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**$^2\text{H}(p,\gamma)^3\text{He}$  cross section measurement using high-energy-density plasmas**

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## D(p, $\gamma$ )<sup>3</sup>He cross section measurement using high-energy-density plasmas

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An absolute cross section for the radiative capture reaction D(p, $\gamma$ )<sup>3</sup>He has been measured at the OMEGA laser facility using inertially-confined plasmas. These high-temperature plasmas are created by imploding a fuel-containing capsule using laser ablation, and are advantageous in that they better mimic astrophysical systems. We measure a S-factor for this reaction of  $0.429 \pm 0.029_{\text{stat}} \pm 0.072_{\text{sys}}$  eV-b at  $E_{\text{cm}} = 16.35 \pm 0.40$  keV, which is higher than the adopted evaluations but consistent given uncertainties. This reaction is important as a source of nuclear energy in protostars and brown dwarfs. It is also a critical reaction during big-bang nucleosynthesis, and a better cross section can be used as a constraint on cosmology.

Fusion of deuterons and protons via the reaction



is the primary reaction for generation of <sup>3</sup>He in nucleosynthesis processes, this reaction is critically important for many astrophysical systems such as main-sequence stars, brown dwarfs, protostars, and the universe during the Big Bang.

Interstellar gas undergoing gravitational contraction can have a brief epoch of halted contraction due to burning of primordial material in the ‘proto-star’ phase[1]. Similarly, in ‘brown dwarf’ stars, which are not massive enough to ignite hydrogen fusion ( $\lesssim 0.07 M_{\odot}$ ) but larger than giant planets ( $\gtrsim 0.01 M_{\odot}$ ), deuterium burning can generate substantial amounts of thermonuclear energy[2–4]. The internal dynamics of these objects depends sensitively on the pD fusion reactivity at extremely low temperatures.

This reaction is highly relevant for Big-Bang Nucleosynthesis (BBN), in which the pD reaction consumes D and generates <sup>3</sup>He needed for the reaction chain to proceed to heavier nuclei such as Li and Be[5, 6]. The deuterium concentration in primordial material is well known, when combined with the relevant cross sections and a BBN model strong constraints on, or consistency tests of, cosmological physics can be done [7–9]; an improved understanding of pD fusion for this purpose has been called for, e.g. by Marcucci et al. [8].

This reaction has been studied at low energy in several accelerator (beam-target) experiments[10–13] and theoretical work[14–16]. Achieving low energies relevant for astrophysical nucleosynthesis is a challenge for accelerator measurements, requiring long-duration runs in underground laboratories to reduce backgrounds. High-energy-density plasmas are an alternative technique, with several

reaction cross sections recently reported for the first time [17, 18], as well as studies of fundamental nuclear physics [19–25]. Cross section measurements in these plasmas require no corrections for beam stopping or electron screening, and thermal plasmas generate many reactions compared to a beam-target system.

In this Letter we report the first measurements of the pD fusion cross section using inertially-confined laboratory plasmas. Our measured S-factor is higher than reported evaluations[8, 26, 27]. This work represents the second use of high-energy-density laboratory plasmas to measure a cross section with direct relevance to current nucleosynthesis problems. These data may be extended to both higher and lower energies, relevant to BBN and protostars/brown dwarfs, respectively, and continue to improve BBN constraints on cosmology.

Spherical plastic (CH) shells filled with various fuel mixtures were imploded with the OMEGA laser[28]. The targets are shown in Fig. 1; the CH shells were nominally 15 $\mu\text{m}$  thick with an outer diameter of 860  $\mu\text{m}$  and a 0.1 $\mu\text{m}$  Al overcoating. The shell was driven by the laser irradiation at  $3\omega$  (351nm) using supergaussian (4th order) distributed phase plates[29], polarization rotation[30], and smoothing by spectral dispersion[31]. The pulse duration was 1ns and the total energy delivered was approximately 25kJ. Four different target fills were used, as shown in Fig. 1. The primary experiment, studying pD fusion, used an equimolar mix of D<sub>2</sub> and H<sub>2</sub> fill gas with 5.33atm of each. Background characterization shots were conducted with either pure D<sub>2</sub> or pure H<sub>2</sub> fills, using a mass-equivalent fill of 8atm of D<sub>2</sub> or 16atm of H<sub>2</sub> gas. While pure ‘hydro-equivalence’[32] is not possible between these gas mixes, keeping the mass density constant maintains similar hydrodynamics between the fills. Detailed setup parameters for each shot, including

