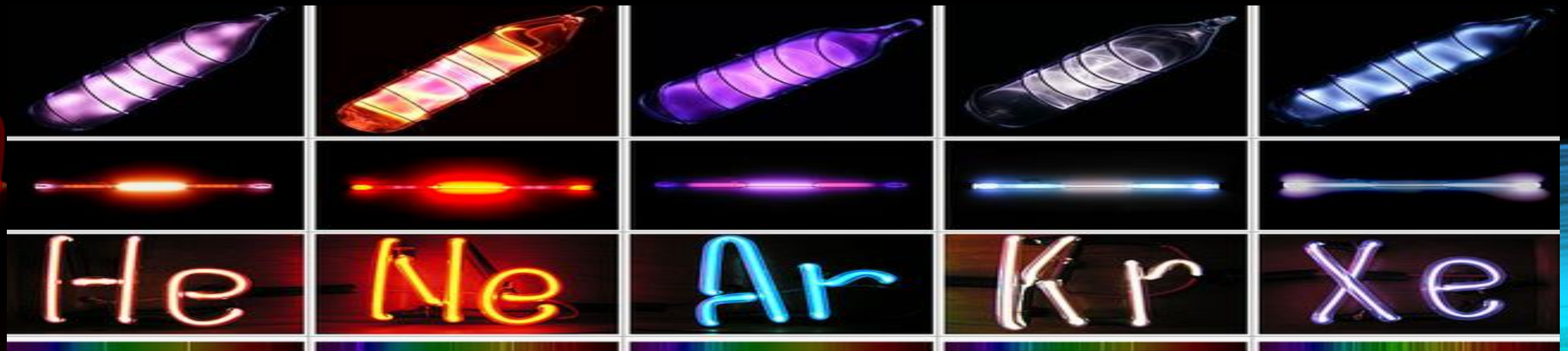# THE ELECTRIC DISCHARGE EXPERIMENTS

A Theorist's Exploration of First Laboratory Plasmas

# I. INTRODUCTION

- Who?
  - Experimentalists interested in electrical properties of matter
- What?
  - Experiments with electromagnetic fields in low-pressure gases
- Where?
  - Germany and Britain
- When?
  - Late nineteenth / Early twentieth centuries
- Why?
  - Unify classical theories for light and matter
  - kinetic theory, electromagnetic theory
- "The study of the electrical properties of gases seems to offer the most promising field for investigating the Nature of Electricity and Matter, for thanks to the Kinetic Theory of Gases our idea of non-electric processes in gases is much more vivid than they are for liquids or solids"– JJ Thomson [Thomson, 1896]



J.J. Thomson won the Nobel in Physics (1906) when he showed electrons were particles..... His son won it in 1937 for showing that electrons are waves.

DAILYBRAINFREEZE.COM

# II. RESULTS

- Failure to unify classical theories for light and matter

- Evidence of complex electromagnetic interactions between light and matter at the sub-atomic level

- Experimental basis for Modern Era of Physics

- "a New Era has begun in Physics, in which the electrical properties of gases have played and will play a most important part." JJ Thomson [Thomson, 1896]

# III. DISCHARGE TUBE



- Discharge Tube
  - Weakly-Conducting Exterior Solid
  - Weakly-Conducting Interior Gas (WCG)
  - Strongly-Conducting Interior Gas (SCG)
  - Applied Interior Pressure (P)

- Electrodes (Cathode and Anode)
  - Model as Ideal Capacitor with Dielectric  (D)
  - Applied Potential Difference (V)
  - Applied Electric Field (E)

