Physics for Scientists & Engineers 2

Spring Semester 2005

Lecture 2

Electric Charge

- When we walk on a carpet on a dry winter's day and then touch a door knob, we often experience a spark
  - This process is called *charging*
    - In this case charging consists of moving negatively charged electrons from the atoms and molecules of the carpet to the soles of our shoes
  - The built-up charge discharged through the metal of the door knob producing a spark
- Similar phenomena involving moving air masses produces lightning

Charge (2)

- Normally objects around us do not seem to be charged
- They have equal amounts of positive and negative charge and are thus electrically neutral
- Demo:
  - If we rub a glass rod with a cloth, the rod will become charged
    - If we bring two charged glass rods together, they will repel each other
  - If we rub a plastic rod with fur, the rod will become charged
    - If we bring together two charged plastic rods, they will repel each other

Law of Charges

- If we bring together the charged glass rod and the charged plastic rod, they will attract each other
- This difference occurs because the glass rod is positively charged (deficit of negative charges) and the plastic rod is negatively charged
- This result leads to the **Law of Charges**
  - Like charges repel and opposite charges attract
- Note that this behavior is different than gravitation in which the force is always attractive

Unit of Charge

- The unit of charge, the coulomb, abbreviated *C*, is named after the French physicist Charles-Augustin de Coulomb (1736 - 1806)
- The coulomb is defined in terms of the SI unit for electric current, the ampere, abbreviated *A*, named after another French physicist, Andre-Marie Ampere (1775 - 1836).
- The ampere is another SI unit like the meter, the second, and the kilogram
- The unit of charge is defined as
  - 1 *C* = 1 *A*•*s*
- Thus the SI system of units is sometimes called the MKSA system

Charge of an Electron

- Because we have not introduced the ampere yet, we can define the unit of charge in terms of the charge of one electron
  - An electron is an elementary particle with charge q = -e where
    - $e = 1.602 \cdot 10^{-19}$ *C*
  - A proton is a particle with q = +e
    - The fact that the proton has a charge with exactly the same magnitude as the electron is amazing considering that the electron is an elementary particle and the proton is composed of three elementary particles (two up quarks and one down quark) with charge q = (+2/3e) + (+2/3e) + (-1/3e) = +1e

Coulomb of Charge

- A coulomb is a very large amount of charge
  - A lightning discharge can contain 10's of coulombs
  - Demo - charge a large capacitor and discharge it
- The number of electrons required to produce 1 coulomb is charge is

$$N_e = \frac{1\ \mathrm{C}}{1.602 \cdot 10^{-19}\ \mathrm{C}} = 6.24 \cdot 10^{18}$$

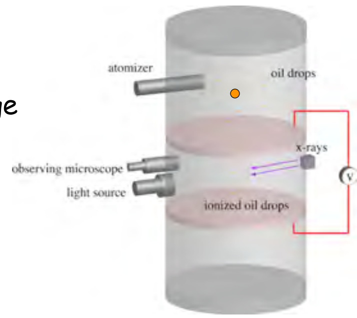
- Because a coulomb is a large amount of charge, everyday applications involving charge typically deal with
  - 1 microcoulomb = 1 μ*C* = 10^{-6} *C*
  - 1 nanocoulomb = 1 n*C* = 10^{-9} *C*
  - 1 picocoulomb = 1 p*C* = 10^{-12} *C*

Charge Conservation

- Benjamin Franklin (1706 - 1790) is credited with establishing the convention of which electric charge is positive and which is negative
- Franklin also proposed that electric charge is conserved
- For example,when a glass rod is charged by rubbing it with a cloth, charge is neither created nor destroyed, but instead electrons are transferred to the cloth leaving a net positive charge on the glass rod
- **Law of charge conservation**
  - The total charge of an isolated system is strictly conserved
- This law adds to our list of conservation laws: conservation of energy, conservation of momentum, and conservation of angular momentum

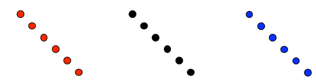
Elementary Charge Quantum

- Electric charge is quantized
- The smallest charge observable is the charge of an electron
- This surprising result was established by Robert Millikan (1868 - 1953) in his famous oil drop experiment



Structure of Atoms

- Atoms are electrically neutral
- Atoms are composed of a positively charged atomic nucleus surrounded by negative electrons
- The atomic nucleus is composed of positively charge protons and electrically neutral neutrons
- The number of protons is the same as the number of electrons
- For example, ^{12}C has 6 protons, 6 neutrons, and 6 electrons