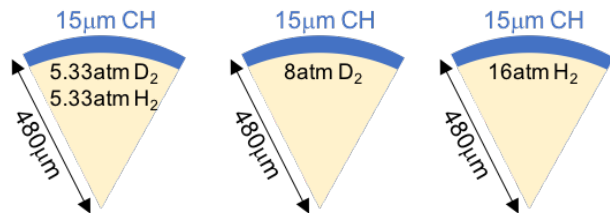


FIG. 1: Schematic of the capsules used in this work, which are 480  $\mu\text{m}$  radius spherical plastic (CH) shells, 15  $\mu\text{m}$  thick, filled with a variety of gaseous fuel mixtures.

measured target information, are given in the Supplemental Material.

Each experiment is diagnosed with a suite of nuclear diagnostics. Neutrons are measured with the standard OMEGA time of flight suite [33] for spectra and yield plus a scintillator-based system to infer the peak nuclear burn time [34]. The  $\gamma$  rays produced by pD fusion are measured with gas Cherenkov detectors (GCD) [35]. These detectors consist of a converter foil where incident  $\gamma$  rays Compton scatter electrons into a gas cell, where Cherenkov light is produced if the Compton electron exceeds the local speed of light ( $c/n$ ). The Cherenkov light is relayed to a photomultiplier tube (PMT) using Cassegrain optics, and the electrical signal recorded on a high-bandwidth oscilloscope. The original GCD, as used in studies of T+<sup>3</sup>He fusion (Ref. 17), was limited to 100 psia of gas, corresponding to a threshold  $\gamma$  energy of 6.3 MeV when using CO<sub>2</sub>. A recent upgraded system has a design that can operate at 400 psia [36], reducing the threshold to 2.9 MeV and enabling these studies of pD fusion, which produces a  $\gamma$  ray at only 5.5 MeV. The response curves of these detectors are calculated with **Geant4** [37] and calibrated *in situ* [38], for additional details see the Supplemental Material.

The oscilloscope signal is corrected for electrical splits and attenuators used in the experiment to recover the signal level at the PMT output. Since peak nuclear production is defined as bang time, the scope trace is aligned in time such that the peak Cherenkov signal is at  $t = 0$ . The trace before and after the Cherenkov signal is used in a background subtraction. The Cherenkov signals for shots with D<sub>2</sub>, H<sub>2</sub>, and D<sub>2</sub>+H<sub>2</sub> are shown in Fig. 2 for each shot (numbered as 74xxx), normalized to the DD neutron yield on each shot. Each fuel type is shown by a corresponding color: HD in reds, D in blues, and H in greens.

The variance in signal level on the HD-filled shots is due to statistics in the detected number of  $\gamma$ s ( $\sim 35$  productive Compton electrons per shot). The H<sub>2</sub>-filled shots were designed as a background test for the Cherenkov detector, since no fusion reactions should occur in these implosions. As expected, all nuclear diagnostics showed

no evidence of nuclear reactions in the H<sub>2</sub> implosions. Some background is observed on shots with only a D<sub>2</sub> fill. The H<sub>2</sub> null shot demonstrates that the signal observed is due to a nuclear process and not due to another process in the implosions (i.e. laser-plasma interactions generating hot electrons). Since the data are shown yield normalized, the DD curves represent the primary source of background in the pD measurement – due to the DD- $\gamma$  (branching ratio  $\sim 10^{-7}$ ),  $(n, \gamma)$  reactions from DD-n interacting with the surrounding material, or mix of hydrogen from the shell into the fuel [39]. The signal level is  $\sim 3 - 4\times$  too high to be explained by mix of hydrogen from the CH shell into the fuel at a level consistent with Ref. 39,  $\sim 4\%$  atomic fraction of H from mix. The estimated contribution from mix and DD fusion nuclear reactions are treated separately when subtracting the background from the pD shots, including propagating uncertainty in the mix fraction and DD contribution. The remaining signal in the pD implosions is attributed to the p+D  $\gamma$  ray (Eq. 1) at 5.5 MeV.

