We have talked about several types of photon interactions with matter. Going from lowest energy to highest energy we have classical scatter, which occurs at very low energy, then we have the photoelectric effect, then as we go higher in energy we have Compton Scatter, and now as we go even higher in energy we will talk about a process called pair production.
In today’s lecture we are going to identify and describe the process of pair production. In addition, we will review the implications of all of the various interaction processes in imaging, radiation shielding, and radiation treatment. We will summarize everything and at the very end we will look at one more process that fits off to the side from the others.
Let’s start with a qualitative view of pair production. Based on our classification of interaction processes, pair production is a Type 3a process. In pair production, a photon interacts with the electric field that surrounds the atomic nucleus and is completely absorbed.
In pair production we have a photon transforming into an electron and positron pair. I remember when I took my undergraduate quantum mechanics course and the instructor introduced pair production. This did not make sense. All of a sudden you have something from nothing but as far as conservation of energy and conservation of momentum is concerned - it’s allowable.

We have a photon coming in. The interaction takes place in the vicinity of a nucleus in order to conserve momentum. This photon transforms itself into an electron and positron pair. How much energy do we need on the part of the photon? First of all, some of the photon energy gets transformed to matter. How much energy gets transformed to matter? 1.022 MeV, which is the rest energy of the positron plus the rest energy of the electron. So the first 1.022 MeV of the photon goes into producing the positron and the electron. The remaining energy becomes kinetic energy that’s shared by the electron and the positron.
Here’s a diagram of the process. A photon comes in with energy $h\nu$. We produce an electron and we produce a positron. We take the photon energy and subtract off the $2m_0c^2$, which corresponds to the mass of the positron and electron pair, and the remaining energy is kinetic energy that’s shared between the electron and the positron.

$$h\nu - 2m_0c^2 = E_{e^-} + E_{\beta^+}$$
Some of the kinetic energy goes into the nucleus, but because the nucleus is so much more massive than the electron or the positron, we can generally ignore the kinetic energy transferred to the nucleus.

We need energy of $2m_0c^2$ to create the pair, so we can identify a threshold energy for pair production to take place. If the incident photon has energy of less than 1.022 MeV, we don’t have enough energy to produce the pair, so pair production cannot occur for energies less than 1.022 MeV.

Because some of the momentum is transferred to the nucleus, and we are not sure exactly how much, we really can’t determine the relative angle between the electron and the positron. We just know an electron and positron are produced. The electron and the positron interact with target material. These are secondary interactions. We will talk about those charged particle interactions in some subsequent lectures. These charged particles will produce more ionizations and deposit more energy.
In some respects, the process of pair production can be looked upon as an inverse process to the production of Bremsstrahlung. Let’s recall the process of Bremsstrahlung production. In the production of Bremsstrahlung, an electron undergoes a transition between two positive energy states, emitting a photon. In pair production the electron can be looked at as undergoing a transition from a negative energy state, creating a positron, to a positive energy state, absorbing a photon.

Mathematically, the theory behind Bremsstrahlung and the theory behind pair production are closely related and are usually treated together.
How do we determine the cross section? This requires a quantum mechanical treatment. The first study was done by Heitler and he basically looked at it as the reverse of Bremsstrahlung production. Recall the analogy we presented earlier. In Bremsstrahlung, we have an electron being deflected, producing photons, whereas in pair production, we have a photon coming in, producing the electron and the positron.

Heitler got this expression for the differential scattering cross section for pair production: \( \frac{d\kappa}{d\Omega} \) is \( \frac{Z^2}{137} \frac{r_0^2}{2\pi} m_0^2 c^4 F_{pair} \) (Recall that 137 is the fine structure constant from quantum mechanics) multiplied by \( r_0^2 \) (the classical radius of the electron squared) divided by \( 2\pi \) multiplied by the square of the electron rest energy multiplied by an atomic form factor for pair production.
The atomic form factor is a complicated function of momentum, energy, and angle of both positron and electron. We are not really going to be giving you the full-blown expression for that form factor. We will not worry about what that expression is but we are going to be interested in the dependence of the form factor, and hence $d\kappa/d\Omega$, on angle. We are going to be interested in the dependence of $d\kappa/d\Omega$ on energy and we will be interested in the dependence of $d\kappa/d\Omega$ on atomic number $Z$. 

Pair cross section

$$\frac{d\kappa}{d\Omega} = \frac{Z^2}{137} \frac{r_0^2}{2\pi} m_0^2 c^4 F_{pair}$$

- $F_{pair}$ is complicated function of momentum, energy, and angle of both positron and electron
- $d\Omega$ is incremental solid angle into which positron is ejected
Let us first look at the angular distribution of the ejected electron and positron. For incident photon energies near the threshold, that is, $2m_0c^2$, the angular distribution is rather complicated, but as the photon energy increases, the positron and electron are ejected in a more forward direction, as would be expected from conservation of momentum.

