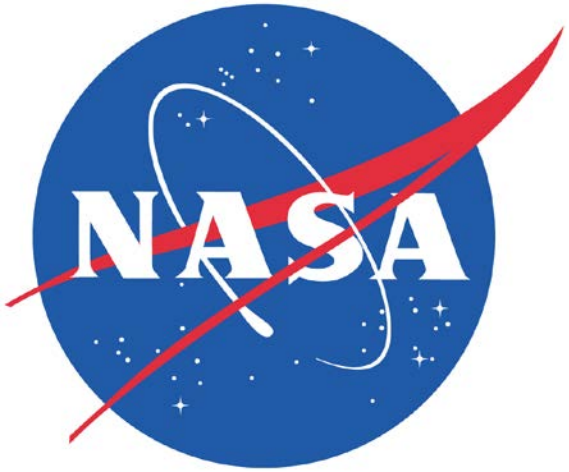

Metallic Hydrogen: A Game Changing Rocket Propellant

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A Game Changing Rocket Propellant-

Why?

Some Remarkable Properties of Metallic Hydrogen

- Recombination of hydrogen atoms releases 216 MJ/kg
- Hydrogen/Oxygen combustion in the Shuttle: 10 MJ/kg
- TNT 4.2 MJ/kg

- **Theoretical Specific Impulse, Isp**
  - Metallic Hydrogen 1000-1700s
  - Molecular hydrogen/oxygen ~460 s (space shuttle)

- Metallic density about 12-13 fold of liquid molecular hydrogen
- Sufficient thrust for single-stage to orbit; explore outer planets

. Cole, I. F. Silvera, and J. P. Foote, "**Conceptual launch vehicles using metallic hydrogen propellant**," in *STAIF-2008*, Albequerque, NM, 2008, pp. 977-984.
J. W. Cole and I. F. Silvera, "**Metallic Hydrogen Propelled Launch Vehicles for Lunar Missions**," in *Space Propulsion and Energy Sciences International Forum (SPESIF)*, Melville, NY, 2009.
J. W. Cole and I. F. Silvera, "**Future propellants for launch vehicles - metallic hydrogen with water and hydrocarbon diluents**," in *Space Propulsion and Energy Sciences International Forum (SPESIF)*, Melville, NY, 2010.
I. F. Silvera and J. W. Cole, "**Metallic Hydrogen: The Most Powerful Rocket Fuel Yet to Exist**," in *AIRAPT 22*, Tokyo, Japan, Journal of Physics: Conference Series, on-line http://iopscience.iop.org/1742-6596/215/1/012194, 2010.

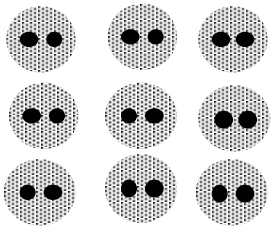
METALLIC HYDROGEN: A LIGHT WEIGHT HIGH ENERGY DENSITY MATERIAL

What is it?

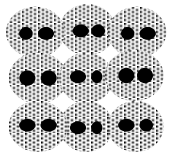
Solid hydrogen is a molecular solid that converts to an atomic metal under pressure.

2-3 megabars? 4-5 megabars?

