Interaction of heavy charged particles with matter

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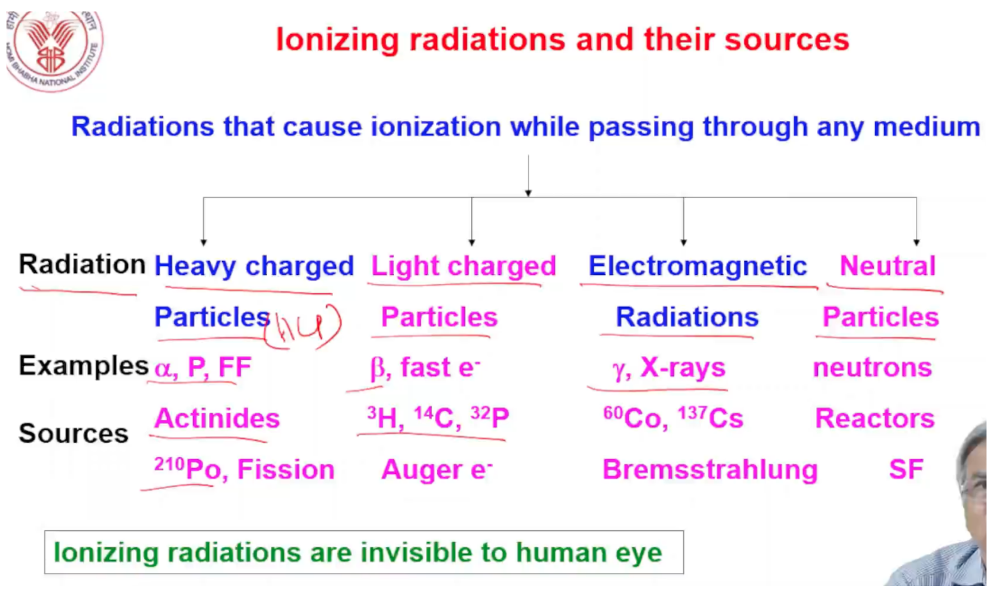
Lecture-7, module-2

Dear students, the last few lectures we have discussed the different aspects of nuclear chemistry namely radioactive decay, the different types of decays like alpha, beta and gamma. And also the structure of nuclei, the different models like liquid drop model, shell model and how these models can explain different properties of nuclei. Now we will start discussing the different types of radiations, how they interact with matter and also that will help us in deciding how to make a detector for these radiations. So in the coming few lectures, I will be discussing upon interaction of radiation with matter and radiation detection and measurements. Let us first discuss what type of radiations that we are trying to discuss. We will call them ionizing radiations.



So the ionizing radiations means that radiations which cause ionization when they pass through the medium and you can then really understand that these radiations have energies higher than the ionization energy of different materials through which they pass. These radiations are in fact invisible to the human eye and so you require detectors if you want to detect these radiations. There are suitable detectors for this purpose. Before that let us discuss, we can try to categorize them depending upon the type of interactions that undergo.

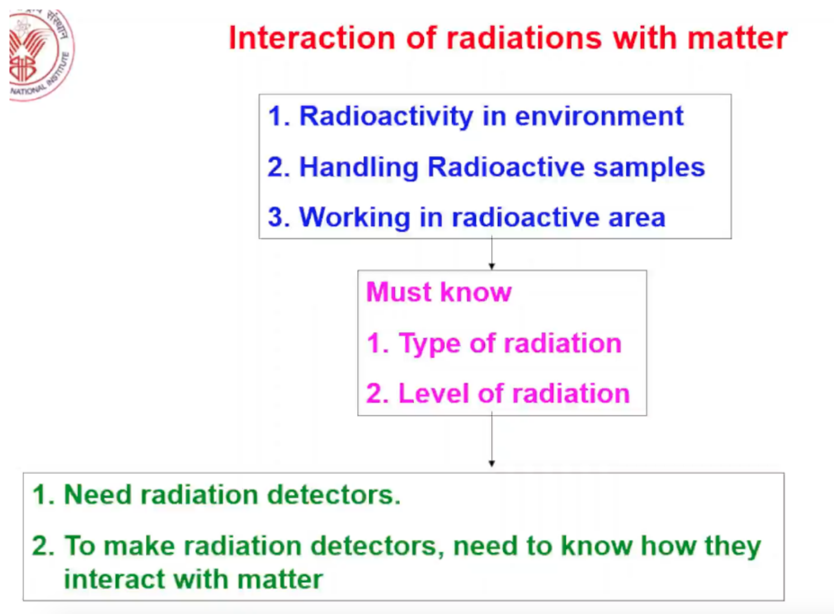
So we will discuss the interactions based on the types of different types of radiations. So you can see here that we have the different types of radiations like heavy charged particles, ones which are of constituents of nucleus, e.g., protons, alpha particles, fission fragments. So these heavy ions which involve a nucleus, we will call them heavy charged particles HCP. Then we have the light charged particles like electrons and positrons. Even the beta particles will come in that category, even Auger electrons will come in that category.

