Neutron Reactions in the Hohlraum at the LLNL National Ignition Facility

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Background: The National Ignition Facility (NIF) uses 192 laser beams to compress a deuterium-tritium target, inside of the hohlraum, to create nuclear fusion. During ignition, the target and hohlraum phase change from their normal phases to a plasma phase. **Purpose:** Observing neutron reactions within the hohlraum allow the physical parameters of the burning capsule to be probed. **Methods:** Daughter nuclei can be used to build a neutron spectrum from the hohlraum. Down scattered neutrons, low energy neutrons, are used to probe the areal density of the hohlraum. Reactions-in-flight (RIF) neutrons, neutrons above the 14 MeV peak, can be used to probe the hydro dynamical mix within the hohlraum. **Results:** A neutron spectrum that has a main peak at 14MeV, the neutron energy for the fusion reaction, was obtained from this experiment. Various energies along this spectrum were used to infer physical aspects of the hohlraum during ignition. **Conclusion:** The acquired neutron spectrum has allowed for future optimization of the hohlraum. This research has opened the possibilities of using other chemical compounds within the target to acquire different measurements. This research has also suggested that radiochemistry can be a good diagnostic for neutron production during ignition.

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Lawrence Livermore National Laboratory is the home of one of the most exciting scientific projects in the world, the National Ignition Facility (NIF). NIF is undergoing research to try to create sustainable fusion. The experiment begins with a single laser that has the energy of about 1 billionth of a Joule. The laser is then split into 48 different optical channels then amplified to a few Joules. Each of these 48 beams is then split into four, creating 192 separate beams. These 192 beams are then amplified to energy of about 4 million Joules combined. The beams are then sent to two ten-story "switchyards" and split into arrays. Each of these arrays carries four of the 192 beams. While passing through these arrays, the lasers are converted from infrared to ultraviolet via an assembly of optics. These optics are used to condition, change the frequency, and focus the beams. The beams then enter the target chamber where they converge at the hohlraum. Each side of the hohlraum is met by 96 of these beams.[1] The lasers then interact with the interior wall of the hohlraum to create x-rays. The x-rays then compress the deuterium-tritium target that lies within the hohlraum. The compression of the hydrogen abundant fuels allow for them to undergo nuclear fusion.

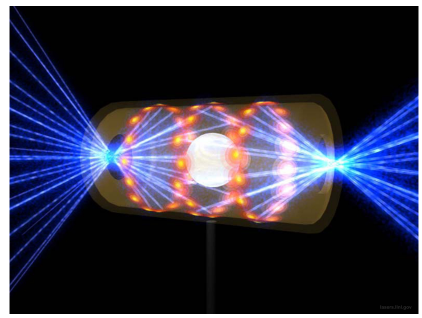

Figure 1, Hohlraum. The lasers converge on each end of the hohlraum and create x-rays as they interact with the interior walls of the hohlraum.

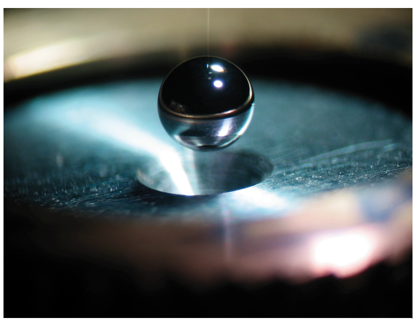

Figure 2, Target within Hohlraum. The polished deuterium-tritium target is lowered into the hohlraum.

During nuclear fusion of a deuterium-tritium target, the two atoms will collide and fuse together. The deuterium (neutron and proton atom) will collide with the tritium (two neutron and one proton atom) and fuse to create a Helium-4 atom (two neutrons and two protons). The extra neutron will then be ejected with energy of 14.1 MeV. During flight, these ejected neutrons can scatter or react before they get detected. Neutrons that scatter will primarily have energies below this 14.1 MeV level. Neutrons that react (Reaction-in-Flight or RIF) will generally have energies above this 14.1 MeV.

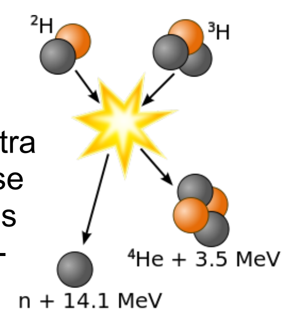

Figure 3, DT Fusion.

Currently, sustainable fusion has not been achieved. The structure and composition of the hohlraum and the fuel contained in it are in question. The first step of fixing the problem is understanding what happens during ignition. With high temperatures that occur during nuclear fusion, it is hard to view the hohlraum and its fuels. The entire assembly is transitioned into a plasma state. The best solution to this is to observe the

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[1] Figure 1 and Figure 2: https://lasers.llnl.gov/media/photo-gallery
Figure 3: https: //en.wikipedia.org/wiki/Nuclear_fusion#/media/File:Deuterium-tritium_fusion.svg

neutrons released during the fusion process. These neutrons can then be used to infer the physical parameters of the hohlraum during fusion.

