

The True Nature of Dark Matter—Elucidated by Reexamining the Interpretation of Triplet Production

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Abstract

Einstein's energy-momentum relationship, which holds for isolated systems in free space, is not applicable in the space inside a hydrogen atom where potential energy exists. Therefore, the author previously derived an energy-momentum relationship applicable to an electron within a hydrogen atom. When this relationship is solved, an electron possesses energy levels that take negative values even when described on an absolute scale. A hydrogen atom has energy levels far lower than in Bohr's proposed model. This paper predicts that an electron at these ultra-low energy levels is one of the two electrons released into nature in triplet production experiments. This paper predicts that previously unknown matter formed from hydrogen atoms and other similar atoms and molecules with electrons at these ultra-low energy levels is the true nature of dark matter, a material present in the universe whose true nature is unknown.

Keywords

Einstein's Energy-Momentum Relationship, Energy-Momentum Relationship in a Hydrogen Atom, Ultra-Low Energy Levels in a Hydrogen Atom, Triplet Production, Dark Matter, Dark Hydrogen Atom

1. Introduction

It is believed that the largest structures in the universe are large-scale structures made of dark matter (DM), a material which cannot be directly observed.

DM exists in vast quantities throughout the universe, yet unlike ordinary matter, it is thought to be impossible to observe it directly. Many researchers are engaged in constant research, trying to discover its true nature. However, WIMPs

and Axions, thought to be the most likely candidates, have yet to be detected despite many years of effort by researchers. From a statistical mechanical perspective, if such unknown matter exists in large quantities, its energy should be low.

This DM forms a large-scale web-like structure. It is thought that galaxies, like the Milky Way where we live, are formed within the filaments of this large-scale structure.

It is believed that DM only interacts with ordinary matter through gravity, and thus cannot be observed using any type of electromagnetic wave.

There is also the following very similar explanation. According to the currently favored model of the formation of the universe (the cold DM model), it is believed that roughly 10 to 11.5 billion years ago large amounts of hydrogen gas expanded out like a web, and astronomical objects such as the fixed stars and galaxies came into being in the mesh of that web.

The large amounts of hydrogen gas that float in space are attracted to each other due to their mutual gravity (universal gravitation) and form into more dense clouds. As the density of hydrogen gas increases, the surrounding hydrogen gas is drawn in, so the clouds grow into larger astronomical objects.

Umehata *et al.* observed, for the first time in the world, some of the hydrogen gas distributed in a web-like form, which had previously been predicted but never actually observed [1].

According to the above explanation, the large-scale structure of the universe is formed of DM and hydrogen gas. The distribution of hydrogen gas is similar to the density distribution of DM.

In any case, DM and hydrogen gas are closely related. Papers pointing out this fact have been published by others as well [2]-[6].

This raises the following questions: Is ordinary matter generated within DM halos? Or is ordinary matter merely drawn to DM by DM's gravity?

This is an important problem that must be elucidated.

Also, though they are in the minority, some scientists believe that undiscovered low-energy states exist in hydrogen atoms [7]-[15]. They predict that cold hydrogen in those unknown states might be the true nature of DM. While this paper differs from their view, it also considers unknown states of hydrogen atoms as candidates for DM.

2. Hydrogen Atoms at Ultra-Low Energy Levels

The following is the most famous formula discovered by Einstein [16].

$$E = mc^2. \quad (1)$$

A body with mass m has an energy of mc^2 .

Also, according to the special theory of relativity (STR), the following relationship holds between the energy and momentum of a body moving in free space [17].

$$(mc^2)^2 = (m_0c^2)^2 + c^2p^2. \quad (2)$$

Here, m_0c^2 is the rest mass energy of the body. And mc^2 is the relativistic energy.

Formula (2), which is called Einstein's energy-momentum relationship, holds when the energy absorbed by a body is all converted to kinetic energy of that body.

Also, Einstein and Sommerfeld defined the relativistic kinetic energy as follows [18].

$$K_{\text{re}} = mc^2 - m_0c^2. \quad (3)$$

The "re" subscript of K_{re} stands for "relativistic."

Can Formula (2), which holds for isolated systems in free space, also be applied to an electron in a hydrogen atom?

Here, let us consider the case where an electron placed at a position infinitely distant from the nucleus (proton) of a hydrogen atom is attracted to the proton and forms a hydrogen atom. The energy initially possessed by this electron is the rest mass energy $m_e c^2$. In this case, the electron does not absorb photon energy, but rather acquires an equivalent amount of kinetic energy by releasing part of its rest mass energy.

Therefore, Einstein's relationship (2) cannot be applied to an electron in an atom.

