Division of Nuclear Physics

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The nucleus can be described as a collection of Fermi particles (protons and neutrons) called nucleons. The mechanics to rule over this microscopic world, such as the quantum mechanics of many-particle systems and quantum field theory, is essential. Three of the four fundamental forces of nature—the strong force, electromagnetic force, and weak force—play important roles in the atomic nucleus, leading to a variety of aspects of reactions and structure that are related to the existence of the matter around us. For example, the sun and the stars in the night sky shine with atomic nuclei as fuel, and they are the lights of the factories that produce the elements. The burning (nuclear reaction) process, which depends on the nature of the forces involved and the nuclear structure, controls the brightness and lifetime of the star, as well as the type and quantity of elements produced.

Nuclear physics has progressed through both experiments using accelerators and theoretical calculations using computers. Numerical calculations are indispensable for quantum many-body problems, such as nuclear problems. The Nuclear Physics division works on developing theories, models, and numerical methods based on quantum mechanics to clarify the nuclear structure, nuclear reactions, structure of stars, and quantum dynamics of matter.

Research Topics

Neutron stars, known as pulsars that emit regular periodic signals, remain shrouded in mystery even more than half a century after their discovery. In recent years, the study of neutron stars has entered a new stage with the observation of neutron star mergers using gravitational waves and the identification of neutron stars with masses that exceed twice the mass of the sun. The atomic nuclei on Earth are all microscopic, with radii of at most approximately 10^{-14} m; no larger atomic nuclei can exist. However, elsewhere in the universe, there are large nuclei with a radii of 10 km. These are the neutron stars. It is conjectured that protons and neutrons form a non-uniform structure near the surface of neutron stars, but existing studies have mainly used the quasi-classical approximation.

We have been developing code for finite-temperature Hartree–Fock–Bogoliubov calculations in three-dimensional (3D) real space to describe the structure of neutron stars in a quantum and non-empirical manner using energy density functional theory, which can universally and quantitatively describe atomic nuclei. Figure 1 shows the structure of the inner crust of a neutron star calculated on this basis. In the inner crust, neutrons spread to fill the space while protons are localized and appear periodically in a manner that resembles a crystalline structure. It was confirmed that the neutrons are in a superfluid state because of the pair condensation.

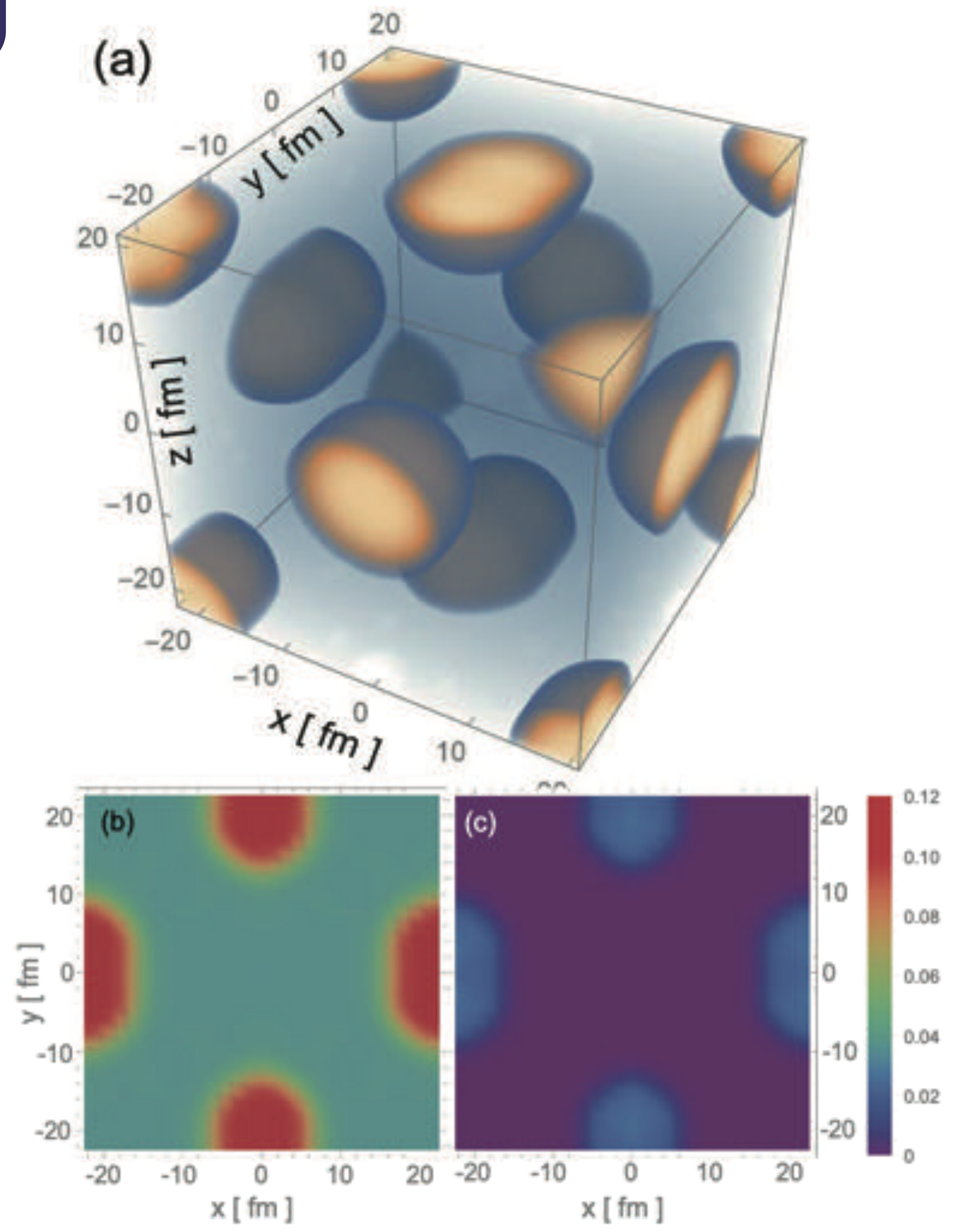

Fig.1 (a) Structure of the neutron star inner crust predicted to appear at a certain temperature and density, assuming a face-centered cubic lattice structure. Within the region indicated by the figure, there exist 136 protons and approximately 4,000 neutrons. The density distributions of (b) neutrons and (c) protons in the xy cross-section.