The hohlraum is made of either gold or uranium with two polyamide entrance holes. Inside of the hohlraum sits a capsule with the target. The capsule has three major components. The first component is the shell, which is made of either Berillium-9 or plastic. For the experiment at hand, the shell is assumed to be made of Berillium-9 with a doping of .03% Copper. Inside of the shell is a thin layer of deuterium-tritium ice, about 90 micrometers thick with a density of one-quarter gram per cubic centimeter. Inside of the layer of ice is a deuterium-tritium gas with a density of 0.0005 grams per cubic centimeter. Mixing of the ice and gas deuterium-tritium components is inevitable and the mixing length has only been calculated theoretically. In these calculations, the mixing length is given in terms of difference of velocities for the compounds in the components. Dimensional analysis allows for the mixing length to be described as a dimensionless variable. This variable has been calculated to be approximately 0.06. The value of this variable would be changed during calculations to observe how the reaction would behave for different mixing lengths. For completeness, the ideal situation (no mixing occurs) should be used as reference point. Therefore the range in which calculations are done should be when the variable is between zero and twice of the theoretical variable value. Actual calculations were done form zero to 0.16. The calculations have found that the deuterium-tritium yield decreases as the mixing length increases. It was also found that at a mixing length of .16, ignition would fail.

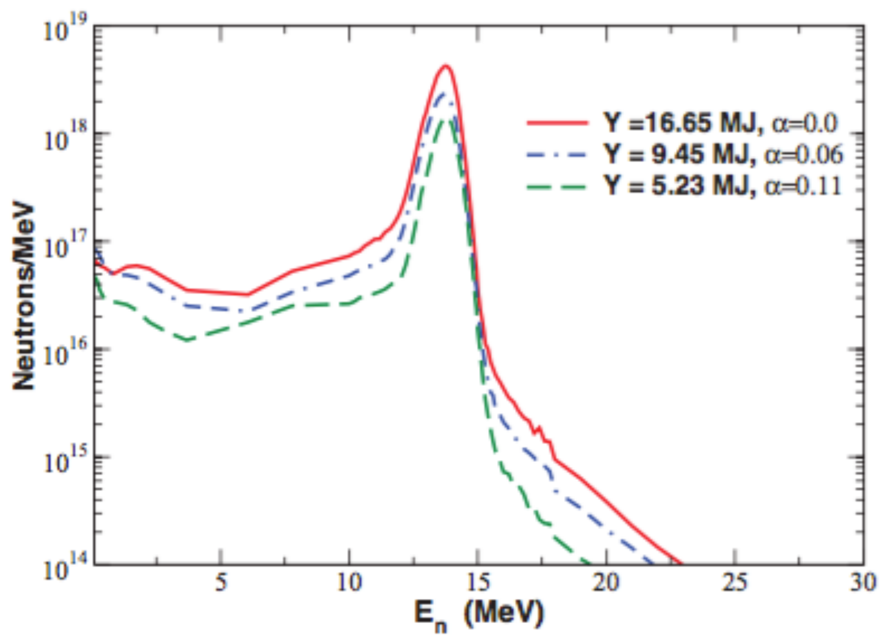

Figure 4, Neutron Spectrum obtained during experiment

This experiment has produced a neutron spectrum that clearly depicts the three energy groups of the neutrons.[2] As previously mentioned, neutrons of energy of 14.1 MeV are ejected during fusion. Free flying neutrons have a nonzero probability of scattering or reacting. The mean free path for these neutrons only gives them a 10% chance of scattering. This allows for the assumption that these lower energy neutrons (neutron energies below 14.1 MeV) represent the areal density of the capsule. Above 6 MeV, the number of neutrons steadily rises due to the differential cross-section of the deuterium and tritium ions. Lower energies are from neutron

[2] Figure 4: P.A. BRADLEY et al. PHYSICAL REVIEW C **86**,014617 (2012)

capture and inelastic neutron scattering. Inelastic neutron scattering would only be detectable via isomers. The isomer that is generally seen is Gold-197 and has a 7.8 second lifetime. The isomers would then de-excite, releasing measureable gamma rays. During neutron capture, the daughter nucleus would undergo beta-delayed gamma decay to the ground state. For the Gold-197 case, it would neutron capture to Gold-198, beta decay to Mercury-198 then gamma decay to the ground state. The lifetime of the Gold-198 is approximately 2.7 days.

The 14.1 MeV neutron fluence, neutrons per unit surface area, is observed by the (n,2n) reaction with the copper in the shell. Although, copper contaminants can occur due to the abundance of copper used in the cooling rings and other areas. As an alternative, the (n,2n) reactions were documented for gold and uranium. The average neutron energy observed remains static around 14 MeV. This implies that the majority of neutrons in the reactions, whether the hohlraum is gold or uranium, have energy of 14.1 MeV.

After fusion, the ejected neutrons are also able to react. The free flying neutron can collide with the deuterium or tritium ion. The ion can then react with another ion. If deuterium and tritium ions collide, they will release a neutron with energy above 14.1 MeV due to the first ion having a high kinetic energy. These neutrons can be detected by observing the products of the $^{197}Au(n,3n)^{195}Au$ reaction. This reaction probes the entire RIF neutron spectrum, and the average energy of the probed neutrons is 19.7 MeV.

This experiment has used radiochemical techniques to map out the three regions of the neutron spectrum that occurs during ignition. It has explained and given evidence for the sources of these energies. It has also explained why we see the intensities of these energies as well. This experiment has used various chemical compositions to provide a wide variety of information on this process. Calculations were done on various mixing lengths to find the deuterium-tritium yields. They were calculated at their extremes to find the point of ignition failure. This experiment has opened the door for future classes of measurement. This experiment has also suggested a more precise way of RIF neutron analysis. These advancements suggest that radiochemistry can be a good diagnostic for neutron production during ignition. Future analysis and diagnostics could lead to a success in sustainable fusion in the coming years.