Frontiers of Physics

Group-7

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1 Cosmology and Particle Physics

Cosmology: The study of the universe's origin, evolution, and ultimate fate.

Particle Physics: The branch of physics that studies the fundamental particles and forces of nature.

1.1 The Big Bang Theory

The best-supported theory of our universe's origin centers on an event known as the big bang. This theory was born of the observation that other galaxies are moving away from our own at great speed in all directions, as if they had all been propelled by an ancient explosive force.

There are several pieces of evidence that support the Big Bang Theory. These are the following:

1. Most of the galaxies appear red shifted, an indication that they are moving away from us and that the universe is expanding.

2. The remnant radiation from the Big Bang is observed today as the cosmic microwave background radiation (CMB), a low-level radiation with a temperature of 2.725 K,

3. The percentage of light elements such as hydrogen and helium agree with the idea that the universe started in a hot and dense phase.

1.2 Structure of the Universe

Large-scale Structure: Galaxies, clusters, superclusters

Dark Matter and Dark Energy:

Dark matter (27%): Influences galaxy formation and motion

Dark energy (68%): Drives the accelerated expansion of the universe

1.3 Cosmic Evolution

The Universe's cosmic evolution begins with the Big Bang, followed by inflation, nucleosynthesis, recombination, and galaxy formation with key epochs including inflation- rapid expansion after the Big Bang and reionization-formation of the first stars and galaxies

1.4 Current Research in Cosmology

Observations: Hubble Space Telescope, James Webb Space Telescope

Projects: Planck Satellite, Large Synoptic Survey Telescope (LSST)

Theoretical Models: Multiverse, cyclic models, quantum gravity

1.5 Fundamental Particles and Forces

The Standard Model of particle physics describes the known fundamental particle and three of the four fundamental force—(electromagnetic, weak and strong forces) and classifying all known elementary particles.It explains how particles called quarks (which make up protons and neutrons) and leptons (which include electrons) make up all known matter.The Standard Model include 12 fundamental ferions(6 quarks and 6 leptons) and 4 fundamental bosons(photon,W and Z bosons and gluons)

Fundamental Forces are the four basic forces that govern all the phenomena we observe in the universe.These four fundamental forces are:

1. **Gravitational force:** gravity is a fundamental interaction which causes mutual attraction between all things that have mass.It is the dominant force on large scales, governing the motion of planets, stars and galaxies.

2. **Electromagnetic force:**is an interaction that occurs between particles with electric charge via electromagnetic fields.It is the dominant force in the interactions of atoms and molecules

3. **Weak force:**is responsible foe certain types of radioactive decay,such as beta decay.it acts on subatomic particles and mediated by W and Z bosons.

4. **Strong force:**the strongest of the four fundamental forces and is mediated by gluons.It binds quark together to form hadrons,such as proton and neutrons.

1.6 Significant Discoveries in Particle Physics

Higgs Boson: Discovered in 2012, provides mass to other particles.

Neutrino Oscillations: Show neutrinos have mass.

Antiparticles and Antimatter: Existence confirmed through experiments.

1.7 Particle Accelerators and Experiments

Large Hadron Collider (LHC): World 39s largest and most powerful particle accelerator.

Notable Experiments

ATLAS: publishes the first direct evidence of high energy light-by-light scattering, a very rare process in which two photons – particles of light – interact and change direction.

CMS: is a particle detector that is designed to see a wide range of particles and phenomena produced in high-energy collisions in the LHC.

Neutrino observatories (e.g., Super-Kamiokande)

2 General relativity and Quantum gravity

The theory of gravity known as general relativity, which was created by Albert Einstein in the early 20^{th} century, that describes gravity as a curvature of spacetime.It has revolutionized our knowledge of the universe and has been thoroughly tested and validated by a plethora of observations and experiments. Conversely, the search for a single coherent theory that can bring general relativity and quantum mechanics together is known as quantum gravity. Given that there appear to be some basic incompatibilities between the two theories, this has proven to be an extremely difficult task.

