Plasma Nuclear Science: An Overview

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The DOE/NNSA has two laser-driven, inertial confinement fusion facilities. Several programmatic goals, e.g. Ignition – propagating thermonuclear burn.

**Laboratory for Laser Energetics**
- 30kJ -- Opened 1970

**National Ignition Facility**
- 1.8 MJ -- Opened 2009

The opportunities for fundamental science at Omega & NIF are expected to increase gradually over the next few decades.
Workshops have been held to discuss science at these facilities: Plasma Nuclear Science has been highlighted.

The plasma nuclear science community is nascent and continues developing a stronger presence at these facilities to articulate goals and needs.
Recent DOE report highlights exciting new areas of research enabled by the interface between plasmas and nuclei at ICF facilities.

**Hot/Dense Plasma**
- \( k_b T \approx 1-20 \text{ keV} \)
- \( \rho \approx 1-1000 \text{ g/cm}^3 \)

**High Neutron Brightness**
- \( \Phi \sim 10^{14-19} \text{ in few ps} \)
- 10% nuclei react

**Stellar and Big Bang Nucleosynthesis in Plasmas**

**Nuclear Probes of Hydro, Kinetics, and Transport**

**Formation of the Heavy Elements and the Role of Excited Nuclear States**
Measurements of fusion rates are very challenging at low energies relevant to stellar and Big Bang nucleosynthesis

- Rates are low
  - Backgrounds become a problem

- S-factor increases at low energy
  - Indicates strong electron screening by the target plasma.
  - This effect is also expected for high density stars.
  - This observation of screening requires additional experiment studies to improve the reliability of S-factor predictions!
Electron screening in accelerator measurements is particularly large for the Sun’s energy-producing reaction: $^3\text{He}+^3\text{He}$

LUNA underground measurement with proton spectrum at $E_{cm}=30\text{keV}$

Omega laser plasma measurement with proton spectrum at $E_{cm}=90\text{keV}$

Low energy experiments at plasma conditions are feasible; this provides a unique opportunity to probe reaction plasma interaction
The sites for the s-process are understood, but there are many open questions re its impact on the origin of heavy elements

Weak s-process in massive stars
Main s-process in AGB stars

Open questions:
1. Neutron sources $^{13}\text{C}(\alpha,n)\ ^{22}\text{Ne}(\alpha,n)$ …
2. Branching points and n-capture on long-live isotopes
3. n-capture on thermally excited and isomeric states
4. Impact on p-process (seed) and r-process (yield) abundances
High Neutron Flux
\( \approx 10^{27-33} \text{ cm}^{-2} \text{ s}^{-1} \)

(fluence=10^{17-22} \text{ cm}^{-2})
NIF is a very challenging environment in regards to understanding the target and neutron spectrum. 

See talks by Dawn Shaughnessy and Lee Bernstein today.

But success could enable new opportunities for studying capture on excited and isomeric states.

*n111103 DT cryo with Y_{14} = 5x10^{14}
Nuclei can be directly excited by plasma atomic transitions and electron captures: Details of these processes might be accessible.

The “chemical” evolution of the plasma is potentially a unique window into capsule dynamics.
It is challenging to create the right plasma conditions for the required timescales of > ~1 ns

Andrea Kritcher has been trying to use Tm and Os hohlraums to generate plasma environment to excite first nuclea state
The most important role of nuclear science is to provide new insights into HED plasmas with advanced nuclear diagnostics.
These nuclear diagnostics are already providing compelling insights for the HED plasma community’s pursuit of ignition.

Nuclear diagnostics indicate that ignition shots have strong low-mode ($Y_{11}$ and $Y_{20}$) variations in density (factor of 2).

Suggests hohlraum environment not uniform.

Analysis courtesy of Charlie Cerjan.
Another puzzle: The observed TT and DD reaction yields relative to the DT yield are higher and lower than expected, respectively.

