THE QUANTUM WORLD

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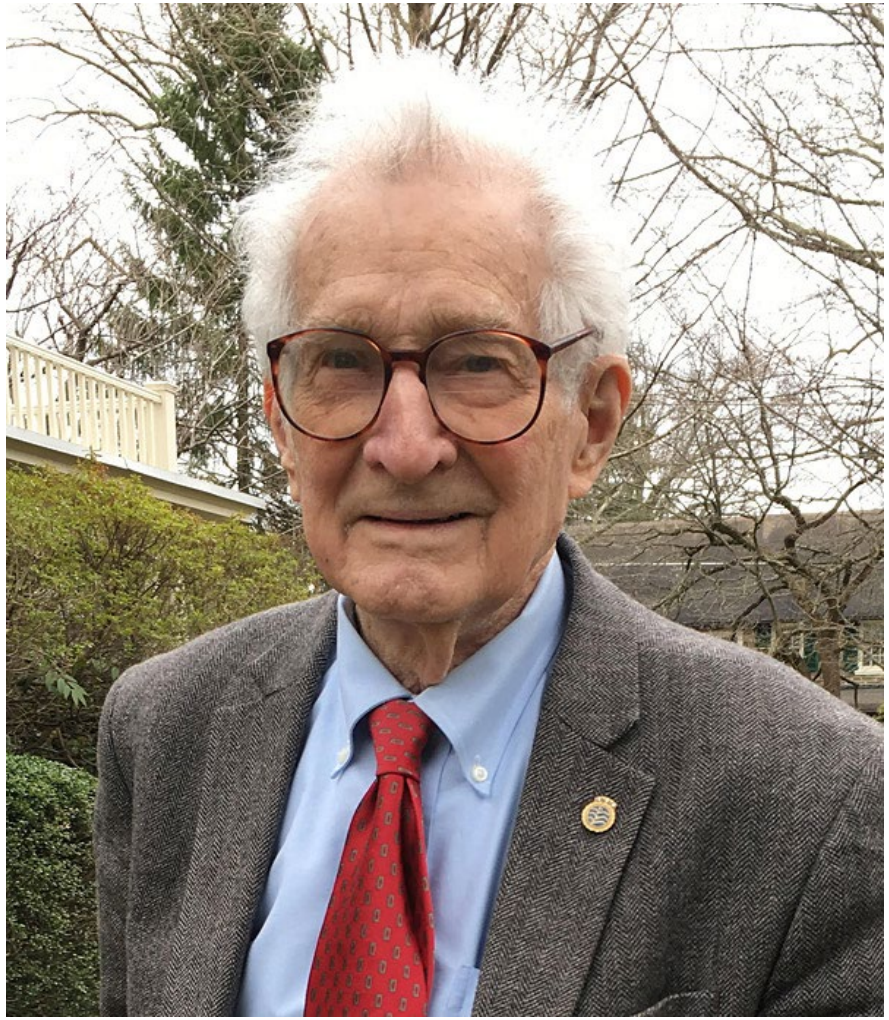


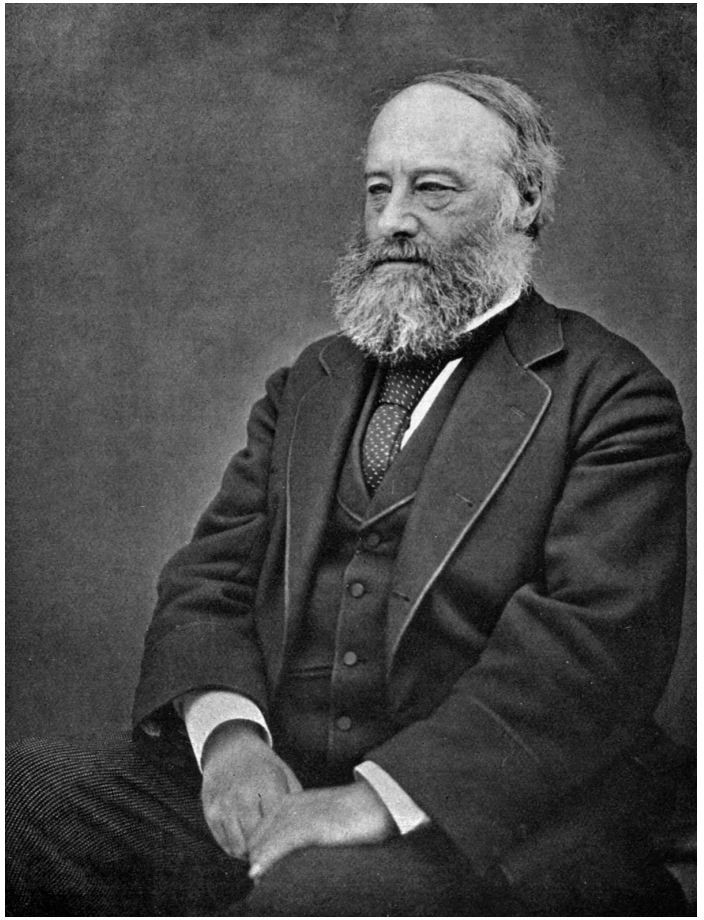
MECHANICS

- When treated as a singular noun, The branch of applied mathematics dealing with motion and forces producing motion. The machinery or working parts of something.
- Example: **Statistical mechanics** describes how macroscopic observations (such as temperature and pressure) are related to microscopic parameters that fluctuate around an average.
- **Quantum mechanics** is the branch of mechanics that deals with the mathematical description of the motion and interaction of subatomic particles.
- **QUANTUM**, the Latin word for amount. Coined by MAX PLANCK (1858-1947) to explain an adjustable parameter he was forced to use to the German Physical Society meeting on 14 December, 1900.