This can be verified with a Cherenkov threshold test. By reducing the GCD gas fill pressure from 400 to 100 psi, the  $\gamma$ -ray energy threshold increases to 6.3 MeV. This threshold scan is shown in Fig. 2 by shots 74614 and 74615 (dotted lines), which were HD-filled implosions conducted with the increased threshold, showing that the Cherenkov signal disappears in the HD implosions as the threshold is increased. This demonstrates that the signal is due to a low-energy  $\gamma$  ray, i.e. the p+D fusion  $\gamma$ .

The  $\gamma$ -ray yield can be calculated for a given reaction  $x$  from the integrated signal ( $V \times s$ ) using the detector equation

$$Y_x = \frac{V \times s}{\Omega \times R \times e \times QE \times G} \times \frac{\chi}{C_x}, \quad (2)$$

where  $\Omega$  is the detector solid angle,  $R$  is the scope input impedance (50 Ohm),  $e$  is the fundamental charge,  $QE$  is the PMT quantum efficiency, and  $G$  is the PMT gain.  $C_x$  is the effective GCD response for reaction  $x$  in photons collected per incident  $\gamma$ , and  $\chi$  is the overall detector efficiency calibration factor [38].

On each HD implosion the  $\gamma$  yield is calculated using Eq. 2, the 5.5 MeV  $\gamma$ -ray response, and the calibration factor. The statistical uncertainty in  $\gamma$  yield results from uncertainty in the integrated signal, DD background subtraction, Compton electron statistics, and the statistical uncertainty in the calibration. The systematic uncertainty results from the uncertainty in the DD background subtraction and from the calibration.

The S-factor for the p+D reaction can be calculated from the pD- $\gamma$  yield using the DD reaction as a reference. The yields for the two reactions are

