interaction between them, also known as quark confinement. Then chemical elements begin to form and substances interact with each other. Gradually the present universe is formed.

In the 1970s, Mr. Tsung-Dao Lee pointed out that quark confinement was a major problem of 20^{th} century physics, in T.D. Lee's article, researchers need to create a state that approximates the beginnings of the Big Bang in order to study quark confinement[1]. Researchers began considering the possibility of using relativistic heavy-ion collisions to produce high-temperature, high-density states. The relativistic heavy ion collider at Brookhaven National Laboratory on Long Island, New York, USA, was finally commissioned in 2000 after 10 years of construction under the impetus of scientists represented by Professor T.D. Lee. At this point, physicists could use relativistic effects in the collider to obtain an environment similar to that at the beginning of the universe and to obtain special quark-gluon plasma.

At present, most physicists feel that we have finally arrived at a closed system of physical laws, with QeD for the strong interaction and a unifying gauge theory for the weak and electromagnetic forces, plus of course Einstein's theory of general relativity [1]. RHIC provides the ideal environment for researchers further to explore the underlying principles of the physical world. In RHIC, the nuclei of heavy atoms are accelerated and then collide together. Such a collision of heavy nuclei instantly generates a large amount of energy, causing some of the nuclei to melt and the temperature to rise sharply, exciting many particles. This creates a high-temperature, high-density environment within a few femtoseconds, producing what physicists call a quark-gluon plasma. These gluons quickly thermalize and form QGP, while the energetic partons traverse this plasma and end in a shower of particles called jets. Analyzing the final particles in various ways allows us to study the properties of QGP and the complex dynamics of multiscale processes in QCD that govern its formation and evolution, providing the simplest form of complex quantum matter we know of. Much remains to be understood, and throughout the review big open questions are encountered [2].

Therefore, the research on heavy particle collisions is very compelling. Research teams from all over the world are keeping an eye on this field. Today such collisions are possible at the RHIC at Brookhaven National Laboratory (BNL) in the United States and at the LHC at CERN.

1.2. Recent progress

In the last five years, physicists have used heavy particle collision experiments to explore the world of fundamental physics step by step while also making great progress. Most of the research in this area revolves around the standard model of particle physics, and in more detail, is based on quantum chromodynamics. Physicists are curious about what states of matter exist in the microscopic world dominated by QCD. In response, a phase diagram in high-energy nuclear physics is similar to the one describing the state of water, called the QCD phase diagram. In fact, most of this graph is obtained by model calculations rather than based on first principles. The study of the QCD phase diagram requires both theoretical and experimental approaches. Theoretically, the best way is through quantum chromodynamic calculations, but this method does not work well due to mathematical difficulties. The main experimental approach is to break the quark confinement by heavy-ion collisions, and thus further investigate the relevant features of the QCD phase diagram.

Researchers calculated and compared the possible values of X(3872) in a series of Pb-Pb collision experiments. It aims to understand quantum chromodynamics by probing the nature of exotic multiquark candidates such as X (3872). Exploring the nature of exotic multiquark candidates such as the X (3872) plays a pivotal role in understanding quantum chromodynamics (QCD) [3]. As a prime example in Figure 1, deciphering the X (3872)state remains a pressing open questions between two popular exotic configurations: a loose hadronic molecule or a compact tetraquark [3]. What’s more, In the RHIC-STAR international collaborative experimental study, the overall spin alignment of particles in the reaction end state was observed for the first time in a heavy-ion collision experiment. The results provide a new possible direction for probing the strong interactions in quark-gluon plasmas. The related research results were published in nature named Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions on January 18, 2023. At the Relativistic Heavy Ion Collider (RHIC), heavy ions (such as gold nuclei) are accelerated up to 99.995% of the speed of light and collide from opposite directions [4]. These collisions offer an ideal environment for studying phenomena related to quantum chromodynamics, the theory of strong interaction among quarks and gluons [4]. The Heavy Ion Collider is very useful in a wide range of ways. As a heavy instrument for exploring the world of particle physics, it is not only used to study QCD phase diagrams, but also to probe quantum entanglement effects. Scientists at Brookhaven National Laboratory have made exciting discoveries using the Relativistic Heavy Ion Collider. For the first time ever, they have captured the interference pattern produced by the entanglement of two particles with different charges. They detailed this result in a paper titled Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions [5].

