Phys102
General Physics II

Electric Charge

Electric Charge

- Topics
  - What is electric charge? Point objects, Size. Atomic model
  - Methods of charging objects. Friction,Contact, Induction, Machines
  - Instruments to measure charge
  - Quantization of charge and conservation of charge
  - Coulombs Law and examples
  - Principle of superposition and examples

  - Charge is analogous to mass

Introduction

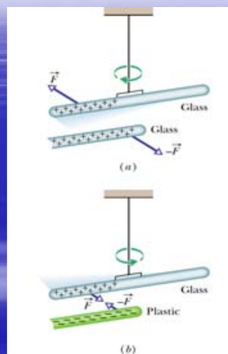
- **"In the matter of physics, the first lessons should contain nothing but what is experimental and interesting to see. A pretty experiment is in itself more valuable than 20 formulae." Albert Einstein**

$$Q = \sqrt{\frac{2Lmgd}{k}\left(\frac{\sec\theta}{\csc^3\frac{\theta}{2} + \sec^3\frac{\theta}{2}}\right)}$$

Charged Hair
Van de Graaff Demo

- How does this gadget produce a mini-lightning bolt?
- What upward forces are keeping your hair up?
- How are these forces produced?
- Why do the hair strands spread out from each other?
- Why do they spread out radially from the head?
- Is hair a conductor or insulator? How can we find out? Does it depend if is wet or dry.
- To understand what is going on we need a model of electricity.

Charged rods on spinner



Introduction Continued

•What is charge? How do we visualize it. What is the model. We only know charge exists because in experiments electric forces cause objects to move.

–Show cartoon comparing mass and charge

•Electrostatics: study of electricity when the charges are not in motion. Good place to start studying E&M because there are lots of demonstrations.

•Atomic Model:

- Show overhead

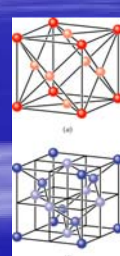
Some preliminaries

- **Electron**: Considered a point object with radius less than 10^{-18} meters with electric charge e= -1.6 x 10^{-19} Coulombs (SI units) and mass m_e= 9.11 x 10^{-31} kg
- **Proton**: It has a finite size with charge +e, mass m_p= 1.67 x 10^{-27} kg and with radius
  - 0.805 +/-0.011 x 10^{-15} m scattering experiment
  - 0.890 +/-0.014 x 10^{-15} m Lamb shift experiment
- **Neutron**: Similar size as proton, but with total charge = 0 and mass m_n=
  - Positive and negative charges exists inside the neutron
- **Pions:** Smaller than proton. Three types: + e, - e, 0 charge.
  - 0.66 +/- 0.01 x 10^{-15} m
- **Quarks**: Point objects. Confined to the proton and neutron,
  - Not free
  - Proton (uud) charge = 2/3e + 2/3e -1/3e = +e
  - Neutron (udd) charge = 2/3e -1/3e -1/3e = 0
  - An isolated quark has never been found

Model of electricity

Consider solid material like a piece of copper wire. The proton core is fixed in position in a lattice like structure. In a conductor, some electrons are free to move about. How many electrons are there free to move about?

1cm long and a radius of 0,005 cm



Copper (Face Centered Cube)

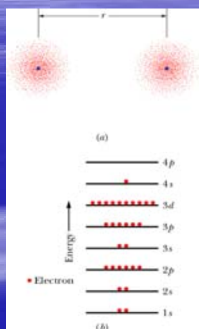
Question: What is the electrical charge in the material that we are talking about? What is responsible for the conduction of electricity? How many electrons are moving about?

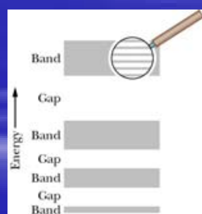
Copper atom:
Z=29(protons), N= 34(neutrons), 29 Electrons

Carbon or diamond

More preliminaries

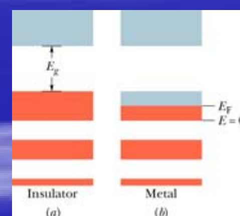
Atoms: Below on the left are two widely separated copper atoms. On the right is shown what happens as they come closer together to in a lattice.



