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Review of antimatter

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Abstract. The theory of antimatter was proposed long ago and thought of as made up of antiparticles. Antimatter was believed to exist based on the theory of relativity and quantum mechanics, which are thought to be two fundamental concepts in modern physics. However, it turned out that scientists had great difficulty in finding antimatter. This has led to a discussion about what dark matter is made of and how it exists. Depending on the context of algebraic quantum field theory, antimatter does not consist of antiparticles, which means that antiparticles are particles that consist of antimatter. The notion of antimatter will be explained through the quantum field theory (QFT) theory. How we define the antimatter depends on our criteria in the physical state space. Recent research in AQFT（Advanced Quantum Field Theory) shows that all different quantum states possess antimatter counterparts, which has greatly expanded the field of antimatter research. Then several possible explanations for the distribution of antimatter and their theoretical foundation will be discussed. After exploration and observation across nearly one century, scientists still cannot get a reasonably clear picture of the distribution of antimatter. Why antimatter appeared and disappeared is still unknown, and attempts to find antimatter that exists in nature are going on. Scientists have had some good success when focused on the center of black holes and supermassive objects in space. There have been a lot of observations of antimatter in progress since decades of years ago.

Keywords: Antimatter, QFT, Universe, Observation.

1. Introduction

In 1928, the theory of matter and antimatter was released by P.A.M. Dirac, who predicted that each particle had a corresponding antiparticle [1,2]. They were supposed to have an identical mass and opposite electric charge. In 1933, Anderson discovered the first electron with a positive charge, which was named the positron [3].

Antimatter was considered to be matter made up of antiparticles. Every elementary particle has an antiparticle with an opposite charge and identical properties. Some types of neutral particles are antiparticles of themselves. However, decades of work in the QFT showed that this theory seems incorrect at the fundamental level. There are no particles at a fundamental level. This likely made the concept of antimatter different from conventionally understood matter. Because if we believe that antimatter is made of so-called “anti” particles, but QFT shows that particles are not fundamental ontology, it implies that matter and antimatter, which consist of “particles”, are not essential parts of the universe. A standard and simple picture of antimatter comes from the definition of antiparticle, which can be dominated by the free relativistic wave equation of quantum mechanics (QM) [4].

Decades of deep study in AQFT have suggested that some particular states have their own antimatter counterparts. If we can ensure that these conditions hold for all QFT states, then matter, and antimatter will hold for all fundamental components of the universe today, not just particle forms. Although these conditions are too restrictive to cover all the possible constituents, theories such as DHR still hold great promise for explaining most of the problems.

As the theory suggests, when a particle meets its antiparticle (actually, matter meets its antimatter), it will annihilate each other. The energy which is produced by annihilation is the same as their total energy, which is equal to their total mass according to the theory of relativity. Then the energy would be transformed into a new combination of new particles, kinetic energy, and ray. The matter-antimatter annihilation can produce the most energy per unit mass among all kinds of ways of energy production. Besides, the superheated electron-positron area, which is called plasma, is considered to play a main part in the early universe. In the last century, scientists have investigated to production of matter and antimatter through electric fields. Even if there's no shortage of evidence that antimatter exists, scientists still haven’t been able to find a large amount of antimatter in the universe nowadays.

Antimatter exists as a direct result of combining two of the most important theory in physics: relativity and quantum mechanics. According to these two theories, antimatter has become an inevitable subject of study in modern physics. Antimatter is thought to be the exact opposite of matter. Under the conjugation of parity (P) and charge (C) and time reversal (T), all phenomena observed in nature are invariant..Because of a poor understanding of the early universe, scientists had a hard time explaining what was going on with the dark matter. As a result, it is challenging to find antimatter other than cosmic rays, and the matter-antimatter asymmetry that currently prevails in the universe is difficult to explain. We can only assume that the universe was built in this form [5].

The existence of antimatter is the result of a combination of two of the most influential theories in physics: relativity and quantum mechanics. According to these two theories, antimatter has become an important research content in modern physics. Antimatter is thought to be the opposite of matter; All phenomena observed in nature are invariant under the conjugation of parity (P), charge (C), and time reversal (T). The lack of direct evidence and theories for the early universe makes it difficult for scientists to tell what happened to antimatter in its earliest days. Therefore, it isn't easy to obtain an explanation for the evolution of antimatter in the nearby universe, and we can only assume that the universe was created in this form.