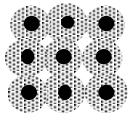
Pressure ► Pressure



Molecular solid insulator

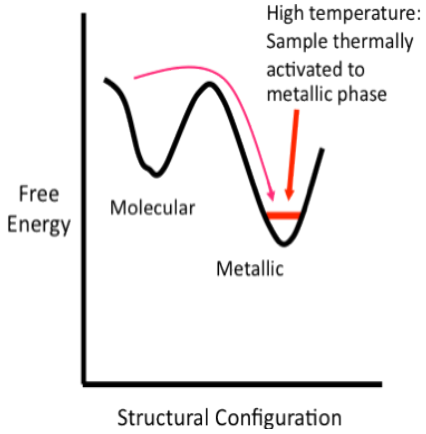


molecular metal

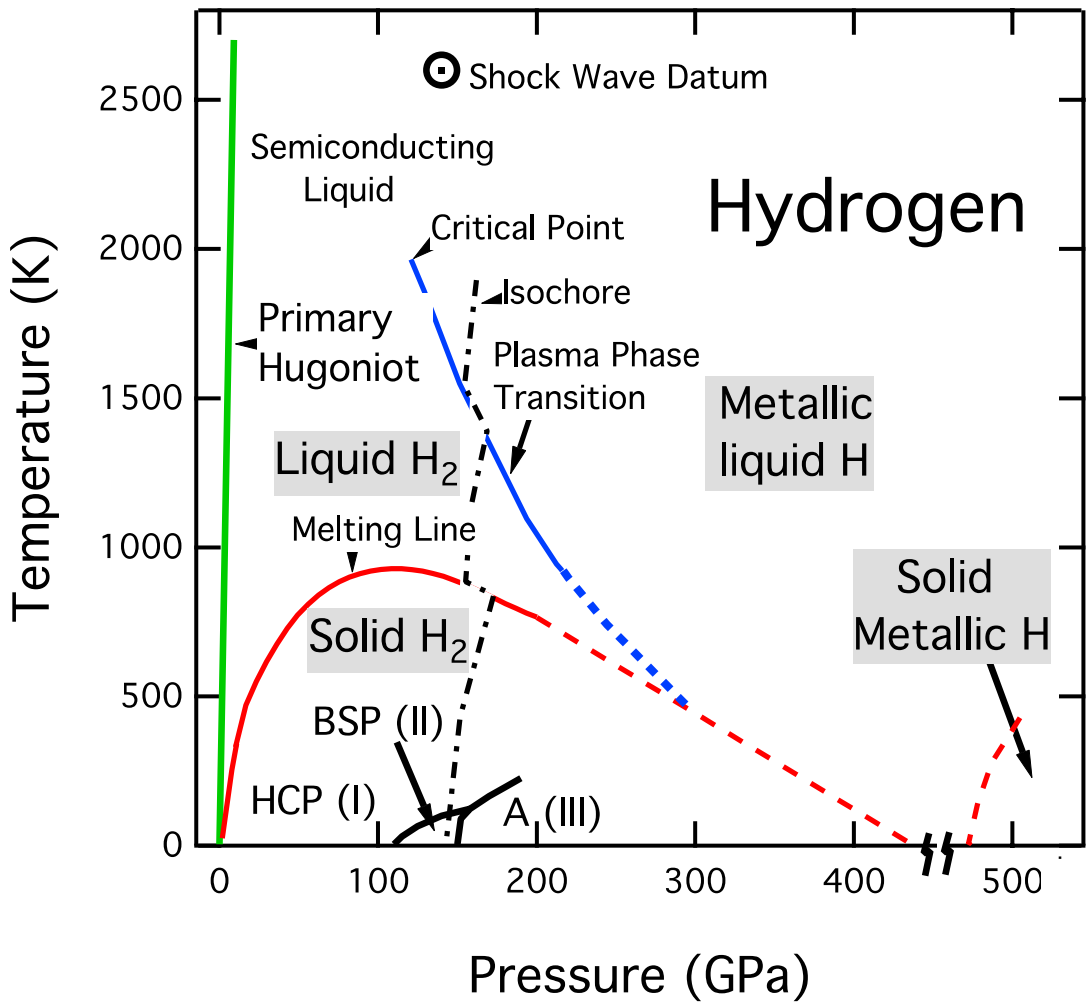


atomic metal

Predicted to be metastable: remove the pressure and it remains metallic.



Phase Diagram of Hydrogen: theory and experiment



I. F. Silvera, "**The insulator-metal transition in hydrogen**" *Proc. of the National Academy of Sciences,* vol. 107, pp. 12743-12744, 2010.

Important Points

- Predicted dissociation Pressure: 4-5 megabars
- If metastable and thermal activation energy is high, controlled heating triggers recombination and releases energy

OUR GOALS

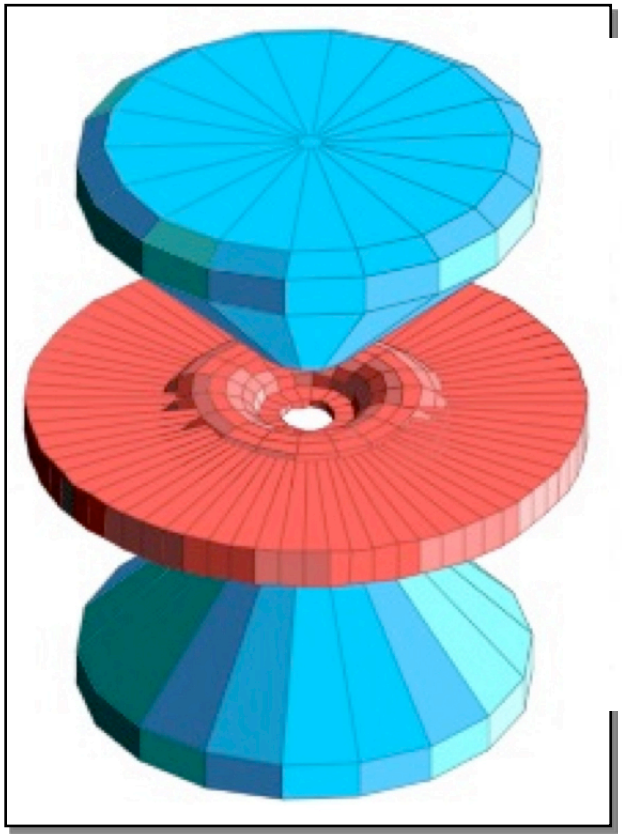
- Produce metallic hydrogen in small quantities
- Test for metastability
- Determine Critical Temperature for conversion
- **Develop a method to scale down the critical pressure**