So these are charged particles but light. They are not nuclear particles; they are the extra nuclear particles. Then we have the electromagnetic radiations, gamma rays, x-rays and then lastly we have the neutral particles like neutrons. These are the four classifications in which we will discuss them one by one. The examples of heavy charged particles are the alpha particles, the protons or even heavy ions, you can have them in an accelerator you can produce carbon ions, lithium ions, oxygen ions.

So how to detect them also is interesting. Fission fragments, when the fragments are emitted from the fissioning nuclei, they are heavily charged particles and therefore their interactions are similar to heavy charged particles. And the sources of these HCPs like alpha particles are emitted by actinides like thorium, uranium, plutonium and so on. Protons are in fact emitted in nuclear reactions or we can have an accelerator producing high energy protons and fission fragments are emitted in spontaneous fission or induced fission. So many times we need to detect the fission fragments.

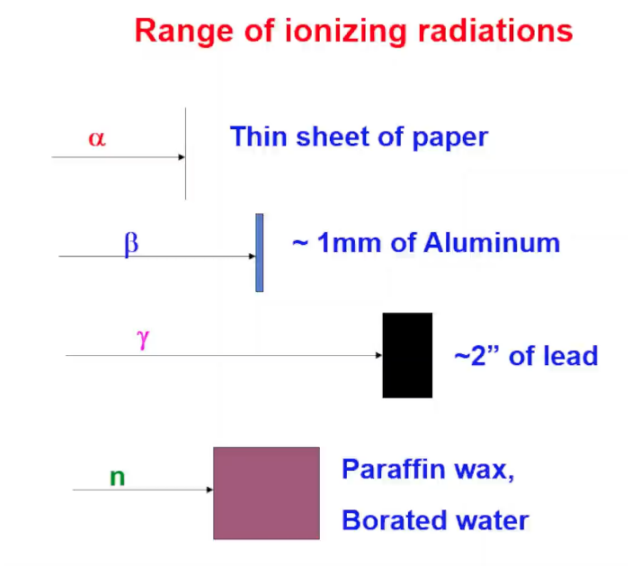
For example, the ^{210}Po is a source of alpha particles, even plutonium-239 or radium-226 are sources of alpha particles. And if you have a spontaneous fissile isotope like californium-252 that is a source of fission fragments. Among the beta particles we have beta particles, beta plus, beta minus, you can have electrons from an accelerator. So tritium, carbon-14, phosphorus-32, these are all beta emitters, they emit beta minus. And in internal conversion or electron capture types of decay, you can have emission of Auger electrons, they are relatively low in energy, but they are having energy more than the ionization energy of different materials.

In the electromagnetic radiation category, we have gamma rays and x-rays. We have already discussed how gamma rays are emitted post beta or alpha decay like cobalt-60 or Cesium-137. And we will also discuss today a type of radiation called Bremsstrahlung, which is emitted when the beta particles or high energy electrons interact with any material. The neutrons are available in the reactors in plenty. They are also emitted from the neutron sources like californium-252 or americium-beryllium or antimony beryllium type of sources.



So we will discuss all these types of radiations and their interactions in these coming lectures. Why we need to study the subject of interaction of radiation matter? We know that radioactivity is there in the environment. All along our body contains radioactivity in terms of carbon-14, potassium-40 and nature contains uranium, thorium in earth crust. So we are in the midst the low levels of radiation and we need to know how much it is. Then we will be handling radioactive samples like actinides or you can have radioactive isotopes for your experiments or even working in a radioactive area.