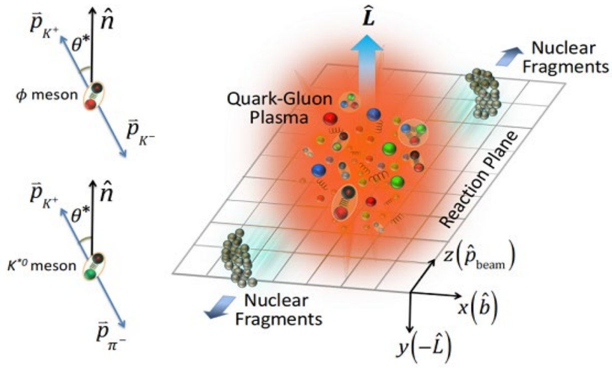

Figure 1. Schematic diagram of spin arrangement of K*0 mesons in heavy ion collisions and neutralization.

1.3. This paper

This paper comprehensively describes heavy ion collision experiments based on the RHIC. Information about RHIC is presented followed by a discussion of the important results and future prospects. Some of the theoretical foundations are presented while focusing on the experiments. The author discusses the significance of heavy-ion colliders and heavy-ion collision experiments, taking into account the history of particle physics and the research prospects of quantum chromodynamics.

This paper is based on the logic of first discussing the principles, then discussing the experimental details and results, and finally looking at the scientific prospects related to heavy particle collisions and RHIC. Firstly, the author will discuss the principles related to the RHIC in the context of the available literature. The main discussions include the selection of suitable particles for acceleration, analyzing the accelerating and colliding portions of the collider and ultimately how to use relativistic effects to create high temperature and high density conditions in the collider to generate a quark-gluon plasma. For example, physicists have used relativistic heavy-ion collisions to discover two vector mesons that appear in surprisingly global spin-aligned modes [4].

More mature heavy ion gas pedals for medical applications have long been available worldwide. The HIMAC (Heavy Ion Medical Accelerator in Chiba) construction project has been promoted by NIRS (National Institute of Radiological Sciences) as one of the projects of 'Comprehensive 10 year Strategy for Cancer Control' HIMAC is the first heavy-ion accelerator dedicated to medicine in the world, and its design parameters are based on the radiological requirements [6]. However, RHIC is very different from the above facilities. It aims to restore the high-temperature, high-density state at the beginning of the Big Bang to melt the colliding heavy ions, thereby allowing quarks to break quark confinement and become free-moving particles, forming a quark-gluon plasma. By studying this state of matter, physicists can better understand quantum chromodynamics and study the QCD phase diagram. But the RHIC does not make things effortless, and there are still many questions for researchers to solve, which just goes to show that research on quark-gluon plasmas and quantum chromodynamics still has a long way to go.

2. Principle of heavy-ion collisions

2.1. Why the collisions of heavy-ion are worth studying?

To answer this question, the authors will discuss some of what is now known about the QCD phase diagram and how it relates to heavy-ion collisions. The figure 2 shows the QCD phase diagram. The horizontal coordinates of the graph indicate the baryon number chemical formula, which corresponds to the net baryon number, while the vertical coordinates indicate the temperature. The QCD phase diagram shows that hadron gas is the main form of QCD matter at low temperatures and densities. When the temperature is increased, a QGP is formed. Quantum electrodynamics is the study of matter consisting

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of molecules or atoms and the study of the phases that these substances may form. In contrast, the nucleus and below are dominated by quantum chromodynamics, so one of the main purposes of studying QCD phase diagrams is to investigate what states of matter dominated by quantum chromodynamics may form and how to study them?

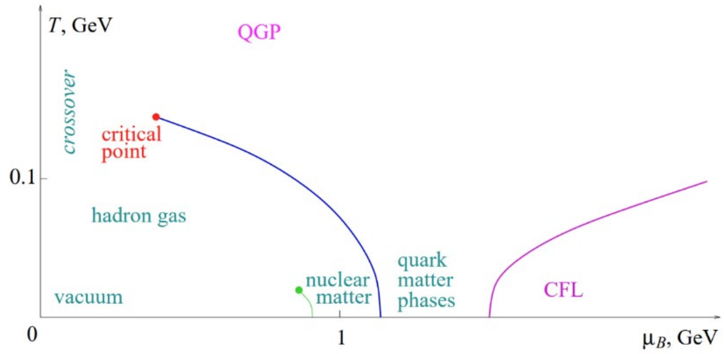

Figure 2. The contemporary view of the QCD phase diagram [7].