- Particle Drifts
  - Electric field transfers energy to charged particles
  - Particles scatter in the gas interior
  - Particles scatter at the solid exterior
  - Maxwellian energy/velocity distributions
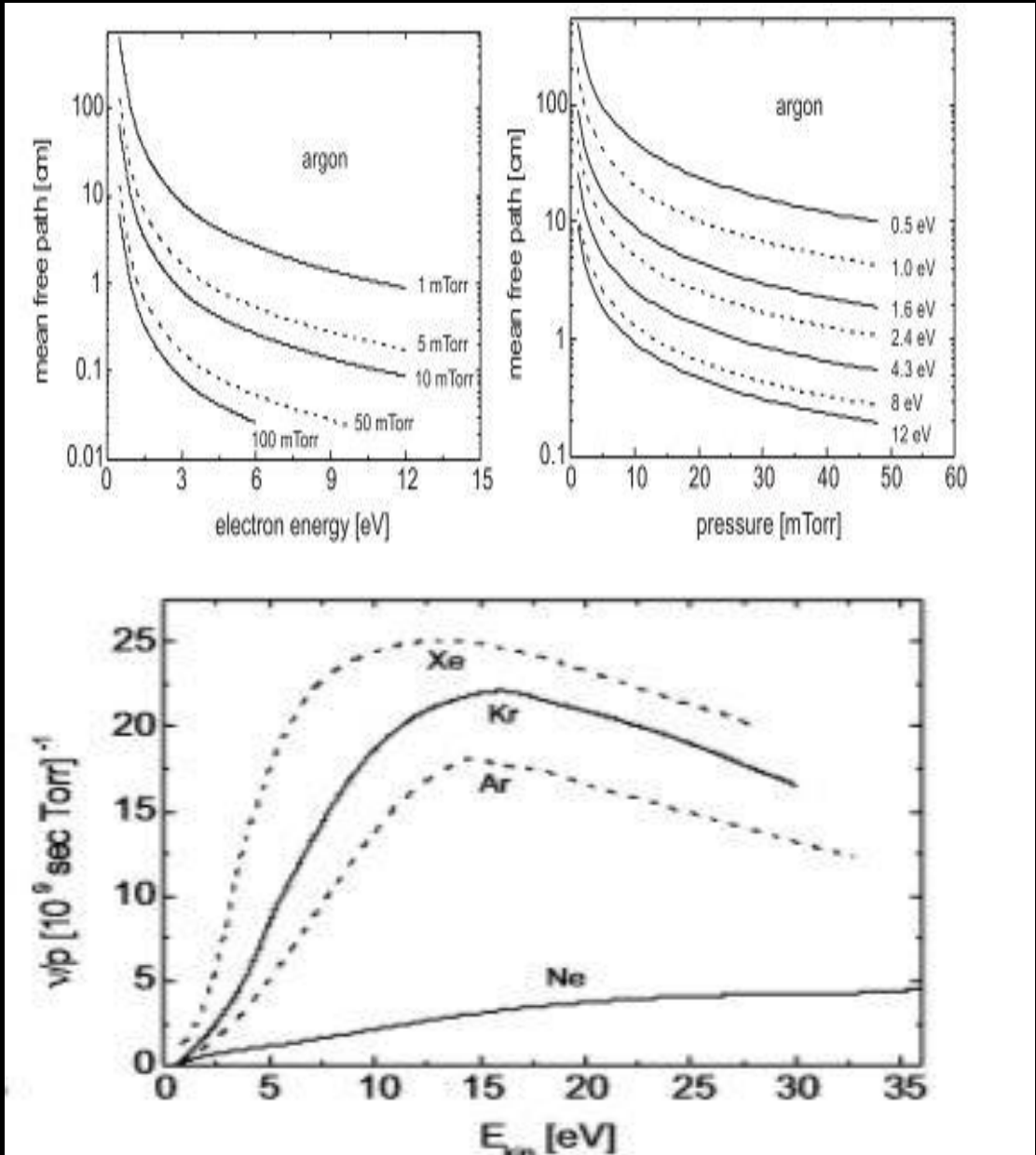
[Franz, 2009]

# IV. BREAKDOWN

- Breakdown Voltage (D)
  - Minimum applied voltage for current
  - Minimum applied voltage for primary ionization
  - Maximum applied voltage for NCG
  - $D_{AIR} = 3$ MV/m [CRC Handbook of Chemistry/Physics]
  - $D_{H2} = 0.5, D_{He} = 0.15, D_{Ne} = 0.25, D_{Ar} = 0.18$
  - $D_{GLASS} = 9, D_{PLASTIC} = 19$

- Avalanche Breakdown Voltage ($V_B$)
  - Minimum applied voltage for significant current
  - Minimum applied voltage for secondary ionization
  - Maximum applied voltage for WCG

- Paschen's Law
  - $V_B$ dependent on macroscopic properties of gas ($\lambda$)
  - $V_B$ dependent on microscopic properties of gas ($\sigma$)
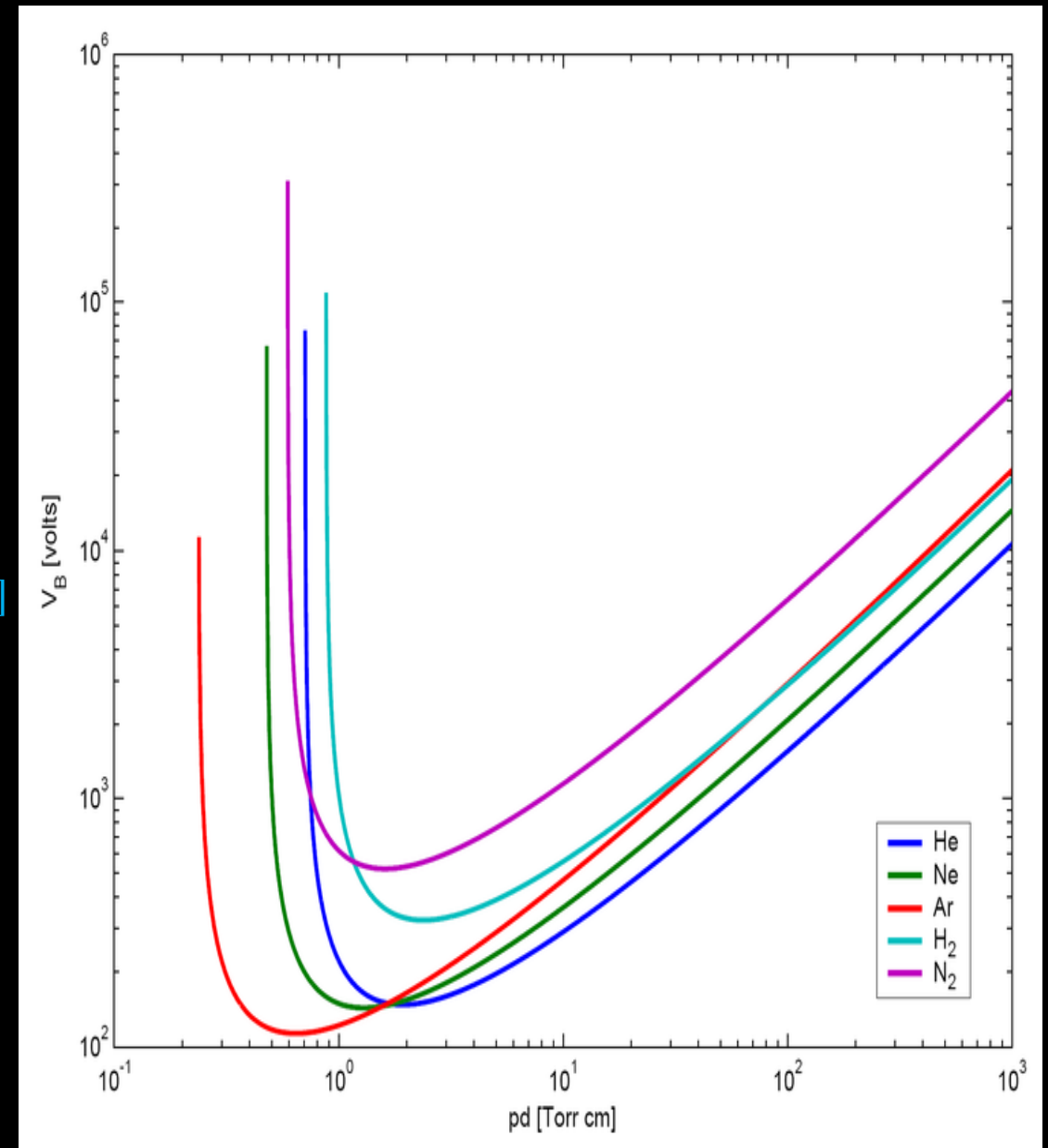


