J Fusion Energ (2008) 27:296–300
DOI 10.1007/s10894-008-9134-5

ORIGINAL PAPER

Condensed Atomic Hydrogen as a Possible Target in Inertial Confinement Fusion (ICF)

Shahriar Badiei · Leif Holmlid

Published online: 20 February 2008

Abstract H atom Rydberg matter (RM) in excitation state $n = 1$ is concluded to be a form of metallic hydrogen [Badiei S, Holmlid L (2004) J Phys Condens Matter 16:7017]. This material can be produced at low pressure. This condensed form of hydrogen may be very useful as a dense hydrogen inertial confinement fusion (ICF) target, being almost metallic and ten times denser than solid (frozen) diatomic hydrogen used at present. Coulomb explosions and plasma formation are initiated in condensed atomic hydrogen even by relatively weak nanosecond pulsed lasers. The protons emitted with high directivity in these explosions are energetic, corresponding to $T = 10^5$ K, and they may be utilized to give strong compression of the material. The fastest protons observed at up to 1 keV indicate a compression considerably higher than that required for "fast ignition" fusion.

Keywords Inertial confinement fusion · ICF · Condensed atomic hydrogen · Dense hydrogen · Fusion target

Introduction

Rydberg matter (RM) is a condensed phase consisting of strongly interacting Rydberg states of atoms or small molecules [1–3]. In the case of hydrogen atoms, all electronic states are Rydberg states, which means that condensed matter formed from hydrogen atoms will be RM even at its lowest energy levels [4–6]. The bonding in RM in general is similar to metallic bonding, and the Rydberg electrons are delocalized and thus stabilized in the conduction band. Most work so far has been done on RM formed from alkali atoms and hydrogen molecules [7–9], but our interest has recently been focused on RM formed from H atoms. Several groups perform studies directed toward RM, with most activities on formation of RM at low temperatures from cold alkali Rydberg gases [10–12]. Successful high temperature studies on alkali RM are also reported from other groups [13]. We will describe this type of matter as H(n), where n is the Bohr quantum number of the atoms, thus the state studied here is H(1). This material is proposed to be a form of metallic hydrogen [4–6].

Condensed atomic hydrogen of this type (other forms probably exist) has a density of 0.5–0.7 kg dm^{-3}, as derived from the measured interatomic distance [6]. It is probably a future combustion fuel with the highest energy density known, close to 175 MJ kg^{-1} [14]. For fusion studies, other properties are more important. The density of diatomic hydrogen ice (H_2) at normal pressure is 0.07 kg dm^{-3}. The material H(1) is thus almost a factor of ten more dense than this solid which is at present used in experiments aimed at inertial confinement fusion (ICF). Hydrogen H(1), which is stable in the laboratory and which seems to be stable and possible to handle even at room temperature [14], should also have other desirable properties as a fusion fuel: it is not a gas but liquid or solid at room temperature. We have investigated the laser fragmentation of this phase to determine the processes initiated by laser pulses in the material [4–6]. Its interaction with intense pulsed light is naturally of fundamental importance for its possible future use as target in nuclear fusion inertial confinement experiments.

Properties of RM

Desorption of RM clusters takes place at slightly elevated temperatures at suitable catalytic surfaces [15–17]. In recent

S. Badiei · L. Holmlid (✉)
Atmospheric Science, Department of Chemistry,
Göteborg University, 412 96 Goteborg, Sweden
e-mail: holmlid@chem.gu.se

experiments [4–6, 18], the properties of RM consisting of H atoms H(RM) have been studied. Cluster fragments H_N^* that are released by the laser pulse are identified using neutral time-of-flight (TOF) measurements, as in several previous studies on hydrogen molecules and alkali atoms [4, 7–9]. Many methods have been used to characterize and study the RM emitters and the processes that form Rydberg species and RM in desorption, as well as the RM phase directly. Stimulated Raman spectroscopy has revealed the existence of potassium Rydberg species K^* and of K^*-molecule Rydberg complexes at RM emitter surfaces [19]. The formation of Rydberg species at alkali promoted catalyst surfaces has been studied by Kotarba et al. [20–22]. In these studies, the Rydberg species are observed by static field ionization. The properties of dense alkali RM in thermal plasmas have been investigated by Yarygin et al. [13]. These studies give independent proof of the properties of the RM phase in general.

