PoS PROCEEDINGS OF SCIENCE

The National Ignition Facility: Studying the Stars in the Laboratory

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The National Ignition Facility, construction for which will be completed in March, 2009, will be the highest energy laser ever built. The high temperatures and densities it will produce will enable a number of experiments in inertial confinement fusion and stockpile stewardship, as well as in nuclear astrophysics, X-ray astronomy, laser-plasma interactions, hydrodynamics, and planetary science.

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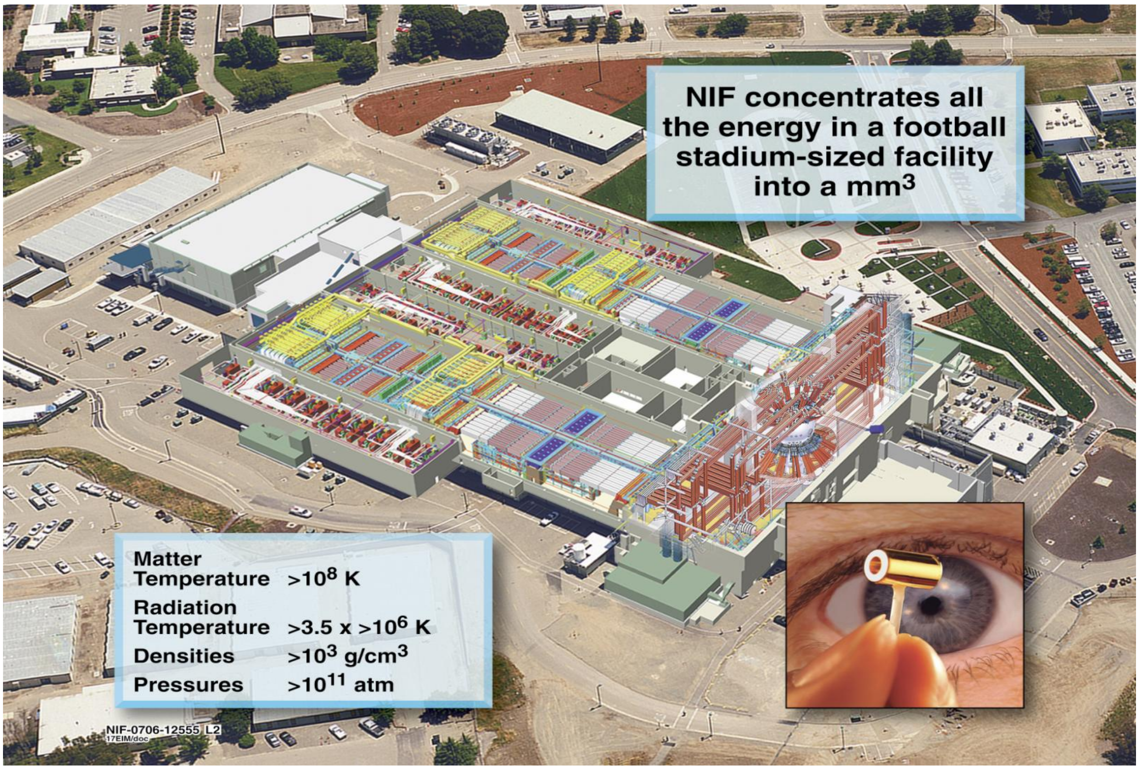
[1] Speaker

1. Introduction

The National Ignition Facility, NIF *(1)*, located at the Lawrence Livermore National Laboratory, (LLNL) is expected to produce inertial confinement fusion (ICF) by delivering sufficient laser energy to compress and heat a millimeter-radius pellet of DT sufficiently to produce fusion to ^{4}He+neutron and 17.6 MeV per reaction. NIF will be completed by March, 2009, at which time a National Ignition Campaign *(2)*, NIC, a series of experiments to optimize the ICF parameters, will begin. Although NIF is a research facility, a successful NIC would have implications for future energy sources. In addition to the goal of ICF, NIF will support programs in stockpile stewardship. However, the conditions that NIF creates will simulate those inside stars and planets sufficiently closely to provide compelling motivation for experiments in basic high-energy-density (HED) science especially, for the first time, in nuclear astrophysics.


