An Interpretation of “Superluminal Neutrinos” Compatible with Relativity in the Framework of Standard Model *)

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According to the measurement of muon-neutrino experiment done by the OPERA collaboration, the speed of high-energy neutrinos exceeds that of light in vacuum by 25ppm. Assuming that this result is correct, a possible resolution of the dilemma between it and the validity of relativity is proposed without changing the framework of the Standard Model of elementary particles. The essential idea is based on a possible resolution, proposed previously, of the color confinement problem of quantum chromodynamics.

§1. Introduction

Very recently, the OPERA collaboration has made a very sensational claim that according to their precision measurement, high-energy muon-neutrinos traveled from CERN to the underground Gran Sasso Laboratory (apart from CERN by 730km) faster than the speed of light measured in vacuum. Let \( v \) and \( c_0 \) be the speed of their neutrinos and that of light measured in vacuum, respectively; their result reads

\[
(v - c_0)/c_0 = [2.48 \pm 0.28\text{(stat.)} \pm 0.30\text{(sys.)}] \times 10^{-5}.
\]

Although the classical theory of relativity does not forbid the existence of the faster-than-light particles, called “tachyons”, which have a purely imaginary mass, it is known that the tachyon field cannot be consistently quantized in the framework of the positive-metric Fock space. Furthermore, from the experimental setting, it is impossible to interpret the OPERA neutrinos as tachyons. Hence, if their neutrinos have traveled truly faster than the speed of light in vacuum, the OPERA experimental result is incompatible with relativity. However, since the validity of relativity is supported by a vast amount of experimental evidences and by the brilliant successes of theories formulated on the basis of relativity, it is totally inacceptable that such a single experimental result as above rules out relativity. The only way-out is to assume that the fundamental constant \( c \) of relativity, “the speed of light in the true vacuum”, is different from \( c_0 \). Then, everything is all right if \( c_0 < v < c \).

The problem is then why \( c_0 \) is smaller than \( c \). As is well known, light travels in a medium slower than in vacuum. Therefore, if there exists an undetectable medium on Earth, then the measured speed, \( c_0 \), of light in such a medium is smaller than the speed, \( c \), of light in the true vacuum. A candidate of such a medium is dark matter. However, if dark matter consists of neutral elementary particles, such as neutralinos assumed in SUSY, then it cannot play the role of a medium, because a medium must consist of charged particles at the microscopic level as the ordinary
matter does. Previously, the present author proposed to explain dark matter by the neutron-like cloud of dispersed quarks. Since quarks are charged particles, this dark-matter candidate can be regarded as a medium. In the present paper, however, we concentrate our attention only to the problem of finding the resolution of the OPERA neutrino problem, forgetting the problem of the total amount of dark matter.

In Section 2, we review the theory of unobservable quarks. In Section 3, we discuss the compatibility of our proposal with the observation of the supernova SN1987A. In Section 4, some comments are made on related works.

§2. Theory of unobservable quarks

According to the Standard Model, hadrons consist of quarks (and antiquarks), but no quarks are observable. Quarks have a color charge, but experimentally it is known that only colorless states are observable. The dynamics of quarks is successfully described by quantum chromodynamics (QCD), but the problem of color confinement is usually regarded as unsolved yet. The conventional approach to this problem is only to discuss the confinement of the quark-antiquark system dynamically. The color confinement is, however, quite a universal phenomenon relevant to any complicated hadron-like system. It is quite unnatural to expect that such a clear-cut qualitative property as color confinement can be established only by means of complicated calculations of dynamics. In 1984, therefore, the present author and Ojima proposed a very simple way of color confinement in the framework of QCD. We review this theory very briefly in the following.