Our direct exploration is limited to the solar system, where we have conducted antimatter surveys of various objects and Spaces. However, evidence for large amounts of antimatter remains disappointingly elusive. In addition to direct detection, scientists can also receive radiation from stars and other matter outside the system, which has become an essential means of analyzing the universe. In these rays, we found the only antimatter available outside the laboratory so far, the anti-electron. However, since the mechanism of electron and anti-electron generation is relatively simple and the threshold is low, it is possible to generate even in an environment composed entirely of matter, so it cannot be used as direct evidence of antimatter. To prove that antimatter does exist in the universe, or once did, scientists need to find heavier antimatter nuclei. So far, none of such antimatter has been found.

Now, we can claim that the main part of antimatter in the universe, if they do exist, is supposed to be located in the center of black holes and supermassive objects in space. Because the density of the antimatter is too high, the essential part of the heavy mass of black holes may belong to the antimatter. Quasars are good examples of supermassive objects [6].

Finally, if antimatter could be put to use, it would significantly solve energy problems and lead to advances in materials and medicine.

2. Antiparticles on the native picture

The early picture of antimatter started with the concept of antiparticles, which can be derived from quantum mechanics (QM) governed by free relativistic wave equations. We can take the Klein-Gordon equation (KGE) as an example; in this case, particles are spin-zero:

$$(\nabla_a \nabla^a + m^2)\varphi(x) = 0$$

The simplest solution can be expressed as a linear combination of plane waves

$$\phi_k = exp(ik_a x^a)$$

The wave vector k satisfies that $k_a k^a = m^2$.In quantum mechanics, the energy corresponds to the operator

$$\hat{E}\varphi = n_a \nabla^a \varphi$$

We must construct a complex structure to form the Hilbert space corresponding to the KGE solution. By decomposing φ(x) by different frequencies into a positive part $\varphi_+(x)$ and a negative part $\varphi_-(x)$, $\alpha\varphi_+(x) + \alpha^*\varphi_-(x)$ can define αφ. Then we can get E that is:

$$\hat{E}\varphi = n_a \nabla^a \varphi(x)$$

which suggests that a negative-frequency wave ϕ_{-k} and positive-frequency one have the same energy. So we cannot get antiparticles in this way [7].

To construct a Klein-Gordon QFT, we build a symmetric Fock space by taking the “one-particle” Hilbert space H of KGE solutions. As relativistic systems need undergo changes in particle number, a Fock space is necessary .Through introducing "creation" and "annihilation" operator, a multi-particle Fock spatial state is constructed.

The creation operator a* produces a particle with a pure frequency wave function, while the "antiparticle" generation operator a* produces a particle with a pure negative frequency wave function and hence the opposite charge.

Then we can get a solution of a free scalar QFT, including negative frequency particles called antimatter and positive frequency particles, which are named ordinary matter. Generally, when we talk about antimatter, we focus on such particles.

3. A general notion of antimatter

In this section, we will show that the true definition of antimatter is not the same as before. At a basic level, a particle and its corresponding antiparticle take the opposite values of all quantum numbers. There are no particles in a realistic QFT, so the definitions of "particle" and "antiparticle" are physically invalid.

3.1. The incompleteness of the native picture

The definition must be premised on the definition of antiparticles since antimatter is considered matter composed of antiparticles. However, the latest research suggests this is not the case.

Fraser's particle-free argument follows from the physical reality of the QFT. To get the particle interpretation, we need to establish the Fock space. However, in QFT, we cannot simply decompose the solution into different frequency modes, so the Fock space cannot be established, and we cannot get an operator that conforms to the particle behavior. So in QFT, the particle solution does not hold.

Another more intuitive view was proposed by Wald(1994) and Halvorson and Clifton(2001) : Particle interpretation is not the only solution. Even in the most straightforward cases, such as KG fields, the particle interpretation is only a solution to complex structures. However, other complex structures can still be obtained in addition to this solution. For example, according to the theory of relativity, each observer has a different complex structure. As a result, the frequency cannot be decomposed into the so-called "future" and "past" according to the inertial frame, and normalization is challenging to complete.

One assumption that quantum numbers have group structure is a valuable explanation

3.2. Theory of antimatter

Indeed, to understand the quantization process and origin of antimatter, we need a general theory through which classical symmetries can be expressed under quantization.

By renormalisation, we can see a field with a reducible symmetry group as a collection of different fields. A N-dimensional field can be treated as N-interacting fields, Through renormalization, particles can be expressed as irreducible representations of symmetric groups [8].

So we can just consider the most straightforward example: Klein-Gordon theory. In this case, through the theory of field, one-particle quantum theory can be divided into two components, and there exists a rotation that acts on these groups of $\exp(\pm i\theta)$, which is different from that in 2. Because space has no standard orientation, two different types of particles can transition in essentially different ways without internal structure. Therefore, the entire group has opposite effects on the two particles; that is, the two particles exhibit opposite behaviors and properties, such as opposite electric charges.