STANDARD INTERNATIONAL UNITS

- Distance: METER, a YARD is 0.9144 m
- Time: SECOND
- Mass: KILOGRAM, a POUND is 0.4535924 kg
- Energy: JOULE, a KILOWATT-HOUR is 3,600,000 J, a HORSEPOWER is 746 Joules per second.

JAMES PRESCOT JOULE (1818-1889)



SCIENTIFIC NOTATION

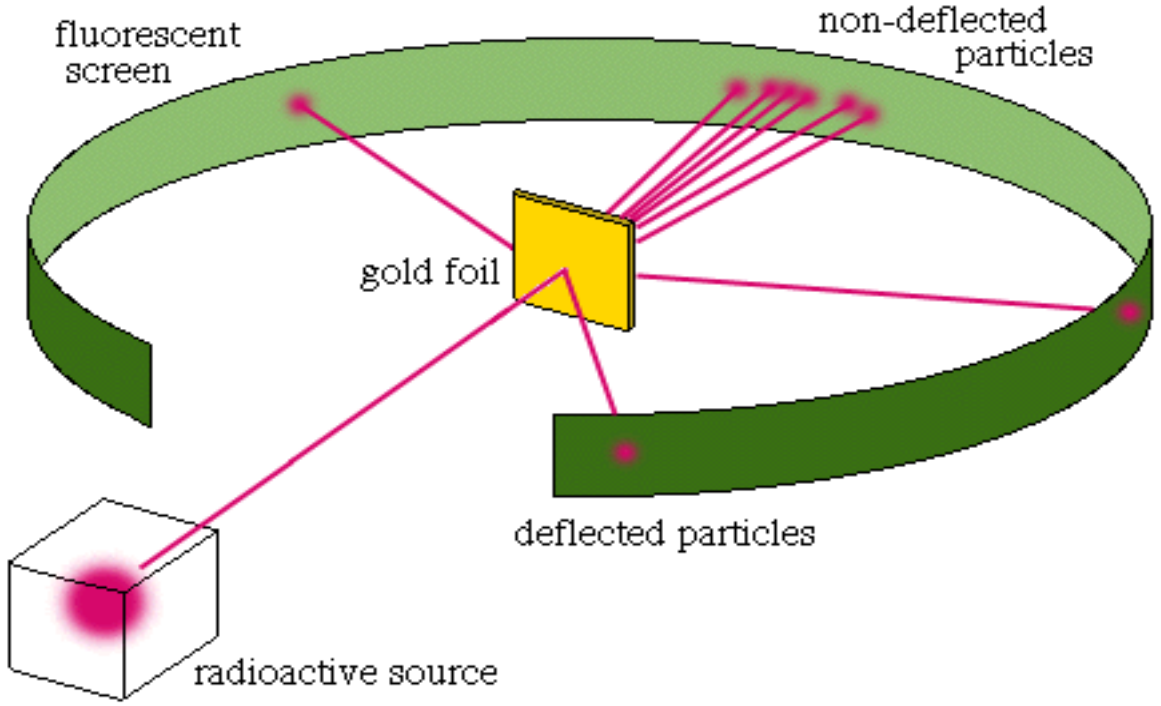
- For both large and small numbers, express as a number between 1 and 10 times a power of ten.
- 1,234 is written as 1.234×10^{3}
- 0.0567 is written as 5.67×10^{-2}
- The advantage of this scheme is that in multiplying and dividing, exponents can be added and subtracted.
- 3×10^{8} times $2 \times 10^{5} = 6 \times 10^{13}$ (8 + 5 = 13)
- 3×10^{8} divided by $2 \times 10^{5} = 1.5 \times 10^{3}$ (8 – 5 = 3)

PLANCK'S CONSTANT

- $h = 6.625 \times 10^{-34}$ Joule-seconds

X-RAY DIFFRACTION HAS ILLUMINATED THE STRUCTURE OF CRYSTALS, SO WHY NOT TRY DIFFRACTION OF ALPHA RAYS TO SEE INSIDE ATOMS?