NIF concentrates all the energy in a football stadium-sized facility into a mm^3

Matter Temperature	>10^8 K
Radiation Temperature	>3.5 x >10^6 K
Densities	>10^3 g/cm^3
Pressures	>10^{11} atm

Figure 1. Schematic view of the National Ignition Facility. The main amplifiers occupy about half the building at the upper left, whereas the target chamber is at the lower right. A hohlraum is shown in the insert at the lower right.

2. Description of the National Ignition Facility

NIF’s beams begin with nJ sized pulses from a solid state laser. These are divided into 192 beams, each 40 cm square in profile, that pass six times through Nd glass amplifiers, ultimately achieving 4 MJ of 1051 nm light. The 192 beams then pass through KDP crystal sheets, which convert the 1051 nm light to 1.8 MJ of 351 nm light. This light enters a 10 meter diameter target chamber, where the beams are focused onto the inside walls of a “hohlraum,” a cm-long heavy metal cylinder that houses the DT pellet. X-rays produced inside the hohlraum ("indirect drive" mode) ablate the shell of the pellet, which compresses and heats the DT target to a temperature and density of several x 10^8 K and several x 10^2 g cm^{-3}. The DT in the pellet should then fuse to produce more than 10 MJ of energy and ~10^{19} neutrons over ~20 ps. A sketch of the NIF is given in Fig. 1.

There are other modes by which the laser energy can be coupled to the target. Direct drive, in which the laser beams impinge directly onto the pellet, couples a greater fraction of the laser energy to the pellet, but is sensitive to beam spot nonuniformities. Beam smoothing techniques are being developed to circumvent this problem *(3)*. In fast ignition (FI) *(4, 5)*, much of the laser energy compresses the pellet, but a short intense laser pulse is directed at the center of the pellet as a "spark." FI was first proposed by Tabak et al. *(4)*. It may provide a way of achieving ICF with a smaller primary laser than in direct drive or indirect drive. However, there are still issues associated with it, so ICF via FI are further into the future than the indirect drive approach that will constitute the first efforts at NIF.

3. Nuclear Astrophysics at NIF

The temperature and density that NIF will produce are seven times their values at the core of the Sun. The neutron density is also extraordinary, albeit for short times (~20 ps). These characterize the conditions of the emerging field of HED science. Several review articles have also been written addressing areas of astrophysics that can be pursued using high-power lasers and Z-pinches *(6, 7)*. NIF's temperature and density should enable observation of some of the nuclear reactions that occur in stars, but have been difficult to measure, or for which discrepancies exist. Furthermore the similarity of the conditions of the NIF target to those in stars will simplify the electron screening corrections that generally need to be made.