$$Y_{pD} = \int d\vec{r} dt n_H n_D \langle \sigma v \rangle_{pD}, \quad (3)$$

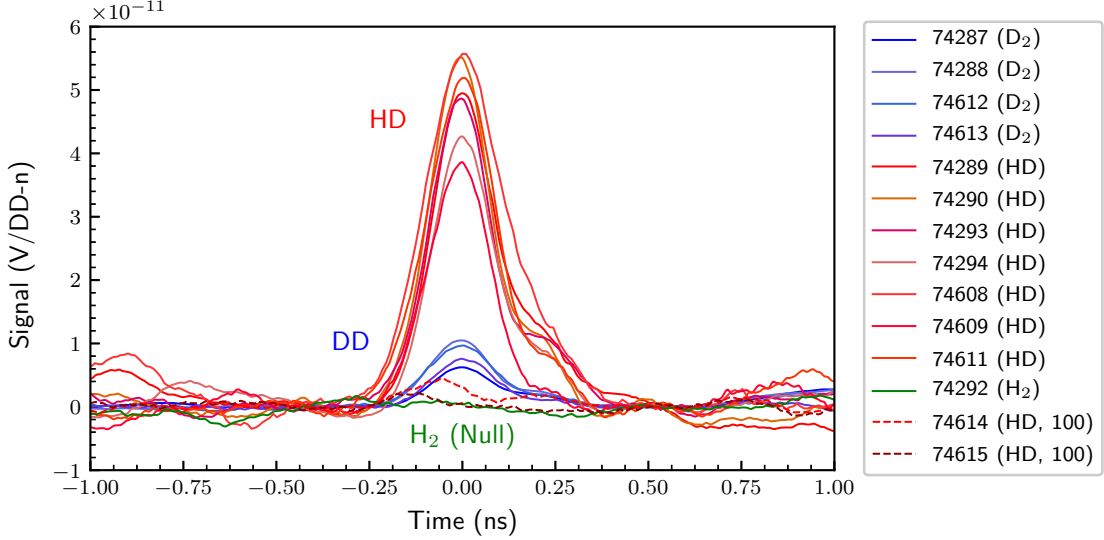


FIG. 2: Cherenkov detector data from each shot as PMT V per DD-n yield versus time, peak aligned at  $t = 0$ . Different capsule gas fills are distinguished by color: D<sub>2</sub> (blues), H<sub>2</sub>+D<sub>2</sub> (reds), and H<sub>2</sub> (green). Two shots with 100 psia of CO<sub>2</sub> (74614 and 74615) instead of 400 psia are shown by the dashed curves.

$$Y_{DD} = \int d\vec{r} dt \frac{n_D^2}{2} \langle \sigma v \rangle_{DD}, \quad (4)$$

where  $n_H$  and  $n_D$  are the proton and deuteron number densities, respectively, and  $\langle \sigma v \rangle$  is the fusion reactivity as a function of temperature;  $n$  and  $T_i$  are typically unknown functions of space and time. The ratio of the two yields is

$$\frac{Y_{pD}}{Y_{DD}} = 2 \int d\vec{r} dt \frac{n_H}{n_D} \frac{\langle \sigma v \rangle_{pD}}{\langle \sigma v \rangle_{DD}}. \quad (5)$$

If there are no ‘profile’ or species-separation effects occurring in these implosions, as demonstrated in the Supplemental Material, then the yield ratio is given by

$$\frac{Y_{pD}}{Y_{DD}} = 2 \frac{n_H}{n_D} \frac{\langle \sigma v \rangle_{pD}}{\langle \sigma v \rangle_{DD}}. \quad (6)$$

where the reactivities are burn-averaged. This assumes that the density and temperature profiles for each reaction are the same, thus the burn duration and volume are also identical. Since these are both non-resonant reactions in this energy range, the reactivity can be written:

$$\langle \sigma v \rangle = \frac{8}{\pi\sqrt{3}} \frac{\hbar}{m_r Z_1 Z_2 e^2} S \xi^2 e^{-3\xi}, \quad (7)$$

which is Eq. 1.56 in Atzeni (Ref. 40), where  $Z_1$  and  $Z_2$  are the reactant charges,  $m_r$  is their reduced mass,  $S$  is the S-factor, and  $\xi$  is related to the Gamow energy ( $\epsilon_G$ ):

$$\xi = \left( \frac{\epsilon_G}{4k_B T} \right)^{1/3}, \quad (8)$$

$$= \left[ \frac{(\pi\alpha Z_1 Z_2)^2 2m_r c^2}{4k_B T} \right]^{1/3}, \quad (9)$$

$$= 6.2696 (Z_1 Z_2)^{2/3} A_r^{1/3} T^{-1/3}. \quad (10)$$

Using this formalism, the yield ratio can then be written as

$$\frac{Y_{pD}}{Y_{DD}} = 2 \frac{n_H}{n_D} \frac{A_{pD}^{-1} S_{pD} \xi_{pD}^2 e^{-3\xi_{pD}}}{A_{DD}^{-1} S_{DD} \xi_{DD}^2 e^{-3\xi_{DD}}}, \quad (11)$$

which is inverted to give an expression for the pD S-factor in terms of the DD S-factor

$$S_{pD} = S_{DD} \times \frac{Y_{pD}}{Y_{DD}} \times \left[ \frac{n_D}{2n_H} \frac{A_{pD}}{A_{DD}} \frac{\xi_{DD}^2 e^{-3\xi_{DD}}}{\xi_{pD}^2 e^{-3\xi_{pD}}} \right]. \quad (12)$$

The DD S-factor is well known from accelerator experiments, the two yields are measured experimentally, and the factor in square brackets is calculated using the DD-n Doppler ion temperature, which is  $\sim 0.1$  for  $T_i \sim 5$  keV. The average center-of-mass energy ( $E_{cm}$ ) for the reactions, the Gamow peak energy, is  $\xi k_B T$  and thus is calculated for the DD and pD reactions separately, though using the same thermal temperature.

