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Origin of the Nuclear Force from Quantum Chromodynamics

-- New findings from Lattice Gauge Theory on a Massive Supercomputer --

More than 70 years ago, Dr. Hideki Yukawa (Nobel Prize Laureate, Physics, 1949) has introduced the pion to account for the nuclear force (the strong force acting among protons and neutrons in nuclei). Much later, it was experimentally found that the proton, the neutron and the pion are all composed of a fundamental particle, the quark. However, due to high complexities of the dynamics governing the quarks, the quantum Chromodynamics (QCD), it has been extremely difficult to study the origin of the strong nuclear force from QCD.

Very recently, Dr. N. Ishii (Univ. of Tsukuba) , Dr. S. Aoki (Univ. of Tsukuba) and Dr. T. Hatsuda (Univ. of Tokyo) have succeeded, for the first time, in unraveling the nature of the nuclear force on the basis of lattice gauge theory originally formulated by Dr. K. Wilson (Nobel Prize Laureate, Physics, 1982). By carrying out massive numerical simulations using the IBM supercomputer "BlueGene/L" in High Energy Accelerator Research Organization (KEK) in Japan, they could prove not only the validity of the Yukawa's meson theory from QCD but also the existence of a strong repulsive core of the nuclear force at short distance. The latter aspect was speculated from the analysis of the nucleon-nucleon scattering data and has been thought to be related to the stability of nuclei and the structure of neutron stars.

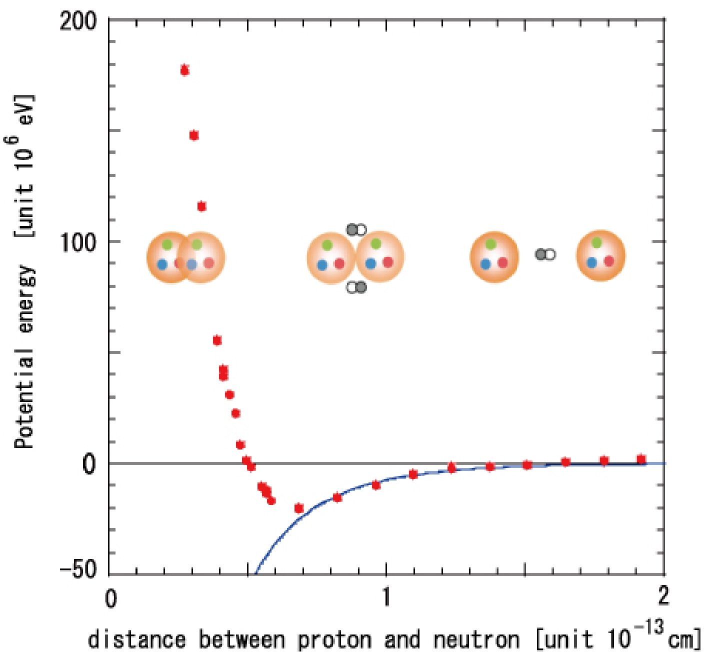

Fig.1: The red dots show nuclear force between proton and neutron with anti-parallel spin obtained by the massive numerical simulations on a super computer BlueGene/L at KEK. The prediction of the Yukawa's meson theory at long distances is shown by the blue line. The cartoon images show that the proton and the neutron exchange pion at long

distances, while they interact directly at short distance.

Shown in Fig.1 is one of the results of the massive numerical simulations with the so-called quenched approximation. The potential energy between the proton and the neutron is plotted against their relative distance. Simulation data agree with the Yukawa's theory at long distance, which is a first numerical proof of the validity of the Yukawa's meson theory after 72 years of its proposal. On the other hand, at distances less than 10^{-13}cm, there appear medium-range attractive force and short-range repulsive core which are consistent with the accumulated experimental data over many years but are not accounted for by the simple Yukawa's theory of the one-pion exchange. Thus the main feature of the nuclear force from long distance to short distance has now acquired firm theoretical ground from QCD.

The nuclear force with the strong repulsive core surrounded by the attractive well is essential for understanding the binding and stability of atomic nuclei, the structure of neutron stars, and the ignition of the Type II supernova explosions. Furthermore, generalization of the above approach to hyperon*-nucleon and hyperon-hyperon interactions constitutes a basis of the hyper nuclear physics to be studied by future experiment such as J-PARC, which is now under construction at Tokai Village, Ibaraki, Japan. By further elaboration of the lattice gauge theory approach to nuclear force, we may eventually be able to answer the deeper question such as "why and how the matter in the Universe exits in its present stable form".

The research of the nuclear force discussed above will be published in June 29, 2007, issue of Physical Review Letter [1]. See also Ref. [2] for a pedagogical account of the results of [1] by Dr. F. Wilczek (Nobel Prize Laureate, Physics, 2004).

[1] N. Ishii, S. Aoki and T. Hatsuda, "Nuclear Force from Lattice QCD",
Physical Review Letters, June 29, (2007).

[2] F. Wilczek, "Hard-core revelations", Nature **445**, 156-157 (2007)

* A baryon which contains strange quarks.

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