Title	Where are the limits of theoretical physics? : from elementary particles inside atoms to supernova explosions
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The star of our current interrogations is Associate Professor Naoki Yamamoto, who is battling the fundamental problem of "the nature of matter" using theoretical physics.

Where are the limits of theoretical physics?

From elementary particles inside atoms to supernova explosions

From elementary particles inside atoms to supernova explosions, all things that exist in this world are compelled by particular "laws of physics," all of which are subjects for research within "theoretical physics." Dr. Yamamoto from the Department of Physics is steadily expanding his research scope in the vast field of "theoretical physics," propelled by the dictates of his curiosity and intuition. This piece will introduce one thread of the research of a young theoretical physicist.

Deduction of a nontrivial phenomenon from a simple theory

Dr. Yamamoto of the Department of Physics at the Faculty of Science and Technology, Keio University is a theoretical physicist engaged in a wide range of research from "nuclear and particle physics" on the quarks and neutrinos at the micro scale through to "astrophysics" at the macro scale.

Paper and pen remain the fundamental tools at his disposal for such dynamic research. "Well, I may have recently replaced these with an iPad and Apple Pen. It may appear that I am simply staring into space during my research," says Yamamoto, reflecting on how he may appear when researching. Nevertheless, a huge amount of mental turnover on Yamamoto's part is required to clarify a non-trivial phenomenon based on a simple theory during these ruminations. The ultimate result may be "a theoretical prediction of a previously overlooked physical phenomenon" or "a new theory to supersede a fundamentally flawed conventional theory."

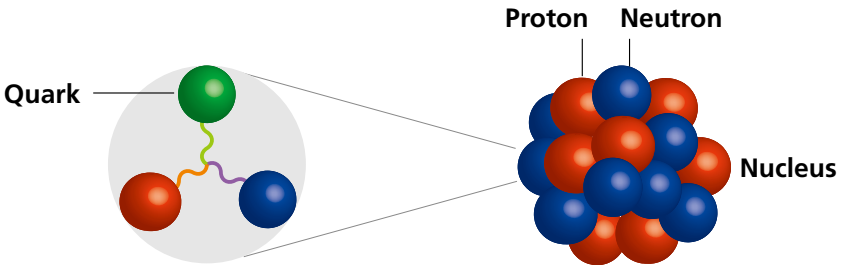
My life's work of "quark confinement"

"Quark confinement"— the original problem which inspired Yamamoto's incursion into theoretical physics (Fig. 1). This is also related to one of seven others in mathematics identified in 2000 as Millennium Prize Problems, with a million-dollar prize being offered to the person who can solve it. However, it remains unsolved today and is one vein of Yamamoto's life's work. But just why is this problem so dastardly difficult? To learn the answer to this, we must familiarize ourselves with the very constituents of matter.

"All matter is made up of atoms"— this is common knowledge to anyone over junior high school age. While atoms were originally thought to be the smallest components of matter, it is now known that they are made up of a "nucleus" surrounded by "electrons." Further, these nuclei are made up of nucleons such as protons and neutrons, with such nucleons in turn comprised of still smaller particles called "quarks." Although yet smaller components may remain to be discovered in the future, quarks, neutrinos, electrons, and their compatriots are currently the smallest known units of matter, and referred to as "elementary particles." The presence of quarks within nucleons has been confirmed in experiments conducted using large accelerators.

In everyday life, just as the movement of matter conforms to the rules of

The problem of "the strong force"



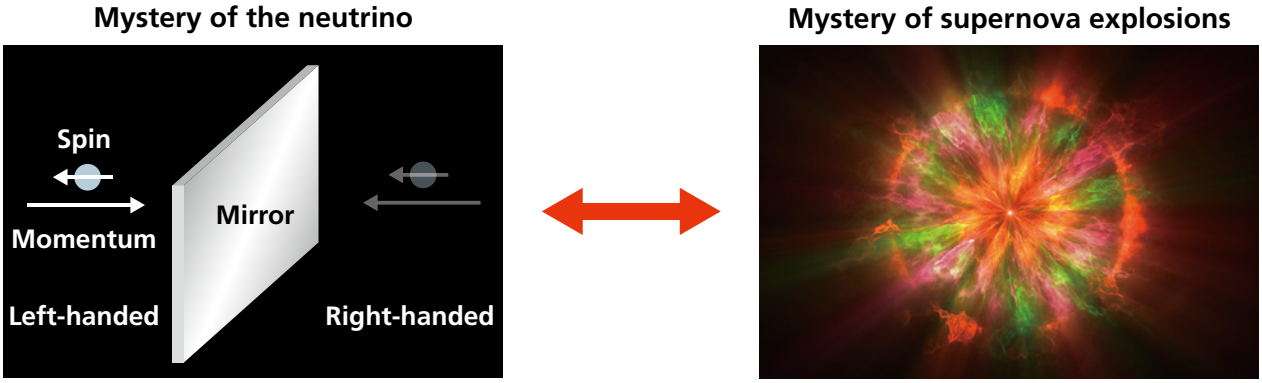
- Quark confinement
- The origin of the mass of matter