2.1 General Relativity

According to theory of general relativity gravity is a result of mass and energy, rather than a force. Spacetime is a continuum consisting of four dimensions, with the curvature or distortions caused by the presence of mass and energy. The force of gravity that humans feel is actually the curvature of spacetime.The principle of general covariance states that physics laws must remain consistent in all reference frames, regardless of their motion or orientation. The fundamental equations of general relativity are the Einstein field equations, which describe the relationship between spacetime and the distribution of mass and energy in the universe. These complex equations provide a precise, quantitative description of gravity's behavior. General relativity has made numerous predictions, including the bending of starlight by the Sun, the precession of Mercury's orbit, the existence of black holes, and the detection of gravitational waves.

2.2 Quantum Gravity

Quantum gravity is a complex area of physics research that aims to unify the principles of quantum mechanics and general relativity to develop a comprehensive theory for the behavior of gravity at the quantum level. The main challenge is reconciling the fundamentally different approaches and assumptions underlying these fields. Quantum mechanics describes the behavior of matter and energy at the smallest scales, while general relativity provides a framework for understanding gravity and spacetime at the largest scales. Leading approaches to quantum gravity include String Theory, Loop Quantum Gravity (LQG), Causal Dynamical Triangulation (CDT), and Quantum Cosmology. String theory proposes that the universe's fundamental building blocks are one-dimensional strings vibrating in a multi-dimensional spacetime, with gravity emerging as a consequence of these interactions. LQG describes space and time as discrete networks of interconnected nodes, while CDT models spacetime as a network of connected simplices (triangles or tetrahedral).

3 Superstring Theory

Superstring theory is a pivotal framework in theoretical physics that proposes all fundamental particles are not point-like dots, but rather tiny, one-dimensional "strings." These strings vibrate at different frequencies, and these vibrations determine the particles' properties. Superstring theory attempts to unify all of the fundamental forces of nature, including gravity, in a single theoretical framework, making it a candidate for the theory of everything (ToE).

3.1 Historical Background

The journey of superstring theory began in the late 1960s and early 1970s with attempts to understand the strong nuclear force. The Veneziano amplitude, proposed by Gabriele Veneziano, was a significant early contribution. Later, theorists such as Leonard Susskind, Holger Bech Nielsen, and Yoichiro Nambu recognized that this amplitude could be explained by the dynamics of one-dimensional strings. The discovery that strings could naturally include a mass less spin-2 particle, which resembles the graviton (the hypothetical quantum of gravity), suggested that string theory could also encompass gravity. This led to the theory's evolution from bosonic string theory, which only includes bosons, to superstring theory, which incorporates fermions through supersymmetry.

3.2 Basic Concepts

1. **Strings and Vibrations:** In superstring theory, particles are seen as different vibrational modes of strings. The energy and type of vibration determine the particle's properties, such as mass and charge. Strings can be open (with two endpoints) or closed (forming loops).

2. **Supersymmetry:**Supersymmetry is a key component of superstring theory. It posits a symmetry between fermions (matter particles) and bosons (force-carrying particles). For every fermion, there is a corresponding boson and vice versa. This symmetry helps in cancelling out certain infinities that arise in quantum field theory, making the theory more mathematically consistent.

3. **Extra Dimensions:**Superstring theory requires more than the familiar four dimensions of space and time. It suggests the existence of additional spatial dimensions—six or seven more, making a total of ten or eleven dimensions. These extra dimensions are compactified, meaning they are curled up in such a way that they are not observable at low energies.

3.3 Types of Superstring Theories

Superstring theory has five consistent formulations:

1. **Type I:** Features both open and closed strings with a unique kind of symmetry.

2. **Type IIA and Type IIB:** These are two types of closed strings with different propertiesregarding chirality (handedness of the string vibrations).