P. Amendt et al., PRL 105, 115005 (2010).

These results suggest that the implosion core becomes tritium rich.
What particle transport mechanisms are responsible for this effect?
There are compelling science questions at the interface of nuclear and plasma physics

- Thermonuclear and charged-particle reactions
  - 3-body continuum, electron screening, S-factors, stellar environments

- Nuclear-plasma interactions and other probes of plasma’s chemical evolution
  - Nuclear level populations in burning plasma

- Nuclear reactions and decay lifetimes of short-lived or excited states
  - New insight into s process nucleosynthesis

- Novel diagnostics of plasma conditions
  - Small scale turbulence, transport, temperature/pressure/density history

- Role of nuclear science in HED physics and inertial fusion energy
  - Similar to nuclear science role in astrophysics
  - Interesting conundrums will pop up, much like in astrophysics
  - Success in these new areas of “Plasma Nuclear Science” has the potential to open new windows for understanding HED plasma physics
HED plasmas are a very different environment from accelerators

Advantages

- Plasma environment like a star
  - No electron screening corrections
  - New phenomena
- Neutron flux is very bright
  - Smaller targets
- Experiment is short (1 ps – 1 ns)
  - No radioactive backgrounds

![Neutron Flux Chart]

- WNR Reactor: $10^{22-24}$
- SNS: $10^{22-24}$
- ~1 cm: $10^{27-33}$
- Capsule: $10^{27-33}$
- NIF: $10^{27-33}$
HED plasmas are a very different environment from accelerators

Disadvantages

- Plasma environment is complex
  - Spatial and temporal profiles
  - Currently not well modeled

- Laser environment is complex
  - Difficult to cover large solid angle

- Experiment is short (1 ps – 1 ns)
  - No coincidence events

We are performing our measurements at the OMEGA laser, U. of Rochester. This 60-beam, 30-kJ facility is ideal for developing these new techniques.
To gain experience, we chose a proof of principle experiment: n-t and n-d elastic scattering at 14 MeV

Plasma serves as both the source and the target.

Laser Power: 30 kJ
1-ns square pulse

3.5 µm SiO₂ → 20 atm DT
~450 µm

SiO₂ glass shell ablated entirely at bang time

Spectrometer

Yₙ = 5 × 10¹³
<Tₙ>ᵣ = 9 keV
ρR ~ 20 mg/cm²

Eₙ = 14 MeV

n' n' n n' DT

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Emboldened by this success, we turned our attention to measuring fusion at stellar conditions – $^3\text{He}+^3\text{He}$

- NIF implosions could be a place to test electron screening corrections:
  - Weak screening in plasma
  - Accelerator measurements extrapolated with a quadratic
  - For $^3\text{He}+^3\text{He}$, terms are $\sim70\%$ uncertain


Complementary techniques allow us to understand how reactions in a plasma environment differ from precision accelerator measurements
We measured proton spectrum from $^3$He($^3$He,2p)$^4$He at OMEGA with a ~12 keV plasma.

Yields near solar temperatures will be very low (better at NIF)

Need to develop techniques to measure protons <4 MeV
By comparing T+T in both accelerator and hot, dense, dynamic plasmas we have made two discoveries

- The T+T reaction mechanism is changing as the reaction energy is lowered
  - $^3\text{He}+^3\text{He}$ probably similar
  - Not understood in the context of R-matrix methods
  - Three bodies in the final state make this complicated
  - Better data is expected shortly from both OMEGA and NIF

- Nuclear physics is helping to shed light on complex behavior occurring in these dynamic experiments
  - Central region of the plasma is tritium-rich as fusion occurs
  - Something else?

There are many other astrophysical reactions which can be studied at these laser-driven plasma facilities relevant to pp-chain, CNO cycle, and BBN
National Ignition Facility

NIF is a three football stadium-sized laser, which delivers ~1.8 MJ to a cm-scaled hohlraum.
There is a rich set of opportunities for novel studies of low-energy nuclear reactions at OMEGA and the NIF

- **Astrophysical reactions**
  - pp chain
    - $T(t,2n)^4\text{He}, ^3\text{He}(^3\text{He},2p)^4\text{He}, D(p,\gamma)^3\text{He}, ^7\text{Be}(p,\gamma)^8\text{B}$
  - CNO cycle
    - $^{15}\text{N}(p,\alpha)^{12}\text{C}$
  - BBN
    - $T(^3\text{He},np)^4\text{He}, T(^3\text{He},d)^4\text{He}, T(^3\text{He},\gamma)^6\text{Li}$

- **Other astrophysical questions**
  - Electron screening: lab vs. plasma
  - Nucleus-plasma interactions
  - Modified decay lifetimes

*Success in “Plasma Nuclear Science” has the potential to open new windows for understanding HED plasma physics*
Laser Fusion facilities reach non-equilibrium matter conditions at the interface of solid and plasma – Warm Dense Matter

National Task Force on High-Energy Density Physics, R. C. Davidson, Chair, Frontiers for Discovery in High Energy Density Physics, OSTP and NSTC joint report, July 20, 2004

Warm Dense Matter
A Magnetic Recoil Spectrometer (MRS) is used to measure the T+T neutron spectrum.