Mass-Energy Equivalence in Nuclear Physics

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Abstract

Like the positron-electron pair production shown in high energy physics, elementary particles can be created and annihilated in phenomena, which means that energy and mass can be exchangeable especially in subatomic physics. However, it should be clear that mass and energy in physics can be converted to each other in some cases but not always equivalent. From the ontological review of the mass-energy equivalence principle in special relativity and the mass defect in nuclear physics with the first principle in 4-D complex space, we can understand how these two distinctive concepts in physics can be interchangeable. Although nuclear force, which makes nucleons, protons and neutrons, bound inside the nucleus, and nuclear interactions, strong and weak interactions, which participate in nuclear fusion and nuclear fission process, have been explained in standard model of particle physics, in which the existence of an intermediate or force-carrying particle (boson) in the interactions has been known for a long time. However, it is not so clear how the intermediate boson makes the interaction possible. For the interactions of subatomic particles, alternatively we can find more agreeable explanation than the one using the intermediate boson in standard model of particle physics. In addition, a brief discussion is followed for the neutrinos in weak interaction and the lifetime of neutron in free space.

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Introduction

The interactions in the atomic nucleus explain how nucleons (protons and neutrons) are bound in the nucleus, which is known as the residual strong force in quantum chromodynamics (QCD); how a nucleon transforms to the other in β-decay, which is weak interaction; and how nuclear fission and nuclear fusion occur. Nuclear force binds nucleons together in the atomic nucleus; the range of the force is much smaller than atomic scale, but intensity of the force is much stronger than electromagnetic force that is dominant interaction in atomic scale. In addition, it has been known to be charge independent.

In phenomenology, the nuclear force has been explained with semi-empirical models introducing internucleon potential inside the nucleus. For example, in 1935, Yukawa potential explained the short-range interaction inside the nucleus with introducing a massive particle being exchanged between two nucleons, which was the pion discovered later. Similarly, QCD in standard model of particle physics explains the nuclear force, which is called a residual of the strong force; however, it is using a similar concept that is exchanging or intermediating massive particle (pion) between two nucleons as in Yukawa potential.

It has been almost a common sense to mention intermediate bosons (gauge bosons) especially in quantum field theory, those of which participate in interactions, such as gluon in QCD, $W^{\pm}$ and Z bosons in weak interaction, photon in electromagnetic interaction, and graviton in gravitational interaction. However, for the explanation that the massive particle such as pion is being exchanged between two nucleons, we might wonder whether there is another way to make it clear or not. Although the strong interaction in such short range can be explained with introducing the massive particle such as pion, it is not so clear how two nucleons are binding together with exchanging the massive particle. Is the massive particle literally being exchanged between two nucleons? Why it is not tugging or not sharing in the middle of them? In general, if the massive intermediate particle (boson) is in free state, it is not stable but decays with a lifetime[2]. It might be wonder what makes the intermediate particle stable in the nucleus and why it decays in free space. What if it is the equivalent energy of vacuum particles resonating with energy $E \sim m_{pion} c^2$ between nucleons in the nucleus. Then, we need review the mass-energy equivalence principle in physics.

In nuclear physics, the mass defect is based on two important concepts in physics, one is the conservation of energy and the other is mass-energy equivalence. The mass-energy equivalence has been proved in experimentations of high energy physics such as particle and antiparticle, a pair creation and annihilation. Energy can create mass in phenomena, matter from nothing; inversely, the mass can be converted to energy and annihilated back to the nothing. However, electron or positron, for example, cannot be created and annihilated alone without its antiparticle, which means that the principle of mass-energy equivalence can be true in general but not always. We need to understand the principle of mass-energy equivalence with physical interactions in 4-D complex space.