An S-factor is calculated for each of the seven HD data shots, which are then used to calculate a weighted mean value:

$$S_{pD} = 0.429 \pm 0.029_{\text{stat}} \pm 0.072_{\text{sys}} \text{ eV-b}, \quad (13)$$

at  $E_{cm} = 16.35 \pm 0.4$  keV. This new result is shown as the red point in Fig. 3, compared to previous data from accelerator experiments [10–13], as well as the evaluated

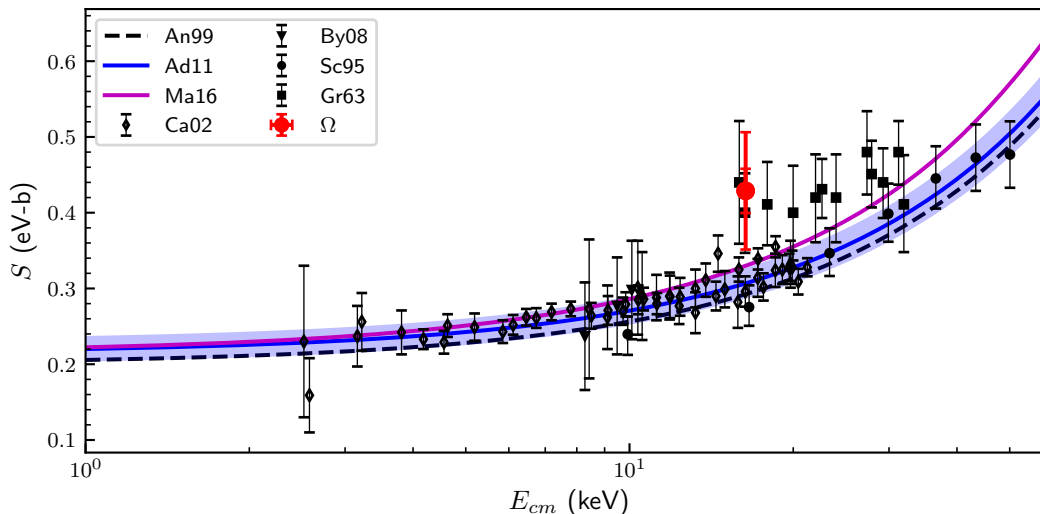


FIG. 3: Our measurement (red point), compared to previous data from accelerator experiments [10–13] (black symbols), as well as the evaluated S-factors reported [8, 26, 27] (black dashed, blue, and purple curves respectively).

The smaller error bar on our measurement is statistical only, while the larger is the combined statistical and systematic.

S-factors reported [8, 26, 27]. Our value is higher than previously reported data at this  $E_{cm}$ , with the exception of Ref. 10, and higher than the adopted evaluations.

In conclusion, in this Letter we report the first measurement of the  $D(p,\gamma)^3\text{He}$  S-factor measured from inertially-confined high-energy-density plasmas, which is only the second cross section measurement directly relevant to nucleosynthesis made with this technique. These plasmas are generated by using intense laser irradiation to implode a fuel-containing capsule, reaching temperatures where thermonuclear reactions occur. Reactions occurring in these plasmas are a more direct surrogate for astrophysical systems, including the universe during the epoch of big-bang nucleosynthesis. We find a cross section higher than most data reported by accelerator measurements in this range, and higher than recent evaluations including the solar fusion II compilation 27 and recent paper by Marcucci et al. (Ref. 8). In addition to relevance for brown dwarfs and protostars, an accurate cross section for pD fusion from fundamental laboratory measurements is critically important as it enables precision checks of the consistency between big-bang nucleosynthesis models and cosmology [8]. Our measurements suggest that additional work on this topic is required. This technique can produce additional data at both higher and lower center of mass energies with further experiments, to continue to constrain astrophysical nucleosynthesis models and cosmological physics.

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