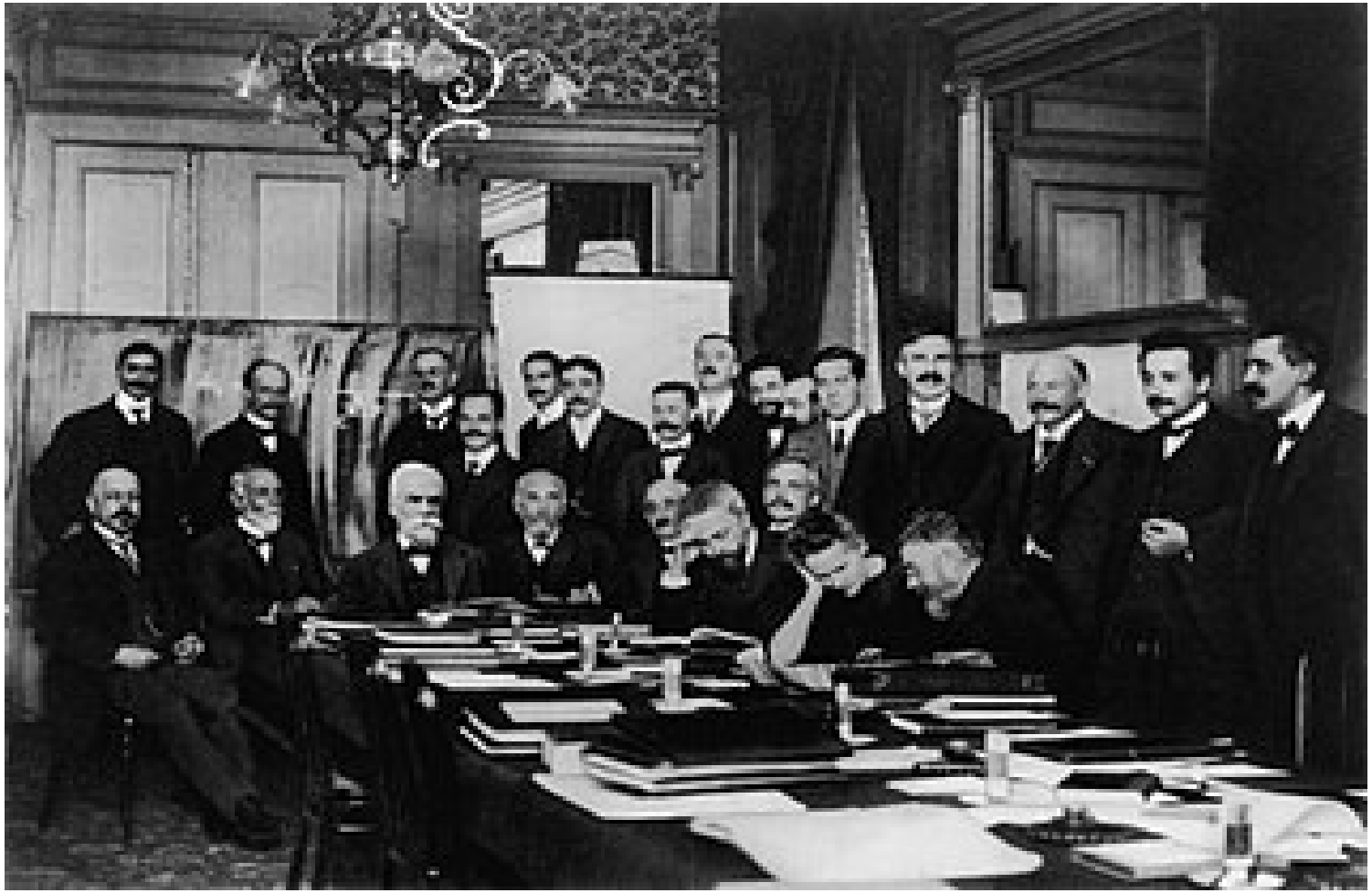
- ERNEST RUTHERFORD (1871-1937) who will appear under another subject on page 107, in 1909 at the University of Manchester bombarded a piece of gold leaf with alpha particles.

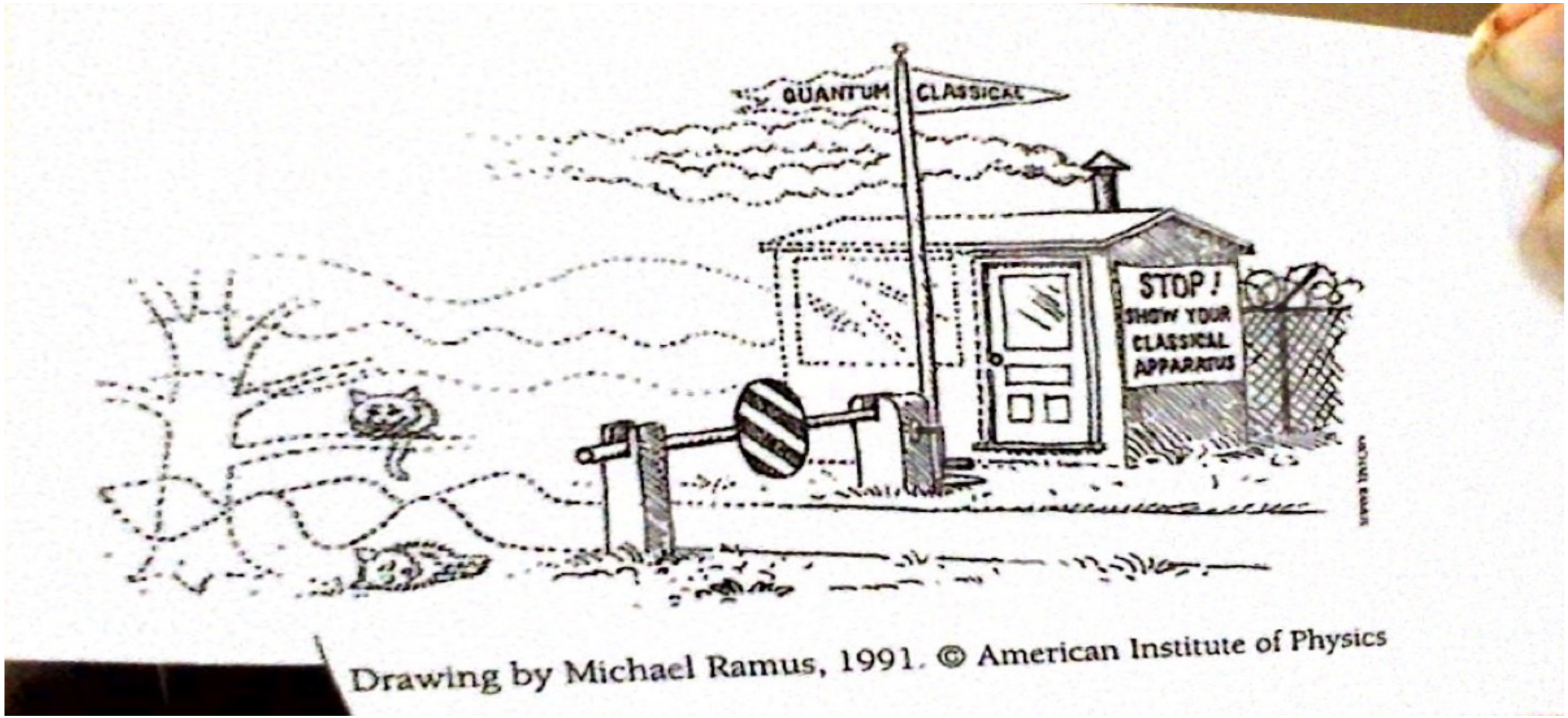


ATOM FACTS

- The nuclei of atoms contain 99.99% of the mass of atoms, yet occupy barely 0.0001% of the volume.
- The vast bulk of the volume of atoms contains a thin cloud of electrons.
- The hardness of substances that depends upon the quantum states of the outer shells of the atom’s electrons.
- If those electrons are in stable orbits with no great connection to the electrons in adjacent atoms, then the substance can be a gas.
- If those electrons are intimately related to their comparable electrons in adjacent atoms, then the substance might be steel or diamond.

