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The National Ignition Facility's primary goal is to generate fusion energy. But the starlike conditions that it creates will also enable NIF scientists to study astrophysically important nuclear reactions.

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When scientists at the stadium-sized National Ignition Facility attempt to initiate fusion next year, 192 powerful lasers will direct 1.2 MJ of light energy toward a two-mm-diameter pellet of deuterium (^{2}H, or D) and tritium (^{3}H, or T). Some of that material will be gaseous, but most will be in a frozen shell. The idea is to initiate "inertial confinement fusion," in which the two hydrogen isotopes fuse to produce helium-4, a neutron, and 17.6 MeV of energy.

The light energy will be delivered to the inside walls of a hohlraum, a heavy-metal, centimeter-sized cylinder that houses the pellet. The container's heated walls will produce x rays that impinge on the pellet and ablate its outer surface. The exiting particles push inward on the pellet and compresses the DT fuel. Ultimately a hot spot develops at the pellet's center, where fusion produces ^{4}He nuclei that have sufficient energy to propagate outward, trigger successive reactions, and finally react the frozen shell. Ignition should last several tens of picoseconds and generate more than 10 MJ of energy and roughly 10^{19} neutrons. The temperature will exceed 10^8 K and fuel will be compressed to a density of several hundred g/cm^3, both considerably greater than at the center of the Sun.

The figure shows a cutaway view of NIF. The extreme conditions that will be produced there simulate those in nuclear weapons and inside stars. For that reason, the facility is an important part of the US stockpile stewardship program, designed to assess the nation's aging nuclear stockpile without doing nuclear tests. In this Quick Study we consider a third application of NIF—using the extraordinary conditions it will produce to perform experiments in basic science. We will focus on measurements of some of the nuclear reaction probabilities that are important to nuclear astrophysics, the field that relates energy production and nucleosynthesis from nuclear reactions in stars and in the Big Bang to the environments in which those nuclear reactions occur. NIF, unlike previous nuclear-physics facilities, will enable measurements of nuclear reactions at the temperatures, densities, and ionization states similar to those that occur in stars.

No need for large extrapolation

Data obtained in conventional nuclear experiments at accelerators must be corrected or extrapolated if they are to be applied to stellar environments. For example, to address the Coulomb repulsion between charged particles, experimentalists at accelerators typically measure reaction probabilities at relatively high energies and then extrapolate them—often over many orders of magnitude—to the lower energies at which stars operate. Moreover, in contrast to the nuclei in accelerator targets, light nuclei in stellar plasmas are highly ionized. That discrepancy requires another set of corrections. At NIF, the conditions in the target will be much more like those in the cores of stars.

In the thermal-plasma environment of a star, electrons shield the positive charges of interacting nuclei, and thus reduce the Coulomb repulsion. Screening occurs in accelerator experiments too—there it involves atomic electrons. Accelerator-based data often require rather large corrections for electron screening or for excited nuclear states present in the stellar plasma. Corrections will also be necessary for the NIF pellet, but they will be qualitatively different. Indeed, NIF experiments can help test the accuracy of shielding corrections that investigators have applied to accelerator results.

Still, nuclear astrophysicists will need to resolve both experimental and conceptual issues if they are to obtain useful information from NIF. One such issue concerns the very short duration of NIF shots, which last for less than 0.1 ns. To what extent does that minuscule time allow thermal equilibrium to be established, and thus for the NIF environment to simulate that of stars? Conventional accelerator experiments determine reaction probabilities at many energies, which must then be averaged over the energy range that would characterize a thermal environment. If thermal equilibrium is established in the NIF target, that energy averaging would be performed automatically. In DT shots, however, the high-energy neutrons produced in the nuclear reactions certainly will not achieve thermal equilibrium. In some experiments, thermal equilibrium may occur, but scientists will need to confirm that it does so in order to produce useful data. In others, thermal equilibrium is not crucial for obtaining meaningful results.

Slow burn

One nuclear reaction that scientists hope to study with NIF is indicated in the lower-right corner of the figure—the proton capture by nitrogen-14 to yield oxygen-15. That reaction, the slowest one in the so-called primary CNO cycle, is the main bottleneck to hydrogen burning in stars somewhat more massive than the Sun. Reducing the uncertainties in its rate would allow for improved age determinations of globular clusters—that is, clusters of stars that were all created shortly after the birth of our galaxy. Astronomers can identify the most massive cluster stars that are still burning their core hydrogen and determine their ages with the help of stellar evolution codes. The age of those stars and thus of the globular cluster provides a lower bound on the age of the universe.

The proton-capture reaction has been studied down to about 70 keV. However, experiments that have been run at low energies do not agree; newly determined reaction probabilities are smaller than the older ones by about 40%. The target for the NIF experiment would include H and ^{14}N together, possibly in the form of ammonia. Investigators should be able to determine the yield of the product ^{15}O by observing its decay in collected shot debris. Nuclear reactions are very sensitive to temperature, so one can introduce additional nuclei such as lithium-6 or boron-10 in the NIF target at trace abundances, then use their yields to determine the temperature at which the principal reaction occurs.

NIF scientists will also be able to study the stellar s-process, a series of slow neutron-capture reactions and β decays that synthesizes half the nuclei above iron. The β decays occur much more rapidly than the captures until the process arrives at a "branch point" isotope for which the neutron-capture and β-decay rates compete. Because the capture probabilities depend on the neutron density, a branch point provides a measurement of that density. However, the hot s-process plasma includes low-lying excited states of branch-point nuclei, and those states modify the capture probability. Experiments that don't access the excited states will not correctly measure the stellar neutron-capture rates that are relevant to the s-process.

