Physics 2415 Lecture 1: Introducing Electrostatics

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Summary of syllabus:

The first 9 lectures, almost a quarter of the course, will be on electrostatics. Like the mechanical statics we covered last semester, this is about systems at rest, but now charges in equilibrium, with the total electrical force on each charge being zero. Actually, the book includes in this section motion of single electrons, or charged objects—what it doesn't include is the motion of huge numbers of electrons down a wire, an electric current—this is covered in the next four lectures.

The next 11 lectures cover magnetism, production of magnetic fields by electric currents, and the forces on electric currents from magnetic fields, the basis of electric motors and dynamos, going on to oscillating circuits, the basis of radio transmission.

In preparation for covering electromagnetic waves, we next go over ordinary mechanical waves, such as waves on strings and sound waves.

The final quarter of the course is on electromagnetic waves, in particular light waves: reflection, refraction, lenses, interference and diffraction.

Introducing Electrostatics: Electric Forces in Atoms, Molecules and Solids

The Atom and its Nucleus

Just to get going here: you all know, of course, that there are two kinds of electric charge, positive and negative, and that like charges repel, unlike charges attract. We'll discuss a little later how this is confirmed experimentally, and all the details. Now, this electric force is what holds atoms together by binding the electrons to the nucleus, and what holds atoms together to form molecules—so it's at the basis of all matter—if you take the atomic nucleus as given, which is fine for chemistry, biology, etc. The nucleus itself, though, is made of neutrons and protons, the protons are positively charged, so repel each other. The nucleus must therefore be held together by stronger force, which is termed, appropriately, the nuclear force. But if the nucleus is big enough, the repulsion between protons wins out, and it flies apart. This imposes a limit on the charge of a nucleus. The reason the electrostatic repulsion eventually dominates is that the nuclear binding force is strong but very short range, almost like a layer of glue on the particles, so only holds together protons and neutrons very close to each other, whereas the electrostatic repulsion is still there, even if lessened, at greater distances. So not only does it limit the size of nuclei, it's also the reason nuclear fission takes place.

In an atom, the nucleus contains Z protons each having charge e, Z is called the atomic number, and total positive charge Ze. The atom also has Z electrons, total charge $-Ze$. The electrons are much lighter than the protons and neutrons (about 1/2000) and they form a cloud surrounding the nucleus, of size around 0.1 nanometers, 10^{-10} meters. The nucleus is of order femtometers in size, 10^{-15} meters.

Just how the electrons are held in place cannot be explained without quantum mechanics. Even the size of the atom is inexplicable without the quantum. But in this course, we'll take it as given. Atoms can lose electrons if they are hit by other atoms or by strong electromagnetic fields. An atom missing one or more electrons is called an *ion*. It is positively charged, since the remaining electrons no longer balance the nuclear charge, so a sodium atom minus its electron is written Na^+. The electronic configurations are such that a sodium atom has one loosely attached electron, easy to lose. On the other hand, a chlorine atom has a gap in the electron pattern and easily accommodates an extra one.   When lots of Na and Cl atoms are put together, it turns out that the Cl attracts the Na's loose electron so powerfully that it leaves home, settling into the Cl. The Na becomes Na^+, the Cl becoming Cl^-, then all these ions form a cubical pattern, with alternate atoms like a 3D chessboard, so each + has six – neighbors, etc., and electrostatic attraction keeps the whole thing together. (But it's not the whole story—there's repulsion between ions that get close. As we'll see later, electrostatic forces alone couldn't hold the ions stably in position. Quantum mechanics is essential.)

Yet if you put the salt into water, it dissolves! What happened to the electrostatic attraction? As we'll discuss later, water partially shields electric fields, it makes them weaker, and so ions near the surface of a crystal can be knocked off by thermal vibrations, and not return.

Conductors and Insulators
But not all solid formation can be explained in electrostatic terms: what if we just have a collection of sodium atoms? They will form a crystal too. It turns out that this time, the loose electrons leave their home atoms and wander throughout the crystal, so it can be visualized as a lattice of positively charged Na ions in a sea of negatively charged electrons. Why should this stay together? Unlike NaCl, where electrostatics does the job once you grant what happens to the atoms, here quantum mechanics is needed to make any progress in understanding—the uncertainly principle, and the electron spin, both quantum concepts, need to be put together with the electrostatic force to explain what's going on. We can't go into it at this point, but one result is important: this solid sodium has **electrons free to travel anywhere** in the crystal. A solid with such mobile electrons is called a **conductor** (of electricity) because the electric charge in it can move around. Good conductors are metals. They are shiny, because, as we'll see later, the mobile electrons reflect light well. They also conduct heat efficiently, again because it's the mobile electrons that carry the heat energy around.

In contrast, in solid salt the electrons are firmly pinned down to their atoms. Charge cannot move around, and—again for quantum mechanical reasons—any extra charge added finds it difficult to move around too. Solids (or fluids) with this property are called **insulators**.

The transfer of electrons from Na atoms to Cl atoms, when they get close, has an analogy on a far larger scale: if you rub a glass rod with a piece of fur, both rod and fur become charged. (The technical name is the **triboelectric** effect—tribo just means friction.) Actually the *work* done in rubbing is irrelevant— the reason for rubbing is just to get the two surfaces in really close contact, so surface atoms on the two can transfer electrons. The glass gets positively charged. You can look up triboelectric series in Wikipedia to find out which way the charge moves—it's not obvious, rubbing glass with rabbit fur transfers electrons to the glass, cat fur has the opposite effect—at least according to some tables.

