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Leif Holmlid

Journal of Fusion Energy

ISSN 0164-0313
Volume 33
Number 4

J Fusion Energ (2014) 33:348-350
DOI 10.1007/s10894-014-9681-x

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ORIGINAL RESEARCH

Ultra-Dense Hydrogen H(−1) as the Cause of Instabilities in Laser Compression-Based Nuclear Fusion

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Abstract Ultra-dense hydrogen H(−1) is a quantum material and the first material which is superfluid and superconductive at room temperature. This has been shown in detail for the deuterium form D(−1). With its experimentally determined H–H bond distance of normally 2.3 ± 0.1 pm, it is up to a factor of 10^5 denser than hydrogen ice composed of H_2 molecules. Its existence means that when hydrogen is compressed to high temperature and density, as in laser-induced nuclear inertial-confinement fusion (ICF), sudden localized spontaneous transitions to H(−1) will give spots in the material where pressure falls strongly. Such pressure drops give a non-homogeneous phase which will not ignite smoothly. The energy released by the rapid transition to H(−1) will further cause non-isotropic motion of the target material. We here propose that the instability problems which plague ICF can be circumvented by using ultra-dense hydrogen H(−1) directly as the fusion fuel.

Keywords Ultra-dense deuterium · Ultra-dense hydrogen · Laser-induced fusion · ICF · Condensation · Instability

Introduction

Advanced large-scale studies of the possibilities to create nuclear fusion in hydrogen by using intense pulsed lasers have been in progress at least since 1980 [1]. Due to the low density of hydrogen or hydrogen ice used as fusion fuel, compression by intense lasers is required to compress and heat the hydrogen fuel to ignition [2]. The problems of instabilities in the high-temperature fusion fuel are however severe. More recently, schemes using lower compression and a fast igniting laser pulse have been developed [3]. On a smaller scale, promising reports on laser-induced fusion reactions in hydrogen clusters exist [4]. Still, the progress in inertial-confinement fusion (ICF) studies is impeded by instabilities in the compressed hydrogen fusion fuel [5]. We here provide the background to understand the instabilities on the smallest scale.

Properties of Ultra-Dense Hydrogen

The H–H distance in the most common form of H(−1) is 2.3 ± 0.1 pm [6–8]. Here, H(−1) indicates all isotopic forms p(−1), D(−1) and T(−1). This gives a density of the ultra-dense material up to 10^{29} cm^{-3} or approximately 140 kg cm^{-3}. H(−1) is a quantum material [9] which is superfluid [10, 11] and superconductive at room temperature [12]. The structure of H(−1) is formed by chain clusters H_{2N} with N integer, formed by H–H pairs rotating around the vortex [10, 13]. A short chain cluster is shown in Fig. 1. N may take values up to 40 and above. The properties of H(−1) may as suggested by Winterberg [14, 15] be due to formation of vortices in a Cooper pair electron fluid. In most experiments, the deuterium ultra-dense form D(−1) has been investigated since it has a simpler structure than ultra-dense protium p(−1). However, recent experiments on p(−1) have resolved the structure also of this material [11]. The theory for H(−1) is not directly concerned with the nuclear spin of the isotopes [16], but differences exist between D(−1) and p(−1). Since both p and T are fermions, it is expected that T(−1) will behave

L. Holmlid (✉)
Department of Chemistry and Molecular Biology, University of Gothenburg, 412 96 Göteborg, Sweden
e-mail: holmlid@chem.gu.se

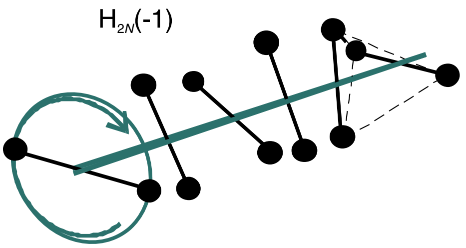

Fig. 1 Short cluster of ultra-dense hydrogen. The H–H distance is commonly 2.3 pm, much shorter than the distance of 74 pm in an H_2 molecule. The H–H pairs rotate around the vortex axis

very similar to p(−1). Related experimental results of a superconductive state are known from very high density hydrogen clusters in voids (Schottky defects) measured by SQUIDS in palladium crystals [17]. The close relation between such clusters and H(−1) has been discussed [18].

Ultra-dense hydrogen H(−1) is the lowest energy form of hydrogen atoms. In fact, a few different excitation levels of H(−1) with different bond distances exist [16]. The characteristic parameter which determines their properties is the spin, being $s = 1$, 2, or 3 in the experimentally studied cases [16]. The ultra-dense material D(−1) is closely related to dense deuterium D(1) which has a D–D distance of 150 pm. The rapid transformation between D(1) and D(−1) was described previously [19]. Similar properties also exist for p(−1). A recent review of Rydberg Matter (RM) gives further background concerning the properties of H(1) and H(−1) [20]. A rapid oscillation between the two forms of deuterium D(1) and D(−1) was indeed observed [7] and was concluded to have a typical time of transformation of less than 0.1 s. The transformation between the two forms is driven by the lower energy of the material in the form D(−1) [8]. This rapid oscillation has not yet been reported for p(−1), but a related process was reported as laser-induced self-compression [21]. Spin and angular momentum conservation are factors that strongly influence the transition back and forth between H(1) and H(−1) [16]. Only a small effective energy barrier is observed for the conversion between D(−1) and D(1) [8]. This is probably related to the difficulty of dissipating the internal rotational energy in D(−1) to other degrees of freedom.