[2] Lifetime of $W^{\pm}, Z^0 \sim 3\times10^{-25}$ sec

Mass-Energy Equivalence

The special theory of relativity has been a firm foundation in modern physics since last century; however, there are some facts to be explained clearly in respect of physical reality and/or in philosophy. In special relativity, truths in phenomena or physics, in which phenomenological facts should be based, is relative depending on the relative motion of observers; hence, the time dilation and the length contraction in the theory seem to be paradoxical. The equivalence of mass and energy was originated from the special relativity in 1905, but its physical interpretation seems to be not crystal clear yet although some philosophers and physicists keep trying to make it clear (Fernflores 2019). Let's review special theory of relativity briefly, which starts with two propositions as light speed is constant and physics laws are invariant in all inertial frames of reference.

Let's describe a physical event (kinetic motion of a physical object) using space-time coordinates in two inertial frames of reference, $O_1(t_1, \vec{x}_1)$ and $O_2(t_2, \vec{x}_2)$, those of which are moving relatively to each other with a constant velocity υ. Let's say, two frames are overlapped at time $t_1 = t_2 = 0$ as $\vec{x}_1 = \vec{x}_2$. A light signal emits from the origin of frame O_1 at $t_1 = 0$ toward positive x_1 direction, and at the same time frame O_2 itself starts moving toward positive x_1 direction with the speed υ in the frame O_1.

In frame O_1, position of the light signal $x_1 = ct_1$ at $t = t_1$, in which c is the speed of light; if an observer is at the origin of frame O_1 and observe the light signal in frame O_2, the signal is at $x_2 = (x_1 - \upsilon t_1)$; however, if another observer is at the origin of frame O_2 and observe the signal in frame O_1, the signal is at $x_1 = (x_2 + \upsilon t_2)$ because the speed of light is constant in both frames. Since $x_2 = ct_2$ and $x_1 = ct_1$ in the frames, O_1 and O_2, respectively, we can expect the relations as $t_1 = (c + \upsilon)t_2$ and $t_2 = (c - \upsilon)t_1$ but it cannot be possible because $(c^2 - \upsilon^2) \neq 1$ in general. Then, we should recognize that the time t_1 that is observed in frame O_2 doesn't have to be the same value as the one observed in frame O_1; in fact, it cannot be the same time except the time $t_1 = t_2 = 0$. Therefore, we can put the relations as $x_2 = \gamma(x_1 - \upsilon t_1)$ and $x_1 = \gamma(x_2 + \upsilon t_2)$ with a proportional factor γ on both equations because of the symmetry in Cartesian Coordinates system of frame O_1 and O_2, which is known as Lorentz transformation with Lorentz factor γ expressed as $\gamma = \frac{1}{\sqrt{1-\left(\frac{\upsilon}{c}\right)^2}}$.

In special relativity, the length and time interval, those of which are related to fundamental variables describing the kinetic motion of physical object, are measured differently in two inertial frames of reference those of which are relatively moving with velocity υ, and which are known as length contraction and time dilation in the theory. The time dilation in special relativity has been confirmed through experimentations and observations such as muon decay process; for example, high energy cosmic rays interact with air molecules and produce lots of secondary particles including muons upper atmosphere of the earth, and those muons are detected at sea level, which cannot be explained without the time dilation in special relativity for stationary observers at sea level because the traveling distance of muon from the upper atmosphere to the sea level $L > c\tau_0$ even if the velocity of muon is close to the speed of light as $\upsilon \sim c$, where τ_0 is the lifetime of muon on its rest frame[3]. Instead, the traveling distance $L \leq c\tau$ in which τ is the lifetime of muon when it is moving with velocity υ and expressed as $\tau = \gamma\tau_0$ in which $\gamma \gg 1$ because of $\upsilon \sim c$. Alternatively, it can be explained with the length contraction expressed as $L_0 = L/\gamma$, which is observed in muon rest frame.

Anyhow, as shown above or in special relativity if we don't overlook the fact that the differences of lengths and time intervals are measured using light signals in two inertial frames relatively moving to each other; then, we need to wonder how the results observed by light signals can be generalized and applied to describe physical events in general.