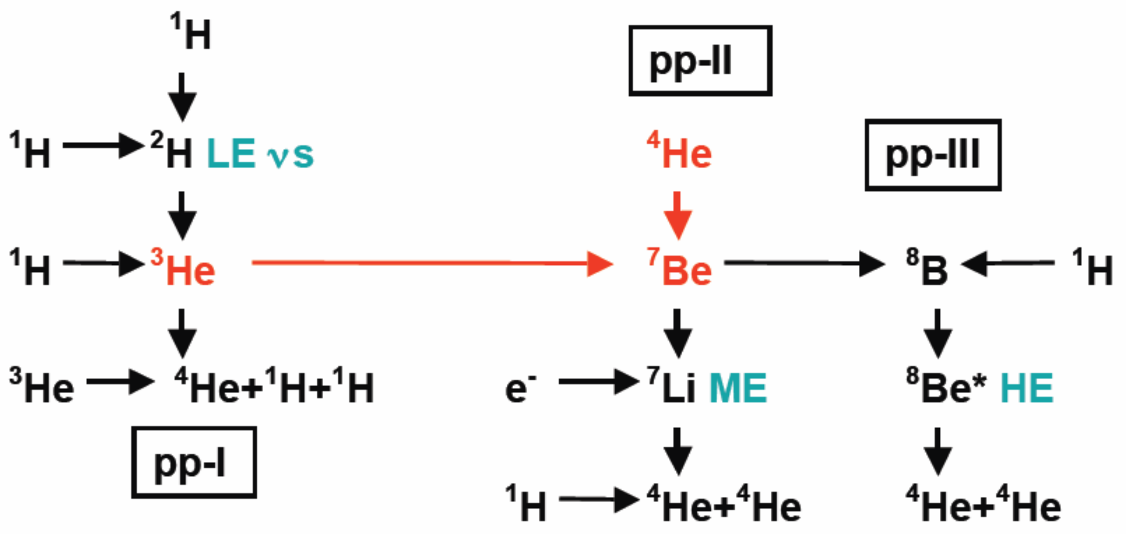


Figure 2. The pp-Chains of H-burning, which dominate energy production in stars of the mass of the Sun or less. Low energy, medium energy, and high energy neutrinos are produced where indicated.

Many nuclear reactions appear to be feasible for study at NIF, among which are ^{3}He(^{4}He,γ)^{7}Be, ^{14}N(p,γ)^{15}O, and some (n,γ) reactions. The first impacts the solar neutrino spectrum *(8)* and the second impacts cosmology *(8)*. The third involves reactions in high temperature environments; the case discussed herein is relevant to the astrophysical s-process.

The ^{3}He(^{4}He,γ)^{7}Be Reaction:

This is the pp-chain reaction that results in high-energy neutrinos (see Fig. 2), so impacts the solar neutrino spectrum *(8)*. Its results have both large error bars and inconsistencies *(9)*. At NIF its reaction product, ^{7}Be (half-life = 53 days), would be collected with a residue collection system, then observed with detection of the ^{7}Be decays. Simulations are in progress to predict the ^{7}Be yield from a NIF shot using NACRE reaction rates (*10)* and hydrodynamics code HYDRA. A NIF target for this reaction study would contain ^{3}He, ^{4}He, and some ^{2}H and ^{3}H, which are necessary to achieve a high enough temperature to produce a detectable reaction yield.

The ^{14}N(p,γ)^{15}O reaction

This is the slowest reaction in the main CNO (H-burning) cycle, which occurs in massive stars (see Fig. 3), so it determines how long such stars burn H in their cores. This has implications for globular clusters, groups of millions of stars all created at the same time early in the galactic history. When the luminosities of these stars are plotted against their surface temperature (their H-R diagram; see Fig. 3), there is a sharp kink that identifies the most massive stars that have completed their H-burning phase. A stellar evolution code then can determine the ages of those stars, providing a lower limit on the age of the universe *(11)*. ^{14}N(p,γ)^{15}O is crucial to that determination.