3. **Heterotic SO(32) and Heterotic E8xE8:** These theories combine the string theory with anotherstructure known as a gauge group, which governs the interactions of particles.

3.4 Mathematical Formalism

1. **Worldsheet and Spacetime:** The dynamics of strings are described by the two-dimensional surface they sweep out in spacetime, known as the worldsheet. The equations governing the string's behavior on the worldsheet are the conformal field theory equations.

2. **Compactification:** To account for the extra dimensions, superstring theory employs the concept of compactification. Popular methods include using Calabi-Yau manifolds for six-dimensionalcompact spaces, which preserve the necessary supersymmetry.

3. **Branes:** In addition to strings, higher-dimensional objects called branes (short for membranes) play a significant role. D-branes are surfaces on which strings can end, and they are crucial for understanding various dualities and the non-perturbative aspects of the theory.

3.5 Current Status and Challenges

Despite its elegance and promise, superstring theory faces significant challenges:

1. **Lack of Experimental Evidence:** Direct evidence for superstring theory remains elusive, and its predictions often occur at energy scales far beyond current experimental capabilities.

2. **Landscape Problem:** The theory predicts a vast "landscape" of possible vacua, corresponding to different ways to compactify the extra dimensions. This makes it difficult to predict which vacuum corresponds to our universe.

3. **Mathematical Complexity:** The mathematical structure of superstring theory is highly complex, requiring sophisticated tools from algebraic geometry, topology, and conformal field

4 Dark Matter and closure

Dark matter is a mysterious component of universe that cannot be directly observed.It does not emit,absorb,or reflect light, making it invisible to our telescopes.However, we know it exists because of its gravitation effects on visible matter and the structure of galaxies and galactic clusters.

Closure refers to the fate of the universe, whether it will eventually stop expanding or continue expanding forever. This depends on the critical density of the universe, which is the density required to halt universal expansion. If the density of matter in the universe is greater than the critical density, the universe will eventually stop expanding and collapse in a "Big Crunch". If it is less than the critical density, the expansion will continue indefinitely.

Luminous matter, such as stars and galaxies, accounts for only a fraction of the critical density necessary for closure. In fact, it falls far short of what is needed to halt the expansion. This means that there must be other forms of matter that we cannot directly observe,and this is where dark matter comes in.

Dark matter is estimated to make up about 27% of the composition of the universe.Its presence is inferred from the gravitational effects it exerts on visible matter. Without dark matter, galaxies would not have enough gravitational pull to hold themselves together,and they would fly apart.

The exact nature and composition of dark matter remain a mystery. Numerous theories have been proposed, including the possibility of undiscovered particles that interact weakly with normal matter. Scientists are actively conducting experiments and observations to detect and understand dark matter better.

One of the main challenges in studying dark matter is that it interacts very weakly with light and other forms of electromagnetic radiation. This makes its detection and direct observation extremely difficult. Scientists rely on indirect methods, such as measuring its gravitation effects and studying its impact on the large-scale structure of the universe.

Recent observations have also revealed the presence of dark energy, a mysterious force that is causing the universe's expansion to accelerate. Dark energy contributes to the overall energy budget of the universe and plays a crucial role in determining the fate of closure. The interplay between dark matter and dark energy is an area of active research.

The search for dark matter is conducted through various experiments, such as the Large Hadron Collider(LHC) and the Dark Energy Survey(DES). These experiments aim to either directly detect dark matter particles or indirectly infer their existence through their interactions with other particles.

Understanding dark matter is not just about solving a cosmic puzzle;it has profound implication for our understanding of the universe's structure and evolution.Dark matter's presence and distribution influence the formation and evolution of galaxies and the large-scale structure of the cosmos.

5 Complexity and Chaos

5.1 Defining Complexity and Chaos:

Complexity and chaos are two intertwined concepts that describe the intricate and oftenunpredictable behavior of systems composed of many interacting parts. While distinct, theyareoften found together, shaping the dynamics of natural and social phenomena.