Incidentally, Bohr derived the following formula for energy levels by assuming the quantum condition [19].

$$E_{\text{BO},n} = -\frac{1}{2} \left(\frac{1}{4\pi\epsilon_0} \right)^2 \frac{m_e e^4}{\hbar^2} \cdot \frac{1}{n^2}, \quad n = 1, 2, \dots \quad (4)$$

Here, $E_{\text{BO},n}$ are the energy levels of a hydrogen atom derived by Bohr. Also, n is the principal quantum number.

Formula (4) can be written as follows.

$$E_{\text{BO},n} = -\frac{m_e c^2}{2} \left(\frac{e^2}{4\pi\epsilon_0 \hbar c} \right)^2 \cdot \frac{1}{n^2} = -\frac{\alpha^2 m_e c^2}{2n^2}. \quad (5)$$

Here, α is the following fine-structure constant.

$$\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} = 7.2973525643 \times 10^{-3}. \quad (6)$$

In classical quantum theory, the total mechanical energy of a hydrogen atom is defined as the sum of the potential energy and kinetic energy of the electron. That is,

$$E_n = V(r_n) + K_n, \quad E_n < 0. \quad (7)$$

Also, the potential energy of an electron is given by the following formula.

$$V(r) = -\frac{1}{4\pi\epsilon_0} \frac{e^2}{r}. \quad (8)$$

According to the Virial theorem, $2K = -V(r)$ in the case of a circular orbit, and thus the energy can be written as follows.

$$E_n = V(r_n) + K_n = \frac{V(r_n)}{2} = -K_n = -\frac{1}{2} \frac{1}{4\pi\epsilon_0} \frac{e^2}{r_n}. \quad (9)$$

Now, if $E_{\text{ph},n}$ is used to represent the photon energy emitted when an electron placed an infinite distance away from the atomic nucleus (proton) of the hydrogen atom is taken into the hydrogen atom, then the following law of energy conservation holds for the electron.

$$V(r_n) + K_n + E_{\text{ph},n} = 0. \quad (10)$$

Here, the “ph” subscript of $E_{\text{ph},n}$ stands for “photon.”

Formula (10) shows that the energy source for the kinetic energy acquired by an electron and the photon energy emitted by the electron is the potential energy of the electron.

The author has previously pointed out that the reduction in rest mass energy of an electron corresponds to the potential energy of the electron.

Here, if the reduction in rest mass energy of the electron is represented as $-\Delta m_e c^2$, then the potential energy of the electron can be defined as follows [20] [21].

$$V(r) = -\Delta m_e c^2. \quad (11)$$

In classical quantum theory, it was promised that the potential energy of an electron placed at the position $r = \infty$ would be zero. It was thought that the energy of an electron in this state would also be zero.

However, the view of the author is that the potential energy of an electron placed at the position $r = \infty$ will actually be zero. Also, this electron has a rest mass energy of $m_e c^2$.

The relationship between the rest mass energy of the electron $m_e c^2$ and the relativistic energy of the electron $m_n c^2$ is as follows.

$$m_n c^2 = m_e c^2 + E_{\text{re},n} = (m_e c^2 + V(r_n)) + K_{\text{re},n}. \quad (12)$$

Here, $m_n c^2$ is the sum of the residual part of the rest mass energy of the electron $(m_e c^2 + V(r_n))$ and the relativistic kinetic energy $K_{\text{re},n}$. $E_{\text{re},n}$ are the relativistic energy levels of a hydrogen atom [20].

The relationship between $E_{\text{re},n}$ and other energy is as follows.

$$E_{\text{re},n} = -E_{\text{ph},n} = -K_{\text{re},n}. \quad (13)$$

The r where potential energy of an electron becomes $-m_e c^2$ can be derived from the following formula. That is,

$$-m_e c^2 = -\frac{1}{4\pi\epsilon_0} \frac{e^2}{r}. \quad (14)$$

Hence,

$$r = \frac{1}{4\pi\epsilon_0} \frac{e^2}{m_e c^2} = r_e. \quad (15)$$

Here, r_e is the classical electron radius.

The author derived the following relationship applicable to an electron in a hydrogen atom (Appendix A).

$$\left(m_n c^2\right)^2 + c^2 p_{\text{re},n}^2 = \left(m_e c^2\right)^2, \quad -m_e c^2 < m_n c^2 < m_e c^2. \quad (16)$$

$p_{\text{re},n}$ is the momentum of an electron whose principal quantum number is in the state n .

The author has previously derived Formula (16) using five methods [22]-[27].