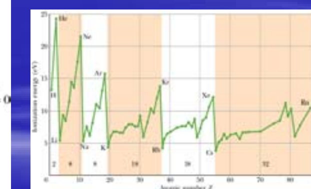


Comparison of which bands are filled and which are empty to explain the difference between metals and insulators

In a metal there are electrons in the ground state of the metal that can easily move to unoccupied levels. In an insulator, there are no free electrons to move about because they do not have enough energy to jump the band gap E_g.



Other criterion

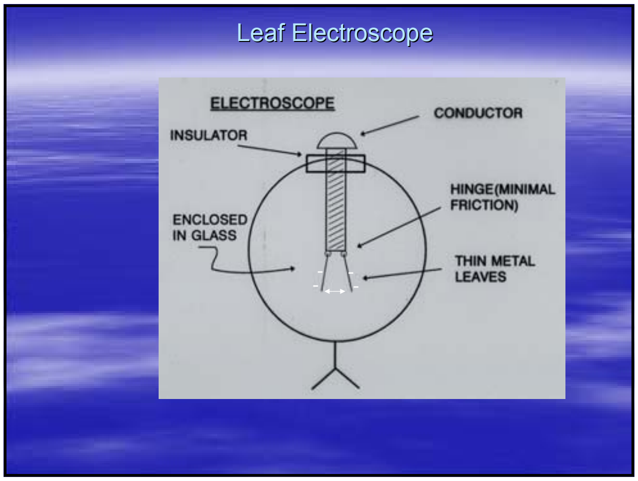


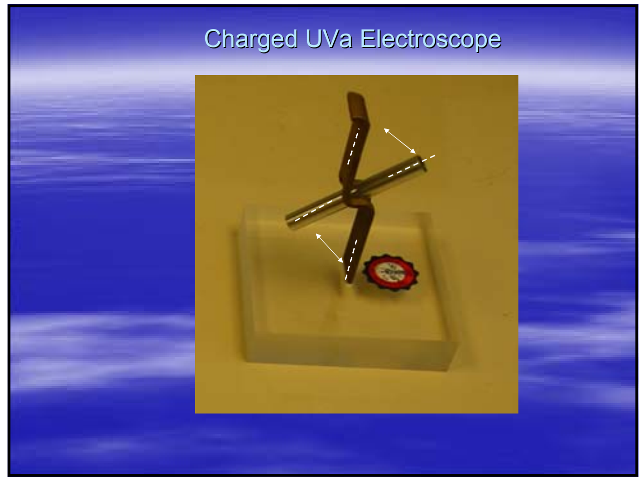
Methods of Charging Objects: Friction, Contact, and Induction

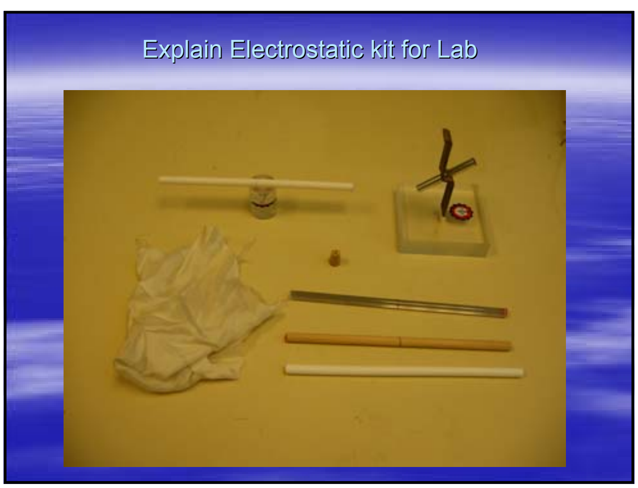
- Normally atoms are in the lowest energy state. This means that the material is electrically neutral. You have the same number of electrons as protons in the material.
- How do we change this?
- How do we add more electrons than protons?

Charging Insulators by Friction/Rubbing

- Rub two materials together: Show teflon/silk
- Show that there is a net charge on the teflon and silk using aluminum leaf electroscope.

