Encapsulated rydberg matter for energy storage

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Abstract

Rydberg Matter is a collection of atoms that had been excited to nearly the point of ionization, but not all the way, and can remain in that state for long times. It had been proposed for use as an extremely energy-dense medium of energy storage in the Orion's Arm worldbuilding project, in the form of ultradense rydberg deuterium. While I could not much find information on ultradense deuterium or deuterium rydberg matter, I could find enough information on hydrogen rydberg matter to run the needed calculations & present my own plausible take on the use of rydberg matter for energy storage.

The result is a material consisting of rydberg matter made from liquid hydrogen trapped inside carbon nanotubes, with a specific energy of 535.5MJ/kg, an energy density upwards* of $89.725 GJ/m^3$ & density upwards* of $167.56 kg/m^3$, fitting within an order of magnitude above best chemical fuels.

*The density of this material would be likely lower by some fraction due to the packing efficiency of the carbon nanotubes, which would scale the energy density as well.

As a secondary conclusion my calculations support the plausibility of the depiction of rydberg matter energy storage as presented in the Orion's Arm worldbuilding project in terms of energy density.

Contents

1 Rydberg matter as energy storage

Rydberg matter is a state of matter certain elements can exist in, where electrons of the atoms are highly excited (ie. have additional energy, and occupy higher orbitals than normally), yet not excited enough for the atom to lose the electron & become ionized. The state of matter is unstable, but can have very long mean lifetime at high excitation, potentially on par with the age of the universe, which is most likely due to larger separation between the ground state and the excited state making a spontaineous transition of the electron back to the ground state less probable.

Rydberg matter is of particular interest in power storage application, due to the fact it's excited electrons store a lot of energy, and is missing very little energy to becoming fully ionized, which would produce ions with a lot of kinetic energy, which may be captured and converted into useable energy by using magnetohydrodynamic generators ie. machinery which extracts energy from the movement of charged particles - such generators had been practically demonstrated with efficiencies up to 30%, they are in theory heat engines just like most other power generation methods, in this case temperature relating to velocity of the particles, but are not limited in upper temperature like other generators whose parts actually reach the operating temperatures, so efficiencies like 90% should be achievable.

Alternatively, for a simpler method of energy generation, rydberg matter may be fully ionized, and then the ions may be allowed to recombine with their lost electrons, which puts the atom back in it's ground state, and the energy is emmited as light of a specific wavelength, which may be used for heating, radiolysis, or other purposes - for hydrogen in particular, the recapture of a free electron means lowering it's energy by 13.6eV, that energy being released in form of a photon, which corresponds to light at 91.165nm wavelength, putting it in Extreme Ultraviolet range.

Rydberg matter becomes unstable in large clusters, yet also naturally maintains extremely low density (the largest cluster reported as of the writing date had 91 atoms), so to store significant amounts of it, it would have to be compressed & encapsulated in another material, likely resulting in a nanoscopically fine dusty substance with significiantly less rydberg matter content than actual pure bulk rydberg matter, lowering the energy storage capability by an order of magnitude or two.

While I claim an exact specific energy for the resulting material, it's important to note it would be highly dependant on the encapsulation, as one can for example use nanotubes with smaller diameter, making the end product more carbon by mass, or larger diameter for the oposite, or potentially somehow separate out only the rydberg matter capsules with the largest diameter to maximize the rydberg matter content and greatly increase specific energy.

2 Density of hydrogen rydberg matter

The density of hydrogen rydberg matter can be deduced from the bond distance between atoms in it, for which a formula exists: (source)

$$d = 2.9 \times n^2 \times a_0$$

where:

- d is the bond distance
- n is the principal quantum number of the hydrogen's electron, which you can think of as it's excitation level. It must be an integer.
- a_0 is the bohr radius, a physical constant denoting the average distance between the nucleus and the electron in a hydrogen atom. It is equal to $5.29177210544(82) \times 10^{-11}m$.
- 2.9 is an experimenally determined constant.

Raising the bond distance to the power of 3 provides the volume which one atom of the hydrogen rydberg matter takes up, and dividing the mass of one hydrogen atom by that volume provides the density of the rydberg matter as a bulk substance. Inverting the volume provides the number of atoms per volume which will be useful later.

The mass of a single hydrogen atom is $1.67 \times 10^{-27}kg$

The bond distance of hydrogen rydberg matter at n=100 is $1.5346\mu m$, coresponding to $3.614\mu m^3$ per atom or $2.767033508 \times 10^{17}$ atoms per m^3.

The resulting density of hydrogen rydberg matter at n=100 is $4.6208203 \times 10^{-10}kg/m^3$

3 Energy density of hydrogen rydberg matter

The amount of atoms in one cubic metre of bulk rydberg matter is known, and the amount of energy stored in a single atom can also be known. A formula exists which provides the energy of the excited electron within the atom compared to a free electron that is not bound to an atom. (source)

$$E_B = -\frac{R_H}{n^2}$$

where:

- E_B is the binding energy, ie. energy of the electron compared to a free electron, which is also the amount of energy required to fully remove that electron from the atom, causing ionization.
- R_H is the Rydberg constant for hydrogen.
  It is equal to 13.6eV or $2.176 \times 10^{-18} J$
- n is the excitation level, which must be an integer.