Solving Formula (16), it is evident that the following relation holds between m_e and m_n .

$$m_n = m_e \left(\frac{n^2}{n^2 + \alpha^2} \right)^{1/2}. \quad (17)$$

The following relation was used when deriving this formula (Appendix B).

$$\frac{v_n}{c} = \frac{\alpha}{n}. \quad (18)$$

In the case of an electron in a hydrogen atom, mass decreases as kinetic energy increases. This requires attention because it differs from predictions of the STR.

Here, the relativistic kinetic energy of an electron inside a hydrogen atom is defined as follows by referring to Formula (3) [23].

$$K_{\text{re},n} = m_e c^2 - m_n c^2. \quad (19)$$

Incidentally, it was once pointed out by Dirac that Formula (2) has a negative solution [28]. In the same way, the author has pointed out that Formula (16) has a negative solution [29].

When Formula (16) is solved, it is evident that ultra-low energy levels $E_{\text{ab},n}^-$ exist in a hydrogen atom in addition to the known energy levels $E_{\text{ab},n}^+$. If the energy of an electron when it is placed at a position infinitely far from the atomic nucleus is taken to be $m_e c^2$, then $E_{\text{ab},n}^+$ and $E_{\text{ab},n}^-$ can be described as follows [30].

$$\begin{aligned} E_{\text{ab},n}^+ &= m_n c^2 = m_e c^2 + V(r_n) + K_n = m_e c^2 + E_{\text{re},n} \\ &= m_e c^2 \left(\frac{n^2}{n^2 + \alpha^2} \right)^{1/2}, \quad n = 0, 1, 2, \dots \end{aligned} \quad (20)$$

$$E_{\text{ab},n}^- = -m_n c^2 = -m_e c^2 \left(\frac{n^2}{n^2 + \alpha^2} \right)^{1/2}, \quad n = 0, 1, 2, \dots \quad (21)$$

The “ab” subscript of $E_{\text{ab},n}$ stands for “absolute.”

It has already been pointed out that a state with $n=0$ exists in the energy levels of a hydrogen atom [31] [32].

Now, Formula (20) absolutely and relativistically describes the photon energy of an electron constituting a hydrogen atom. In contrast, Formula (21) indicates previously unknown energy levels.

The energy levels of a hydrogen atom $E_{\text{re},n}$ are given by the following formula.

$$E_{\text{re},n} = m_n c^2 - m_e c^2 = m_e c^2 \left[\left(\frac{n^2}{n^2 + \alpha^2} \right)^{1/2} - 1 \right], \quad n = 0, 1, 2, \dots \quad (22)$$

In addition, Butto, N. has also discussed electron spin when discussing momentum of the electron [33]. However, electron spin is not incorporated into the formula derived in this paper.

Therefore, it may not be the final formula.

Next, when the part of Formula (22) in parentheses is expressed as a Taylor expansion,

$$E_{\text{re},n} \approx m_e c^2 \left[\left(1 - \frac{\alpha^2}{2n^2} + \frac{3\alpha^4}{8n^4} - \frac{5\alpha^6}{16n^6} \right) - 1 \right] \approx -\frac{\alpha^2 m_e c^2}{2n^2}. \quad (23)$$

From this, it is evident that Formula (4) is an approximation of Formula (22).

Next, the following table summarizes the energies of a hydrogen atom obtained from Formulas (4) and (22) (**Table 1**).

Table 1. Comparison of the energies of a hydrogen atom predicted by Bohr's classical quantum theory and this paper.

n	Bohr's Energy Levels, $E_{\text{BO},n}$	This Paper, $E_{\text{re},n}$
0	—	−511 keV
1	−13.6057 eV	−13.6052 eV
2	−3.40142 eV	−3.40139 eV
3	−1.51174 eV	−1.51174 eV

Now, Formula (20) absolutely and relativistically describes the photon energy of an electron constituting a hydrogen atom. In contrast, Formula (21) indicates previously unknown energy levels. The mass of an electron at negative energy levels becomes negative.

The author has previously pointed out that matter formed from a proton (hydrogen atom nucleus) and an electron at this ultra-low energy level (21) is the true nature of DM, a source of gravity whose true nature is currently unknown [34] [35]. The author has also given the name “dark hydrogen atoms” (DHA) to hydrogen atoms at this ultra-low energy level.

An electron with negative mass forming DHA exists near the atomic nucleus (proton) [23] [36] [37].