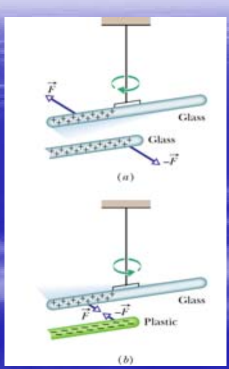

Leaf Electroscope
ELECTROSCOPE
CONDUCTOR
INSULATOR
HINGE(MINIMAL FRICTION)
ENCLOSED IN GLASS
THIN METAL LEAVES


Charged UVa Electroscope


Explain Electrostatic kit for Lab


Two teflon rods on spinner

Charged rods on spinner



Summary

- Silk(+) on teflon(-)
- Silk (-) on acrylic (+)
- Wood doesn't charge
- Charged objects always attract neutral objects

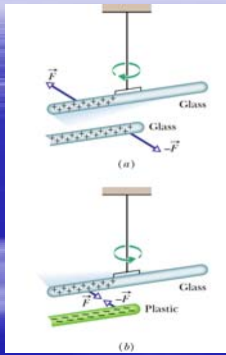
- Show Triboelectric series
- Not only chemical composition important, structure of surface is important - monolayer of molecules involved, quantum effect. (nanotechnology)

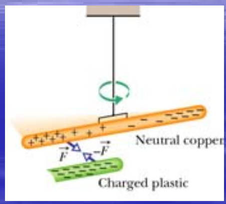
Triboelectric series

http://www.sciencejoywagon.com/physicszone/lesson/07elecst/static/triboele.htm

Positive (Lose electrons easily)
Air
Human Hands
Asbestos
Rabbit Fur
Glass
Mica
Acrylic
Human Hair
Nylon
Wool
Fur
Lead
Silk
Aluminum
Paper
Cotton
Steel
Wood
Amber
Sealing Wax
Hard Rubber
Nickel, Copper
Brass, Silver
Gold, Platinum
Sulfur
Acetate, Rayon
Polyester
Styrene
Orlon
Saran
Balloon
Polyurethane
Polypropylene
Vinyl (PVC)
Silicon
Teflon
Negative (Gains electrons easily)

Charged rods on spinner

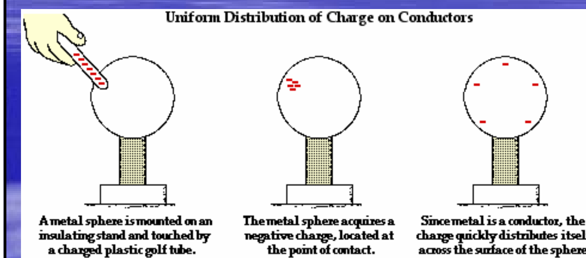




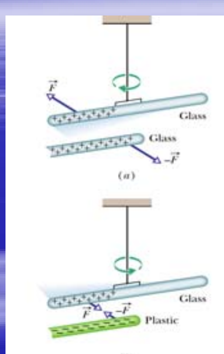
Charging by Contact / Induction using conductors

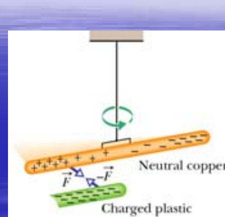
- Show electronic electroscope (EE) with cage: gives magnitude and sign of charge. Use teflon and acrylic
  to show difference
- Show uniformity of charge around sphere using EE.
- Show induction:
  - using conducting spheres and EE
  - using electroscope
  - electrophorus
  - using water stream deflection need to know about electric dipoles
- Show hanging charged/conducting pith ball: first attraction by induction, then contact, then conduction of charge, then repulsion

Uniform Distribution of Charge on Sphere using EE

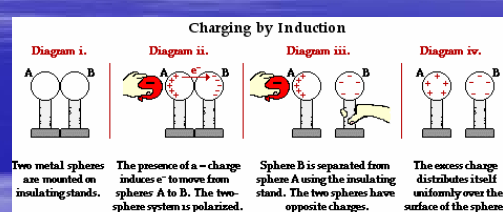


Charged rods on spinner

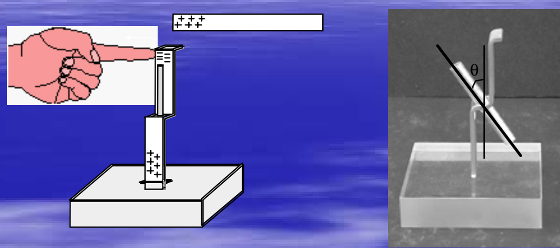




Induction using two conducting spheres and EE



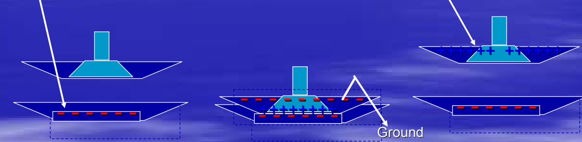
Induction using electroscope (small effect)