Of course, QCD is a non-abelian gauge theory. It is well known that the introduction of an indefinite-metric Hilbert space is indispensable in the manifestly covariant quantization of gauge theory. In order to secure the probabilistic interpretability, one must set up a subsidiary condition to define the physical subspace. The manifestly covariant formalism of a non-abelian gauge field is most satisfactorily formulated by using the BRS invariance. Then, according to the Noether theorem, the BRS charge $Q_B$ exists. The physical subspace $\{|\text{phys}\rangle\}$ is defined by the Kugo-Ojima subsidiary condition

$$Q_B|\text{phys}\rangle = 0.$$  \hspace{1cm} (2.1)

Now, the proposal made in the previous paper is as follows. QCD is an $SU(3)$-invariant gauge theory; correspondingly, there exists the color charge $Q^a$, where $a$ denotes the color index. In addition to (2.1), we introduce an extra subsidiary condition

$$Q^a|\text{phys}\rangle = 0.$$  \hspace{1cm} (2.2)

Because $[Q^a, Q_B] = 0$, (2.2) is compatible with (2.1). Under this setting-up, all colored states are unphysical; hence they should be unobservable.

Although color confinement has been globally realized by the above setting-up, this does not necessarily imply that it is so locally. There is the problem of “behind-the-moon”. Suppose that we have wished to make all electrically charged states unphysical by introducing a subsidiary condition $Q|\text{phys}\rangle = 0$, where $Q$ is the
electric charge. But this necessarily becomes unsuccessful: For example, consider a state consisting an electron at hand and a positron behind the moon. Then we can practically have an electron only. Mathematically, our physical state is a direct product of the electron state whose wave packet is located here and the positron state whose wave packet is located behind the moon. However, this is the speciality of the abelian symmetry. Since SU(3) is a non-abelian symmetry, there is quantum entanglement in a many-particle state; that is, any colorless state cannot be a direct product of several colored states consisting of unoverlapping wave packets. Precisely speaking, we can prove the following theorem: "Let $\varphi_1$ and $\varphi_2$ be the local operators whose supports are restricted to spacetime domains $\Omega_1$ and $\Omega_2$, respectively, which are mutually spacelikely separated. Furthermore, let $|0\rangle$ be the vacuum state and $Q^a$'s be the charge operators of a semisimple group. If $Q^a\varphi_1\varphi_2|0\rangle = 0$, then we have $Q^a\varphi_1|0\rangle = 0$ and $Q^a\varphi_2|0\rangle = 0.$" Therefore, any colored particle is unobservable under the subsidiary condition (2.2). Detailed mathematical considerations based on the gauge-theoretical extension of the axiomatic quantum field theory are presented in a previous paper.

Thus, in high-energy reactions involving hadrons, isolated quarks (and anti-quarks) may be created, but they cannot be observed as particles. In this sense, color confinement is achieved. Since the physical subspace no longer has the Fock structure with respect to asymptotic fields, the cross section of an inclusive reaction can be truly larger than the total sum of the corresponding exclusive reactions, because there may exist the reactions emitting unobservable quarks.

At the beginning of the universe, a large amount of such unobservable quarks might be created. They would constitute, so to speak, “cloud” of dispersed quarks. It should be electrically neutral in the large scale, though each quark is charged. It has gravitational interaction in the same way as the ordinary matter, and hence will behave like dilute gas at the macroscopic level. On the other hand, it has electromagnetic interaction at the microscopic level, but its existence cannot be detected by the usual spectroscopy.

§3. Constraint from the supernova SN1987A

Now, our hypothesis is that we are surrounded by the cloud of dispersed quarks, which play the role of an undetectable medium of light. What we measure as the speed of light in vacuum is nothing but the speed $c_0$ of light in this medium. In this section, we examine whether or not our hypothesis is compatible with the observation of the supernova SN1987A.

As is well known, in 1987, neutrinos coming from the supernova, named SN1987A, in Large Magellanic Cloud were observed in KAMIOKANDE and two other places. In spite of the distance of about $1.68 \times 10^5$ light-years, SN1987A was optically observed only 3 hours later. From this fact, it is seen that the difference of the speed of neutrinos and that of light is of order $10^{-9}c$ in sharp contrast with the OPERA data.