Next, if the electron orbital radii corresponding to the energy levels in Formulas (20) and (21) are taken to be, respectively, r_n^+ and r_n^- [35].

$$r_n^+ = r_e \frac{(n^2 + \alpha^2)^{1/2}}{2(n^2 + \alpha^2)^{1/2} - n}. \quad (24)$$

$$r_n^- = \frac{r_e}{2} \frac{(n^2 + \alpha^2)^{1/2}}{(n^2 + \alpha^2)^{1/2} + n}. \quad (25)$$

Formulas (24) and (25) can be written as follows.

$$r_n^+ = \frac{r_e}{2} \left[1 + \frac{n}{(n^2 + \alpha^2)^{1/2} - n} \right]. \quad (26)$$

$$r_n^- = \frac{r_e}{2} \left[1 - \frac{n}{(n^2 + \alpha^2)^{1/2} + n} \right]. \quad (27)$$

Now, the following ratio is obtained from Formulas (24) and (25).

$$\frac{r_n^-}{r_n^+} = \frac{(n^2 + \alpha^2)^{1/2} - n}{(n^2 + \alpha^2)^{1/2} + n}. \quad (28)$$

Here, if we set $n = 1$,

$$\frac{r_1^-}{r_1^+} = \frac{(1 + \alpha^2)^{1/2} - 1}{(1 + \alpha^2)^{1/2} + 1} = 1.3312484168 \times 10^{-5} \approx \frac{1}{75120}. \quad (29)$$

Also, if the radius of the proton r_p is assumed to be $r_e/4$, then the ratio of r_p and the maximum radius of a DHA r_1^- is as follows.

$$\frac{r_1^-}{r_p} = \frac{r_e}{2} \frac{(1 + \alpha^2)^{1/2}}{(1 + \alpha^2)^{1/2} + 1} \cdot \frac{4}{r_e} = 1.0000133124. \quad (30)$$

In Formula (27), the electron approaches toward $r_e/4$ as n increases.

The following shows classical illustrations of an ordinary hydrogen atom and a DHA (**Figure 1**).

The figure at left is a classical illustration of an ordinary hydrogen atom. The distance from the center of the atomic nucleus to the electron is r_n^+ . In contrast,

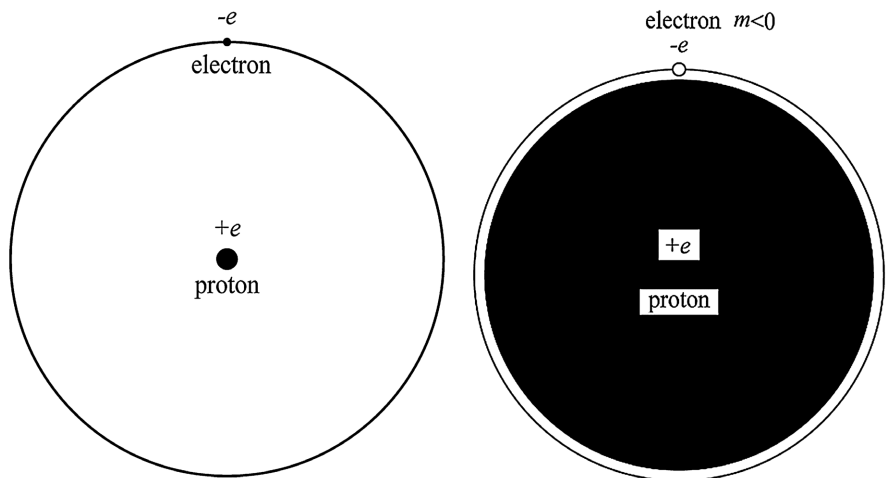


Figure 1. Classical illustrations of a hydrogen atom and a dark hydrogen atom (DHA).

the figure at right is an illustration of a DHA at the ultra-low energy level. The distance from the center of the atomic nucleus to the electron is r_n^- . As is evident from Formula (30), an electron with negative mass which forms a DHA is present near the proton (black circle part). It can be predicted that a DHA is matter extremely similar to a neutron.

Recent experimental results measuring neutron lifetimes have led to consideration of the possibility that some neutrons may become DM [38]. Under the DM model presented in this paper, it is believed that such a possibility is quite plausible.

Incidentally, according to Einstein's STR, the rest mass energy of the electron is $m_e c^2$. Inside a hydrogen atom, the rest mass energy of the electron is depleted when the electron approaches the atomic nucleus up to the point $r = r_e$. However, the electron acquires a kinetic energy of $m_e c^2 / 2$ at this time.

Therefore, according to this paper, the energy of an electron which has approached the atomic nucleus to the point $r = r_e / 2$ is as follows.

$$V(r_e/2) = -m_e c^2, \quad K = 0, \quad E_{ab} = 0. \quad (31)$$

However, under these conditions, the electron cannot approach closer than this to the atomic nucleus. We must consider how the electron can reach ultra-low energy levels.