Description of Atoms

- The number of protons, which is the same as the number of electrons, is called the atomic number
  - Z
- The number of protons and neutrons together is called the atomic mass number
  - A
- The number of neutrons is called the neutron number
  - N
- The chemical, elemental properties of the atom are determined by the number of electrons
- Isotopes of atoms have different numbers of neutrons but the same number of protons/electrons

Example - Net Charge

- Suppose we want to create a positive charge of 10 μC on a block of copper metal with mass 2.00 kg. What percentage of the electrons in the copper block would we have to remove?

The atomic weight of copper is 63.55

The number of atoms of copper is

$$N_{atom} = \frac{(2.00\text{ kg})(6.02 \cdot 10^{23}\text{ atoms/mole})}{0.06355\text{ kg/mole}} = 1.89 \cdot 10^{25}$$

The atomic number of copper is 29, which means there are 29 electrons per atom

$$N_e = 29 N_{atom} = 29 \cdot 1.89 \cdot 10^{25} = 5.49 \cdot 10^{26}$$

The number of electrons in 10 μC is

$$N_{e,10\mu C} = \frac{10 \cdot 10^{-6}\text{ C}}{1.602 \cdot 10^{-19}\text{ C}} = 6.24 \cdot 10^{13}$$

Percentage removed is

$$\% = 100 \cdot \frac{N_{e,10\mu C}}{N_{atom}} = \frac{6.24 \cdot 10^{13}}{5.49 \cdot 10^{26}} = 1.14 \cdot 10^{-11}\%$$

Insulators and Conductors

- The electronic structure of materials determines their ability to conduct electricity
  - Conducting electricity means the transportation of electrons
- Materials that conduct electricity well are called conductors
  - Electrons can move freely
    - Metals
    - Water with dissolved materials
- Materials that conduct electricity poorly are called insulators
  - Electrons cannot move freely
    - Plastics
    - Pure water

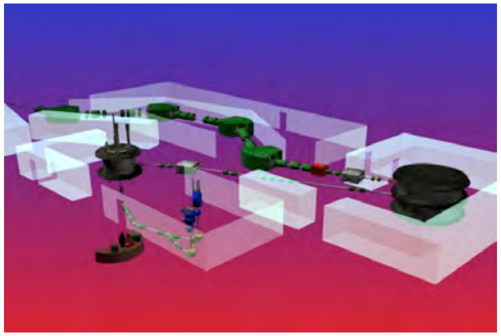
Superconductors

- Materials that conduct electricity perfectly with no losses are called superconductors
- Certain materials become superconducting at low temperatures such as the temperature of liquid helium
- Once electrons are put in motion, there is nothing to stop the motion
- Normal conductors transport most of the electrons but some are lost

Applications of Superconductors

- MSU Superconducting Cyclotrons
  - World's first superconducting cyclotrons
    - K500 Superconducting Cyclotron, 1982
    - K1200 Superconducting Cyclotron, 1989
  - Superconducting coils are used to produce very high magnetic fields
  - The MSU cyclotrons produce beams to study
    - The origins of the elements
    - The structure of exotic nuclei
    - The properties of nuclear matter

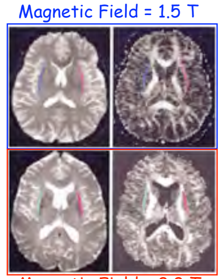
NSCL Fly-by



Magnetic Resonance Imaging - MRI

- MRI stands for nuclear magnetic resonance imaging
  - The word nuclear is left off
- MRI produces high quality images of living tissue without causing any harm
- The quality of an MRI image (signal-to-noise) is proportional to the the magnitude of the magnetic field
  - High field mean high quality images
- Superconducting magnets can produce up to four times the magnetic field of a room-temperature magnet

Magnetic Field = 1.5 T



Magnetic Field = 3.0 T

Yue Cao, Stephen Whalen, Jie Huang, Kevin L. Berger, and Mark C. DeLano, Human Brain Mapping 20:82-90(2003). (MSU Radiology)

Semiconductors

- Semiconductors are material that can be switched between being an insulator and being a conductor
- Semiconductors are the backbone of modern electronics and computers

Replica of first transitor in 1947

Modern computer chip with millions of transitors