SOLWAY CONFERENCES 1911-1928





Drawing by Michael Ramus, 1991. © American Institute of Physics

SPOILER ALERT (FORD, PAGE 3)

- Matter, and not just light, has wave properties.
- The fundamental laws of nature are laws of probability, not laws of certainty.
- There is a limit ***in principle*** to the accuracy with which the properties of matter and energy can be measured.
- Electrons appear to spin about an axis that can point in only two possible directions, which we call “up” and “down”.
- It is predicted by theory that for every sub-atomic particle there is a companion anti-particle.
- A single electron or photon can be moving in two or more different ways ***at the same time.***
- No two electrons can be in the same quantum state at the same time.

"About your cat, Mr. Schrödinger—I have good news and bad news."

Erwin Schrödinger in *The New Yorker.*

FORD'S SEVEN BASIC POSTULATES AS GIVEN IN A TYPICAL TEXTBOOK

- Every possible state of a system is described by a function ψ (PSI).
- The probability of measuring that system in that particular state can be calculated from ψ .
- Every observable property of a system is represented by a mathematical operator.
- There are equations (most familiar form is Schrodinger's equation) that describe the time-dependent state function involving ψ.
- There is another such equation that yields the average value of any observable property of the system.
- There is another such equation relating the value of an observable property to its operator.
- The "correspondence principle" says that any quantum mechanical equation must approach the same form as an equation from classical Newtonian mechanics if the masses and times in that equation are increased sufficiently.

FORD'S QUESTIONS

Why is the subatomic world so strange, so weird, so wonderful?

Why do the laws governing the very small and the very swift defy common sense?

Why do they stretch our minds to the limit?

FORD'S ANSWER

Walter Cronkite's sign-off, "That's the way it is."

CARL SAGAN'S ANSWER: If you spend 10 years of study you can understand HOW quantum mechanics works but never know WHY.

RICHARD FEYNEMAN'S NON-ANSWER: Don't think about it, you'll only get confused and have a headache.

GROWTH IN NUMBER OF PARTICLES

- ELECTRON discovery by J.J.Thompson in 1897. (1)
- PROTON discovered by Ernest Rutherford in 1920. (2)
- NEUTRON discovered by James Chadwick and the POSITRON by Carl Anderson in 1932. (4)
- MUON discovered by a team at U. of California in 1937 (5)
- PION and KAON in 1947 (7)
- LAMBDA BARYON in 1950 (8)
- ANTI PROTON in 1955 (9)
- ELECTRON NEUTRINO in 1956 (10)
- MUON NEUTRINO in 1962 (11) (I.I. Rabi"s temper tantrum. Nobel Prize in 1944 for NMR)
- 1969 on, dozens of direct and indirect discoveries. (in the hundreds)
- HIGGS BOSON at CERN in 2012. But by then most of the 1960s particles had been explained as compound particles made of QUARKS, GLUONS and as excited states of other PARTICLES. The STANDARD MODEL now recognizes 24 FUNDAMENTAL PARTICLES (and their ANTIPARTICLES) from which hundreds of COMPOUND PARTICLES can be made.

CLASSES OF FUNDAMENTAL PARTICLES

- LEPTONS, examples electron, positron and neutrinos.
- QUARKS, which cannot exist alone.
- BOSONS or FORCE CARRIERS, examples of which are photons and gluons.
- LEPTONS and QUARKS are FERMIONS, which obey entirely different laws than do BOSONS.