Thus, taking a hint from the idea of renormalization theory, the author has previously assumed that the energy of an electron placed at the point $r = r_e / 2$ is not actually zero, and that this electron additionally has a photon energy $m_e c^2$ and a negative energy specific to the electron of $-m_e c^2$ [25] [26].

It is strange that negative energy levels exist even though energy is described with an absolute scale. To resolve this contradiction, the author has previously predicted the existence of photons with negative energy [20] [25] [31] (Figure 2).

Incidentally, Daviau, C. has already discussed the cloud of photons of an electron. For details, please see that paper [39].

In the state $E_{ab} = 0$, the photon energy $m_{e,B} c^2$ and negative energy $-m_e c^2$ cancel each other out, resulting in a state where energy is zero. An electron in the state where $E_{ab} = 0$ still has photon energy, so it can emit another photon and drop to a negative energy level.

Incidentally, the author has shown in a recent paper that Formula (16) can be written as follows [27] [40].

$$(m_n c^2)^2 + c^2 p_{re,n}^2 = m_{e,A} c^2 \cdot m_{e,B} c^2, \quad -m_{e,B} c^2 < m_n c^2 < m_{e,A} c^2. \quad (32)$$

That is, the following is evident from Formulas (16) and (32).

$$(m_e c^2)^2 = m_{e,A} c^2 \cdot m_{e,B} c^2 \quad (33)$$

If the existence of photon energy $m_{e,B} c^2$ illustrated in Figure 2 can be proven, it would simultaneously prove the existence of negative energy $-m_e c^2$ specific to the electron.

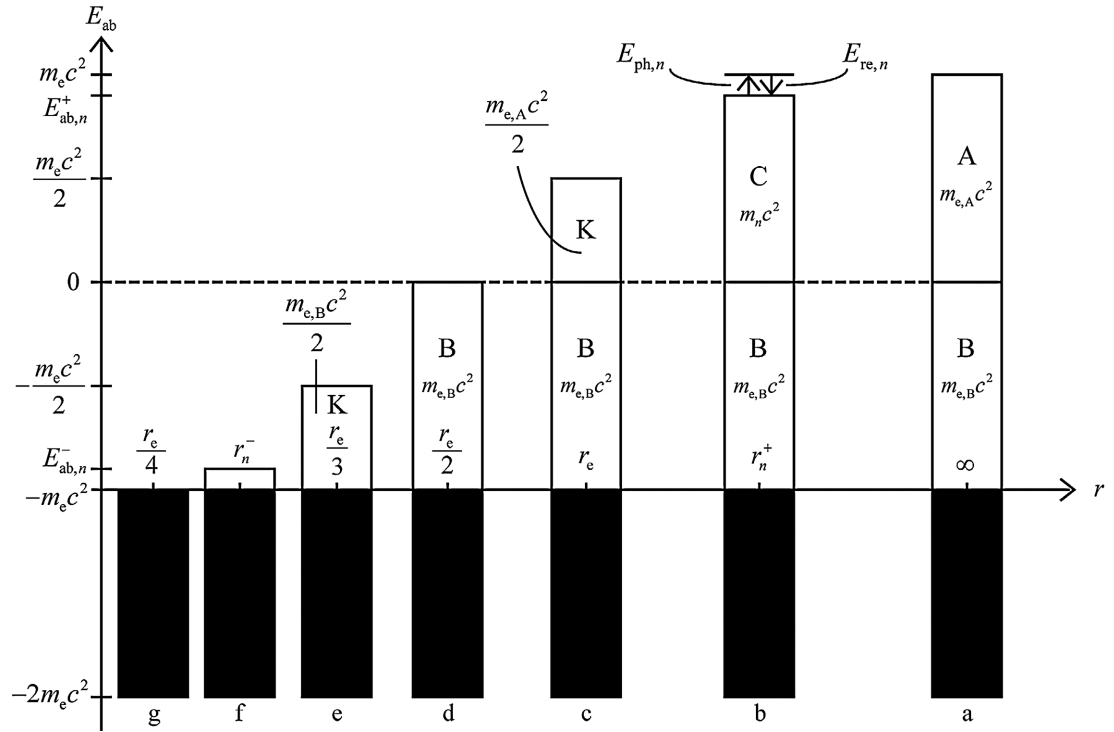


Figure 2. Photon energies of electrons in different states, and negative energy. Energy A is an energy we understand well. The energy recognized in existing physics is $0 \leq E_{ab}$. This paper asserts the existence of the B part ($m_{e,B}c^2$). Also, the negative energy specific to the electron $-m_e c^2$ corresponds to the black rectangle. This figure shows that the original photon energy of an electron with rest mass energy $m_e c^2$ is $2m_e c^2$. (However, this figure is just a conceptual illustration. The r coordinate on the x -axis is not accurate). Also, the energy K of state c and e is kinetic energy of the electron. The electron in state e is in strange state where it has negative mass but positive kinetic energy.