Note the negative sign, as the energy of the electron that is still bound to an atom is lower than that of a free electron. A completely unexcited electron in a hydrogen atom has 13.6eV less energy than a free electron, which is also the energy that is released when a free electron binds with a proton (ionized hydrogen atom).

At n=100, the binding energy is 0.00136eV or $2.176 \times 10^{-22} J$, meaning the energy compared to a fully bound electron is 13.599eV or $2.17578 \times 10^{-18} J$. Given that we also know that at n=100 there are $2.767033508 \times 10^{17}$ atoms per m^3, at $2.176 \times 10^{-18} J$ per atom it gives $0.6 J/m^3$ energy density.

Given that we know the density of the rydberg matter at n=100 we can calculate it's specific energy to be $1.29847075 \times 10^9 J/kg$ which is quite impressive, nearly 1.3GJ/kg.

4 Comparison of rydberg matter properties at various excitations

Here I present a table where I ran the same calculations as in the previous 2 sections for various specified excitation levels. Do however note that at excitation n=12 the mean lifetime of a rydberg matter cluster is roughly 25 seconds, so it would likely not be very good at energy storage applications, meanwhile n=80 yields mean a mean lifetime similar to the age of the universe.

n	density	energy density	specific energy
10	$4.621 \times 10^{-4} kg/m^3$	$596 KJ/m^3$	1.29GJ/kg
20	$7.22 \times 10^{-6} kg/m^3$	$9384 J/m^3$	1.3GJ/kg
30	$6.339 \times 10^{-7} kg/m^3$	$825 J/m^3$	1.302GJ/kg
40	$1.128 \times 10^{-7} kg/m^3$	$147 J/m^3$	1.302GJ/kg
50	$2.957 \times 10^{-8} kg/m^3$	$38.5 J/m^3$	1.302GJ/kg
60	$9.904 \times 10^{-9} kg/m^3$	$12.9 J/m^3$	1.303GJ/kg
70	$3.928 \times 10^{-9} kg/m^3$	$5.12 J/m^3$	1.303GJ/kg
80	$1.763 \times 10^{-9} kg/m^3$	$2.3 J/m^3$	1.303GJ/kg
90	$8.695 \times 10^{-10} kg/m^3$	$1.13 J/m^3$	1.303GJ/kg
100	$4.621 \times 10^{-10} kg/m^3$	$0.6 J/m^3$	1.303GJ/kg

It would appear that reaching higher excitation levels only makes it last longer, and judging from the naturally bigger volume I would imagine also harder to compress. The specific energy does not drop significantly until the low excitations like 1 and 2.

5 Rydberg Matter from liquid hydrogen encapsulated in Carbon Nanotubes

I would consider rydberg-matter-filled carbon nanotubes most plausible, as ways for production of carbon nanotubes are known to exist, and carbon nanotubes can also exist in a closed state where the ends are capped off, trapping hydrogen inside. An assumption is required that it is possible to create rydberg matter from the hydrogen that is already trapped within the carbon nanotube.

The longest carbon nanotube ever grown had been whole 550mm long, over half a metre, so I feel setting an arbitrary example of a 100-micrometre-long nanotube is not unreasonable.

Ways to grow large-diameter carbon nanotubes (50nm to 150nm range) had been demonstrated (source) so I will assume an example of a 100nm-diameter carbon nanotube here.

Bonds between carbon atoms are typically around 0.356nm long, so the available space inside the nanotube would be calculated by a cylinder with a radius of 49.644nm, meanwhile the space the nanotube takes with a radius of 50.356nm. Given a 100-micrometre-long nanotube that corresponds to an internal volume of $7.743 \times 10^{-19} m^3$ and external volume of $7.966 \times 10^{-19} m^3$

Liquid hydrogen has a density of $70.85 kg/m^3$ (source) so if the nanotube were to be filled with liquid hydrogen & closed, that $7.743 \times 10^{-19} m^3$ of internal volume would contain $5.4856 \times 10^{-17} kg$ of hydrogen. That means the density of hydrogen across the entire volume the nanotube takes up is $68.86 kg/m^3$. Knowing this allows judging the energy density of such a material.

Taking the 1.303GJ/kg figure from earlier, knowing that there is $68.86 kg/m^3$ of hydrogen in such material, the **resulting energy density is 89.725GJ/m^3**

For the mass of the carbon nanotube itself, substracting the internal volume from the external volume gives the volume taken up by the carbon atoms, which would come out to $2.237 \times 10^{-20} m^3$, and given carbon's density of $3515 kg/m^3$ means the carbon nanotube itself masses $7.8624 \times 10^{-17} kg$, and if not filled with the hydrogen would have a density of $98.697 kg/m^3$ [1]. Together the density of the material ends up at $167.56 kg/m^3$ ignoring packing efficiency.

[1] I tried this method out with 2nm sized carbon nanotubes and it did in fact give the usual expected density of $1.3 g/m^3$ to $1.4 g/m^3$

Now, combining the energy density of the contained hydrogen rydberg matter with the total density of the material gives the final specific energy:

535.5MJ/kg.