[Lieberman/Lichtenberg, 2005]
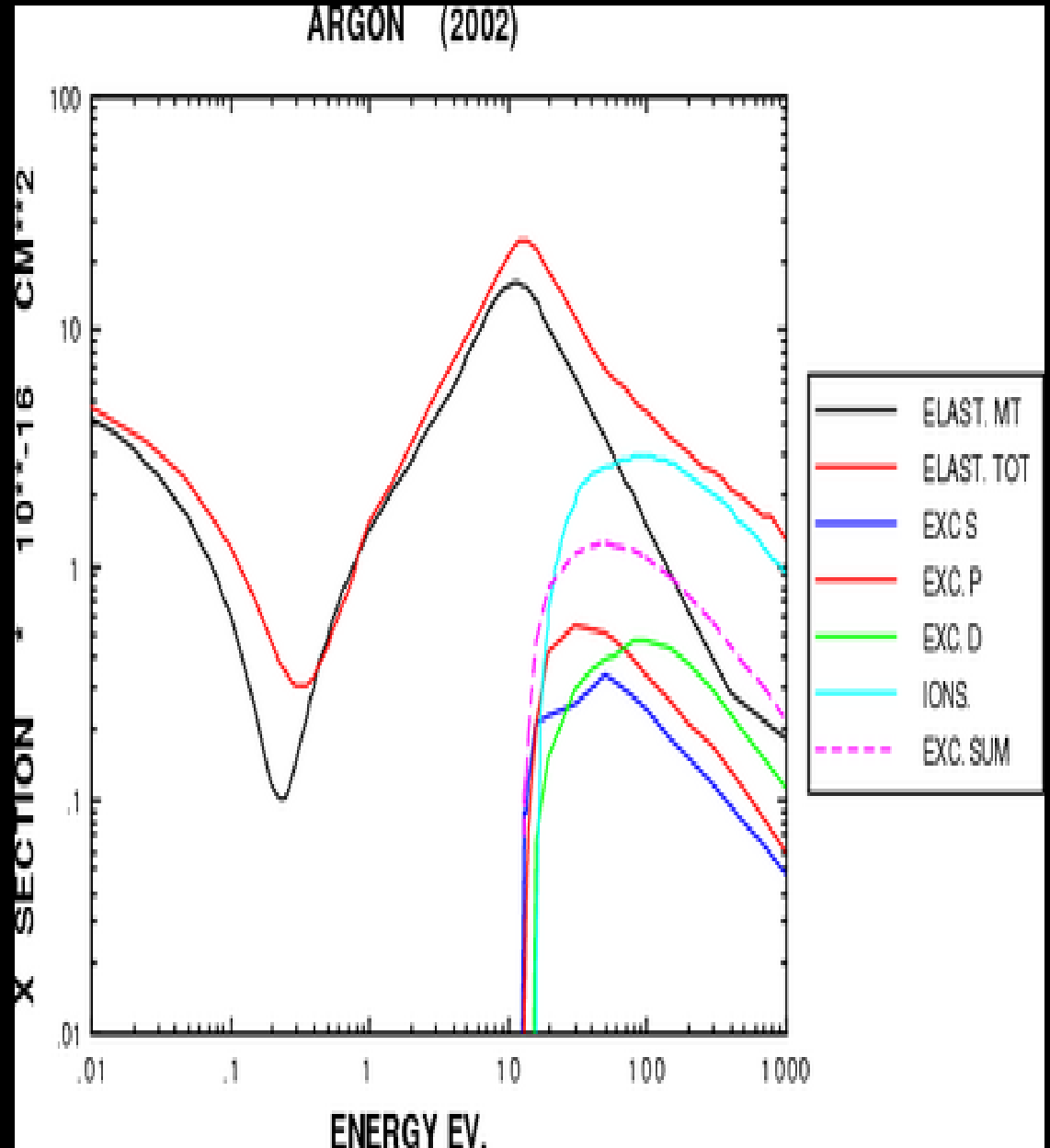
# V. DISCHARGE