Electrophorous(Induction)

http://www.physicsclassroom.com/mmedia/estatics/epn.html

- Rub foam surface with silk.
- Place aluminum pan with insulating handle on to charged surface.
- Touch aluminum pan to ground it.
- Separate pans. What is the charge on the pan?
- Repeat indefinitely



Key: Negative charge(electrons), immobile on foam surface, repels electrons in conducting aluminum pie plate. When you ground the aluminum pan, those electrons are repelled to ground leaving the pie plate positively charged. Discharge pie plate and then repeat process as long as foam is charged

Conservation of charge

- Rubbing does not create charge, it is transferred from object to another
- Teflon negative - silk positive
- Acrylic positive - silk negative
- Nuclear reactions $\gamma^0 = e^+ + e^-$
- Radioactive decay $^{238}U_{92} = {}^{234}Th_{90} + {}^4He_2$
- High energy particle reactions $e^- + p^+ = e^- + \pi^+ + n^0$

What is meant by quantization of charge?

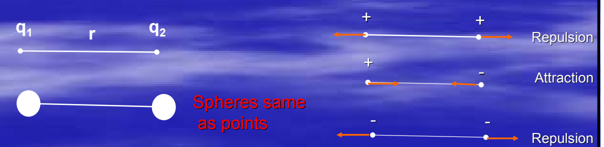
- Discovered in 1911 by Robert A. Milikan in the oil drop experiment
- The unit of charge is so tiny that we will never notice it comes in indivisible lumps.
- Example: Suppose in a typical experiment we charge an object up with a nanoCouloumb of charge (10^{-9} C). How many elementary units of charge is this?
- **$Q=N*e$ so $N= Q/e = 10^{-9}$ C/ $1.6*10^{-19}$ C/e = $6*10^9$ =** six billion units of charge or 6 billion electrons.

Summary: Electrostatics is based on four empirical facts

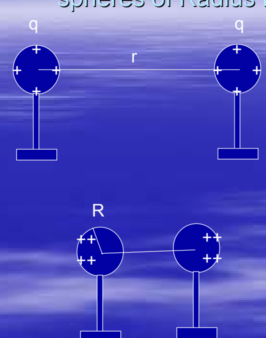
- Conservation of charge
- Quantization of charge
- Coulombs Law
- The principle of superposition

Coulombs Law

- In 1785 Charles Augustin Coulomb reported in the Royal Academy Memoires using a torsion balance two charged mulberry pithballs repelled each other with a force that is inversely proportional to the distance.
  - $F = kq_1q_2/r^2$ where $k=8.99*10^9\ Nm^2/C^2$ in SI unit
    $k \sim 10^{10}\ Nm^2/C^2$



Uniformly charged metal spheres of Radius R



$F=kq^2/r^2$

$F\sim kq^2/(r+R)^2$

Coulombs Law examples

•What is the force between two positive charges each 1 nanoCoulomb 1cm apart in a typical demo? Why is the force so weak here?

$F = kq_1q_2/r^2$

$F = 10^{10}\ Nm^2/C^2\ (10^{-9}\ C)^2/\ 10^{-4} m^2 = 10^{-4}\ N$

(equivalent to a weight of something with a mass of 10^{-5} kg = 10^{-2} gm or 10 mg - long strand of hair)

Coulombs Law examples

What is the force between two 3 gm pennies one meter apart if we remove all the electrons from the copper atoms? (Modeling)

– **$F = kq_1q_2/r^2 = 10^{10} * q^2/1^2$** So what is q?

The atom Cu has 29 protons and a 3 gm penny has **$(3/63.5) * 6*10^{23} = 3* 10^{22}$ atoms.**

– The total charge is **$q = 29*3*10^{22} *1.6*10^{-19} = 1.4*10^5$ C**

– The force is **$F = 10^{10} (1.4*10^5)^2 = 2.0*10^{20}$ N**

What is their acceleration as they separate?