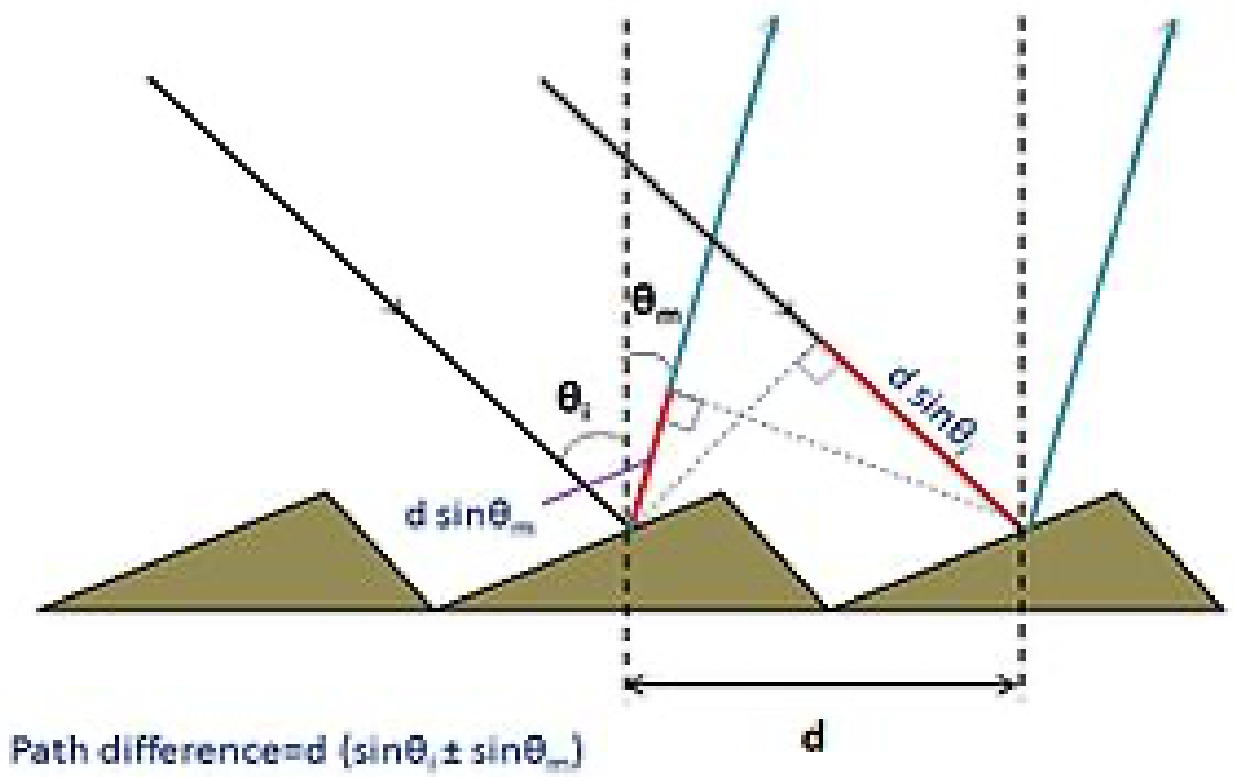
SMALL LENGTHS

- Nuclei are of the order of 10^{-15} meters (FERMIs or femptometers).
- Atoms are measured in Ångstrom Units, 10^{-10} meters.
- Visible light has wavelengths varying from the ULTRAVIOLET at 400 nanometers (4×10^{-7} meters, frequency 1.3×10^{15} sec^{-1}) to the INFRARED at 700 nanometers (7×10^{-7} meters, frequency 2.3×10^{15} sec^{-1}).
- We can measure or work with objects that are microns long ($> 10^{-6}$ meters).

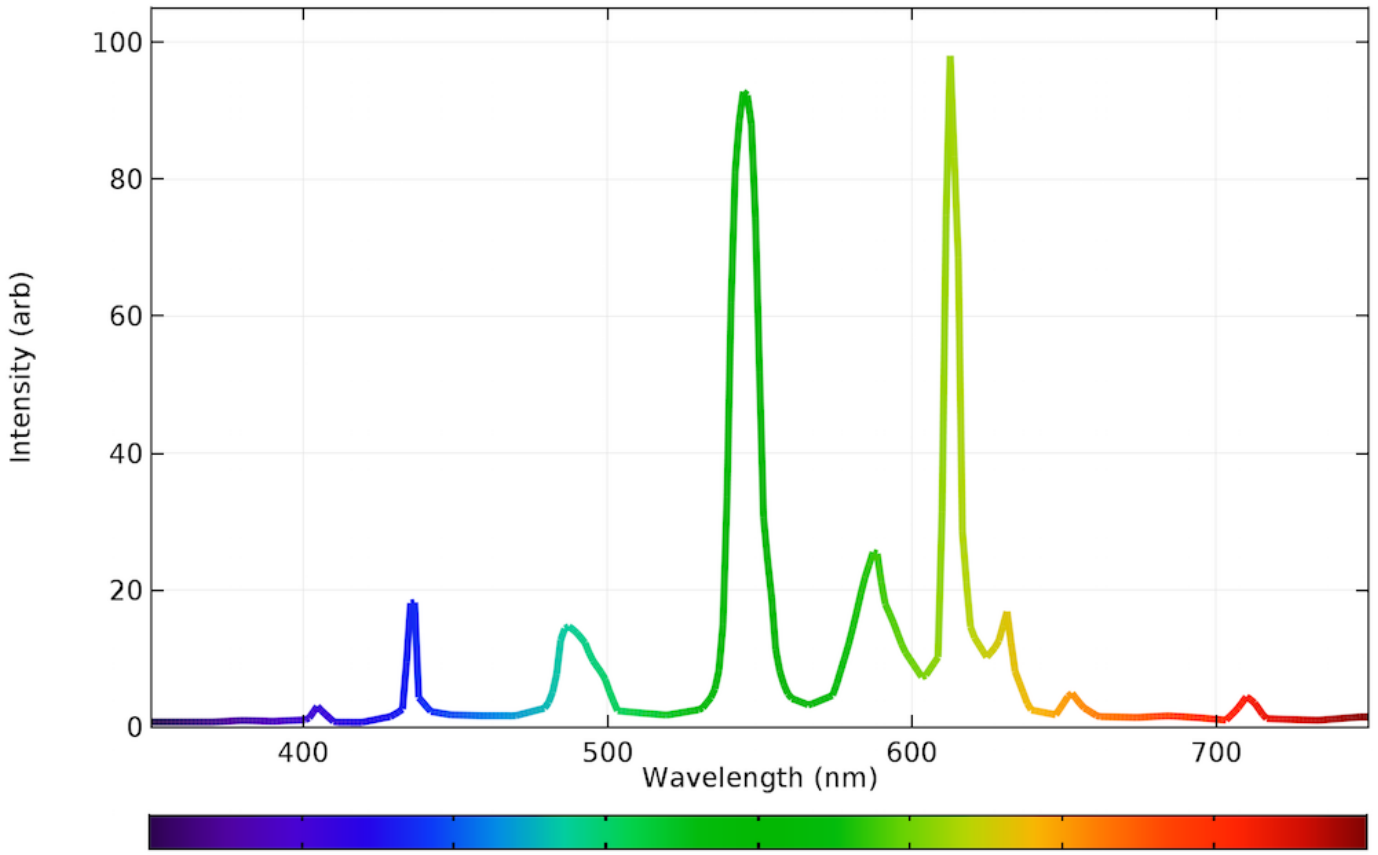
WAVE LENGTHS OF LIGHT

- DAVID RITTENHOUSE (1732-1796) was an American watch-maker, amateur scientist and first director of the U.S. mint. He invented the DIFFRACTION GRATING.
- JOSEPH VON FRAUNHOFER (1787-1826) was a Bavarian lens manufacturer who developed and sold diffraction gratings and invented the SPECTROGRAPH.
- Throughout the 19th century scientists could measure the wavelengths of the emission lines of substances. New elements were discovered by finding substances with new emission lines, often decades before they were chemically isolated.
- DIMITRI MENDELEEV (1834-1907) developed the PERIODIC TABLE OF THE ELEMENTS with many places in the table vacant