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* But the converse is not possible because we cannot prepare the physical state consisting of dispersed quarks
Although the energies of the SN1987A neutrinos are around $E=10\text{MeV}$, while the mean energy of the OPERA neutrinos is $17\text{GeV}$, both energies are ultra-relativistic for neutrinos, and hence it is unnatural to suppose that there exists an essential difference between them. Rather, it is natural to expect that the essential difference comes from the experimental situations; the SN1987A observation is cosmological, while the OPERA experiment was done on Earth.

If we assume that the SN1987A neutrinos with mass $m$ traveled in the cloud of dispersed quarks in the whole distance, from (1.1) we have

$$m = E\sqrt{1 - \left(\frac{c_0}{c}\right)^2} \simeq 85\text{keV},$$

which is too much larger than an upper bound of the neutrino mass. Hence, they must travel in the true vacuum in almost all portion of the distance. That is, we should suppose that the clouds of dispersed quarks exist only in the neighborhoods of the supernova and the Solar system (on the neutrino path). Since 3 hours $= 3.4 \times 10^{-4}$ years, an upper bound of the length of its existence region is $3.4 \times 10^{-4}c/2.5 \times 10^{-5} \simeq 13.7$ light-years. This value is sufficiently larger than the radius of the Solar system. Thus, if we assume that the cloud of dispersed quarks exists only in the regions of high matter density, our hypothesis is consistent with the observation of SN1987A.

§4. Discussion

We have proposed a hypothesis, on the basis of the Standard Model with the color confinement condition (2.2), which gives a possible interpretation of the OPERA experimental result without bringing any contradiction with the validity of relativity. If the cloud of dispersed quarks is assumed to exist mainly near the regions of high matter density, our hypothesis is consistent also with the observation of SN1987A. This assumption is natural because the cloud of dispersed quarks has the gravitational interaction exactly in the same way as the ordinary matter does. Furthermore, the existence of the cloud of dispersed quark will bring no anisotropy of the speed of light caused by the rotation of Earth because it behaves like air (but probably much lighter) in contrast with the aether.

We emphasize that if our interpretation of the OPERA experimental result turns out to be correct, it will mean that the proposed resolution of the color-confinement problem of QCD is experimentally supported.

Finally, we make some comments related to our hypothesis.

(1) According to the experiment done in SLAC\(^5\) by using a time-of-flight technique, the speeds of gamma ray and of electrons in the energy range 15-20GeV can be different within only $2 \times 10^{-7}$ times the speed of light. Since this experiment was performed in the end 1/3 part of the linear accelerator, it is natural to understand that not only air but also the cloud of dispersed quarks were removed from there, that is, the measurements were made in the true vacuum. Hence the speed of the gamma ray, which was not measured in this experiment, is not $c_0$ but $c$. Thus the result does not contradict our hypothesis but merely confirms the validity of relativity.
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(2) Cohen and Glashow\textsuperscript{9} theoretically criticized the OPERA experimental data. According to them, if superluminal neutrinos were really emitted from CERN, many electron-positron pairs should have to be produced via bremsstrahlung before arriving at the OPERA neutrino detector, so that such high-energy neutrinos as observed could not survive. Their reasoning is based on the possibility that the processes $\nu \rightarrow \nu + \text{something}$ are kinematically allowed if the neutrino is really superluminal. Their criticism is, however, no longer applicable if $c_0 < v < c$, because then we can always take the rest frame of the neutrino. A similar comment has been made independently also by Oda and Taira\textsuperscript{10}.

(3) A possible energy dependence of photon speed was observed in an experiment done several years ago.\textsuperscript{11} According to the claim based on the missing energy observation in HERA Compton polarimeter data, photons with 12.7GeV energy were moving faster than light by 5.1(1.4)mm/sec. On the other hand, no energy dependence of the speed of light was detected in the observation, done by Fermi Gamma-ray Space Telescope (in 2009), of the gamma-ray burst which had taken place at a distance of $7.3 \times 10^9$ light-years. Because an extremely small difference in the photon speeds would induce a significantly large difference between the times of arrival when accumulated over a tremendously remote distance, this result is a very severe denial of the energy dependence of the photon speed in vacuum. It is interesting to note, however, that both observations are compatible if one supposes that there exists such a medium as the cloud of dispersed quarks in the neighborhood of Earth.

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