3. The True Nature of Dark Matter—Elucidated by Reexamining the Interpretation of Triplet Production

When a photon (γ -ray) with energy of 1.02 MeV ($2m_e c^2$) passes near an atomic nucleus, the γ -ray disappears in the Coulomb field of the nucleus, and an electron-positron pair is created. This is electron-positron pair production.

Electron pair annihilation, the phenomenon opposite to this electron pair production, is a phenomenon where a positron created by electron pair production collides with a surrounding electron and disappears. When these two types of particles annihilate, two γ -rays are produced. The energy of each γ -ray produced at this time is 511 keV ($m_e c^2$).

Also, triplet production is a phenomenon in which 2 electrons and 1 positron are produced when a γ -ray with energy of 2.04 MeV ($4m_e c^2$) loses energy. This is ordinarily interpreted as adding up to 3 particles: the electron and positron produced from the vacuum plus an orbital electron of a hydrogen atom. However, thinking about this in simple terms, the explanation does not make sense energetically.

These phenomena will be explained below using existing theory and the model

proposed by this paper, and the relative merits of the models will be determined.

First, let us examine Dirac's hole theory, which first predicted the existence of antiparticles. It is known that solutions to the Dirac equation, which is the relativistic wave equation for electrons, include negative energy solutions in addition to positive solutions. However, electrons with negative energy are not observed in the real world. Therefore, Dirac assumed that the vacuum is filled with electrons having negative energy, so that electrons cannot fall into negative energy states. Dirac then interpreted that when one electron in the vacuum is excited and jumps out into free space, the hole (vacancy) left behind behaves as a positron (antiparticle of the electron) with positive charge (however, Dirac himself initially thought this hole was a proton) (Figure 3).

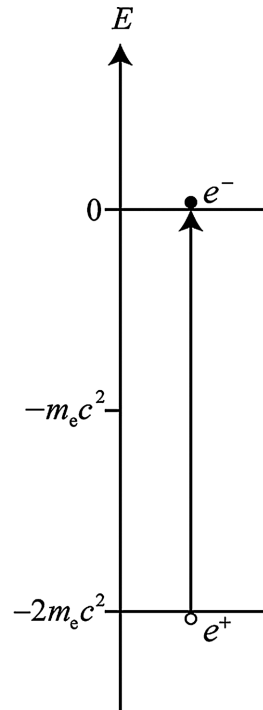


Figure 3. Electron-Positron pair production explained with the Dirac hole theory.

In Dirac's hole theory, when the γ -ray gives all of its energy to the virtual particles comprising the vacuum around the atomic nucleus, a virtual particle acquires rest mass, and is emitted as an electron into free space, while the hole opened in the vacuum is the positron. However, even if Dirac's model can explain pair production, it cannot explain pair annihilation.

According to Dirac's hole theory, when electron-positron pair production occurs, only the electron absorbs the 1.02 MeV γ -ray. Therefore, in the reverse phenomenon of pair annihilation, the electron must emit a 1.02 MeV γ -ray and fall into a negative energy state. Dirac's vacuum exists in the energy region where $E < -m_e c^2$. Therefore, Dirac's model cannot explain the phenomenon of pair annihilation where two γ -rays with energy of 511 keV ($m_e c^2$) are generated. What happens if we assume that virtual electron-positron pairs exist in the region where

energy is $E < -m_e c^2$? (Figure 4).