$a = F/m = 2.0*10^{20} / 3*10^{-3} = 0.7*10^{23}\ m/s^2$

Principle of Superposition

- In the previous example we tacitly assumed that the forces between nuclei simply added and did not interfere with each other. That is the force between two nuclei in each penny is the same as if all the others were not there. This idea is correct and is referred to as the Principle of Superposition.
- Another Example

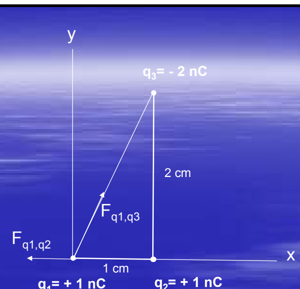
– Three charges lie on the x axis: q_1=+25 nC at the origin, q_2= -12 nC at x =2m, q_3=+18 nC at x=3 m. What is the net force on q_1? We simply add the two forces keeping track of their directions. Let a positive force be one in the + x direction.

– **$F = -k\ q_1\ (q_2 / 2^2 + q_3 / 3^2)$**

– **$= -10^{10}\ 25*10^{-9} (-12*10^{-9} /4 + 18*10^{-9} /9)$**

– **$= +2.5*10^{-7}$ N.**

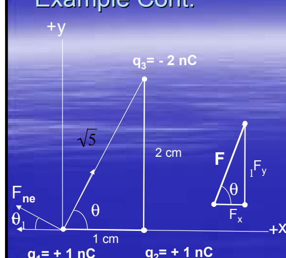
Example



Question: What is the net force on q_1 and in what direction?

Hint : Find x and y components of force on q_1 due to q_2 and q_3 and add them up.

Example Cont.



$F = kq_1q_2/r^2$

Sign convention

x - y Components of force due to q_2

$F_x = - 10^{10} (10^{-9})^2 / (10^{-2})^2 = -1x10^{-4}$ N

$F_y = 0$

x - y Components of force due to q_3

Magnitude of Force due to q_3

$|F|$ = $+ 10^{10} (2x10^{-9})(1x10^{-9}) / (5x10^{-4}) = 0.40x10^{-4}$ N

θ = atan 2/1 = 63.43 deg

$F_y = F \sin\theta = 0.40$ N $\sin 63.43 = (0.4)(0.894) = 0.358x10^{-4}$ N

$F_x = F \cos\theta = 0.40$ N $\cos 63.43 = (0.4)(0.447) = + 0.179x10^{-4}$ N

Sum $F_x = - 1x10^{-4} + 0.179x 10^{-4} = - 0.821x10^{-4}$ N

Sum $F_y = 0 + 0.358 x10^{-4}$ N $= 0.358x10^{-4}$ N

$$F_{net} = \sqrt{F_x^2 + F_y^2} = +\sqrt{(0.821)^2 + (0.358)^2}\ 10^{-4} N$$

$$F_{net} = +0.802\ 10^{-4} N$$

θ_1 = atan F_y/F_x = atan $0.358x10^{-4} / - 0.821x10^{-4}$ = 23.6 deg

In an atom can we neglect the gravitational force between the electrons and protons? What is the ratio of Coulomb's electric force to Newton's gravity force for 2 electrons separated by a distance r ?

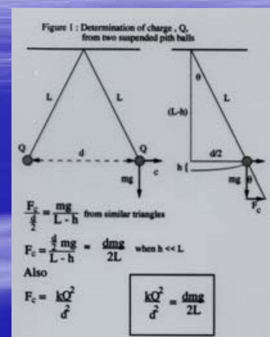
q r q m r m

F_c= kee/r^2 F_g=Gmm/r^2

F_c/ F_g = ke^2 /Gm^2

- F_c/ F_g = 10^{10} Nm^2/C^2 (1.6*10 $^{-19}$C)^2 /6.67*10^{-11} Nm^2/Kg^2 (9.1*10^{-31} Kg)^2
- = 4.6*10^{42}
- Coulomb / Gravity = 4.6*10^{42}
- Huge ratio and pure number.

Find charge Q on two pith balls separated by distance d



$$Q = \sqrt{mgd^3/(2Lk)}$$

Suppose d =2 cm, L=20 cm, and m = 0.20 g, Find Q in nanoCoulombs.

Change to proper units:m,kg,s,N,C

$$Q = \sqrt{.0002*9.81*(0.02)^3/(2*0.20*10^{10})}$$

$$Q = \sqrt{2*10^{-4}*9.81*(2*10^{-2})^3/(2*0.20*10^{10})}$$

$$Q = \sqrt{16*10^{-10}*9.81*/(0.4*10^{10})}$$

$$Q = \sqrt{40*10^{-20}*9.81} = \sqrt{400*10^{-20}} = \sqrt{4*10^{-18}}C$$

$$Q = 2\ nanoC$$

Why are neutral objects always attracted to positive or negative charged objects.