For the question why the lifetime of muon increases with the Lorentz factor γ when it is moving, in fact, the explanation with time dilation in special relativity is not enough because *time*, which is one of variables to describe phenomena in physics, is like a bystander in a situation, in which it doesn't do anything. Then, there should be a physical reason to increase the lifetime of muon when it is in kinetic motion.

To describe kinetic motions in physics or physical events consistently in all inertial frames, the Lorentz transformation is expressed with 4-vector notation and 4-vector conservation (Lorentz invariance) in Minkowski space. Similarly, the energy and momentum of physical object moving with velocity υ can be expressed with energy and momentum 4-vector notation in the Lorentz transformation, in which the energy of physical object is expressed as $E = m_0\gamma c^2$ and the relation of momentum is expressed as $E^2 = (pc)^2 + (m_0c^2)^2$ in which momentum $\vec{p}$ is defined as $\vec{p} = m_0\gamma\vec{\upsilon}$ since momentum conservation should be valid in all inertial frames of reference, m_0 is rest mass, and m_0c^2 is called rest mass energy. In general, $E = mc^2$ where $m = m_0\gamma$, which means that mass and energy is equivalent and the physical mass increases with velocity υ. However, the kinetic energy of physical object moving with velocity υ is expressed as $T = m_0\gamma c^2 - m_0c^2$, which is more realistic and used to be acceptable energy of the physical object in classical physics.

Now, we need to review what the mass-energy equivalence really means. The question is how the mass, which is real matter in the form of solid, liquid, gas, or plasma and composed of molecules, atoms, etc., can be energy, which is an abstract concept expressed as kinetic, potential, or thermal energy, etc.; how it can be increased with a relative motion; and inversely, how the energy can be the mass.

Once the 4-vector notation for energy and momentum is introduced with the Lorentz transformation as the 4-vectors of space-time coordinates, physical phenomena can be expressed consistently and conveniently in all inertial frames. However, at this point we should recognize that the relation of mass and energy (mass-energy equivalence) is not the one derived with the two postulates, but a theoretical proposition added in the theory of special relativity (Einstein 1905).

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[3] $\tau_0 = 2.2 \times 10^{-6}$ sec

If the rest mass energy m_0c^2 never be realized in physical realty, which can be true in classical physics, it is just a redundancy in the theory. However, there have been many supportive evidences for the mass-energy equivalence such as the mass defect in nuclear process, electron-positron pair creation and its annihilation in high energy physics, etc. Nevertheless, we cannot explain how the mass of moving object increases; for example, there is a stationary object with mass m_0 for observer O_0; however, the mass of the object can be different as mass $m = m_0\gamma(\upsilon)$ for observers moving with velocity υ relative to the stationary observer O_0, which means, the mass of the object m can be different for every observer with different relative velocity υ to the stationary observer O_0. Then, the mass in special relativity is not real but representing energy increase in a relative motion with the rest mass.

Physics in 4-D Complex Space

As long as physical event is related with lights or electromagnetic interaction, we should accept the relation of space-time coordinates in inertial frames or the Lorentz transformation as facts to describe physics properly. Then how we can interpret the mass-energy equivalence? Is it just a redundancy appeared in the Lorentz transformation that can be derived from the measurements of light signals in two inertial frames of reference, one is for an observer and the other is for the light source moving relative to the observer? The special relativity says, there is no absolute frame of reference to describe phenomena but relative to other reference frames, which is expected naturally because the speed of light is constant in all reference frames. Then, why the speed of light is constant and why it is the upper limit that cannot be reached by any massive object in phenomena?

For fundamental questions such as why the speed of light is constant in all reference frames, how the time dilation and/or length contraction in special relativity can be understood, and what the mass-energy equivalence means in physics, and so on, we can find comprehensive explanations with the first principle in 4-D complex space (Kim 1997) (Kim 2008) (Kim 2017).