- Electric Discharge between electrodes (I)
  - E&M Field transfers energy in
  - Scattering transfers energy in the interior
  - Scattering transfers energy to the exterior
  - E&M Radiation transfers energy out
- Dark Discharge
  - Non-Breakdown / Breakdown
  - No Visible Light
- Glow Discharge
  - Normal Glow / Abnormal Glow
  - Low-Intensity Visible Light
- Arc Discharge
  - Non-Thermal Arc / Thermal Arc
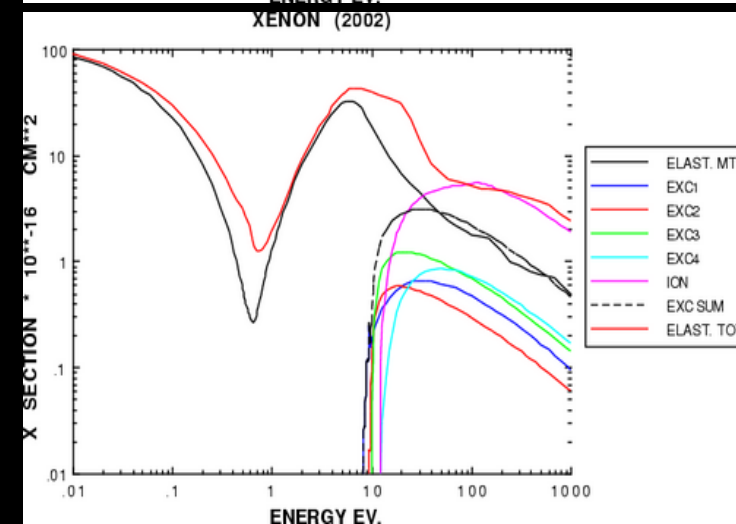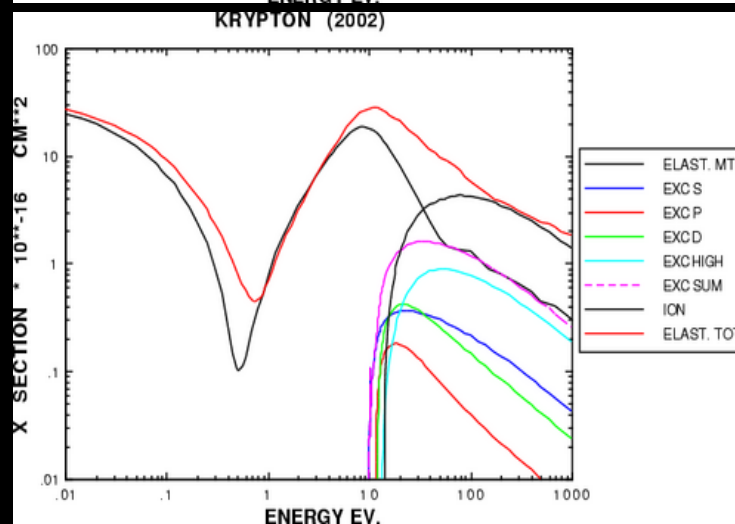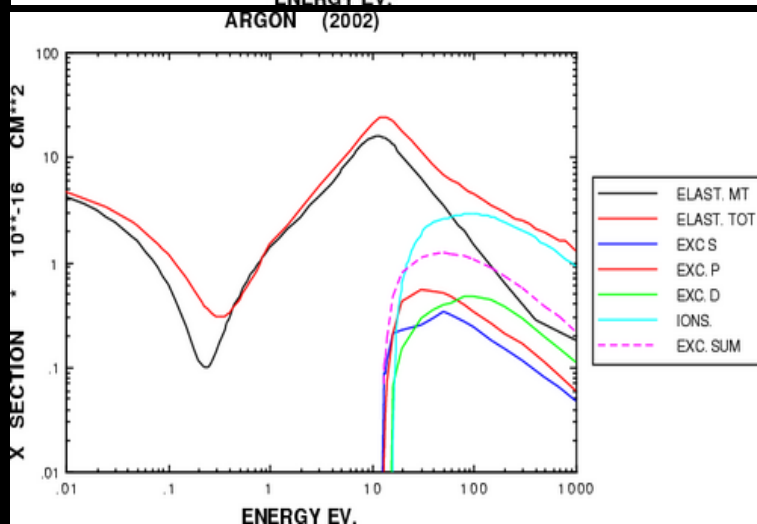  - High-Intensity Visible Light
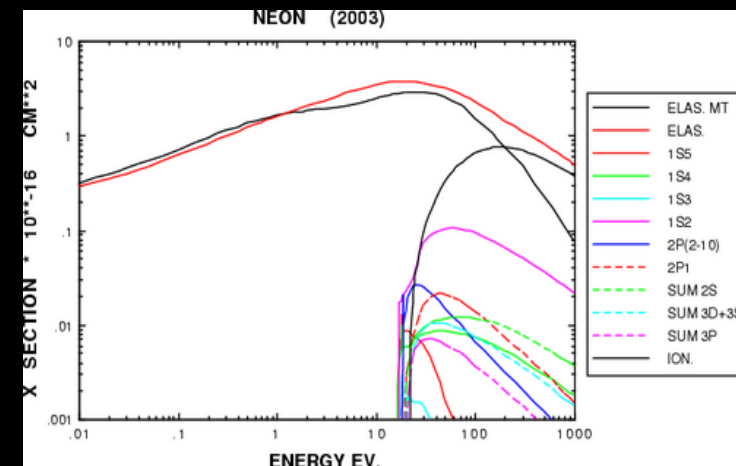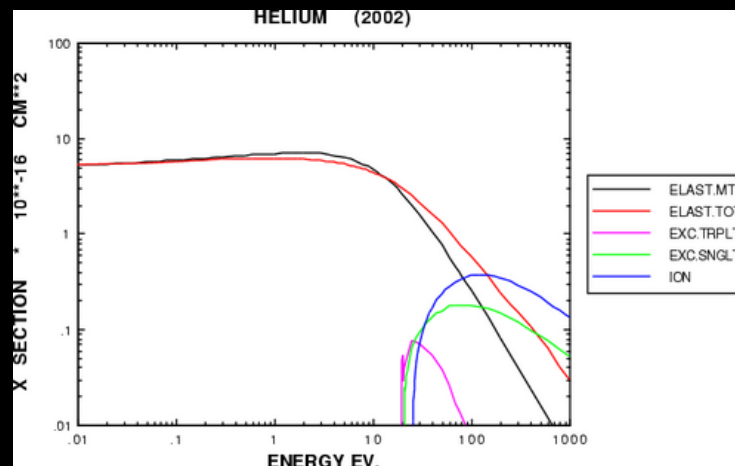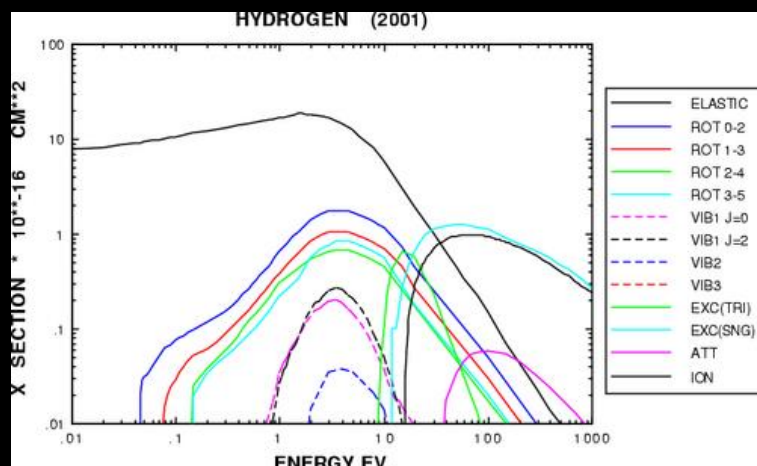- Non-Linear V-I Characteristic
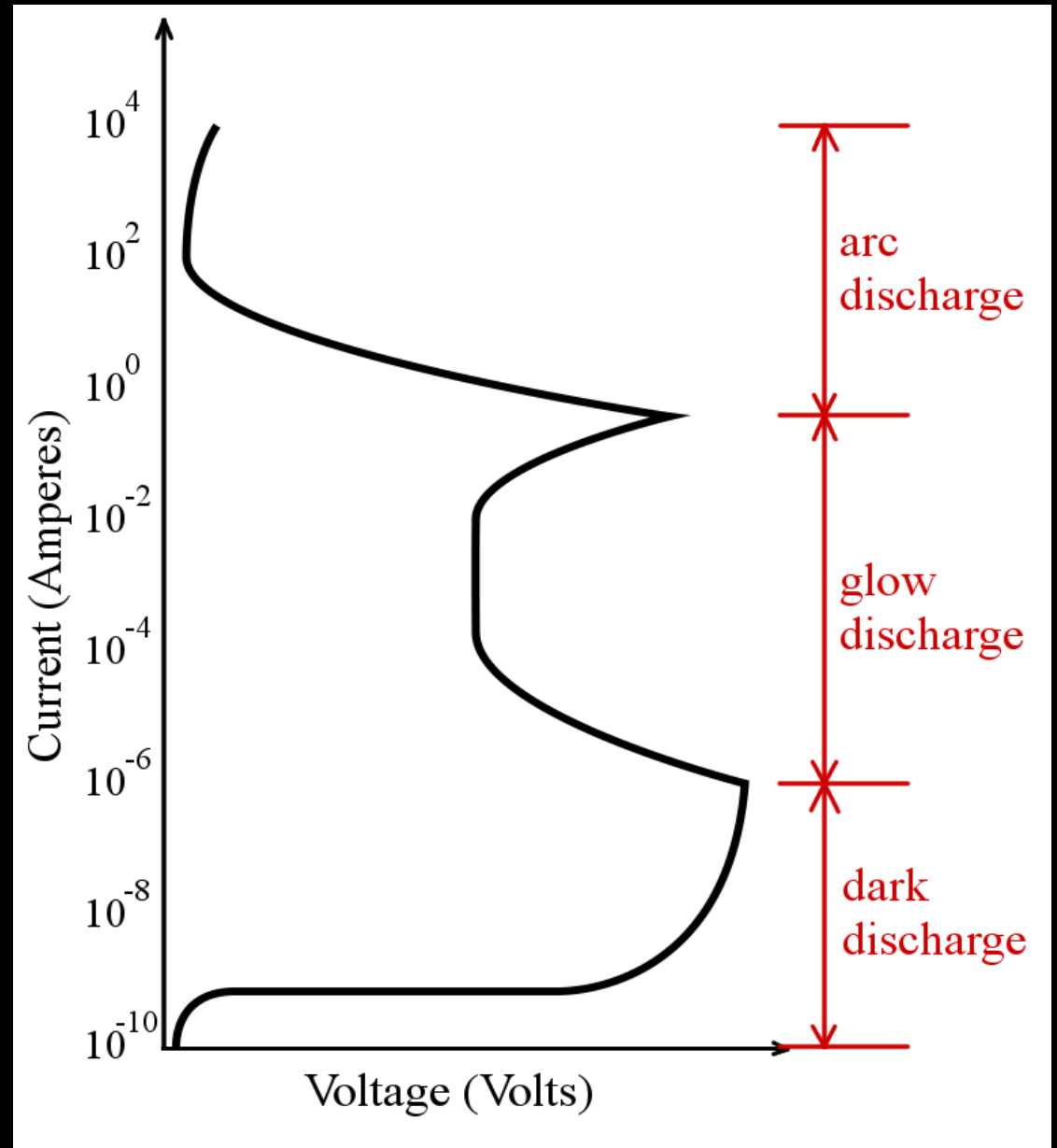