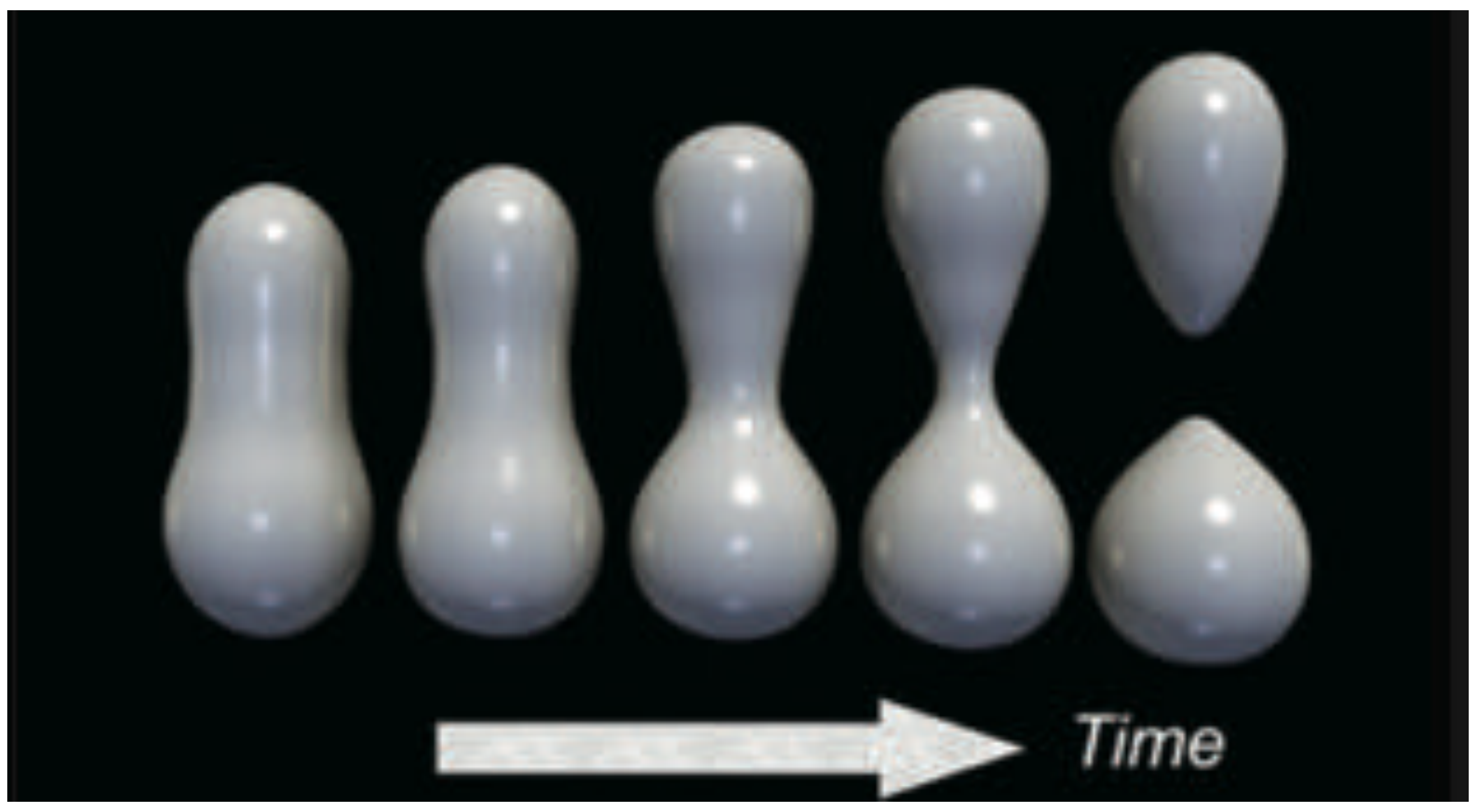

Fig. 2 Simulating nuclear fission of the Pu nucleus in real time. The time span from the left to the right ends is about 2×10^{-20} s.

By extending this density functional theory to a time-dependent version, it is possible to study the response, reaction, and excitation modes of nuclei. There are many unresolved issues in low-energy nuclear reactions, such as nucleon-pair transfer from the pair-condensation phase and the nuclear shape change during the reaction. We are performing real-time simulation calculations in 3D space taking into account the nuclear superfluidity, as well as microscopic determination of nuclear reaction paths based on a theory of large-amplitude collective motion. In the analysis of the fission phenomenon shown in Figure 2, the mechanism whereby a large amount of xenon and nearby nuclei are generated as fission fragments in a nuclear reactor was illuminated. Iodine-135, which is produced by nuclear fission in a nuclear reactor, reduces the power output of the nuclear reactor when it is converted to xenon-135 and accumulated, which is called xenon override. This well-known phenomenon is thought to be the cause of the Chernobyl accident, but until now, the mechanism whereby iodine-135 nuclei are produced in large amounts had yet to be explained.