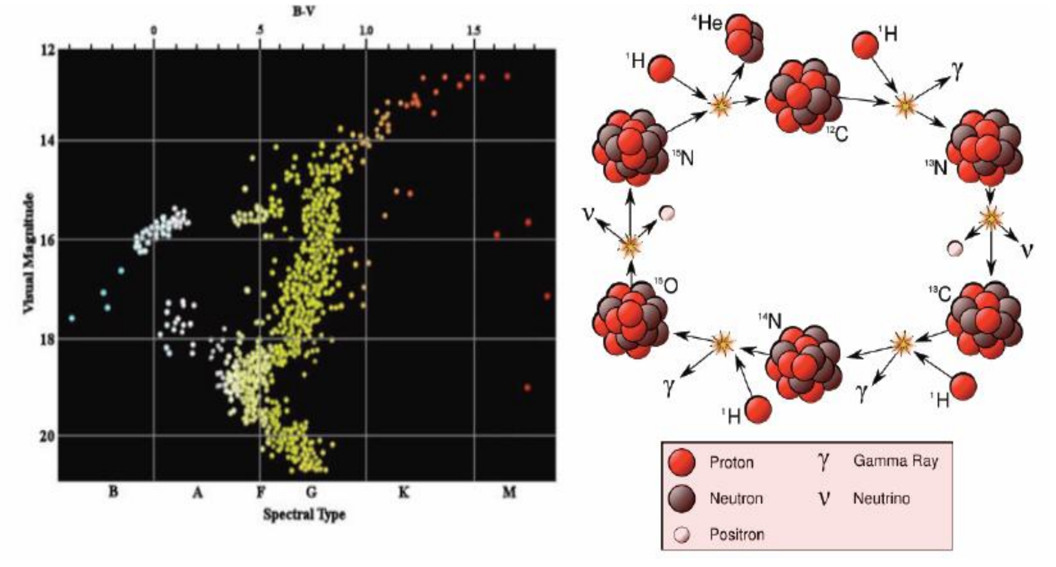


Figure 3. Several aspects of the ^{14}N(p,γ)^{15}O reaction, including the primary CNO cycle on the right, and the H-R diagram for globular cluster M3 on the left. From *(12)*.

A recent measurement of this reaction *(13)* found a rate that was 60% of the previously determined rate. Because of its importance to both cosmology and our understanding of stellar evolution, it is important that a remeasurement be made, and with a technique that is as different from the previous ones as is possible; NIF will provide this opportunity. The NIF target for this experiment would be ammonia: NH_3.

Measuring (n,γ) Cross Sections in a High Temperature Environment

The slow neutron capture or s-process of nucleosynthesis synthesizes half the nuclei heavier than iron *(14)*. Its main component acts in the helium burning shells of Asymptotic Giant Branch (AGB) stars at two temperatures k_BT= 8 and 30 keV. It proceeds along the neutron-rich edge of stability via a series of (n,γ) reactions and β-decays until an unstable isotope is synthesized that has a long enough lifetime (typically ~1 year) that the (n,γ) rate competes with β-decay. This produces a "branch point", (see Fig. 4); these nuclei provide information about the temperature and density, in the s-process environment.

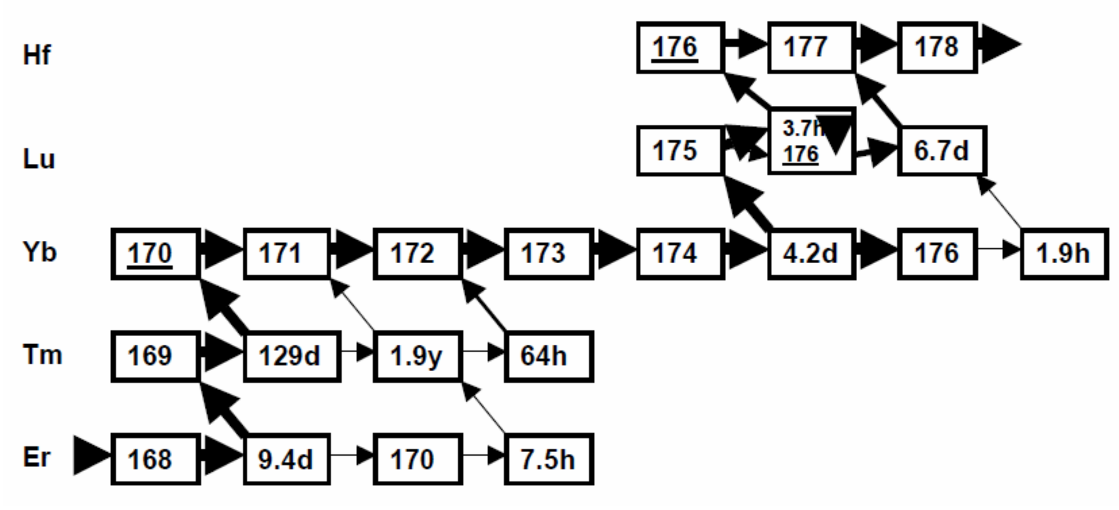


Figure 4. s-process pathway from ^{168}Er to ^{178}Hf. Branch points exist for both the Tm and Lu nuclei. At ^{175}Lu, neutron capture goes primarily to the ^{176}Lu isomeric state, which populates the ground state, which then undergoes a subsequent neutron capture to ^{177}Lu.