[Open Source]

# VI. SCATTERING

- Cross Section ($\sigma$)
  - Relative frequency of physical processes
  - QFT is fundamental to Scattering Theory

- Elastic Scattering
  - Low energy transfer.
  - No emission spectra.

- Direct Inelastic Scattering
  - Excitation
  - Ionization
  - High energy transfer
  - Discrete emission spectra.

- Indirect Inelastic Scattering
  - No energy transfer.
  - Continuous emission spectra.



ARGON (2002)

Legend:
- ELAST. MT
- ELAST. TOT
- EXC. S
- EXC. P
- EXC. D
- IONS.
- EXC. SUM

X SECTION * 10**-16 CM**2

ENERGY EV.

[Magboltz, 2014]

# VII. CROSS SECTIONS

# VIII. IONIZATION

- Ionization
  - Atomic electrons must escape nuclear potential
  - Atomic electrons escape nuclear potential by tunneling
  - To increase $\omega$ , increase E or decrease $V$

- Field Ionization
  - Electron escapes nuclear potential non-classically

- Photo-Ionization
  - Electron escapes nuclear potential classically

- Thermo-Ionization
  - $\alpha$-Ionization (electrons and atoms in interior)
  - $\beta$-Ionization (atoms and atoms in interior)
  - $\gamma$-Ionization (electrons and atoms at exterior)
  - Electron escapes nuclear potential classically
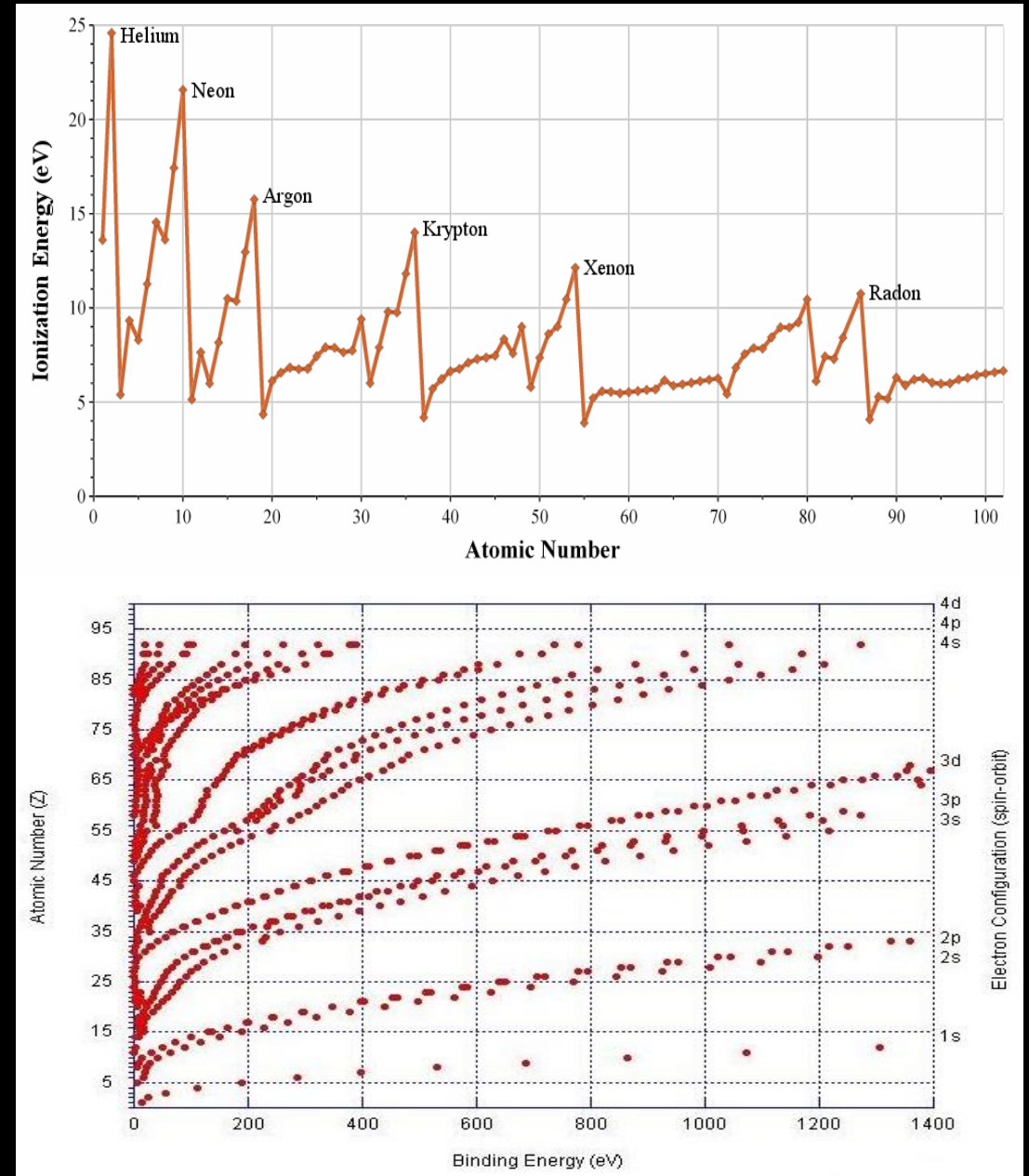
[Open Source]