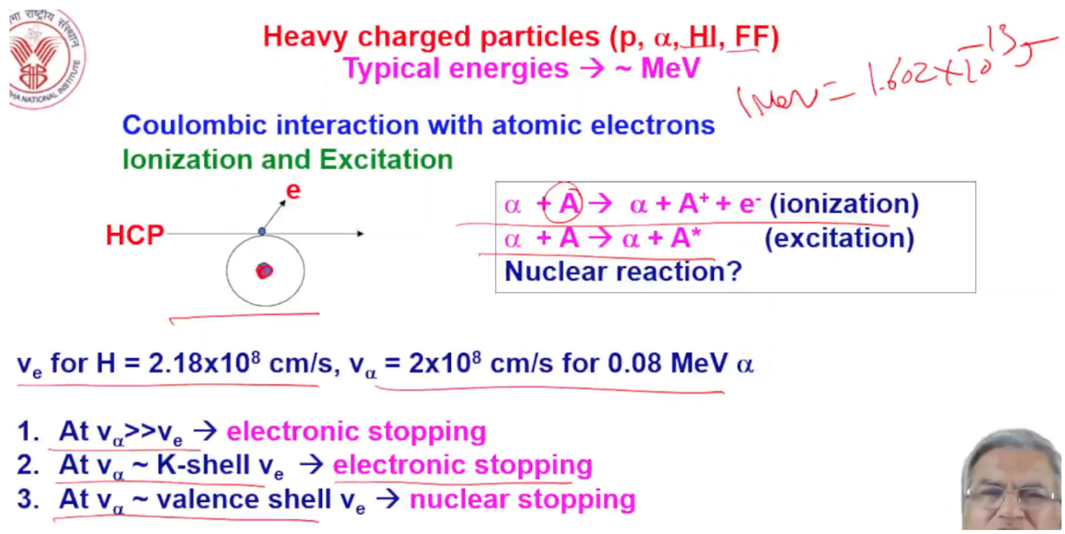
So you need to know what type of radiation you are going to have in the area. What is the level of that radiation? So for all these since the radiations are invisible, we need to have detectors suitable detectors when we go to a radioactive area or when we want to count radiations. Then to make the radiation detectors, we need to know how these radiations interact with the matter. Depending upon that, we can discuss how to make a detector for a particular type of radiation. So before we go to the actual interaction of different radiations with matter, I thought just give to you a feel of how much they can travel in any medium.



So this slide just gives you kind of distances these different radiations can travel in a material. For example, alpha particles. So alpha particle is nothing but doubly charged helium atom, He^{2+} and it can be stopped even by a thin sheet of paper. So may be few hundreds of microns. Suppose you are wearing surgical gloves, they are enough to stop the alpha, it will not reach your hands.

The beta particles of energy 1 to 2 MeV can be stopped even by one or two millimeters of aluminum metal foil. So you can see they can travel more distances, so their ranges are higher. The gamma rays are waves, electromagnetic radiations, so they can travel much more distance and you require a high Z material as we will discuss later on. Almost a two inch thick lead brick is required to stop the gamma ray.

And the neutrons, neutrons are neutral particles, but certain materials have very high neutron absorption cross-sections like paraffin wax. In fact, paraffin wax is a low Z material, it can stop the neutrons very fast and then if you have it, it contains some neutron poisons like boron, cadmium, gadolinium like that, so they can be used to shield ourselves from the neutrons. So typically paraffin wax, borated water are used as neutron shield. This also will be few inches thick shield for neutrons.



So now let us come to the interaction of heavy charged particles with matter. So as I mentioned, the heavy charged particles are particles associated with the nuclei like protons, alpha particles, heavy ions, HI means heavy ions and the fission fragments.

So the fission fragments actually, you know, like for example, in Californium-252 fissions, you will have fission fragments of masses 100 to 150 and then their charges would be 20+. So heavily charged ions, so their interactions are also included when we discuss. But for the sake of simplicity, I will be taking example of protons and alpha, the same relations hold for heavy ions and fission fragments. The typical energies of this radiation is involved like in alpha decay, as I mentioned earlier, the energy of alpha particles are in the range of 4 to 8 MeV.

So 1 MeV = 1.602×10^{-13} joule, 1 electron volt 10^{-19} joules and so you can calculate, what is the energy. So this, normally will be in joules whatever their bond energies, you say kilocalories per mole, kilojoule per mole, that is per mole. When we are talking about MeV, 1 MeV per decay, one single alpha particle will have energy of 4 MeV or 8 MeV. Similarly, the protons of energy 2 MeV to even 10 MeV can be produced in nuclear accelerators and in nuclear reactions, protons will have energies 1 to 2 MeV. Fission fragments have energy of the order of 100 MeV and the heavy ions can be of energy of few 10s of MeVs.

So we are talking about energies which are in the range of millions of electron volts, which is much above the energy required to ionize a particular material. And so because of their charge, they interact with the material basically by Coulomb interaction with the atomic electrons. Now in the material, the major volume is occupied by electrons. As you know by this time that the nuclei occupy a very small volume in an atom. For example, this is an atom, the nucleus occupies very small volume and the rest is all electrons are occupying.

So when the heavy charged particle is coming and interacting with the material, it will be seeing mostly the electrons. So the nucleus offers electrons which the heavy charged particle is interacting. And it is like in a collision now. So it's a collision between a heavy ion and an electron. So you can see the heavy ion is very, very heavy, massive particle compared to electron.

