Plasma: the 4th State of Matter and a Path to Fusion Energy use in Electricity Production

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Outline of presentation

- States of matter - s, l, g, p
- Plasma - what it is
- Plasma - examples inside and outside the lab
- Nuclear fusion - in nature, in the lab
Plasma is referred to as the 4th state of matter - it is the 1st step toward fusion.
A review of simple atomic states

Ground state
(neutral)

Excited state
(neutral)

Ionized state
(plasma)
Spontaneous emission of electromagnetic energy

Some high energy (excited OR ionized) state

e falls to lower energy level

Light emitted

Lower energy state
A group of ions form by adding energy to neutral atoms.

Neutral atoms having electrons associated with parent atom.

Add energy.

Plasma having electrons free to move about parent ions.
What is a plasma?

- A plasma is --- an ionized gas.
- Plasma is called the “4th state of matter”
- About 99% of the visible mass of the universe is in a plasma state of matter. (However, this is relatively little of the overall matter of the universe - only about 5%!) 
- ‘Plasma’ was coined by Tonks and Langmuir in (1929):

  “...when the electrons oscillate, the positive ions behave like a rigid jelly...”
Why are we interested in plasmas?

- **Astrophysics**
  - Understanding plasmas helps us to understand stars and stellar evolution.

- **Upper atmospheric dynamics**
  - The ionosphere is a plasma.

- **Plasma Applications**
  - Plasmas can be used to build computer chips and lasers, to clean up toxic waste, and drive space craft.

- **Fusion Energy**
  - Potential source of safe, clean, and abundant energy.
We used to know more than we do now....

This isn’t your father’s (or mother’s) universe....

Composition of the Cosmos

- Heavy elements: 0.03% - 0.1%
- Ghostly neutrinos: 0.3%
- Stars: 0.5%
- Free hydrogen and helium: 4%
- Dark matter: 30%
- Dark energy: 65%
Where do we find plasmas?

- **Examples of plasmas on Earth:**
  - Lightning
  - Neon and fluorescent lights
  - Laboratory experiments

- **Examples of astrophysical plasmas:**
  - The sun and the solar wind
  - Stars, interstellar medium
Part of the 0.5%..
Plasma Characteristics

- Equal amounts of positive and negative charge are ‘free’ to move about.
- Broad range of particle density, \( n \), of charged particles (so many per volume - not mass per volume!)
- Broad range of thermal energy of the electrons (1 eV \( \sim 10,600 \) C)
- Plasmas differ depending on the type of ions (positive or negative) and gas species.
- Plasmas interact strongly with electric and magnetic fields.
- Plasmas support many different types of waves and oscillations.
Plasma-based industrial products

- Computer chips and integrated circuits
- Computer hard drives
- Electronics
- Machine tools
- Medical implants and prosthetics
- Audio and video tapes
- Aircraft and automobile engine parts
- Printing on plastic containers
- Energy-efficient window coatings
- Anti-scratch and anti-glare coatings on eyeglasses and other optics
The solar ‘wind’ can be the origin of planet aurora

Aurora require:
- plasma source
- ion trapping mechanism
- atmosphere for interaction

On Earth ...
- Sun as plasma source
- magnetic field as ion trap
- nitrogen and oxygen atm.

On Jupiter (Io helps as a source) & on Saturn also
Interactions between the earth’s magnetic field and a plasma can have spectacular results

- The northern lights (aurora borealis)
- The southern lights (aurora australis)

Photo by David Fritz
http://dac3.pfrr.alaska.edu:80/~pfrr/AURORA/INDEX.HTM
The solar wind vs. Earth’s magnetic field

- Large solar flares can cause problems with electrical grid, satellites and other spacecraft.

- Without the Earth’s protective magnetic field, no atmosphere would have developed because it would have been swept away by highly energetic particles long ago.

- Without an atmosphere, ionizing radiation would have kept life from forming.

- Let’s hear it for the magnetic field of Earth!!
In the classroom

- Be sure to include the Earth’s magnetic field as an important component of the Earth

- Emphasize the interactions among charged particles and magnetic fields

- Earth science is a compilation of ‘universe’ science interactions and processes - not isolated particulars

- Benjamin Franklin championed plasma discharges without knowing it! (Experiments and Observations made on Electricity, 1751)
Classical DC Discharge in a Tube

Negative Glow

Positive Column

Note: Cathode is electron emitter (recall cathode ray tube of older TV sets)
Plasma appearance is affected by density and mean free path.

<table>
<thead>
<tr>
<th>Density</th>
<th>Mean free path</th>
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<tbody>
<tr>
<td>High</td>
<td>Low</td>
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<tr>
<td>Medium</td>
<td>Medium</td>
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<tr>
<td>Low</td>
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Density and Mean Free Path

Some examples of density \( n \) as defined by \#particles/cm\(^3\):

Use Avogadro’s number and known relationships to find \( n(\text{ideal gas}) \) at STP: \( N_A = 6.023 \times 10^{23} \) per 22.4 l

\[
\text{n(air, N}_2, \text{ O}_2, \text{ Ar)} \approx \frac{(6.023 \times 10^{23})}{22.4 \times 10^3 \text{ cm}^3} = 2.69 \times 10^{19}/\text{cm}^3
\]

Using \( \rho(\text{Hg}) = 13.5\text{g/cm}^3 \) & mass of Hg atom = \( 3.33 \times 10^{-22} \) g leads to:

\[
\text{n(Hg)} = \frac{(\text{Hg atom}/ 3.33 \times 10^{-22} \text{g})(13.5\text{g/cm}^3)}{} = 4.05 \times 10^{22}/\text{cm}^3
\]

\( \text{n (sun center)} \approx 9 \times 10^{25} /\text{cm}^3 \)!
Examples of mean free path