Low-lying excited states of branch point nuclei can be excited in the s-process plasma producing a different *effective* β-decay lifetime than would exist for ground state nuclei *(15)*. The excited states can also have different (n,γ) reaction rates from those of the ground states, which can change the *effective* (n,γ) reaction rates. Many measurements of (n,γ) cross sections for stable nuclei along the s-process pathway *(16)* exist, but none exists on excited state nuclei *(17)*. Measured or estimated cross sections on isomeric states were generally very different from those on the ground states, potentially leading to large differences in the thermally averaged cross sections, and in the resulting s-process abundances *(18)*.

The conditions achieved in a NIF target (k_BT≈2-12 keV, ≈several hundred g/cm^3) are very similar to those in an s-process site. The low-energy neutron fluence in these targets, ~10^{17} neutrons/cm^2 (not a DT target), is ~10^{10} times that in the AGB stellar interior, thus subjecting a tracer nucleus to an equivalent neutron exposure of ~300+ years in an AGB stellar interior. An (n,γ) cross section relevant to the s-process could thus be measured by adding branch point nuclei to a NIF target. These, together with their (n,γ) reaction products, could be collected, following the NIF shot, to determine the cross section.

The Thulium isotopic chain (fig. 4) produces two s-process branch points (^{170,171}Tm), both of which are radioactive and which neutron capture to radioactive reaction products. Also, ^{171}Tm has a first excited state at 5.025 keV that would certainly be significantly populated in an AGB stellar interior, and in a NIF shot. Thus this would be an important case for study.

4. Conclusions

Some experiments in nuclear astrophysics appear to be feasible at NIF. These will have the advantage over accelerator based experiments of being temperature averaged; this will produce the reaction rate information necessary for nuclear astrophysics directly, and in some cases enable experiments that could not be done with any other facility. The potential for a wide range of nuclear astrophysics experiments is still being investigated.

Acknowledgements

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References

[1] https://lasers.llnl.gov/,
[2] National Ignition Campaign Execution Plan, LLNL report UCRL-AR-213718, NIF-0111975-AB, May, 2006
[3] S. Skupsky et al. (2001), *Inertial Fusion Science and Applications 2001*, ed K.A. Tanaka *et al.* (Paris: Elsevier) p 240
[4] M. Tabak et al., Phys. Plasmas **1** (1994) 1626
[5] M.H. Key, Phys. Plasmas **14** (2007) 055502
[6] B.A. Remington, R.P. Drake, and D.D. Ryutov, Rev. Mod. Phys. **78**, (2006) 755
[7] H. Takabe, Prog. Theo. Phys. Suppl. **143**, (2001) 203
[8] R.N. Boyd, *An Introduction to Nuclear Astrophysics*, (University of Chicago Press, Chicago) 2008
[9] Gy. Gyuerky et al., Phys. Rev. **C 75** (2007) 035805
[10] http://pntpm.ulb.ac.be/Nacre/nacre_d.htm
[11] G. Imbriani et al., Astron. Astrophys. **420** (2004) 625
[12] http://en.wikipedia.org/wiki/Globular_cluster
[13] A. Lemut et al., Phys. Lett. **B634** (2006) 483
[14] M. Busso et al., Annu. Rev. Astron. Astrophys. **37** (1999) 239
[15] K. Takahashi and K. Yokoi, At. Data Nucl. Data Tables **36**, (1987) 375
[16] Z. Y. Bao, et al., Atomic Data and Nuclear Data Tables **76** (2000) 70
[17] H. Beer, F. Kappeler, K. Yokoi and K. Takahashi, Astrophys. J. **278** (1984) 388
[18] K. Wisshak *et al.*, Phys. Rev. **C61** (2000) 065801; K. Wisshak *et al.*, Phys. Rev. **C73** (2006) 015802