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

- One unsolved problem in the Standard Model of particle physics
- Millennium Prize Problem in mathematics

Fig.1 Constituent elements of nuclei and QCD. Three quarks are confined in nucleons such as protons or neutrons.
The dynamics of quarks is described by QCD (equation).

The problem of "the weak force"



Supernova = System with the largest violation of the left-right symmetry in the universe

Fig.2 Supernova explosion (right) and the neutrino property with the potentially important role (left)
Neutrinos are left-handed only, and mirror image right-handed neutrinos do not exist, resulting in the violation of the left-right symmetry.

"Newtonian Mechanics," the miniscule world of quarks is animated by the rules of "Quantum Chromodynamics (QCD)." This is not to say that quarks have actual "colors."Rather, the three primary colors of light are paralleled to the three degrees of freedom which quarks have.

"It is not possible to extract a single quark from a nucleon. It's certainly a puzzler," says Yamamoto. This is the "quark confinement" problem. While it is expounded that "quarks are connected by the strong force," to date no one has been able to offer analytical proof of this based on QCD.

I wish to learn "the nature of matter"

"Unless we solve the problem of 'quark confinement,' we will never truly understand the matter in which quarks are contained. There are any number of fundamental things which we have yet to explain about matter, not confined to this particular problem." Yamamoto's theoretical research is simultaneously oriented towards clarification of "the nature of matter" and the pursuit of the challenge of "quark confinement."

So, just how does he go about approaching these objectives?

"Theoretical physics often presupposes extreme states. For example, these quarks which now cannot be isolated from the nucleon earlier existed in a disjointed plasma state in the extremely high temperatures which directly followed the Big Bang, known as 'quark-gluon plasma.' What then, conversely happens when this matter is compressed into an ultra-high-density state? It is thought that quarks ultimately assume superconducting and superfluid states. For now, though, our attention is on the nature of the states they go through before reaching this point." This is the way that Yamamoto is seeking to clarify "the nature of matter."

Can "Chiral Transport Theory" clarify the mystery of supernova explosions?

Yamamoto's recent research focus has been on supernova explosions. Elements which are formed in stars are scattered throughout space in the massive explosion which marks the end of a heavy star. Supernova explosions are thus the source of everything — as these elements are the constituents of the matter and biological life which surround us. However, explosions do not readily arise under the conventional theory. We may be able to find the solution to this problem by applying the "Chiral Transport Theory."

Chiral Transport Theory, presented in a paper by Yamamoto in 2012, offers a theoretical description of the transport phenomena with their roots in the nature of elementary particles referred to as "chirality."

One familiar transport phenomenon is Ohm's Law, which states that a current will flow when an electrical field is applied. However, in this case heat is generated with the current and energy is lost. Meanwhile, the nature of chirality is such that particle transport without energy loss not normally seen in regular matter becomes possible.

Under conventional supernova theory, there is the issue of the elementary particles known as neutrinos being expelled without having imparted enough energy to the surrounding matter to cause an explosion. However, this overlooks the property that "only left-handed chirality is found in the neutrino, causing the left-right symmetry to be violated" (Fig. 2). Since Chiral Transport Theory also accounts for the phenomena of transport without energy loss, due to the property of neutrinos, it is suggesting and elaborating new directions in research to explore the mysteries of the supernova explosion.

"This world" chock full of things we don't understand

The diligently research-driven Yamamoto meanwhile recounts that, "There are many things that I wish to unravel, with over 50 problems which I have yet to turn my hand to still in my 'jottings book.'" Among these, he says, are those which require vast calculations and years to figure out before the full picture is revealed. This includes research into the supernova explosion. Meanwhile, there are also those which would take around a week to turn into a paper if the right ideas were to make themselves known. Whatever the problem, if solved these will result in a "new world" revealing itself. I am getting more and more excited at the prospect of the worlds Dr. Yamamoto has yet to reveal to us.

(Interview and text writer: Akiko Ikeda)