Firstly, the propagation of light is made through vacuum particles, those of which are bound with negative energies in imaginary subspace that is orthogonal to real subspace in 4-D complex space; and the energy of light is realized in phenomena with interactions in physics. Hence, the speed of light is constant in all reference frames.

Next, the interaction of vacuum particles with a physical object exists in phenomena with the first principle given in 4-D complex space. Field energies in physics, such as gravitational, electric, magnetic energy, etc., are energies stored in vacuum particles rearranged in the imaginary subspace. If the physical object is in motion, the interaction of vacuum particles itself follows the physical object, which is a wave motion of vacuum particles in imaginary subspace[4] of 4-D complex space and which corresponds to kinetic energy of the physical object. However,

[4] let's name it **physical vacuum space**.

the wave motion of vacuum particles can be considered like a wave packet wrapping and following the physical object although it is in physical vacuum space.

If the physical object has rest mass m_0 and moves with velocity υ, The kinetic energy $T = m_0\gamma c^2 - m_0c^2$ in special relativity, in which the kinetic energy is proportional to the rest mass as $T = m_0c^2(\gamma - 1)$ if the rest mass $m_0 \neq 0$. Here, the speed υ of the object cannot be reached to the speed of light c because $\gamma \to \infty$ if $\upsilon \to c$, which means that infinite energy or work is needed.

In physical phenomena involved in electromagnetic interactions or observed with light signals, the theory of special relativity should be valid; however, the time dilation and/or length contraction in the theory are relativistic effects in phenomena, in which electromagnetic interaction is made through vacuum particles in physical vacuum space. In fact, the time dilation and/or length contraction in special relativity is for physical vacuum space, in which the propagation of light is made through vacuum particles.

Here, we can find the reason for the upper limit of speed ($\upsilon < c$) in special relativity not from the mathematical expression in the theory as above, but in the ontological interpretation of kinetic energy and length contraction: In the wave motion of vacuum particles following a physical object moving with speed υ, which is realized as kinetic energy of the object, the wave motion gets shrunk due to the distance shortened between vacuum particles, which is not an effect in phenomena but true for the length contraction in special relativity. If the speed υ gets close to the speed of light c, it means that the distance between vacuum particles gets close to zero. To make the distance close to zero, it is expected that the energy or work to be supplied gets increase enormously, and actually the zero distance between vacuum particles or the speed $\upsilon = c$ is not possible.

Now, we can explain how the lifetime of muon increases if it is moving relative to a stationary observer. Let's say, the muon lifetime is τ_0 in its rest frame, in which $E_{m_0} = m_0c^2$; then, if it is moving with velocity υ, the lifetime $\tau = \gamma\tau_0$ with the Lorentz factor γ, which is interpreted as the time dilation in the theory; however, as mentioned before, we need to ask a fundamental reason how it is possible.

We know the energy of muon increases with factor γ as $E_m = \gamma m_0c^2$ and the lifetime also increases by the same factor. Here, we see, the lifetime of muon is dependent on its total energy, rest mass energy and kinetic energy, in which the kinetic energy is corresponded to a wave motion of vacuum particles following the rest mass of muon. Hence, we can interpret that the lifetime of muon is dependent of total energy of muon. This kind of view or interpretation can be viewed more clearly if the muon is supposed to be a resonating state of vacuum particles in physical vacuum space.

In 4-D complex space, physical interactions, such as electromagnetic, gravitational interaction, and so on, are supposed to be described with the number density of vacuum particles (Kim 2008) (Kim 2017); for example, an attractive interaction between two nucleons means that less number density of vacuum particles between the nucleons than surrounding in physical vacuum space, and the less number density of vacuum particles can be interpreted as less negative energy density in physical vacuum space, which means that it appears as a positive mass or energy in the interaction of two nucleons in phenomena.