The mass of proton is of the order of 2,000 times the electron. So it will just give its momentum, significant part of its momentum, electron will be knocked out. So that will be called as ionization. So the ionization you can see here, alpha particle when it is interacting with an atom, A, then A will be ionized. For example, argon atom, it will become Ar^+.

$^4He + Ar \rightarrow Ar^+ + e^- + {}^4He'$

But in addition to ionization, many a times, even though the energy of the alpha particle or charged particle is much higher than the burning energy of electrons, the atoms may remain in the excited state instead of ionization.

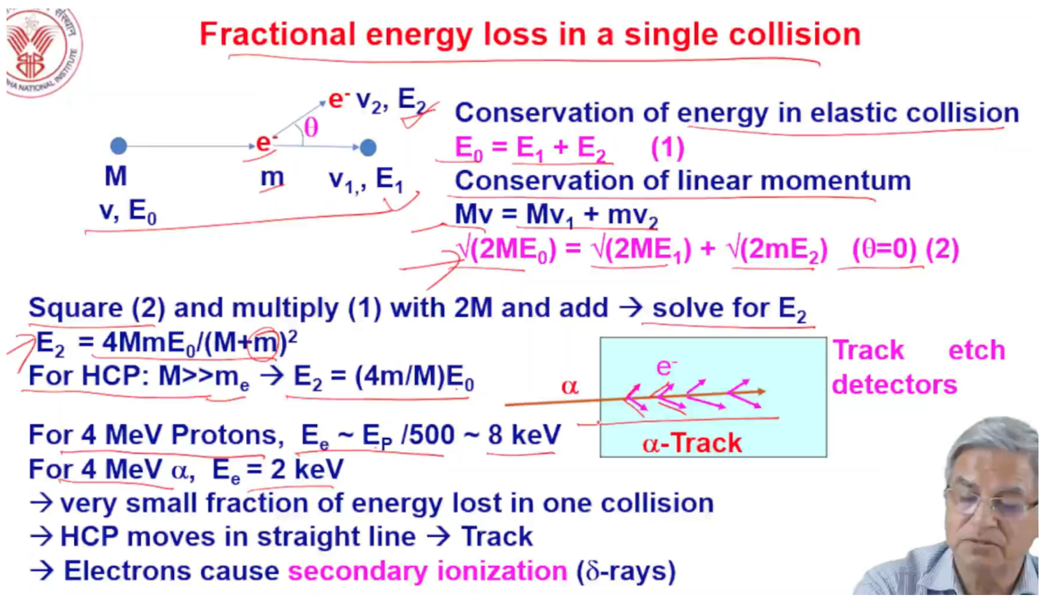
$^4He + Ar \rightarrow Ar^* + {}^4He'$

So ionization and excitation are these two modes of interaction of any charged particle with any matter. Now you may ask why nuclear reaction cannot take place. So as I discussed earlier, the nuclear reaction requires a certain coulomb barrier to be crossed.

So first of all, the probability of interacting with the nucleus is very small because the nucleus is occupying very small volume in the material. And secondly, even if it is colliding with the nucleus, then the energy of the heavy charged particle should be sufficiently high to cross the coulomb barrier of this nucleus to induce any nuclear reaction. So predominantly, like the energy that we are talking about alpha protons of few MeV, we will resolve that it is mostly electronic interaction, interaction of electrons that is coulombic interaction. So ionization and excitation are the two modes of interaction. We will call it electronic stopping.

Now just to give you a feel for the energies and the velocities of ions, when the alpha particle comes out of a nucleus, it remains as doubly charged helium atom just to compare the velocity of alpha and the electrons velocity in atoms. So for a hydrogen atom, the velocity of electron is 2.18×10^8 centimeter per second. And see the alpha particle of, the comparable velocity is for an alpha particle of 0.08 MeV. So you can imagine that if you have a 5 MeV alpha particles, it will have much higher velocity than the velocity of electrons orbiting around the nucleus. So what happens when the alpha particle comes out of a nucleus is velocity is much, much higher than the velocity of electrons in its orbitals. And therefore alpha particle remains as a helium plus only when the velocity of alpha particle becomes comparable or less than the velocity of electrons in its orbits, it will start picking up the electrons and become a helium atom. So that is why the alpha particle will keep on removing, knocking out electrons from the atoms until its velocity becomes less than the velocity of electrons in the orbits. So at velocity of alpha more than the velocity of electrons in the atomic orbitals, we call it electronic stopping means interaction with electrons by ionization and excitation.