DIFFRACTION GRATINGS



EMISSION SPECTRA



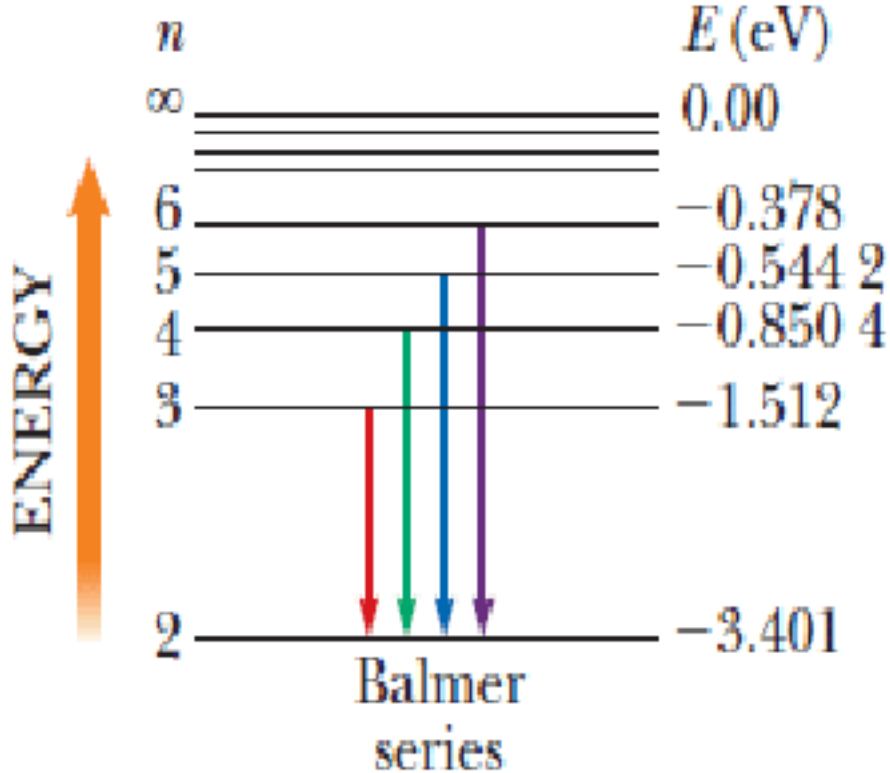
19th CENTURY SPECTROSCOPY

- Some emission lines were SHARP (s)
- Some were dominant or PRINCIPAL (p)
- Some were DIFFUSE (d)
- Some were FINE (f)
- These lines progressed from s to p to d to f as the element in question appeared farther down the PERIODIC TABLE.

JOHANN JAKOB BALMER (1825-1898)