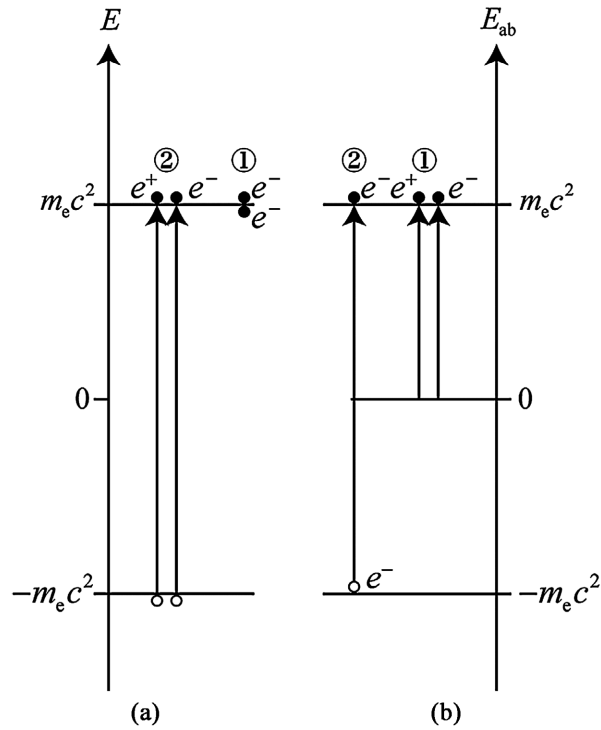


Figure 4. (a) is a model based on Formula (2). In this model, $E < -m_e c^2$ is the vacuum region. Virtual electron and positron pairs in this energy region constitute the vacuum. In contrast, in the model of this paper derived from Formula (16), shown in (b), virtual electron and positron pairs in the state where $E_{ab} = 0$ constitute the vacuum. In (a), 2.04 MeV ($4m_e c^2$) of energy is required for electron-positron pair production ②. Therefore, this model can explain triplet production but cannot explain pair production and pair annihilation.

Incidentally, in modern quantum field theory, energy equal to or greater than the sum of the rest mass energies of the produced electron and positron is required for electron (particle) and positron (antiparticle) pair production to occur. In other words, electron-positron pair production requires at least 1.02 MeV ($2m_e c^2$) of energy. In quantum field theory, when bare electrons and positrons without photons have zero energy, these virtual particle pairs are regarded as constituting the vacuum. However, to claim that the state in a hydrogen atom where $E_{ab} = 0$ is a vacuum state, Formula (16) rather than Einstein's relationship (2) must be used as the relation applicable to the electron. However, Formula (16) has not yet been accepted in modern physics.

Finally, let us examine the model proposed by this paper that uses Formula (16) (Figure 4(b)). The virtual electron-positron pair before absorbing a γ -ray has zero relativistic energy, that is, it is in a state where $E_{ab} = 0$. This is the vacuum state in this paper. When a virtual electron-positron pair in this state absorbs half the energy of a γ -ray with 2.04 MeV ($4m_e c^2$) of energy, an electron-positron pair is produced. Then an electron at an ultra-low energy level subsequently absorbs the

remaining 1.02 MeV ($2m_e c^2$) of energy and becomes excited. This situation can be explained in more detail as indicated in the following diagram (**Figure 5**).

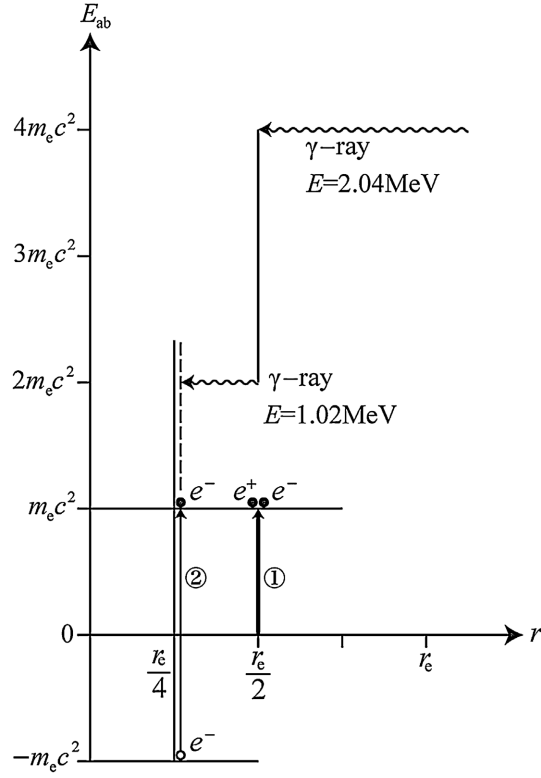


Figure 5. Interpretation of this paper regarding triplet production.

Consider the case where a γ -ray with the energy of 2.04 MeV ($4m_e c^2$) is incident on an atomic nucleus (proton). This γ -ray will give 1.02 MeV of energy to the virtual particles at $r = r_e/2$, and an electron-positron pair will be created ($\uparrow$ ①). When this γ -ray approaches closer to the atomic nuclear, and the electron in the orbital around the proton absorbs this energy, the electron will be excited and appear in free space ($\uparrow$ ②). As a result, 2 electrons and 1 positron will appear in free space.

Using the model in this paper, all phenomena of electron pair production and annihilation, as well as triplet production, can be explained without difficulty.

4. Conclusions

This paper concludes that one of the two electrons generated by triplet production is an electron from DHA that was at an ultra-low energy level.