It is not enough and exceptionally difficult to study the matter in QCD phase diagrams, such as quark-gluon plasma, only at the theoretical level, so studying QCD phase diagrams experimentally is logical. However, in order to obtain the matter in the QCD phase diagram, it is necessary to create a high-temperature and high-density environment. To illustrate the "high temperature and high density", imagine the environment inside a neutron star and the environment at the universe's beginning, which is needed in the experiment. This environment can be created in a heavy ion collider, which is the best tool for physicists to study the QCD phase diagram.

Furthermore, it can be argued that the manifestation of complex matter is the one that is most intimately linked to the basic laws governing all matter in the universe. This form of complex matter is none other than the basic theory of Quantum Chromodynamics (QCD) [7]. Through further studies of QCD matter, physicists may be able to uncover more fundamental and broad questions, all of which require medium-particle collisions to achieve the environment needed for research. Medium-particle collisions will become a powerful tool in the hands of physicists.

2.2. The principle of heavy-ion collisions

The logic of the medium-particle collision experiment is such that the experimenter controls both the exact location of the heavy ion collision and at what energy the collision occurs, and then uses the results of the experiment to infer as much as possible the position of the nucleon in the nucleus and its momentum. It is obvious from Heisenberg's inaccuracy $\Delta q \Delta p \geq h/4\pi$ that the experimenter cannot measure both the position and the momentum of the particle with a high degree of accuracy in the experiment. Heavy ion collisions can find good approximations in nuclear and particle physics. Since heavy ions (e.g., gold ions) are accelerated to a very high velocity in an accelerating device, these nuclei can be described by a collection of nucleons, taking into account relativistic effects. Thus for relativistic heavy ion collisions this physical model can be modeled as a hard sphere with energy dependent radius [7].

In this model, the radius of the sphere is $\sqrt{\sigma_{pp}/4\pi}$, here it means total inelastic pp cross section. The heavy ion collision model is based primarily on heavy ion energies and scientists' hypothetical hard spheres. One of the more common types of collisions, pA collisions, is considered, where a proton hits another nucleon. Also the theoretical probability of this process occurring can be derived from the ratio of inelastic scattering cross sections, which allows the $N_{coll} = N_{part} - 1 = A\,\sigma_{pp}/\sigma_{pA}$ to be measured directly. In another collision type, the AA collision, scientists have found that the above equation can no longer be directly measured. Still, experimenters have found that through the experience of pA collisions and the measured probability distribution a theoretical procedure can be established to describe this

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collision process as best as possible. Heavy ion collisions can be classified into the nucleus-nucleus, proton-nucleus, and proton-proton collisions.

3. Heavy ion collision experiment and heavy ion collider

3.1. The RHIC

First, the author will discuss information about RHIC, which is located at Brookhaven National Laboratory in uptown New York, U.S.A. The accelerator at RHIC uses the storage ring model. Before moving on to other information about RHIC, let's look at the characteristics of an accelerator with a storage ring. The storage ring is a ring gas pedal that stores 3.5 GeV electron beams and emits high-quality synchrotron light. The main components of the storage ring are the magnet, the power supply, the vacuum section and the control system, which enable the experimenter to obtain the desired high-energy particles. The main function of the storage ring is not to accelerate the particles, but to accumulate them, i.e., to continuously inject and accumulate particles with high energy, so that the stored beam reaches the required value and circulates in the gas pedal for a longer period. Of course, after accumulating enough charged particles, they can also be accelerated to higher energies and then stored for a long time in the same machine for experimental purposes.

Table 1. Basic information about RHIC

	RHIC
Accelerator/beam/target type	Storage ring/heavy ion/collider
Circumference	3834 m
Location	Upton, New York
Institution	Brookhaven National Laboratory
Something about the accelerator	RHIC uses an energy storage ring gas pedal in which two independent energy storage rings circulate heavy ions in opposite directions as a way to achieve collisions of heavy ions at a very high speed.

RHIC is a huge and complex high-powered machine. About RHIC's beam properties, the maximum luminosity of RHIC is $1.6 \times 10^{32}/(cm^2 \cdot s)$. The above data is from Wikipedia.