# IX. EXCITATION

- Rotational Excitation
  - Non-radiative energy transfer E ≈ 0.001 $eV$
- Vibrational Excitation
  - Non-radiative energy transfer E ≈ 0.1 $eV$
- Outer Electronic Excitation
  - Characteristic radiative energy transfer E ≈ 1 $eV$
  - Significant in interior
- Inner Electronic Excitation
  - Characteristic radiative energy transfer $E$ ≈ 10 keV
  - Significant at exterior
- Vibronic Excitation
  - Characteristic radiative energy transfer $E$ ≈ 10 keV
  - Significant at exterior
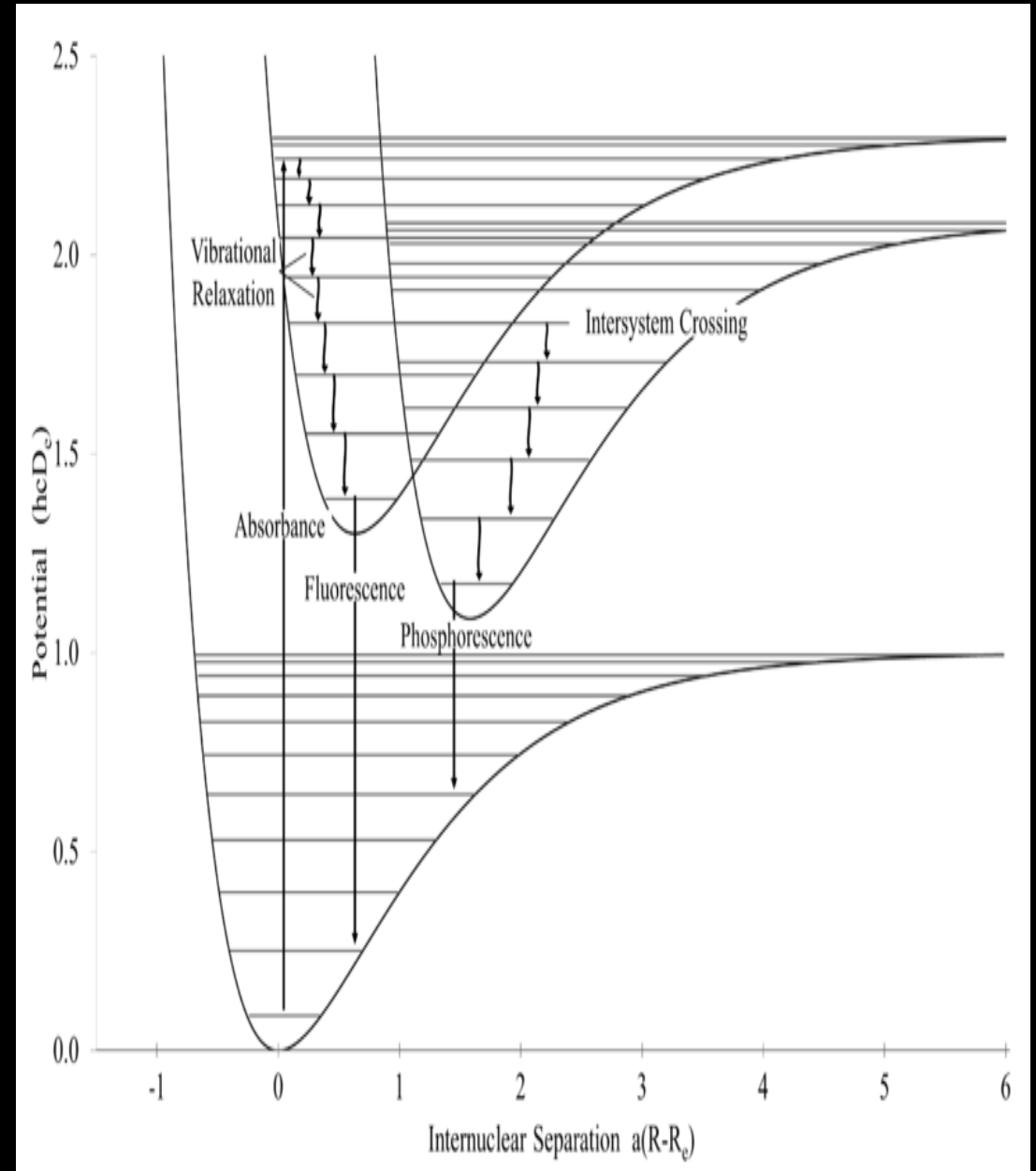