DM existing in the filaments of the universe's large-scale structure can not only attract ordinary matter through its gravity, but can also produce ordinary matter such as hydrogen atoms and other atoms and molecules by absorbing γ -rays with energy of 1.02 MeV ($2m_e c^2$) or higher. The reverse phenomenon is also thought to be possible, *i.e.*, where ordinary matter emits γ -rays and becomes DM.

This paper predicts that the true nature of DM is an unknown substance formed

from dark hydrogen atoms and other atoms and molecules in ultra-low energy states.

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Author Contributions

The author confirms sole responsibility.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix A

Taking Formula (3) into account, Formula (2) can be rewritten as follows.

$$\begin{aligned} c^2 p^2 &= (mc^2 - m_0 c^2)(mc^2 + m_0 c^2) \\ &= K_{\text{re}} (mc^2 + m_0 c^2). \end{aligned} \quad (\text{A1})$$

From this, the following formula for relativistic kinetic energy can be derived.

$$K_{\text{re}} = \frac{p_{\text{re}}^2}{m + m_0}. \quad (\text{A2})$$

Here, $p_{\text{re},n}$ is the relativistic momentum of the electron. The relativistic kinetic energy of an electron inside a hydrogen atom is defined as follows by referring to Formulas (3) and (A2).

$$K_{\text{re},n} = m_e c^2 - m_n c^2. \quad (\text{A3})$$

$$K_{\text{re},n} = \frac{p_{\text{re},n}^2}{m_e + m_n}. \quad (\text{A4})$$

Linking the right sides of Formulas (A3) and (A4) with an equals sign and rearranging, the following relationship can be derived.

$$(m_n c^2)^2 + c^2 p_{\text{re},n}^2 = (m_e c^2)^2. \quad (\text{A5})$$

This energy-momentum relationship is applicable to an electron inside a hydrogen atom.

Appendix B

Bohr's orbital radius $r_{\text{BO},n}$ is normally described with the following formula.

$$r_{\text{BO},n} = 4\pi\epsilon_0 \frac{\hbar^2}{m_e e^2} n^2. \quad (\text{B1})$$

Bohr thought the following quantum condition was necessary to find the energy levels of the hydrogen atom.

$$m_e v_n \cdot 2\pi r_{\text{BO},n} = 2\pi n \hbar. \quad (\text{B2})$$

In Bohr's theory, the energy levels of the hydrogen atom is treated non-relativistically, and thus here the momentum of the electron is taken to be $m_e v$. Also, the Planck constant h can be written as follows [41].

$$\hbar = \frac{h}{2\pi} = \frac{m_e c \lambda_C}{2\pi}. \quad (\text{B3})$$

λ_C is the Compton wavelength of the electron.

When Formula (B3) is used, the fine-structure constant α can be expressed as follows.

$$\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} = \frac{e^2}{2\epsilon_0 m_e c^2 \lambda_C}. \quad (\text{B4})$$

Also, the classical electron radius r_e is defined as follows.

$$r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2}. \quad (\text{B5})$$

If r_e/α is calculated here,

$$\frac{r_e}{\alpha} = \frac{\lambda_C}{2\pi}. \quad (\text{B6})$$

If Formula (B1) is written using r_e and α , the result is as follows.

$$r_{\text{BO},n} = 4\pi\epsilon_0 \frac{\hbar^2}{m_e e^2} n^2 = \frac{e^2}{4\pi\epsilon_0 m_e c^2} \left(\frac{4\pi\epsilon_0 \hbar c}{e^2} \right)^2 n^2 = \frac{r_e}{\alpha^2} n^2. \quad (\text{B7})$$

Formula (B7) containing r_e is superior to Formula (B1) from a physical standpoint.

Next, if $\hbar$ in Formula (B3) and $r_{\text{BO},n}$ in Formula (B7) are substituted into Formula (B2),

$$m_e v_n \cdot 2\pi \frac{r_e}{\alpha^2} n^2 = 2\pi n \frac{m_e c \lambda_C}{2\pi}. \quad (\text{B8})$$

If Formula (B6) is also used, then Formula (B8) can be written as follows.

$$m_e v_n \cdot 2\pi \frac{r_e}{\alpha^2} n^2 = 2\pi n \frac{m_e c r_e}{\alpha}. \quad (\text{B9})$$

From this, the following relationship can be derived [42].

$$\frac{v_n}{c} = \frac{\alpha}{n}. \quad (\text{B10})$$

Due to Formula (B10), it is possible to identify discontinuous states that are permissible in terms of quantum mechanics in the continuous motions of classical theory.