In fact, RHIC and LHC are not the same. They have a different focus. Here author focus on the physical content of RHIC, through the acceleration device to make two beams of gold ions in motion at close to the speed of light collision. The collision in this case will melt the proton and neutron, and then their quarks and gluons will be free for a short time, i.e., breaking the quark confinement. After this collision occurs, the area will cool down and thousands of particles will re-form simultaneously. These particles will later provide clues for physicists to analyze what is happening in this region. An interesting fact about RHIC is that it is the first-ever human device capable of recreating an environment close to that of the early days of the Big Bang. RHIC is like a stage built by humans to mimic the past, except that the main character is a heavy ion and the scene is the hot and dense early days of the universe. Because of the special nature of RHIC and the universality of this field as fundamental research, physicists around the world are extremely interested in it, and the data provided by RHIC can have a great impact in many fields such as nuclear physics, particle physics, cosmology, and condensed matter physics. We hope to hear more good news from RHIC in the future. In the following, the author will discuss several experiments related to RHIC.

3.2. Some related discoveries

Among the experimental phenomena associated with RHIC, one of the more famous may be the quark-gluon plasma state created using RHIC. On February 15, 2010, scientists accelerated gold ions to near the speed of light and then collided them, in this way they created a high temperature of nearly 4 trillion degrees Celsius in RHIC, under which the gold ion-gold ion After the collision, the protons and neutrons

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will be 'melted' to form a QGP state of this material. The discovery of the RHIC is a positive step forward in raising new questions about quantum chromodynamics. On the official website of Brookhaven National Laboratory, they state that in the next few years, in order to prove the theory and solve related problems, the scientists plan to upgrade RHIC, specifically by increasing its collision rate and detection capacity. The researchers are still working on obtaining the quark-gluon plasma state better and simulating this environment at the beginning of the universe.

What is even more exciting is that RHIC may be used to test some related theories of string theory, which is different from the previous impression of string theory, which was often linked to 'not being experimentally verifiable', but RHIC offers the possibility to break this impression. This of course does not mean that string theory has been confirmed. On the contrary, it is inevitable that researchers still have a long way to go in order to confirm string theory. So back to the original concern, why is RHIC relevant to string theory? In fact, the quark-gluon plasma state plays an important role in this, and what initially surprised scientists was that this new matter is not in the predicted gaseous state but in the liquid state, in other words they flow like a liquid. When Brookhaven National Laboratory announced this discovery in 2005, it described it as 'the most perfect liquid ever observed'. However, whether this matter is perfect for a physicist studying string theory remains debatable. String theory allows a string theorist to calculate the ratio of the viscosity of a liquid to the entropy of the fluid, which would reveal how perfect this liquid is. On the other hand, this work can also be used to test string theory itself, so it is a win-win situation. In this way, the string theorists and the experimental physicists at RHIC have collaborated in two fields that are rarely seen.

RHIC plays an important role in many other areas as well. For example as figure 3, in 2021 physicists discovered the heaviest known anti-nucleus and the first anti-nucleus containing an anti-chiquark through the collision of gold particles in RHIC, a newly discovered anti-nucleus in a negatively charged antimatter state. Antimatter has been discussed for its peculiar nature since scientists proposed it. This antimatter will annihilate while producing energy when it collides with the corresponding positive matter. People have been searching for antimatter since Dirac first theorized its existence in 1928. But in fact, since in a world dominated by normal matter and antimatter annihilates with normal matter, anti-atoms composed of antiprotons and antineutrons are expected to be extremely rare. In these terms, the efforts of the STAR group at RHIC to discover antimatter have been enormous. The following author will talk about some specifics of this work. First of all, why is antimatter so rare in our universe? The answer is obvious, because antimatter 'disappears' by annihilating with its conventional counterpart. So it has been speculated that at the beginning of the Big Bang, our universe did have a lot of antimatter, but it soon disappeared due to annihilation with positive matter. But RHIC provides an excellent environment for physicists searching for antimatter by accelerating the collision of gold ions to produce temperatures of nearly 400 million degrees Celsius. Such temperatures are so high that the 'quark confinement' between quarks and gluons in atoms is broken, and nuclei rapidly 'dissolve' into a soup of quarks and antiquarks. To form the new antihydrogen isotope, first an anti-strange quark binds with an antiup and antidown quark to make an antilambda — an antineutron-like particle. The antilambda, which is fractionally heavier than a neutron, must then combine with a conventional antineutron and an antiproton. The chances of this happening are very slim: out of 100 million collisions, RHIC generated just 70 of the new antihydrogen isotopes [8]. This shows that even though RHIC has created such a unique environment, finding antimatter is still a very difficult job, like finding a needle in a haystack. To solve this difficulty, Jinhui Chen [9] and Zhangbu Xu [10] have developed a complex software program to pick out promising new anti-nuclei among so many nuclei. This shows that physics is a discipline full of possibilities. Many disciplines intersect with physics and often lead to unexpected and wonderful 'reactions' that yield many interesting results or overcome previously insurmountable difficulties.