5.1.1 Complexity

Complexity refers to the intricate organization and interconnectedness of a system, wherethewhole is more than the sum of its parts. It is characterized by:

Emergence: The emergence of novel properties and behaviors that cannot be predicted from the individual components.

Self-organization: The ability of a system to organize itself without external intervention, oftenleading to the formation of intricate patterns and structures.

Non-linearity: The output of the system is not proportional to the input, making it difficult topredict its behavior.

Feedback loops: Processes where the output of the system influences its own input, creatinga cycle of interaction and adaptation.

5.1.2 Chaos

Chaos describes the unpredictable and sensitive behavior of systems where small changesininitial conditions can lead to drastically different outcomes. It is characterized by:

Sensitivity to initial conditions: The butterfly effect, where tiny variations in the starting point can lead to vastly different long-term behaviors.

Long-term unpredictability: Even with perfect knowledge of the initial state, it is impossibletopredict the system's behavior with perfect accuracy over extended periods.

Fractal patterns: The presence of self-similar patterns that repeat at different scales, creatingintricate and visually stunning structures.

5.2 Exploring Complexity and Chaos in the Real World:

These concepts manifest in various real-world systems, influencing their behavior and presenting both challenges and opportunities:

Weather patterns: Chaotic systems that exhibit unpredictable and complex behavior, makinglong-term forecasting challenging.

Financial markets: Complex systems influenced by numerous factors, leading to inherent difficulty in predicting their movements.

Biological systems: Highly complex systems with emergent properties and self-organizingcapabilities, posing challenges for understanding their intricate workings.

Social systems: Complex systems composed of individuals interacting with each other, leading to emergent behaviors and challenges in managing social dynamics.

5.3 Implications for Science, Technology, and Society

Understanding complexity and chaos has profound implications for various fields:

Science and technology: It can lead to new scientific discoveries and technological innovations, such as the development of artificial intelligence systems that can learn andadapt to complex environments.

Society: Awareness of these concepts can help us better understand and manage social systems, leading to more effective policies and interventions.

Managing complexity and chaos: Developing strategies to deal with the challenges posedbythese systems, such as implementing adaptive management approaches that can respondto changing conditions.

6 High Temperature and Superconductors

The concept of superconductivity was introduced by Heike Kamerlingh Onnes in 1911 in order to characterize a material with zero electrical resistance, unknown at that time . The discovery of superconductivity was unintended, and the main reason to conduct the experiment was the liquefaction of the last noble gas helium. In order to utilize liquid helium the resistance of an as pure as possible metal was measured, namely mercury, with the aim to explore the temperature dependence of the resistivity at very low temperature. At that time there existed several theories and speculations about the low temperature behavior of metals, which ranged from continuously decreasing to unusual upturns, requiring experimental verification. Unexpectedly, liquid mercury showed zero resistance below 4.2 K which corresponds to 268°C.

6.1 History

Superconductivity was discovered in 1911 by Kamerlingh Onnes and Holst in mercury at the temperature of liquid helium (4.2 K). It took almost 50 years until in 1957 a microscopic theory of superconductivity, the so-called BCS theory, was developed. Since the discovery a number of superconducting materials were found with transition temperatures up to 23 K. A breakthrough in the field happened in 1986 when Bednorz and Müller discovered a new class of superconductors, the so-called cuprate high- temperature superconductors with transition temperatures as high as 135 K. This surprising discovery initiated new efforts with respect to fundamental physics, material science, and technological applications.

6.2 The BCS Theory

After demonstrating superconductivity in mercury, a series of metals were found to be superconducting at ultra-low temperatures. The highest transition temperature in elemental metals was found in niobium with a Tc of 9.25 K. To enable applications of superconductors, liquid helium was used, which is expensive. In the 1950s, A15 superconductors were discovered, reaching a maximum Tc of 23.2 K. In 1986, Bednorz and Möller discovered cuprate high-temperature superconductors, with the highest Tc of 135 K at ambient pressure.