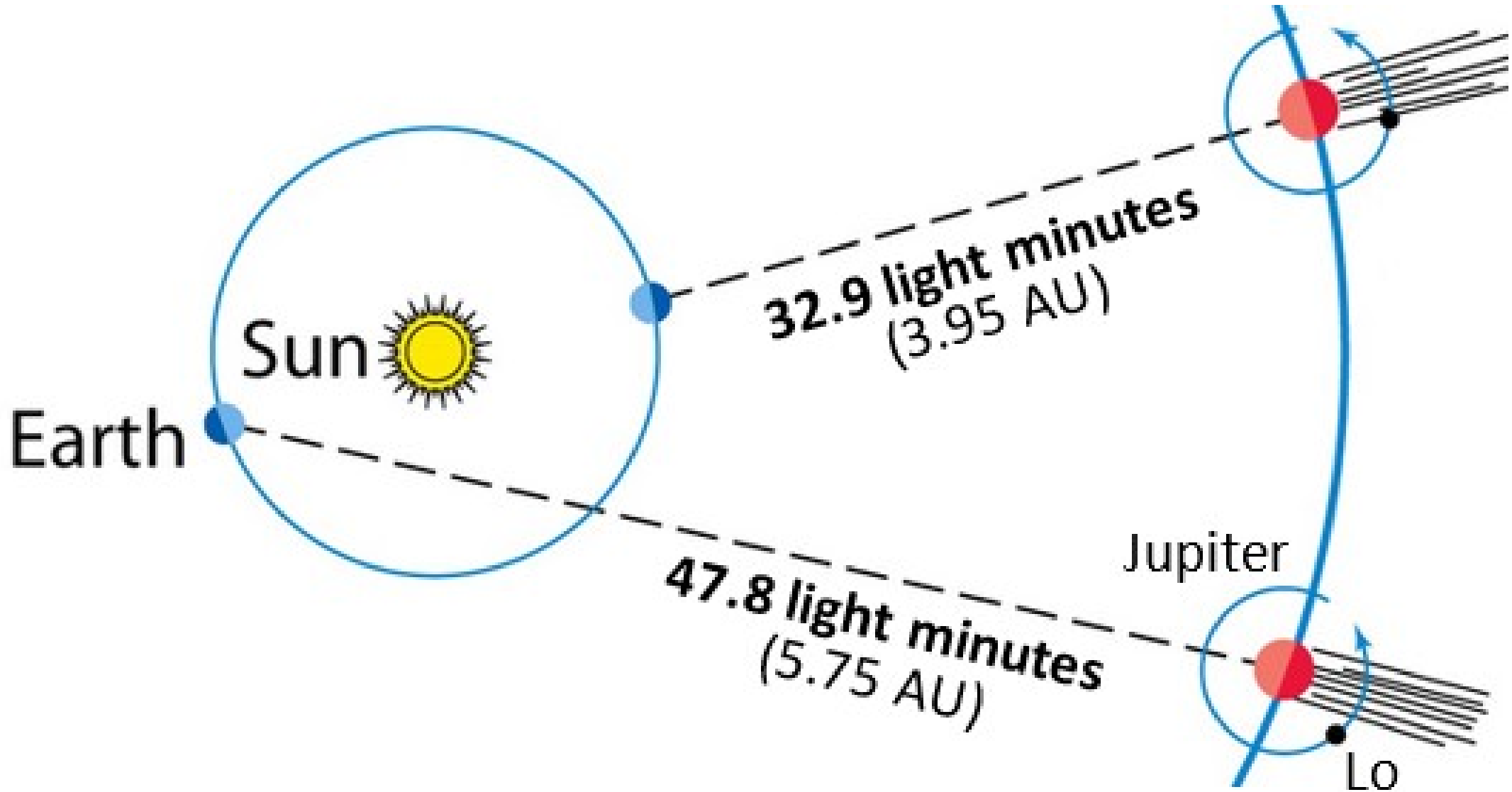
BALMER SERIES

- The reciprocal of the wavelengths of the HYDROGEN EMISSION lines is proportional to difference between the reciprocals of the squares of small integers.
- 1/(wave length) = CONSTANT ($1/m^2$ - $1/n^2$) with n>m, and for Balmer's series, m=2.
- When other elements' emission lines are considered, the CONSTANT is discovered to be proportional to the ATOMIC NUMBER of the element.


n
E (eV)
∞
0.00
6
−0.378
5
−0.544 2
4
−0.850 4
3
−1.512
2
−3.401
ENERGY
Balmer
series

FAST SPEEDS

- OLE ROEMER, 1676, estimated the speed of light from the 15 minute difference in the transit times of Jupiter's moon Io between extremes in the orbital separation of the two planets.
- Speed of light in vacuum = 299,792,458 meters/second.
- Particles with no mass must travel at the speed of light.
- Particles with any mass at all cannot travel as fast as the speed of light. $E=mc^2$, so as the speed (kinetic energy) of a massive particle increases, so does its mass. Effective mass = REST MASS + E/c^2 .


Sun
Earth
32.9 light minutes
(3.95 AU)
47.8 light minutes
(5.75 AU)
Jupiter
Lo

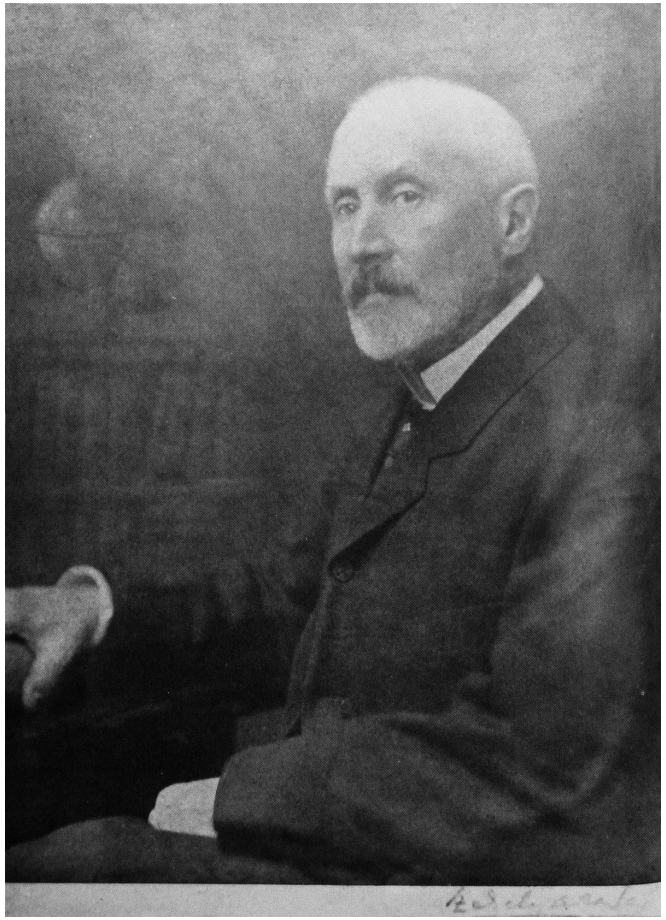
TIME IS RELATIVE

- Longest known time elapsed is 13.7 billion years (10^{18} seconds).
- Time passes more slowly in space where the gravity field is small, and more quickly if the gravity field is higher. The clocks onboard the GPS satellites must be continuously corrected in order for the service to work (38 microseconds/day).
- Black holes are collapsing quickly in enormous gravity fields, but we, in the puny gravity of Earth, seem to think it's taking ten billion years for the process to even get started.

MASS IS EQUIVALENT TO ENERGY

- $E=mc^2$
- Particles that have only energy but no mass (think photons) are affected by gravity, but only mildly.
- It takes an enormous amount of energy to be equivalent to a wee amount of mass. The speed of light squared c^2 is 9×10^{16} in standard units.
- A small amount of mass is equivalent to an enormous amount of energy. The fission of one gram of uranium releases about one megawatt-day of heat energy.