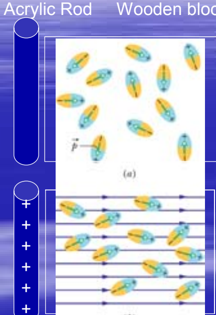
For example:
- Rubbed balloon is attracted to wall
- Comb is attracted to small bits of paper
- Clothes in the dryer stick together.

1. Put wood on the spinner and place charged teflon and plastic rods near it. Try a twig from a tree.
2. Put the 2 x 4 on a curved glass surface and try it.
3. Place charged rod on spinner and place your hand Near it.

What is the explanation of all of these phenomena?

Explanation: The neutral objects atoms and molecules orient themselves in the following way so that the Coulomb forces due to attraction are greater than those due to repulsion because the latter are further away. (Inverse square Law)

Acrylic Rod Wooden block



F= kq_1q_2/r^2

Acrylic Rod Wooden block

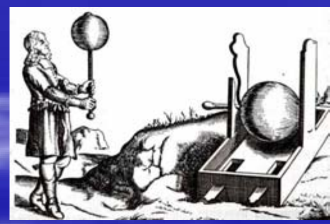
Attractive forces >> Repulsive Forces

Charging Objects using Electrostatic Machines

- Otto von Guericke in 1660 charged a 7” Sulphur sphere
- Lord Kelvin Water Drop Generator (Early 18’th century)
- Wimshurst Machine (1880)
- Van de Graaff Generator (1931)

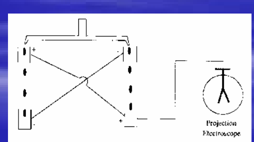
Otto von Guericke in 1660 charged a 7” Sulphur sphere

- The Sulphur Ball: Otto von Guericke (1602-1686) who became famous for his Magdeburg vacuum experiments invented a first simple electrostatic generator. It was made of a sulphur ball which rotated in a wooden cradle. The ball itself was rubbed by hand. As the principles of electric conduction had not been discovered yet, von Guericke transported the charged sulphur ball to the place where the electric experiment should happen. Guericke made the ball by pouring molten sulphur into a hollow glass sphere. After the sulphur was cold, the glass hull was smashed and removed. Some day, a researcher found out that the empty glass sphere itself provided the same results.



Lord Kelvin Water Drop Generator (Early 18’th century)

http://www.angelfire.com/ak/egel/kelv1.html



Kelvin Water Drop Generator

Wimshurst Machine

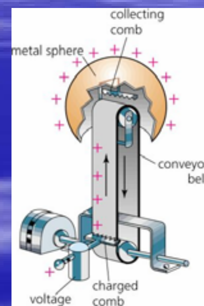
The Englishman, James Wimshurst (1832-1903), spent most of his professional career working with the shipping industry as a surveyor and evaluator of ships, serving as the consulting engineer for the British Board of Trade.. At the same time he had a parallel career in science. We know him for his work with electrostatic generators in the early 1880s, when he improved Voss' electrostatic generator.

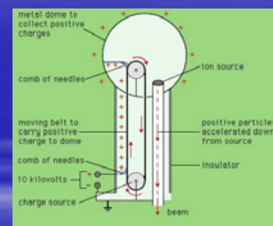
In Wimshurst design, the disks contra-rotate. The metal foil sectors on the disks induce charges on each other, which are picked off with metal brushes and stored in Leiden jars.

Robert Van de Graaff Generator (1931) Tuscaloosa, Alabama

http://chem.ch.huji.ac.il/~eugeniik/history/graaff.

Van de Graaff Accelerator





Warm up set 1

1. HRW6 22.P.019. [52295] What is the total charge in coulombs of 83.0 kg of electrons?

Number of electrons = 83.0 kg/9.11*10^{-31} kg = 9.11 *10^{+31} electrons

Q= 9.11 *10^{+31} *-1.60*10^{-19}C =-1.46e+13 C= =-1.46 10^{+13}C

2. HRW6 22.P.023. [52297] How many electrons would have to be removed from a coin to leave it with a charge of +1.5 10-7 C?

Assume the coin is neutral.

Number of electrons = 1.5*10^{-7} C/ 1.60*10^{-19}C = 9.38e+11C = 9.38 10^{+11} C