Large-scale simulations of quarks promise precise view of reactions of astrophysical importance

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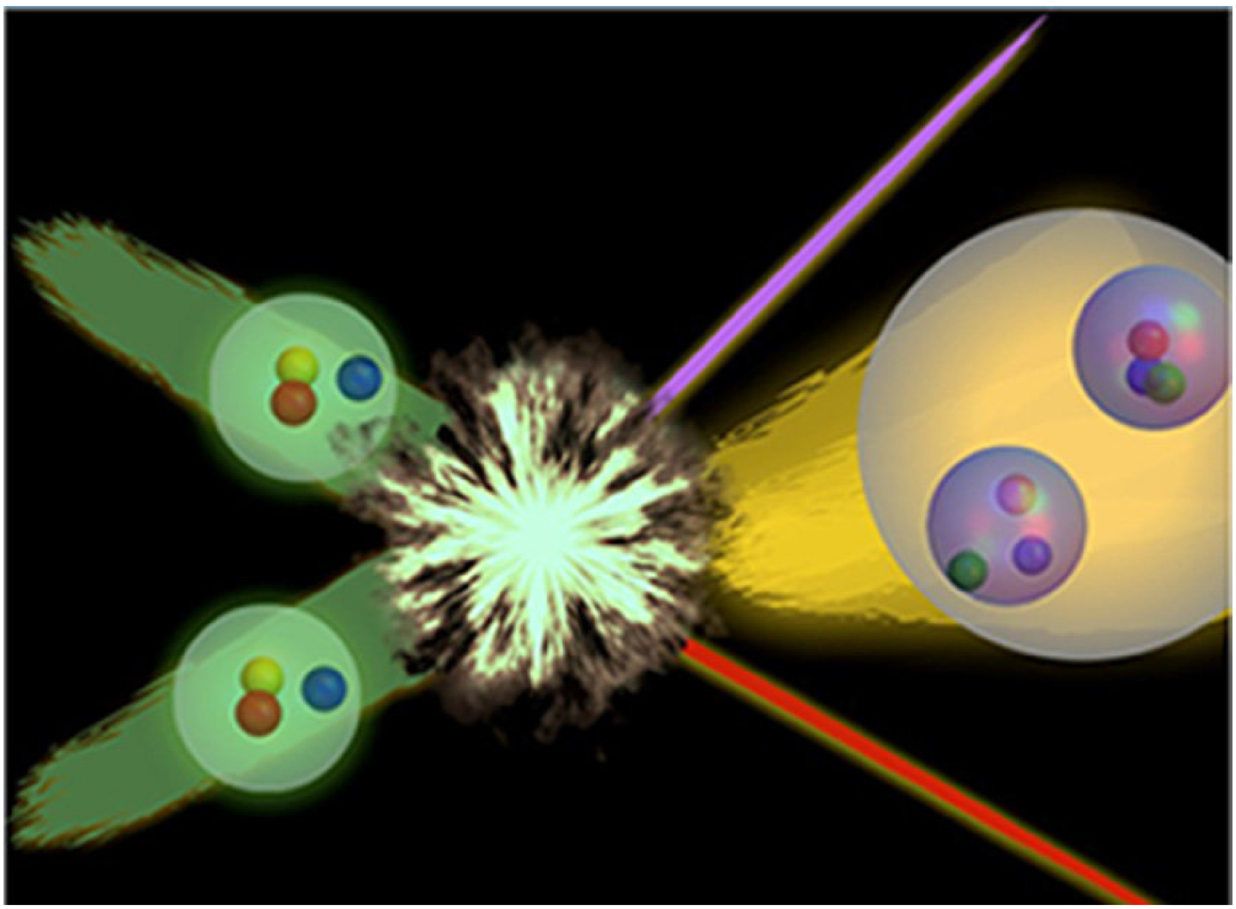

Two protons (green), after “tunneling” through their repulsive electrostatic barrier and undergoing weak and strong interactions, fuse together to produce a deuteron (the lightest nucleus) (yellow), a positron, and a neutrino. Credit: William Detmold

The fusion of two protons initiates the primary nuclear cycle that powers the Sun. The rate of this low-energy, weak-interaction fusion is too small to be measured in the laboratory. While nuclear model predictions for this reaction are impressive, calculations without models would reduce uncertainties and offer a more accurate view of proton-proton fusion and related processes. Using a technique called lattice quantum chromodynamics, scientists performed the first successful model-independent calculation of the proton-proton fusion rate directly from the fundamental dynamics of quarks and gluons (the building blocks of protons and nuclei).

This work paves the way to calculate the rate of proton-proton fusion, and similar nuclear reactions of astrophysical importance, with new levels of precision.

The Nuclear Physics with Lattice Quantum Chromodynamics Collaboration (NPLQCD), under the umbrella of the U.S. Quantum Chromodynamics Collaboration, performed the first model-independent calculation of the rate for proton-proton fusion directly from the dynamics of quarks and gluons using numerical techniques. The rate of this process is too small to be measured in the laboratory today for two reasons: the electrostatic repulsion between the low-energy protons and the small weak interaction rates. The team achieved the theoretical prediction for this process through calculations in which electrostatic repulsion was removed and the weak interaction rates were increased to provide access to the critical elements of the process.

These were then restored using systematic approximations to the underlying physical theory (effective field theory techniques) in making the prediction for the reaction rate. The first lattice quantum chromodynamics calculation of the strength of the weak transition between the triton and helium-3 (which carry significant information of spin interactions in nuclear medium) was also performed in this work and found to be consistent with experimental measurements. These calculations used lattice quantum chromodynamics, a technique in which space-time is represented by a finite grid of points, and the quantum fields describing the quarks and gluons are defined on these points and the links between them, respectively. This method provides an evaluation of the quantum chromodynamics path integral, through Monte Carlo sampling of the quantum mechanical motion of the quarks and gluons (the subatomic particles that bind the quarks together).

This method is completely controlled and can be systematically improved and refined by reducing the physical distance between the grid points, by increasing the volume of space-time, and by increasing the sampling of the path integral. This work used configurations ("snapshots" of the quantum-mechanical vacuum) generated using the Chroma software suite developed within DOE's Scientific Discovery through Advanced Computing funded U.S. Quantum Chromodynamics Collaboration. Existing algorithms and code for forming nuclear correlation functions in lattice quantum chromodynamics calculations and new algorithms including the interactions of quarks with external probes, developed within NPLQCD, were used to calculate the key quantities that determine the rate for proton-proton fusion.

The results of these calculations were connected to nature using effective field theory techniques. Understanding gained in NPLQCD's calculations of the thermal neutron capture process $n+p \rightarrow d+\gamma$ was used in making this connection. With increased computational resources, these calculations can be systematically refined to provide an uncertainty in the rate for proton-proton fusion, and similar nuclear reactions, which is significantly smaller than is possible with other techniques. This breakthrough was made possible by algorithmic developments and high-performance supercomputing resources.

More information: Martin J. Savage et al. Proton-Proton Fusion and

Tritium β Decay from Lattice Quantum Chromodynamics, *Physical Review Letters* (2017). DOI: 10.1103/PhysRevLett.119.062002

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