Other Properties

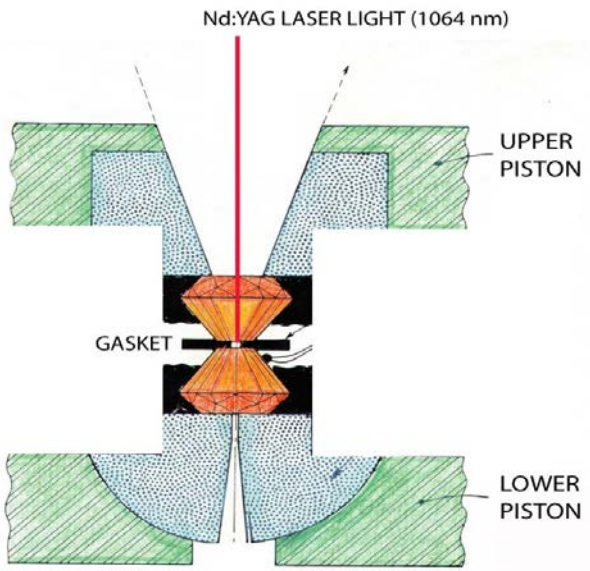
- Room temperature or higher Superconductivity
- Possible liquid at T=0 K and high pressure

Megabar Pressures Generated in a Diamond Anvil Cell

Diamonds and Gasket
(about 3-4 mm linear dimensions)



The Heart of a DAC



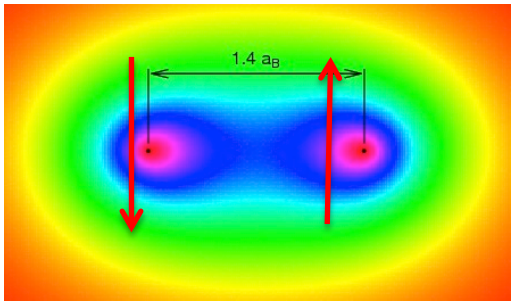
Sample confined in small hole in gasket
Optical access to sample

Diamond Anvil Cell
(about the size of a Coca-Cola bottle)

How Can We Reduce the Critical Pressure for Metallization?

Implanting electrons in solid molecular hydrogen should do the trick!

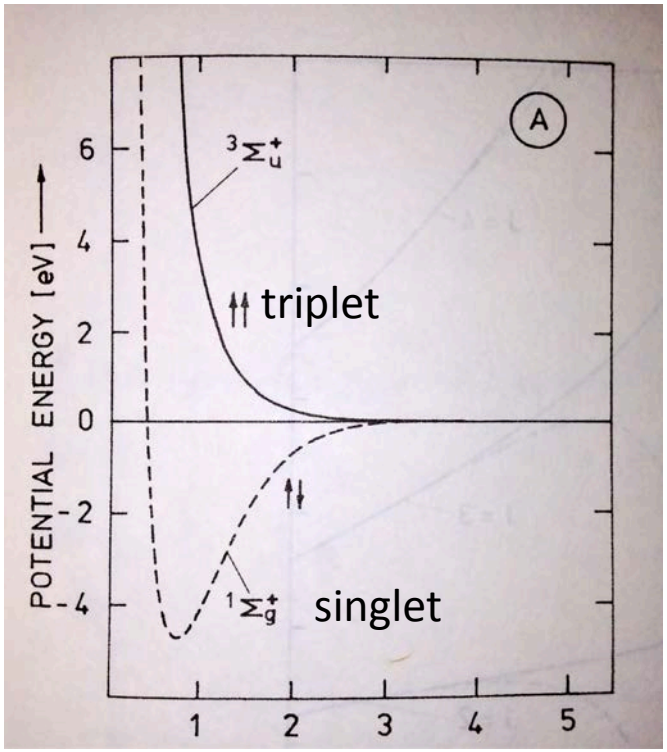
Hydrogen Molecule:
2 protons
2 electrons with antiparallel spins



Pauli Principle
Electrons are fermions:
Only 1 quantum state/electron can be occupied

Antiparallel spins: 1 state

Parallel spins: 3 states



For an electron to overlap a molecule, the molecule must be in the triplet state which is non-bonding

Impurity atoms doped into hydrogen can reduce the critical pressure!