Then as the particle slows down and assumes energy of the K shell velocity of electrons, even then it is stopping by electronic mode, but it may start picking up electrons, particularly in the K shell. And when the velocity of alpha particle has become comparable to the velocity of electrons like valence shell electrons, then now the charged particle will pick up electrons and become neutral. And now the neutral atom, neutral like helium atom, when it is now interacting with the material, it will be colliding with the atoms. So that we call as a nuclear stopping. The nuclear stopping happens at the end of the, when it is about to get completely stopped in the medium.



Now let us see in more details the interaction, the energy lost by the charged particle when it is in a single collision. So just to see the kinematics of a charged particle of mass, M, velocity v and initial energy E_0 colliding with an electron of mass small m and the electron goes at θ angle with respect to the initial beam direction. And the energy of electron is E_2, velocity v_2. So we can set up the kinematics equation of conservation of energy in an elastic collision. So initial energy of charged particle is nothing but sum of the energies of remaining alpha particle and the electron that is emitted.

$E_0 = E_1 + E_2 \quad (1)$

You can set up the equation for conservation of linear momentum. So initial momentum mv is a final momentum of two particles, the residual particle alpha and the electron. So you can convert this momentum into energy, $(2mE)^{1/2}$. So for the initial alpha, the remaining alpha and the emitted electron.

$\sqrt{(2ME_0)} = \sqrt{(2ME_1)} + \sqrt{(2mE_2)}$ $(\theta=0)$ (2)

So alpha particle is losing some energy. So that is why we call remaining alpha. And for θ= 0, we will not bring in the θ dependence, but you can set up the equation for theta also. So what you need to do is solve these two equations for E2. What is E2? Energy of electron. So what is the energy given by alpha to electron? That is what we are discussing here.

And if square this equation-2, and multiply the first equation with 2m and solve for E_2, you get the equation E_2 is the energy of the electron. In fact, this is the maximum energy that electron will gain because at θ=0, electron energy is maximum, that becomes $(4MmE_0/(M+m)^2$. So now for the heavy charged particle, the mass of the ion is very high compared to that of the electron. And so you can actually neglect this m compared to M. And so this becomes

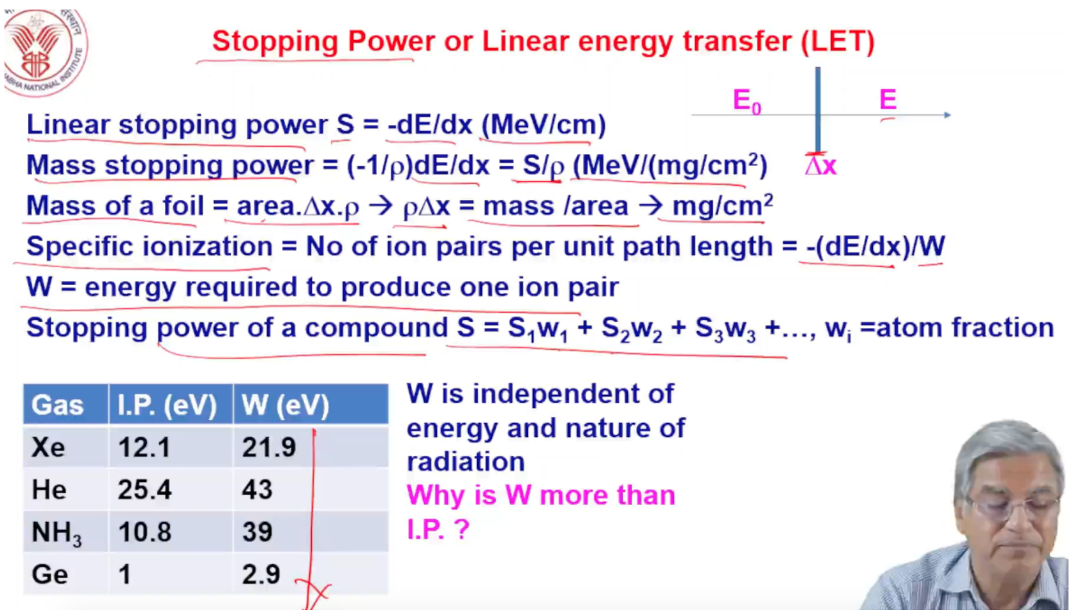
$E_2 = (4m/M)E_0$ where E_0 is the initial energy of the alpha particle.

So you can just see the values for 4 MeV proton, E_e energy of electron will be energy of proton that is $E_0 x 4m/M$. So energy, mass of electron upon mass of proton 1 / 2000 multiplied by 4 is 4 / 2000 is 1/500. So MeV upon 500 is the energy of electron. For 4MeV, we can calculate that electron will be acquiring 8 keV energy. So proton of 4MeV loses 8 keV energy in one collision.