H(−1) is relatively easy to produce, but the amount assembled is limited by the superfluidity which means that the film of H(−1) creeps away over the surfaces where it is deposited or formed [9]. The H(−1) material is stable on metal surfaces and inside the catalyst used for its formation during several days in a vacuum (high or medium). This was reported specifically for D(−1) [7]. The chain-forming clusters D_{2N} probably give the superfluid properties of D(−1) at room temperature [10]. The same conclusion is found also for p(−1) [11]. At elevated temperature, a phase transition exists in D(−1) and the high-temperature phase is not yet well characterized. A non-superfluid (normal) part of the D(−1) phase has further been studied, in the form of clusters D_4 [22]. D(−1) forms superfluid layers only on metal and metal oxide surfaces. On polymer surfaces, the nucleation to D(−1) is prevented [23]. On metal surfaces, the superfluid layer may be more than one monolayer thick with the clusters standing vertically to the surface, while on polymer surfaces, the layer is thinner than one cluster length and the clusters lie on the surface [23]. Most of these properties are believed to apply also for isotopic forms of H(−1).

Instabilities

The background for the instabilities expected during laser-compression of hydrogen is here discussed with reference to Fig. 2. There, the different states for hydrogen atoms and hydrogen molecules H_2 as well as for the ultra-dense material H(−1) are shown. The blue horizontal arrow

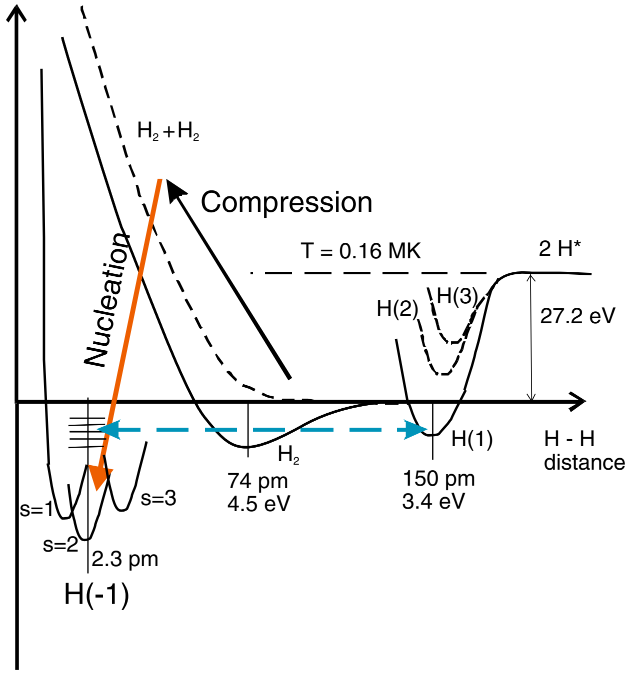

Fig. 2 Potential energy diagram for hydrogen, showing the ultra-dense H(−1) levels with spin quantum number $s = 1$, 2 and 3 to the left and metallic hydrogen (dense hydrogen) as H(1) with 150 pm inter-atomic distance to the right. $s = 2$ gives an H–H distance of 2.3 pm. The rapid transition between H(1) and H(−1) is indicated with the horizontal *blue arrow*. Also molecular hydrogen is shown at 74 pm H–H distance. The *parallel dotted curve* depicts the interaction of two hydrogen molecules. Compression of hydrogen in molecular form will give spontaneous condensation to H(−1) and strong pressure instabilities (Color figure online)

indicates the rapid switch (with oscillation) between the states H(−1) and H(−1); this is a quantum mechanical effect and is not believed to be well described by a continuous transition and potential energy curve. Also, the higher Rydberg matter states H(1), H(2) and H(3) are shown. The axes are not to scale, but the overall situation should be clear from the figure. The three spin excitation levels $s = 1, 2$ and 3 observed experimentally for H(−1) [16] are shown. The higher states in H(−1) indicated may be thought of as coupled internal H–H rotational states in the clusters [11, 13] and high-orbit states of the superconductive electrons [24]. It should be noted that Fig. 2 is drawn for two H atoms, while the condensed phases H(−1), H(1), H(2) and H(3) require many-body interactions to form. The mainly repulsive interaction between H_2 molecules in ordinary hydrogen ice is thus also included for completeness. The energy level for H(1) was calculated in [25], but the energy for the three spin levels of H(−1) is not known precisely.

During laser compression in a time span of a few nanoseconds, the hydrogen fuel used in the laser target is both compressed and heated. This means that the system initially follows a trajectory resembling the repulsive part of the H_2–H_2 potential energy. However, a transfer to the low-energy states of the form H(−1) is possible energetically. At high density and temperature, even spin–forbidden transitions (which may be involved) become rapid enough in the condensed dense material to transfer spontaneously to H(−1). This spontaneous process will probably not take place smoothly over the whole volume of the fuel but start at random spots, as most condensation processes do. This condensation gives a rapid decrease in local pressure due the formation of condensation nuclei probably in the form of short H_{2N} clusters and further condensation, causing pressure instabilities and possibly ejection of material from the fuel volume. As seen in Fig. 2, this condensation will also release large amounts of energy which may heat the fuel rapidly and give hot spots, where fusion may take place prematurely and unevenly. This situation resembles the “knocking” process in internal combustion engines, giving uneven burning of the fuel. Thus, the ICF process does not work as expected in an assumedly smooth isotropic compression.

Conclusions

It is shown in several publications that fusion can be initiated quite easily in ultra-dense deuterium D(−1) [26–30]. Thus, it is suggested that ICF even on a large scale would benefit from the use of this type of fuel which can be produced easily at room temperature [8].

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