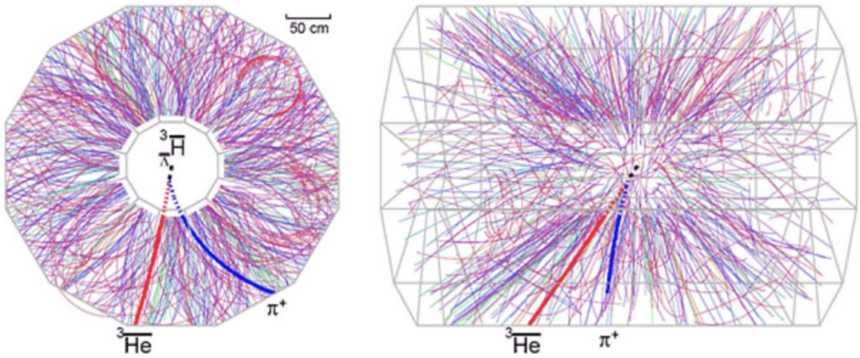

Figure 3. This figure shows the indicated trajectories left by the particles in the STAR detector. The identification of this new antinucleon was accomplished by analyzing their characteristic decay into light isotopes of anti-He and positive π mesons after the collision [8].

4. Conclusion

Research on heavy ion collisions is extremely important. The main reason is that by colliding heavy ions, such as gold ions at a very high speed, the energy produced can 'melt' the nucleus and release free quarks and gluons due to relativistic effects, which was previously difficult for humans to achieve the above process, but when the theory is developed to certain level, relevant experiments are indispensable. So people built the RHIC, or Relativistic Heavy Ion Collider, through the theories of Lee T.D. and others on heavy ion collisions, in which an environment close to the beginning of the Big Bang was realized. One of the most remarkable results is the great development of the study of the QGP state, and the promotion of a continuous new understanding of quantum chromodynamics, a quark-gluon 'soup' that has great appeal to scientists. Of course heavy-ion collisions can do more than that. In the author's opinion, heavy-ion collisions are like a place where many fields intersect, or its principles and phenomena contain a lot of knowledge. For example, the search for antimatter, the verification of string theory, the answer to some questions of cosmology, and so on. Through heavy ion collision theory and RHIC, one can obtain more experimental data to build new theories, which are all full of possibilities.

Since it was built and put into operation, the RHIC at Brookhaven National Laboratory in uptown New York has made many new discoveries, but these are not nearly enough. Regarding RHIC, scientists are trying to use innovative acceleration techniques in 2021, while updating the STAR detectors in it to obtain better data results. There are still many unresolved issues in the field of heavy ion collision-related issues, for example, despite the observation of quark-gluon plasma states, more experimental as well as theoretical derivations are needed to probe more deeply into the phase structure and equation of state of quantum chromodynamics; more rightly, for example, to explore the spectral properties of quarks, gluons and hadrons in the medium and magnetic field, to find the origin of the collective flow of small systems, etc. These problems are not in the same discipline but are all related to heavy ion collisions. Hopefully, it would be very exciting to see the resolution of related problems someday.

The future of experiments in the field of heavy-ion collisions is bright. With the construction of new colliders, such as the future Ring Collider (FCC) and the proposed Electron-Ion Collider (EIC), there is hope for more major breakthroughs in our understanding of the universe. In order to explore the unknown in the field of particle physics, it is necessary to carry out theoretical research along with corresponding physical experiments. Heavy-ion collision experiments are currently offering scientists more possibilities to explore the field of particle physics due to their special ability to break the confinement of quarks.

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