Charge Conservation is Always True

In an ordinary electrically neutral object, the total negative charge of the electrons exactly balances the total positive charge of the nuclei. Various experiments involving rubbing, or adding electric fields, etc., just move the electrons around, they do not change the number of electrons (they might become unbound, of course.) The total electric charge isn't changed. If we go for a moment beyond the energy range relevant for this course, in high energy (relativistic) collisions, electrons can disappear, but experimentally in such collisions either new negatively charged particles will be created, or positively charged particles will disappear: the *total* electric charge is *always* conserved.

Observing Electrostatic Forces

This is easy: if you run a rubber comb through your hair, it will become negatively charged, and will pick up small pieces of paper, which it wouldn't before. But wait a minute—the bits of paper weren't electrically charged! What happens is that when the charged comb is brought near, the electric field distorts the charge distribution within molecules in the paper. The electrons within molecules will move a bit away from the comb, leaving the positive charges slightly closer—even though no charge escapes from its own molecule. The net effect is that the positive charges, attracted by the comb, are slightly closer than the negative charges, which are repelled, so there is a net attraction.

Little Charged Spheres

When we charge up the comb, or a glass rod, the charge is distributed in some complicated way on the surface of the rod. It can't spread itself evenly, since the rod is an insulator, so it's difficult to pin down exactly where the charge is. To make life simpler, we use small metal spheres, hung with insulating string (see the picture below). We rub the rod against the sphere, so some charge moves onto the sphere. Since the sphere is a conductor, the charge on it will spread evenly. If we charge two such spheres and hang them close to each other, but not touching, we see that they repel each other. Like charges repel—and the glass is positively charged. But if instead we use a Lucite rod, it's negatively charged on rubbing, and we can confirm that a positively charged sphere will attract a negatively charged one.
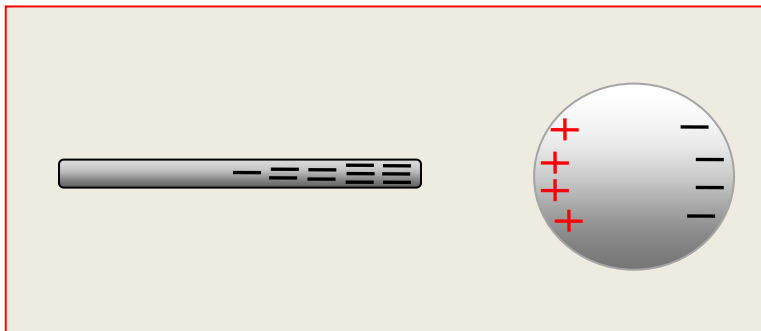
The Electroscope

An electroscope detects the presence of charge by using repulsion of like charges. The simplest is the gold leaf electroscope: two very light leaves, of gold foil, hang down close to each other from a conductor. If charge is places on the conductor, it spreads onto the leaves, and they repel each other.

A slightly fancier version has a central column and a pivoting light rod, all made of metal, so if charge flows into the column and rod, the the repulsion causes the rod to swing away—this is the object on the right, the big circle, in the picture below.
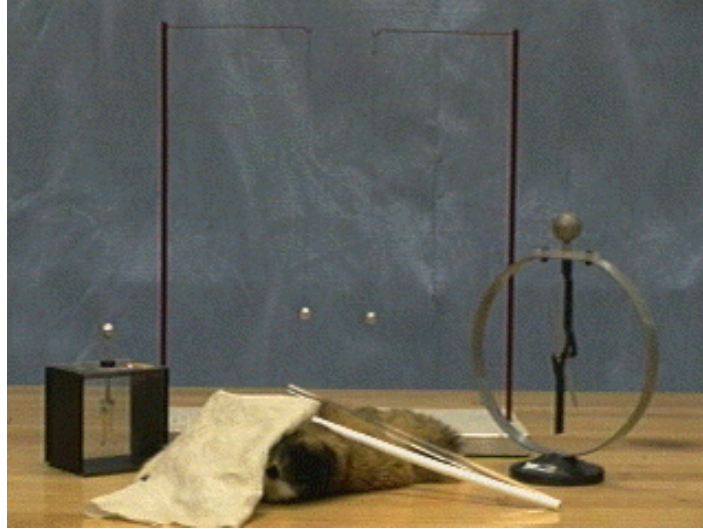
Charging by Induction

If a negatively charged (by rubbing with silk) Lucite rod is brought close to, but not in contact with, a conductor, charge will redistribute on the conductor: the electrons will move away from the vicinity of the Lucite, that part of the conductor will therefore have net positive charge. But if we have two conductors in contact, so charge can flow from one to the other, and the Lucite rod is brought close to one of them, that conductor will have a net positive charge. If, now, the two conductors are separated (by moving one, using some insulated contact) while the Lucite rod is close, the charge imbalance will of course remain even when the Lucite is removed, since the imbalanced charge will not be able to flow back. The Lucite rod never did touch the conductors: the electric charge on the rod itself did not move on to the conductors, but nevertheless the two conductors are now electrically charged, one positive the other equally negative. This process is called charging by induction.

The electroscope can be charged in this way: one puts one's finger on the sphere at the top, and brings, let's say, a positively charged glass rod close to the ball. This will attract electrons from the earth, through one's body and finger, on to the electroscope. If one now takes one's finger away, with the glass rod still in place, then removes the glass rod, the electroscope is now negatively charged, the needle will settle at some angle to the vertical. If now, the glass rod reapproaches, this angle decreases—because electrons are being drawn from the needle up to the ball.