Thulium-171, for example, is branch-point nucleus with an excited state at 5.025 keV above the ground state. The excited state, which is populated in the s-process environment, will also be populated in the NIF target. Thus, NIF will, for the first time, enable measurement of the effective ^{171}Tm neutron-capture probability, that is, the probability appropriate for the superposition of the ground and excited states of ^{171}Tm found in an s-process plasma. To make the measurement, an experimenter could add ^{169}Tm and ^{171}Tm to a target and collect their neutron-capture reaction products after the NIF shot. The neutron-capture probability for ^{169}Tm is known, so the ratio of ^{172}Tm to ^{170}Tm—obtained from β decays—determines the effective ^{171}Tm neutron-capture probability. As with the ^{14}N proton-capture reaction, one can add trace amounts of other nuclei to the target to determine the temperature. The temperature can also be deduced from the width of the 14-MeV neutron peak obtained when D and T fuse to yield ^{4}He and a neutron.

Out with a bang

NIF may also enable scientists to test some aspects of Big Bang nucleosynthesis. BBN calculations predict the primordial abundances of ^{2}H, ^{3}He, and ^{4}He fairly well at the universal baryon to photon ratio determined from the 2.7 K cosmic microwave background fluctuations. However, the predicted abundance of ^{7}Li is three times higher than observed, and that of ^{6}Li is 2–3 orders of magnitude lower. Physicists have made heroic efforts to reconcile the ^{7}Li discrepancy, but have not been completely successful. The observed ^{6}Li abundance is less robust than that for ^{7}Li, and astronomers are not in complete agreement about its value.

Although the density and time scale are different, the nuclei and reactions for BBN and for a NIF DT ignition shot are identical. Thus measurement of the ^{6}Li, ^{7}Li, and beryllium-7 (a BBN product that decays to ^{7}Li) produced in a NIF shot could test scientists' understanding of the processes that produce them. To eliminate background from the hohlraum, the experiment will require that NIF's laser beams impinge directly on the target. And because Li is a common impurity, experimenters will have to design a system that only collects shot debris from the target. The experiment, though, is important and ultimately might suggest that new physics is required to reproduce the observed primordial Li abundances.

NIF will provide unprecedented environments for nuclear astrophysics and several other fields of astrophysics when it begins its full facility tests later this year. We hope it motivates physicists to explore ways to stretch the boundaries of science beyond their present limits.

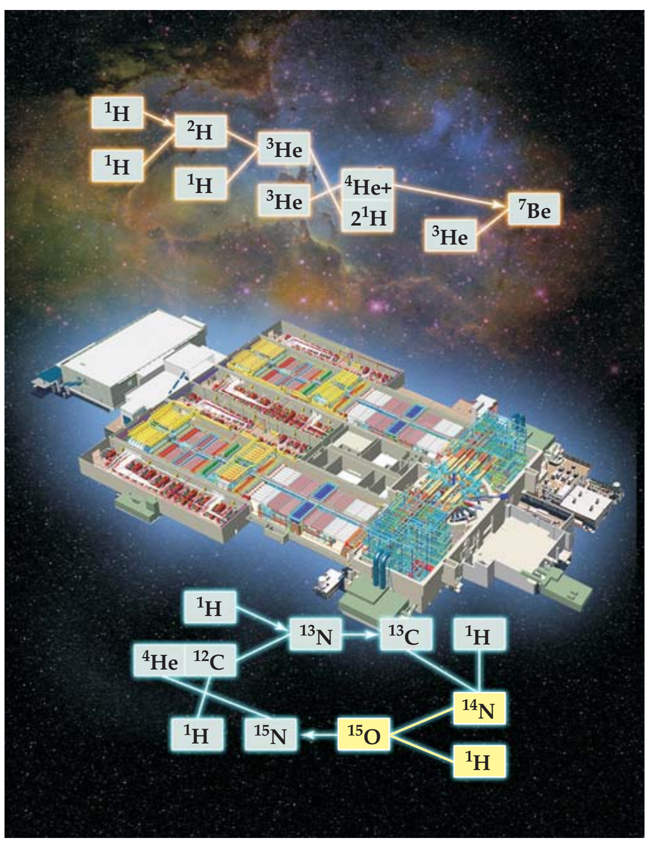
Further reading

▶ National Ignition Facility and Photon Science website, https://lasers.llnl.gov.

▶ E. I. Moses et al., *Phys. Plasmas* **16**, 041006 (2009).

▶ R. N. Boyd, *An Introduction to Nuclear Astrophysics*, U. of Chicago Press, Chicago (2008).

The National Ignition Facility. The symmetrically located multicolored regions to the center–left represent the laser amplification system. NIF's 192 beams will be directed to the circular reaction chamber seen at center–right. Although NIF's primary goal is to generate fusion energy, the facility can also study nuclear reactions that take place in stars. The upper reaction sequence is part of the pp-chain hydrogen burning cycles that occur in low mass stars. The lower sequence is the main CNO cycle, the combination of proton captures and β decays that describes the hydrogen burning that powers more massive stars. The reaction highlighted in yellow is the bottleneck in the cycle, and should be amenable to study at NIF.



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