Before going into more details of the phenomenon of superconductivity, some fundamental explanations are needed, related to metals, insulators and their properties. In a metal, free charges, namely electrons, are present which provide the electrical current. In contrast, in an insulator all charges are strongly bound to the ion and cannot move freely through the crystal.

If an electric field is applied to a conductor, the charges move and provide the current. The electrical conductance of a material can be characterized by its resistivity which has small values for good conductors (metals) and very large values for bad conductors (insulators). It is interesting to note, that the metals with the highest electrical conductivity, namely silver, copper, and gold are not superconductors, whereas metals with a low electrical conductivity such as aluminium, lead, and mercury are superconducting. How can one visualize the resistivity which is typically observed in any metal? In a metal the electrons which carry the current are scattered by the atoms/ions which vibrate due to thermal motion. Since this motion is reduced with decreasing temperature, the resistance is reduced as well and levels off in the low temperature regime . It remains, however, finite at all temperatures. This is in strong contrast to a superconductor, where the resistivity of the superconductor becomes unmeasurably small at the transition temperature Tc. There is a distinct difference between a normal metal and a superconductor. In a metal the electrical resistivity decreases with temperature and reaches an almost temperature independent finite value at low temperature, in a superconductor the resistivity is typically larger than in a metal at high temperature – signaling the behavior of a metal with low electrical conductivity – and at Tc it drops to zero signifying perfect electrical conductance. Two fundamental properties are intimately interrelated with the superconducting state, namely (i) perfect conductance and (ii) the so-called Meissner-Ochsenfeld effect by which a magnetic field is completely expelled from the superconductor, whereas in the normal state it penetrates the superconductor. The Meissner-Ochsenfeld effect is the reason for magnetic levitation.

6.3 Discovery of high temperature superconductor

Ceramic cuprates have revolutionized superconductivity research, with their high-temperature superconductivity reaching record temperatures exceeding liquid nitrogen values. However, their ceramic nature makes them brittle, breakable, and difficult to handle. In 2001, Akimitsu and coworkers discovered another high-temperature superconductor, MgB2, with a Tc of 39 K, which exceeds conventional values. In 2006, Hosono and coworkers demonstrated high-temperature superconductivity in iron-based layered compounds, with a maximum Tc of 56 K. In 2015, Eremets and coworkers turned H2S into a superconductor by applying extremely high pressures, reaching a Tc of 200 K. This finding shows that hydrogen-bonded systems are potential candidates for room-temperature superconductivity. Both cuprates and iron-based superconductors share a similar phase diagram, with the number of added carriers determining the magnitude of Tc. Both are magnetic as long as they are insulating. The label high-Tc should be reserved for materials with critical temperatures greater than the boiling point of liquid nitrogen, but some materials, including the original discovery and recently discovered pnictide superconductors, have critical temperatures below 77 K but are commonly referred to as high-Tc class.

7 Some unanswered questions in physics

1. Is there a unifying theory that combines quantum mechanics and general relativity?
2. What is dark matter and dark energy, which seem to constitute most of the universe39;s mass and energy?
3. Can we achieve a complete understanding of the nature of black holes, including their behavior at the singularity?
4. What caused the asymmetry between matter and antimatter in the early universe, leading to the predominance of matter?
5. Is there a theory of quantum gravity that reconciles quantum mechanics with the gravitational force?
6. How did the universe begin, and what, if anything, came before the Big Bang?
7. Can we understand the true nature of time and its relationship with space on a fundamental level?
8. What are the ultimate limits of computation and information processing in physical systems?
9. Can we discover new fundamental particles beyond those already known in the Standard Model of particle physics?
10. Are there extra dimensions of space beyond the three spatial dimensions and one time dimension we currently observe?