[Atkins et all, 2009]

# X. RADIATION

- E&M Radiation after inelastic scattering
- Direct Inelastic Scattering
  - Discrete radiation spectra
- Indirect Inelastic Scattering
  - Continuous radiation spectra
- Dependent on the number density of medium
  - $\lambda$ minimum
  - Significant at the exterior
- Dependent on the charge density of medium
  - Atomic electrons shield the atomic potential
  - Free electrons shield the ionic potential
  - $\sigma$ maximum
  - Significant in the interior



[AZoOptics, 2012]
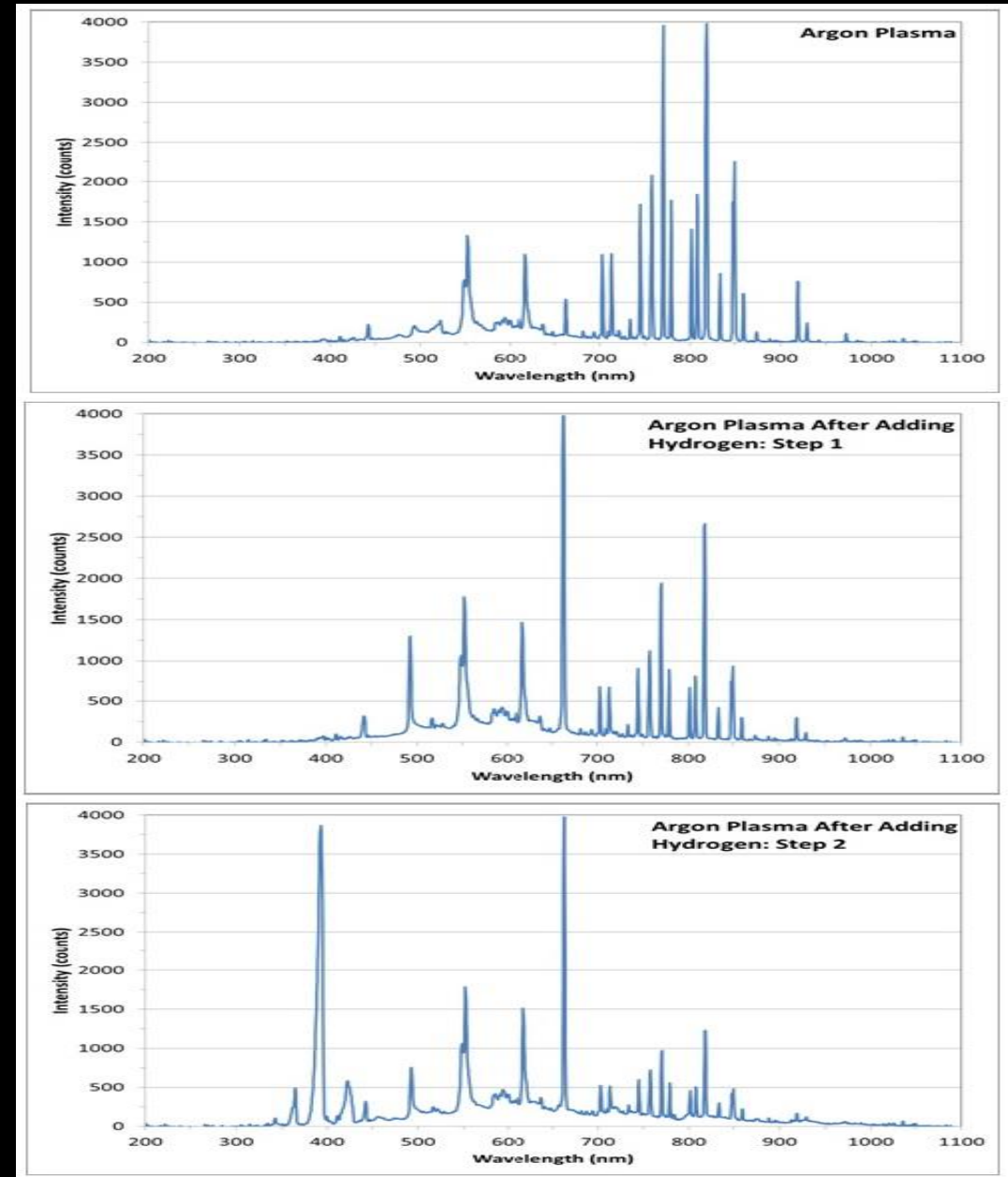
# XI. CONCLUSION

- Electrical discharges are rich in complex physical phenomena

- We have learned much about the nature of light and matter

- There is still much to learn!

- "The difficulties which would have to be overcome to make several of the preceding experiments conclusive are so great as to be almost insurmountable" – JJ Thomson [Maxwell, 1891]

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