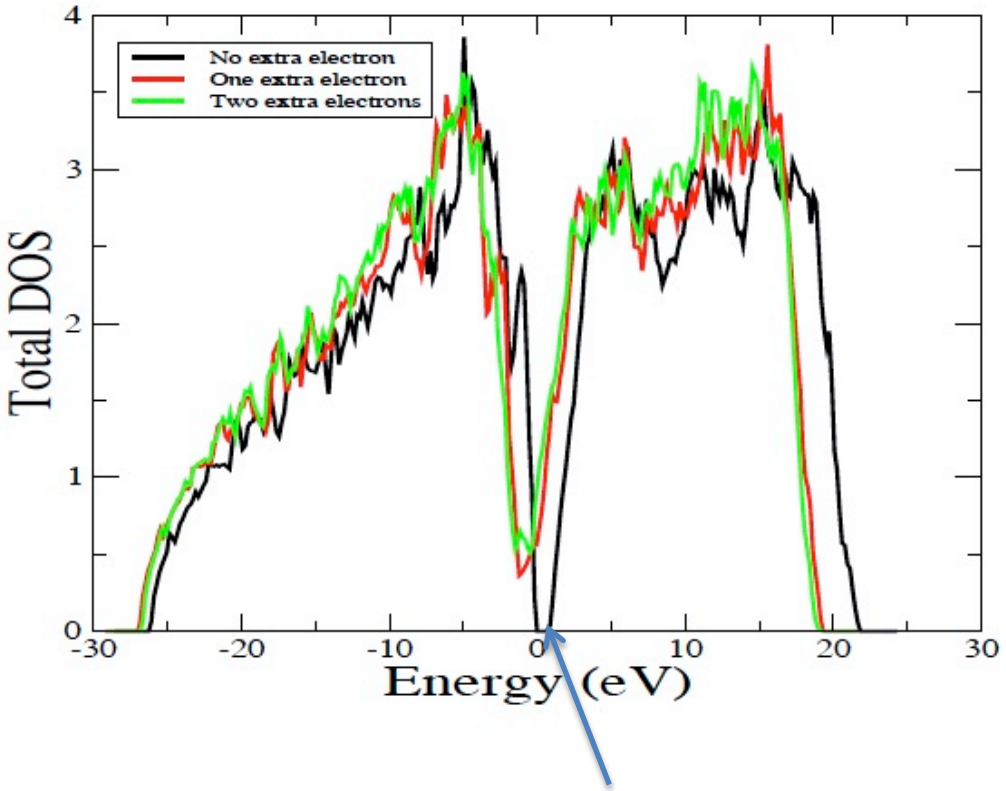
A. E. Carlsson and N. W. Ashcroft, Phys. Rev. Lett. **50**, 1305-1308 (1983).