In the case of 4MeV alpha particle, it will lose 2 keV in one collision. So you can see a very small fraction of energy is lost by the alpha particle or any other heavy charged particle in a single collision. So essentially, you know, it loses with small energy and goes undeflected in the same direction. That is why we say the heavy charged particle moves undeflected.

So it follows a track. This is what is the track of alpha particle. Alpha particle moves in a straight line and along this path, it is removing the electrons from the medium and these electrons, the pink ones, these electrons are having energies of 2 keV and they will cause further ionization in the medium. They are called the δ-rays. So the important point is that the heavy charged particles move in a straight line, which we call as the track and the electrons that are emitted during this passage of this heavy charged particle to the material, these electrons can further cause ionization, which we call secondary ionization or δ-rays. In fact, this principle of track is used in track etch detectors.

That means if you take a dielectric material, then this, the path of the alpha particle, it will create a channel that damage in the material, which doesn't get annealed and you can etch it with some acid or alkali and you can see the path of the alpha particle in a microscope. So each track you can count in a microscope. That is one of the principle of track etch techniques.



Let's go into little more details of the interaction of heavy charged particles. So we call it a term called stopping power. Stopping power of the medium, how fast it can stop the particle or the linear energy transfer. That means in one unit distance path length, how much is the energy transferred by alpha to the medium. So we define the linear stopping power as

S = -dE/dx (MeV/cm) energy lost per unit thickness. And since it is a loss, it is negative. So dE/dx is the stopping power and it has the units of MeV per centimeter.

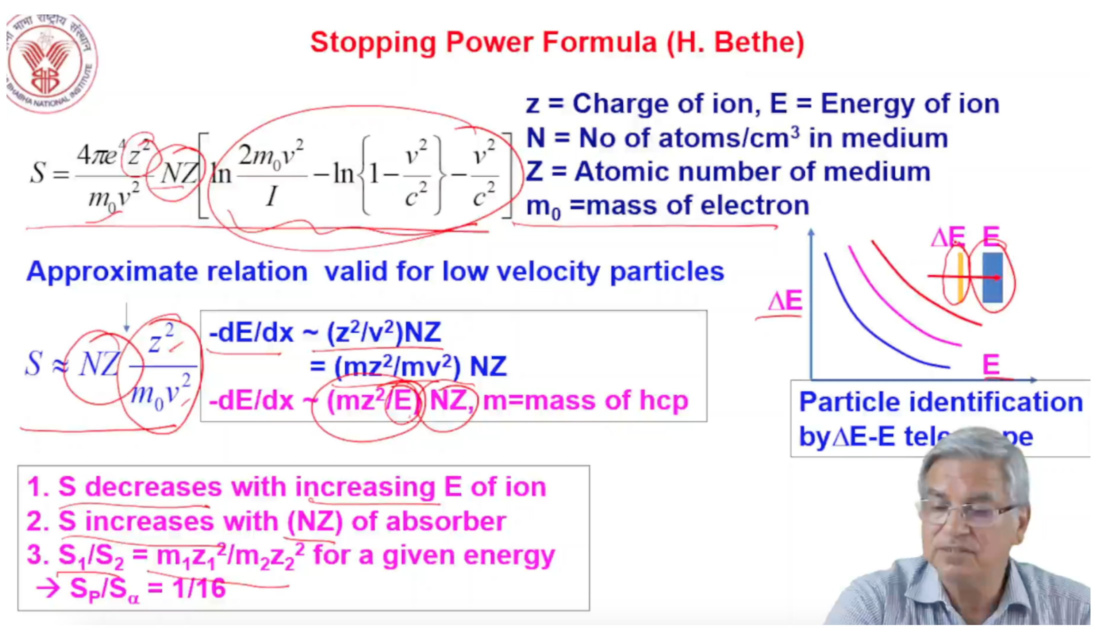
So you have the initial energy E_0 passing through a small thickness of the absorber material Δx, outgoing energy E. So E_0-E, we can say ΔE/Δx is called the stopping power. In this particular subject, actually we are more comfortable with the mass stopping power because the stopping power depends upon the density. So if you divide the stopping power by ρ, the density, we call it mass stopping power.

So S/ρ, we'll call it the mass stopping power. So if this MeV upon centimeter, you multiply, divide by density, that means gram per centimeter cube, then it will be left with MeV upon gram per centimeter square or milligram per centimeter square. Very simple, to put it in a simple way, if you want to find out the thickness of a thin foil, either you use a Vernier or you use a micrometer, much simpler than that is you take the area of the foil and multiply it by the density. So area into thickness if volume and volume into density, that is the mass. So you take the mass, divide by the area, we will call it the thickness. So mass upon area is ρdx, having units as milligram per centimeter square.