On the other hand, in nuclear process such as nuclear fusion or nuclear fission, comparing the mass difference before and after the process, we can figure out how much energy can be liberated, which is called mass defect expressed as $\Delta \mathrm{E} = \Delta m\, c^2$. If the mass of a nucleus is bigger than the sum of all the mass of constituents in the nucleus, the fission process can happen; then, the liberated energy is corresponded to the mass defect. If the mass of a nucleus is smaller than the sum of all the mass of constituents in the nucleus, the nucleus is known to be stable; however, if a fusion process happens, in which all the constituents are fused from their free states into the nucleus, the same amount of energy as the mass defect is liberated through the fusion process.

Now, the mass defect in nuclear physics or the mass-energy equivalence principle in special relativity can be explained with the physical interactions in 4-D complex space as above. For stable atomic nucleus the mass of the nucleus is smaller than the mass sum of all composing nucleons in free states because the nucleons are bound together in the nucleus. Here, the 'bound together' means that the interaction between nucleons should be attractive; thus, the number density of vacuum particles in the physical vacuum space corresponding between nucleons is less than surrounding, and that the attractive interaction can be expressed as a positive energy or mass between the nucleons in phenomena; however, more vacuum particles surrounding the mass and nucleons are expected, which makes the mass of nucleus smaller and the nucleus gets stable.

Nuclear Force

In nuclear physics, it has been known that nuclear force is charge independent, in which proton and neutron are two different isospin quantum states of the same nucleon (one identity) in SU(2) and in general the state of a nucleon is a mixed state of proton (isospin up) and neutron (isospin down), and attractive much stronger than electromagnetic force in such short range inside the nucleus. In the atomic nucleus nucleons (protons and neutrons) are bound together through the exchange of massive particles (intermediate bosons) among the nucleons.

Instead of two different states described in SU(2), proton and neutron can be viewed as two different internally composite objects with electric charge distributions and dynamic motions (spin). Then, the nuclear force inside the nucleus, which has been known as residual strong force in standard model in particle physics, can be explained as a special case of electromagnetic interaction (Kim 2022). Now, we can explain for the binding of nucleons in the atomic nucleus with a temporally resonating vacuum particles in physical vacuum space between nucleons, in which number density of vacuum particles in inner space[5] between nucleons is less than outside;

[5] it is physical vacuum space corresponding to the real subspace.

thus, the attractive interaction can be interpreted as a positive energy or mass in physical phenomena, which corresponds to the massive intermediate particle (gauge boson) in subatomic physics, in general, or the mass term in the propagator represented in momentum space in quantum field theory. Now, the intermediate or force carrying particle in nuclear interaction is considered as the equivalent mass of resonating energy of vacuum particles participating in the interaction.

According to the standard model in particle physics, elementary particles, such as $\gamma, W^{\pm}, Z,$ etc. (gauge bosons), quarks, leptons (e, μ, τ, etc.), are not composed of other particles, and all the intermediate bosons (gauge bosons) have lifetimes and tau τ and muon μ (charged leptons) also decay except photon γ and electron e. It's interesting that all of those particles except electron e involved in weak interaction are decayed.

The gauge bosons $W^{\pm}$ and Z, which are force carriers in weak interactions, exist only during the interactions and the energy-momentum relation $E^2 = pc + m_0c^2$ is not required; thus, the gauge bosons are called virtual particles in quantum field theory. Then, those intermediate bosons and charged lepton tau τ and muon μ with such short lifetimes can be considered as the equivalent mass ($W^{\pm} \sim 80\ GeV/c^2$, $Z \sim 90\ GeV/c^2$) to the resonating energy of vacuum particles in physical vacuum space.

Discussion

With physical interactions in 4-D complex space, we can understand how the time dilation and/or length contraction in special relativity is related to physical phenomena and how the mass-energy equivalence principle makes sense in nuclear physics. In addition, the intermediate boson in nuclear interaction is nothing but the equivalent mass of resonating vacuum particles participating in the interaction. For those transient intermediate bosons and elementary particles with such short lifetime, if we say, they are particle-like expressions for the equivalent energy of resonating vacuum particles in physical vacuum space, is it gone too far? If that is true, we might wonder how many elementary particles can exist in nature.