LORÁND EÖTVÖS (1848-1919)



EÖTVÖS EXPERIMENT

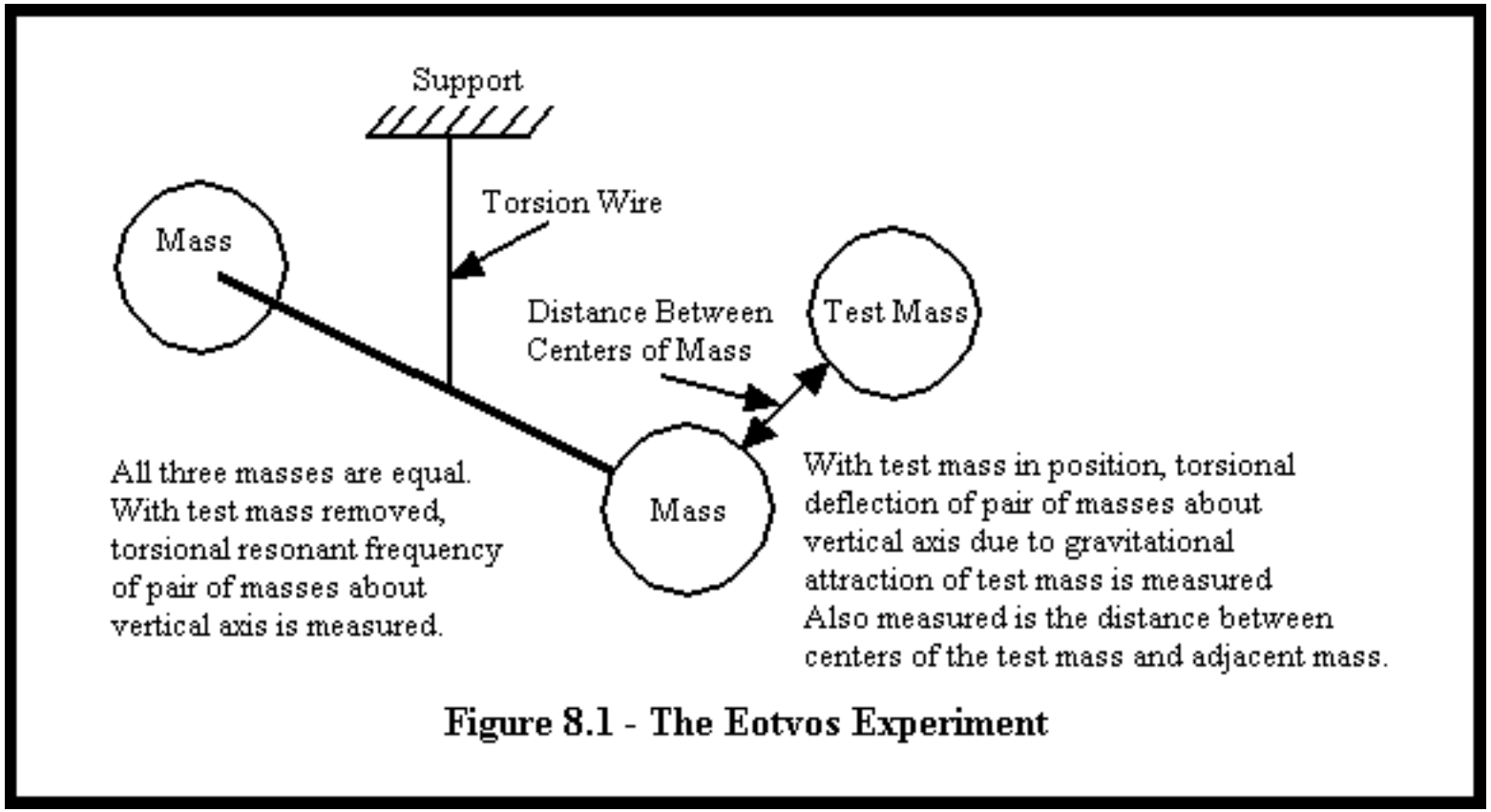


Figure 8.1 - The Eotvos Experiment

ENERGY

- If you try to accelerate a particle with mass, the amount of energy needed increases greatly as the particle's velocity approaches that of light, approaching infinite.
- Energy needed to accelerate at velocity v is given by LORENTZ contraction TOTAL ENERGY = KINETIC ENERGY/$(1 - v^2/c^2)^{1/2}$

ELECTRIC CHARGE

- Like charges repel, unlike charges attract. With the inverse square law, the force of either attraction or repulsion becomes infinite as the separation distance goes to zero.
- In the nucleus, the protons repel one another and are held together by GLUONS. As the number of protons in a nucleus increases, the nucleus becomes less stable, and all nuclei above lead in the periodic table are subject to radioactive decay.
- The convention that electrons are negatively charged and protons are positively charged was decided by BENJAMIN FRANKLIN, believing that electricity was a property of matter that had to flow from plus to minus.
- A COULOMB is an AMPERE-SECOND. The electron and proton charges are $1.60217646 \times 10^{-19}$ Coulomb. QUARK charges are either 1/3 or 2/3 of this charge, and must combine to be either 1 or 0 electronic charges.

SPIN – KINETIC ENERGY OF ROTATION

- SPIN refers to rotation of a particle about its own axis. ORBITAL ROTATION refers to the rotation of a particle about another particle.
- In the physics of spin, the quantization always involves a factor of two times Pi, so it is convenient to use a unit of "h-bar," or PLANCK's constant divided by two pi, 1.05 X 10^{-34} Joule-seconds.
- Particles that possess half integral (e.g., ½, 3/2) hbars of spin are called FERMIONS (QUARKS AND LEPTONS). Particles that possess integral hbars of spin are BOSONS (PHOTONS and GLUONS).
- During the period (1950s and 60s) when many new particles were being discovered, it was not appreciated that some were merely known particles with a different spin.

NATURAL UNITS

- It would be nice if the units used to measure things were based on standards that appeared spontaneously in nature. As our units of time were based of the rotation of the planet we live on and now upon the emission line frequency of a convenient element.
- Planck's constant (***energy times time***) and the velocity of light (***distance divided by time***) are possible bases for natural units, but a third base is needed, either a pure time or some ratio of energy and distance.
- For the convenience of type-setters and physicists writing on blackboards, it common for units to be taken such that c=1.