So thickness of a foil, take the weight, mass in milligram and area in centimeter square, you can find out thickness, which is multiplied by the density, thickness into density is mass per unit area. So we in fact also call it the specific ionization, that means how many ion pairs are formed during unit length in a medium, we will call it stopping power upon W. W is the energy required to produce one ion pair. So in unit thickness, ΔE is the energy lost, that if the energy required to produce one ion pair is W, dE/(dx*W) is the specific ionization per unit thickness, how many ion pairs are produced. That is also an important quantity when you are stopping the ion in a medium.

So the E is the energy required to produce one ion pair. Many times now when the ion is passing through a medium, which is a compound, so we don't have an individual atom, but we have several atoms. So the atom fractions are weighted together to find the stopping power of a compound for the area in a medium. So we can see that the w1, w2, w3 are the atom fractions and S1, S2, S3 are the stopping powers in those different atoms. So you can have a scaling law to find out the stopping power of a compound. But now just to give you a feel of the values that the W value, energy required to produce one ion pair is that the W values in different media.

Actually speaking, the W value should be equal to the ionization potential or ionization energy of a medium. So for xenon ionization potential 12.1 eV, but actually W value is higher, helium 25.4 eV ionization value is 43 eV, ammonia 10.8 eV, 39, eV, germanium 1 eV and actually 2.9 eV. So you can see that W values are much higher than the ionization potential. Why it is so? Because every time the charge particle interacts, it may not lead to ionization, it can lead to excitation also. So that's why the average value of W much higher than the ionization potential.



Now this stopping powers actually Hans Bethe in 1930s, derived a formula, we will not go into details of the stopping power formula. But the stopping power essentially depends, the formula is

$$S = \frac{4\pi e^4 z^2}{m_0 v^2} NZ[ln\frac{2m_0 v^2}{I} - \ln ln\left\{1 - \frac{v^2}{c^2}\right\} - \frac{v^2}{c^2}]$$

So this z here is the charge of the ion, e is the charge of an electron, E will not come into picture here, but you can later on convert into energy of the ion. v is the velocity of the ion, m_0 is the mass of the electron and NZ is the electron density. So number of atoms per cc into the atomic number that becomes the electron density, number of electrons per cc in the medium and m_0 is the mass of electron. Now let's not bother about this, this is actually this term is the relativistic term.

For high energy particles, you have to consider the relativistic term. So try to simplify this for the non-lativistic low velocity particles. So stopping power becomes NZ, this is the absorber property and this is the ion property, z^2/v^2, z is the charge of the ion, e velocity of the ion. So there are two terms, one term depends upon the particle and other term depends upon the medium. So you can see here that stopping power –dE/dx is proportional to (z^2/v^2)NZ.

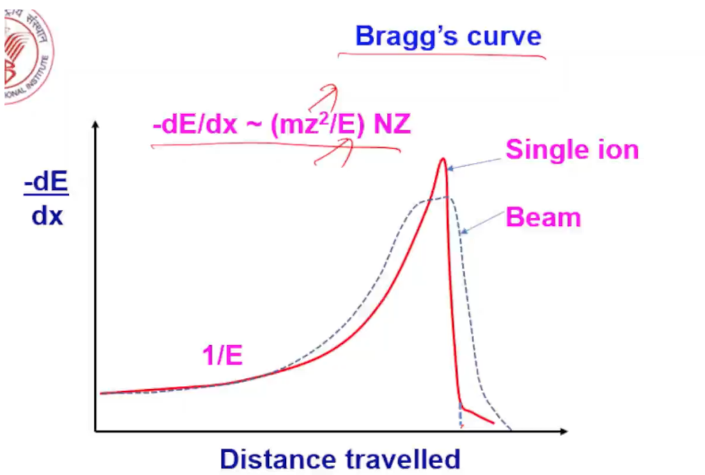
$$S{\sim}NZ\frac{z^2}{m_0 v^2}$$

Now you can just do some jugglery, multiply by the mass of the ion. So we have (mz^2/mv^2)NZ and mv^2 is nothing but E, 1/2 mv^2, kinetic energy. So you can say (mz^2/E)NZ. So this is the mz^2/E dependence of the ion and this is the electron density of the medium. So you can see here, the stopping power decreases with increasing energy of the ion. So because it is in the denominator. As the energy of the ion increases, stopping power decreases because it is moving very fast.

The stopping power increases with the NZ electron density, higher the electron density of the medium, higher is the stopping power. And the ratio for two ions, stopping power ratio is nothing but $m_1 z_1^2/\ m_1 z_2^2$ for a given energy. Just to translate for protons and neutrons, you can see the stopping power of proton to stopping power of alpha will be 1/16 because it will be 4 into 2 square equal to 16. So 1/16. So you can see proton will have a much smaller stopping power than the alpha particle.