Now our definition still cannot rule out non-particle systems. However, by using similar ways of thinking, we can find that dynamical behavior is not the final definition.

Taking CPT symmetry into consideration, we can find that the irreducible actions of the symmetry group on the two sectors are conjugate of each other (which are so-called “particle” and “antiparticle”). In fact, in QFTs there are no particles, and quantum numbers are labels for superselection sectors. One of the solutions is DHR representations, which is proposed by Doplicher in 1969.

So the conclusion is that matter is composed of particles and antiparticles in some cases, but in others, the concept of particle does not hold. Particles emerge in domains where the quantum field can be treated as approximately linear, which is a fluke, and their symmetry group of is the kind of internal symmetry group of the underlying field [4].

4. Antimatter in the present universe

Through indirect detection methods, we can get the distribution of antimatter in the universe. There are two possible distributions: both matter and antimatter are homogeneously mixed; that is, matter exists mainly in space but contains a certain proportion of antimatter, or large swathes of matter and antimatter coexist. In both cases, the annihilation process produces large amounts of X-rays and gamma-rays.

4.1. The baryon asymmetry of the universe

In the consensus model of cosmology (ΛCDM), the asymmetry of baryons can be estimated by the ratio of baryons to photons and confirmed by two different methods from the relative abundance of light elements in IGM and the temperature fluctuation spectrum of CMBS. Since Sakharov, various models have been proposed to explain this situation. Most theories suggest that the matter-antimatter asymmetry is directly generated in the baryon sector, first creating the lepton asymmetry and then transferring the lepton asymmetry to the baryon sector. However, we cannot find any evidence for it at the moment -- we still cannot observe much antimatter in the universe [9].

4.2. A patchwork universe

There is a theory that the universe is a patchwork of regions dominated by matter or antimatter. What we want to get is the size and distribution of these regions. Much has been discussed about the possibility of a single antimatter star system. These stars pass through the ISM without an annihilation signal, so we can conclude that their proportion in the galaxy is less than 10^{-4}. Since it is almost impossible for such a system to exist in a realistic model of galaxy formation, we can conclude that it is zero [10].

We can believe that the universe is made up of a patchwork of vast regions of matter and antimatter. From measurements of the Cosmic Diffuse Gamma-ray (CDG) background, we can conclude that if we choose this theory, each region would be about the size of the universe we currently observe. However, we still have not been able to explain the creation and development of matter and antimatter.

Current observations yield very little antimatter, and some baryons are thought to be remnants of antimatter from the early universe.

4.3. A mixed universe

The EGRET Space telescope was used to impose an upper bound on γ fluxes for 55 cluster samples[11]. The results suggest that these clusters are composed entirely of matter or approximately of antimatter. If there are regions made of antimatter, they must be at least as far away from the cluster as the size of the Mpc.

4.4. Exploration of antimatter

In the 1970s, the results of the teams of R. Golden in the United States and E. Bogomolov in Russia led to an extensive program of direct antimatter research.

Several balloon-borne experiments were performed in collaboration with WiZard (Mass89-91, TS93, Caprice94-98), HEAT, and BESS. AMS01 flew on the Space shuttle in 1998. A magnetic spectrometer and several detectors for hadronic and electromagnetic separation are at the heart of all these instruments.

The PAMELA and AMS-02 space missions search for heavy antinuclear and non-baryonic particles outside the Standard Model. PAMELA (Antimatter Exploration and Light Nuclear Astrophysics Payload) was launched from Baikonur Cosmodrome in Kazakhstan on a Soyuz-U rocket aboard the Russian satellite DK1 June 15, 2006 [12].

Polar balloon flights are another way to look for antimatter. In December 2007, BESS, a Japanese-American cooperation agency, will conduct its second polar flight, which is expected to take about 20 days.

The general antiparticle spectrometer (GAP) experiment is probably the best method to measure the antideuteron. The gap is an Antarctic balloon mission searching for low-energy (< 0.25 GeV/n) cosmic ray antinuclear in the southern summer of 2021. The gap is designed to accurately measure the flux of antideuterons, antiprotons, and antihelium from low-energy cosmic rays.

5. Conclusion

Antimatter is a theory that has been proposed for a long time and refined with cosmology's development. The existence of antimatter, mainly anti-electrons, has been confirmed, but most antimatter in the universe has yet to be discovered. This has led to several theories about how and where antimatter could exist. With the development of quantum field theory, the nature of antimatter has significantly been understood. So far, scientists have made many efforts to detect antimatter in the universe and expect to get more results.

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