If then, one step further, the weak interaction, in which the identity of nucleon is changed with generating an electron or positron and a neutrino (antineutrino), also should be explained with electromagnetic theory including neutrino[6] and the modeling of $W^{\pm}$ and Z^0 bosons without introducing the spontaneous symmetry breaking and Higgs mechanism, etc. Moreover, it should be found the fundamental reason that neutrino is generated only in electroweak interaction and photon is highly suppressed in such short-range interaction inside the nucleus.

[6] neutrino is a bundle of longitudinal vacuum string vibrations in physical vacuum space in 4-d complex space.

In weak interaction, not only does neutrino participate, but also parity violation appears; hence, it has been believed that only left-handed neutrinos exist in phenomena. However, the most fundamental principle in nature is equal probability or fairness in phenomena. If we can measure only left-handed neutrinos in experiments, it doesn't mean that, strictly speaking, right-handed neutrinos do not exist in nature. What if the measurement itself makes the helicity of neutrino be left-handed? For example, my dog is always running toward me whenever I open the door no matter it is the front door or the back door in my house, in which *door opening* itself makes the dog pay attention to me.

Neutron is one of subatomic particles composing atomic nucleus in which nucleons (neutrons and protons) are holding together with nuclear force that has been known as the residual strong force in QCD (quantum chromodynamics), which occurs, by exchange of virtual light mesons, such as virtual pions, etc. (Wiki-Nuclear-Force)

Neutron is electrically neutral and heavier than proton ($\Delta m \sim 2.53\, m_e$) and it is not free in free space and decays in about 15 minutes to proton with electron and neutrino, which is β-decay or weak interaction in the standard model of particle physics; however, it is stable with protons inside stable nuclei, which can say that the interaction with protons in the nuclei makes it stable and that the repulsive coulomb interaction among protons is also suppressed by virtue of neutrons. However, neutron can be converted to proton and vice versa in unstable nuclei, which makes the nuclei stable.

The lifetime of free neutron has been measured for decades with two distinctively different methods, called as bottle method and beam method (Gonzalez, F. M. et al. 2021) (F. E. Wietfeldt, et al. 2014) (NIST 2021), in which the neutron lifetime measured from both methods is supposed to be consistent or close enough to each other with an uncertainty. However, the discrepancy of lifetime in experimental measurements with the two methods doesn't get smaller or disappears, but it shows clearly a difference that makes people to consider some other systematic reason (Wolchover 2018) (Serebrov 2019) (L. J. Broussard et al. 2022) that cannot be found in the standard model of particle physics. Then, the anomaly of neutron lifetime has been a so-called puzzle and generated even some exotic ideas, such as dark matter candidate, mirror neutron, etc.

However, if we consider the classical picture for nucleons as composite objects with electric charge distributions and spins, we can find a clue for the reason that the difference occurs in the neutron lifetime measurements. Inside stable nuclei, neutrons are stable with protons due to the electric polarization against the positive charge of proton and the spin-spin magnetic interaction with proton's magnetic moment, which is nothing but electromagnetic interaction (Kim 2022). Now, we might have a reasonable suspicion that the strong electric field and magnetic field applied in the beam method might makes the difference of neutron's lifetime measurements because the neutron lifetime from beam method is bigger than from bottle method ($\tau_{beam} > \tau_{bottle}$), in which $\Delta\tau \sim 9\ sec$ (Clavin 2021).

This short letter is not to criticize or refute the standard model of particle physics that has been built for a long time. However, we need to consider an alternative view to understand natural phenomena comprehensively not just in phenomenological approach but also in the fundamental point of view. For example, with a proper modeling of W and Z bosons, an alternative but comprehensive explanation can be found for such fundamental questions as why only left-handed neutrinos have been measured, whether neutrino has rest mass really or just mass effect, how neutrino oscillation is possible, etc.

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