And this concept is very well utilized in the identification of particles by a set of two detectors. So this is one detector, a thin detector, this is large detector, thick detector, let us say silicon. So if you see the relationship between dE/dx and E. Thin detector determines the ΔE energy lost and this one determines the total energy.

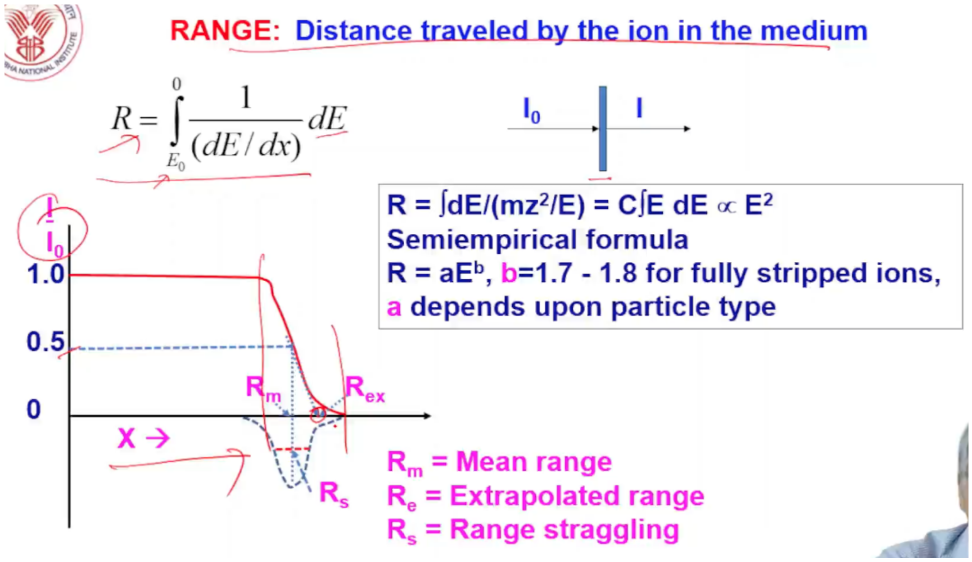
The plot of ΔE versus E will be giving you hyperbola for different ions, protons, alpha, carbon, so on. And you can resolve them to find out the different ions. So they are in fact called telescopes to detect the different ions.



At the low energy end of the track the ion picks up electrons and stops.

Now, another important property of this heavy charge particle is the Bragg's curve. Bragg actually showed how along the distance travelled by the ion, how the stopping power changes. So just now we saw that the stopping power changes with mz^2/E. And so as the energy of the ion decreases along the path, that is travelling in the medium, energy is decreasing, so stopping power is going up as 1/E. And then gradually when the ion is about to pick up electrons, when it starts picking up electrons, the Z becomes low because the ionic charge will reduce and the stopping power decreases. Finally, it will pick up electron, become neutral atom and finally get stopped.

Now, this is for a single ion, but when we have the beam of ions, then it is different, since it is a statistical process, every time it will not produce the same number of ion pairs. So for a beam, there will be a straggling. So the stopping power will not be that narrow, but it will have a wide distribution. So at the low energy end of the track, the ion picks up electrons and stops. So this Bragg curve is actually very much used in fact in the, even now in the cancer treatment, the Bragg curve is being used for heavy ions.



And lastly, the range of the ion, how much distance the ion travels in the material, it can be calculated by the integration of the 1/E stopping power over dE. So initially you have E_0 and at stop E=0. So 1/dE /dx ×dE, if you integrate, then you get the range. And simply you can do experiment. Take initial intensity I_0 and then small thickness if it is traveling, it will pass through it. So if you measure the I and I_0, then the plot of I/I_0 versus the distance traveled gives you what is called as the transmission curve. And this transmission curve for alpha particles will be like this or for that matter for heavy ion, heavy charged particles.

So it does not get lost. You see here, all the heavy ions will pass through certain distance and then when they start picking up electrons, the intensity will go down. In a very narrow zone, all the ions will stop. So when the intensity has become half, we call it main range. And if we extrapolate this decreasing term, this plot we call it extrapolated range. So this, why this decreases because of the stochastic nature of the electron stopping power.

So you take a derivative of this falling part, then you get a Gaussian and the width of that is called the range straggling. So the range is a very important property of the heavy ion, heavy charged particles. And there is now semi-imperial relationship of R range equal to aE^b, where b is close to 2 and a depends upon particle type. So we will discuss now about other ions like electrons and gamma rays later on. For the moment, I will stop here. Thank you.