Our idea: inject electrons into hydrogen as impurities; overlap with

Hydrogen singlet bonds weakens the bond and closes the gap

Calculations: S. Bonev

Density of electronic states



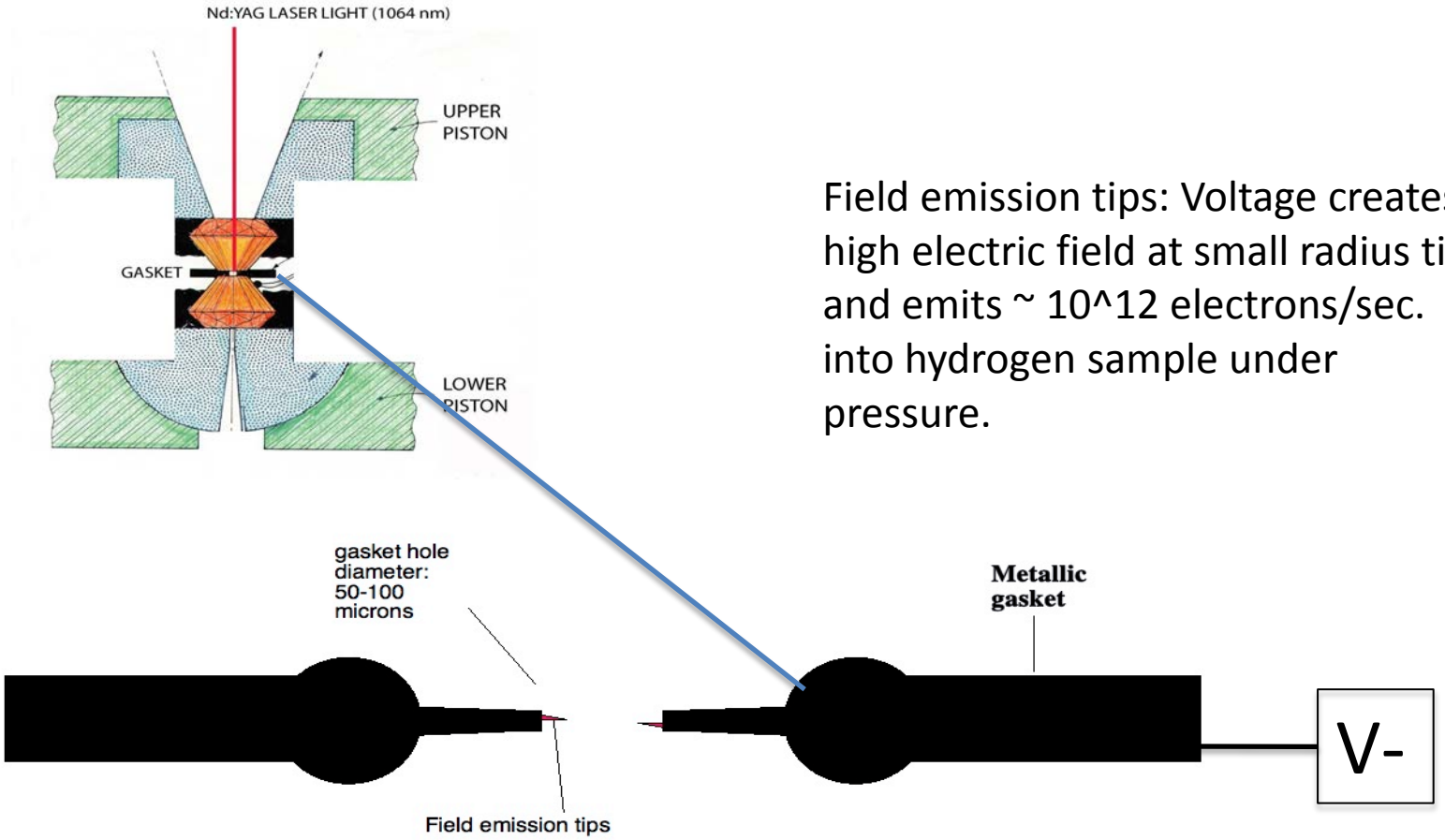
Band gap

Proton or electron irradiated solid hydrogen at ambient conditions-zero pressure:

Electrons are localized in cavity-like states in the lattice.

A new spectral feature appears in the near IR for these states.

S. K. Bose and J. D. Poll, "**Interference effects in the infrared absorption of solid hydrogen due to localized electrons**," *Can. J. Phys.,* vol. 65, pp. 58-66, 1987.



Field emission tips: Voltage creates high electric field at small radius tip and emits ~ 10^12 electrons/sec. into hydrogen sample under pressure.

Experimental Plan

- Study conditions: first in large gaskets at modest pressures less than 1 megabar:
  1. Make gaskets
  2. Attach Field emission tips (FETs)
  3. Load Diamond Anvil Cell (DAC) and inject electrons
  4. Measure IR spectrum and study thermal conditions to localize electrons
  5. High Pressure runs to make metallic hydrogen

Status:
A DAC is prepared as well as bare gaskets.

FETs: Metallic Carbon nanotubes will operate as FETs.

Next week we start growing them in the inside wall of the gasket.

Final Comments

A few months ago Eremets and Troyan published a paper claiming to have made metallic hydrogen

M. I. Eremets and I. A. Troyan, **"Conductive Dense Hydrogen**," *Nature Materials,* vol. 10, pp. 927-931, 2011.

We do not believe that they produced metallic hydrogen and have written a paper posted on the Condensed Matter Archive:

W. J. Nellis, A. L. Ruoff, and I. F. Silvera. (2012, **Has Metallic Hydrogen Been Made in a Diamond Anvil Cell?** *arXiv:1201.0407v1*.

Thank you for your attention