Electrons in the RM clusters are characterized by their quantum number n (from the Bohr atom model), which is called the excitation level of the cluster. Quasi-classical stability calculations with electron correlation [3] show that, even though the RM electrons are delocalized in the RM clusters, it is still possible to describe them accurately at the classical limit as moving in stable orbits that are scaled by n^2. From these calculations, it was concluded that bonding may only exist when all electrons have the same excitation level in the RM cluster, since otherwise the cluster will break down into smaller fragments. For each value of n there exists a quantized interionic bond length in the cluster $d = 2.9n^2a_0$, with a_0 the Bohr radius. The scale factor (dimensional ratio) 2.9 was first determined by calculations [3]. Recent rotational RF spectroscopy studies in the MHz range on RM clusters K_N [23] show that this factor varies slightly with n and with the number of atoms in the cluster N. Smaller values are found for larger N and lower n, down to 2.83 ± 0.01 for $N = 91$, $n = 5$.

The electric field of the laser beam interacts with RM. As a laser pulse passes through the RM cloud, the photons may excite the bonding electrons of two adjacent Rydberg atoms so that the ion cores become exposed to each other. The Coulomb repulsion makes the ions move apart rapidly in a Coulomb explosion (CE) process. This process is often asymmetric, such that a small fragment is emitted which carries away most of the repulsion energy from a larger cluster. The kinetic energy release (KER) given to the fragment released is equal to the Coulomb repulsion energy

$$W = \frac{e^2}{4\pi\varepsilon_0 d}. \quad (1)$$

Here e is the elementary charge, ε_0 is the vacuum permittivity and d is the quantized bond distance $d = 2.9n^2a_0$. The KER is given for small excitation levels (Bohr model quantum numbers) n in Table 1. The TOF of the fragments is $t = s/(v_0 + v)$, where s is the effective flight path length to the detector, v_0 is defined by $v_0 = (2\ W/m)^{1/2}$ and v is the thermal initial velocity component in the same direction as v_0. The experiments often show a slight broadening of the TOF peaks due to the initial temperature of the RM cloud. This broadening, down to 20 K [7], is often much lower than expected for a cloud in contact with an emitter surface at 600–900 K. From the detection of very efficient stimulated emission both in the IR [24–26] and at radio frequencies [27], it is concluded likely that the self-cooling of the RM is due to such effects. In the case of hydrogen H(1), the cooling is not very strong [6] but this may be due to the rather short time for equilibration of the energy released in the $n = 3 \rightarrow 1$ transition between laser shots.

Laser Fragmentation of Condensed Atomic Hydrogen

The UHV chamber where the hydrogen in cluster form H_N^* is produced has a base pressure of 10^{-8} mbar, and hydrogen gas is admitted to a pressure of $\leq 2 \times 10^{-5}$ mbar. The catalyst producing the various forms of RM is an industrial iron oxide catalysis sample impregnated with K (8 wt%). The catalyst is heated to 700−900 K. The heating increases the diffusion rate through the porous emitter material to the external surface and also the rate of desorption of Rydberg species. A Nd:YAG pumped dye laser gives 5 ns pulses at wavelength 564 nm (2.2 eV energy). The laser beam is focused at the center of the chamber by a single lens with a focal length of 40 cm. The Gaussian laser beam with 3 mm width, at the wavelength 564 nm used, can be focused to a minimum beam waist diameter of 100 μm [28]. The maximum power density of the beam at the center of the chamber is then 7×10^{10} W cm^{-2}. The weak-field ionization detector used in the TOF experiments detects the flux of field ionizable Rydberg species from the laser fragmentation of the RM cloud. Fast peaks are observed with kinetic energy 9.4 eV per mass unit (u), i.e., the energy expected at $n = 1$ from Table 1. Two other peaks are also observed, at 24 and 18 eV per u, as shown in [6]. Such a high kinetic energy can only exist for hydrogen Rydberg atoms H^* [4–6] accelerated initially as ions by CEs in the material. The value 9.4 eV corresponds to a

Table 1 Energy release in CEs and interionic distance in RM as a function of the excitation level, corresponding to the Bohr quantum number n for the Rydberg species

Excitation level n	1	2	3
Energy release W (eV)	9.38	2.35	1.04
Interionic distance d (nm)	0.153	0.61	1.38