- MFP is proportional to the energy of the particle and inversely proportional to its cross sectional area and pressure
  \[ \text{mfp} = \frac{1}{(1.41)\pi d^2 p} \]

- \text{mpf (atm)} \approx 90 \text{ nm}
- \text{mfp (high vac, 10-5 atm)} \approx 10 \text{ m}
- \text{mfp (sun center)} \approx \text{a few H diameters}
Small fluorescent tube

- Plasma is conductive -- shown by the arc behavior on the glass
- Electric fields alone can ionize a gas
- The plasma can not be seen if a phosphor coating is present
- Each example here is an argon and mercury plasma
Large Light Bulb Plasma Ball

- To notice
  - Plasma Colors
  - Shape
  - Attraction
  - Arc Distance
  - Diffusivity
Motion of charge particles in an electric field

- Random thermal activity
- Electric field forces: \( \mathbf{F} = q \mathbf{E} \) (\( q \) is charge, force is in linear direction of electric field)
- Mobility decreases as pressure (particle density) increases
- An electron-atom collision can produce one electron-ion pair
- Electron-ion pairs grow exponentially with distance
Motion of charged particles in a magnetic field

Charged particles (ions and electrons) follow a circular path perpendicular to magnetic field \( \mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \). The force at any point in space is linear, but because its direction is changing, the final path is circular.

They follow a spiral path if they have some velocity parallel to the magnetic field \( \mathbf{F} = q(\mathbf{E} + (\mathbf{v} \times \mathbf{B})) \).
Magnetic fields cause charges to move in circles

- To notice
  - Plasma Colors
  - Shape
  - Attraction

- Magnetic fields have an effect on moving charged particles
- \( F = q (v \times B) \) causes circular motion
- \( F = q (E + v \times B) \) What type of motion results?

Magnet
Plasma discharge

DIII-D National Fusion Facility

General Atomics
NUCLEAR FUSION
Fusion - basic idea

Atom + Atom → Large Atom + ENERGY
Conditions must be right for fusion to occur

Just as in a chemical reaction, fusion reactions are governed by probabilities. For fusion to occur, the product of the density \( n \), temperature \( T \), and energy confinement time \( \tau \) must be greater than some value. This is known as the Lawson criteria,

\[
\text{LawCrit} = n \times T \times \tau > 10^{21} \text{ keV s/m}^3
\]

This is good, because in the lab, we can’t make \( n(\text{lab}) = n(\text{sun}) \) but we can make \( T(\text{lab}) \gg T(\text{sun}) \)!
High temperatures are required to overcome Coulomb forces of plasma ions

Like Charges Repel
The temperature scale covers more than 10 orders of magnitude.

-196 °C liquid nitrogen
-273 °C absolute zero
-269 °C liquid helium (He)
-78 °C dry ice, solid CO₂
0 °C ice
100 °C water boils
1,500 °C iron (Fe) melts
3,400 °C tungsten (W) melts
6,000 °C sun's surface
10,000 °C fluorescent light plasma
16,000,000 °C sun's center
100,000,000 °C H nuclei fuse in lab
Billions °C massive stars, supernovae

The temperature scale covers more than 10 orders of magnitude.
Fusion Built the Periodic Table of Elements - a self portrait

- Mostly of BB origin
- Mostly of H/He fusion origin
- Mostly of SN origin
- Nuclei relatively stable
In a nutshell (summary point!), the ultimate goal of the world-wide fusion research effort is...

To use energy from the process of fusion on Earth to

1. heat water
2. make steam
3. turn a turbine (propeller set)
4. turn an electrical generator
5. make electricity
Why do we need new sources of energy?

The graph shows the projected energy consumption from 1900 to 2300 AD. The blue line represents the current energy consumption, while the red line indicates the future consumption. The graph highlights that a shortfall in energy must be supplied by alternative sources around the year 2100 A.D.
Review of hydrogen isotopes

- Hydrogen = $^1\text{H}$
- Deuterium = $^2\text{H}$
- Tritium = $^3\text{H}$
Mass ‘goes’ into energy in fusion reaction

Although we say the process “turns mass into energy,” a more correct way to put it is: the origin of the released energy is the rearrangement of nuclear bonds.
Advantages of fusion as an energy producer

- Fusing deuterium and tritium to produce significant energy is achievable

- No CO₂ (or other greenhouse gas) output

- Fuel resource will last many millions of years
  Deuterium, a hydrogen isotope, is found in the ocean

  - Tritium is a byproduct of the process and is harvested for reuse

- No radioactive wastes - although there will be local activation of structural materials
Methods for confinement

- Hot plasmas are confined with gravitational fields in stars.
- In fusion energy experiments, magnetic fields are used to confine hot plasma, and inertial confinement uses lasers.
Magnetic fields exert a force on moving charges

Plasma can be controlled by a magnetic field, and the effects are observable if the mean free path is long enough.
The Magnetic Fusion Reactor

- **How can we fuse these light atoms?**
  - Make a plasma---ionize the gas atoms
  - Heat the plasma---use particle beams and electromagnetic energy (RF, microwave)
  - Hold on to the plasma---use a magnetic field
  - Harness the energy---use a series of heat exchangers involving liquid metals and other fluids
Controlling fusion with magnetic fields

- Most magnetic confinement devices in use today have a toroidal shape.
- Large magnetic fields are created by driving currents through coils wrapped around the torus.

http://demo-www.gat.com/
DIII-D Tokamak contains high temperature deuterium plasma
DIII-D with plasma and with no plasma
Outside DIII-D - industrial scale experiment
Joint European Torus: the largest confinement device ever built
ITER - “The Way” in France

International
Large scale
Produce fusion energy
No electricity production