**Angular distribution**

- Energy near $2m_0c^2$ – angular distribution much more complicated
- High energy – mainly forward direction
Energy distribution

- Energy of electron and positron shared in any proportion; on average each gets half of available energy
- Slight asymmetry in distribution
  - Nucleus attracts electron, but repels positron
  - Small amount more kinetic energy given to positron

Moving on to the energy distribution, we are unable to predict the precise energy distribution unless we could determine the kinematics in detail.

But, on the average, each of the two ejected particles gets about half of the available energy. A slight asymmetry in the energy distribution is observed because the nucleus attracts the negatively-charged electron, but repels the positively-charged positron. Thus a small amount more kinetic energy is given to the positron. The difference in kinetic energies is typically less than 0.25 MeV.
Here’s a picture of what a typical energy distribution graph looks like.

The graph (taken from Johns & Cunningham) indicates the relative probability per fractional energy interval. The relative probability is normalized so that the integral under the curve is unity, since the total relative probability is 1.0.
Notice that the split in energies changes with energy.

For low energy photons, for example, 5 MeV photons, we see that the most probable energy split is roughly 50/50 – half the kinetic energy goes to the positron and half the kinetic energy goes to the electron. So if we have a 5 MeV photon, we subtract off 1.022 MeV to produce the pair giving us a little under 4 MeV of kinetic energy to be split between positron and electron. The most probable distribution is that 2 MeV goes to the electron and 2 MeV goes to the positron.

At higher energies the split is more asymmetric, about 25% to 75% being the most probable. As you can see it’s a fairly broad peak, leaving a uniform distribution really out to about 15% to 85% all the way across.

For 5 MeV photons the most probable energy distribution is peaked at 50/50. For high energy photons the most probable energy distribution is roughly 25/75; but in general, it’s flat from about 15% to 85%.
Notice that, not counting the small asymmetry we mentioned earlier, the energy distribution is symmetric; either particle has the same relative probability so they’ll share the energy equally. The average energy transferred to either particle is half of the difference between the incident photon energy and the energy needed to produce the pair. This enables us to calculate energy transfer cross sections. We start with the average energy transferred, which, in this case, is $h\nu-2m_0c^2$. We divide that by the energy of the incident photon $h\nu$ and multiply by the linear attenuation coefficient $\kappa$, and that gives us the energy transfer coefficient. Remember how we calculate energy transfer coefficients. Take the average energy transferred, divide it by the incident photon energy, and multiply it by the linear attenuation coefficient for the interaction.
We can use this information to work out some problems. Here’s an example: Again, we are going to try to track the energy. We want to know how many positrons in the energy range 6.9 to 7.1 MeV are set in motion when we have a layer of carbon of thickness $3 \times 10^{26}$ atom/m$^2$ is placed in a 20 MeV beam of $10^6$ photons. Let’s see how to solve this problem.
Our task is to calculate the number of pairs created. The number of pairs is given by the number of incident photons, that is, the photon fluence multiplied by the fraction of those photons per unit absorber thickness that undergo interactions multiplied by the absorber thickness. And again, we have a thin absorber.

We could use the exponential attenuation form if the absorber were thick, but for the time being, we are going to assume that the absorber is thin, and we will calculate the number of pairs in this manner.

Example

- Calculate the number of pairs created
- Number of pairs = photon fluence $\times$ fraction of photons undergoing interactions per unit absorber thickness (absorption coefficient) $\times$ absorber thickness
We know the photon fluence; we were given that it is $10^6$ photons. We know what the absorber thickness is, $3 \times 10^{26}$ atoms per square meter. What is the attenuation coefficient for pair production? We can look that up in Johns & Cunningham. That number can be found in Table A-4b in the appendix of Johns & Cunningham. I hope you are taking advantage of your Johns & Cunningham tables as they are very useful. We find that the attenuation coefficient is $0.1321 \times 10^{-28}$ meters squared per atom.

So the number of pairs produced is the fluence, $10^6$, multiplied by the attenuation coefficient, $0.1321 \times 10^{-28}$, times the absorber thickness, $3 \times 10^{26}$ atoms per square meter. Doing the multiplication gives us that $3.96$ times $10^3$ positron-electron pairs are produced.
Next we need to find out how the energy is distributed between positrons and electrons.

First of all, how much energy is available? The energy that’s available is 20 MeV, the incident photon energy, minus the energy that’s needed to produce the positron-electron pair, which is 1.02 MeV. So, approximately 19 MeV is available to be given to the pair.

Next, we want to determine how many positrons of a given energy are produced. We’re looking at positrons of energies between 6.9 and 7.1 MeV; let’s call that 7 MeV. 0.368 is the fraction of energy given to the positron.
What is the relative probability per energy interval of generating a positron with this energy? According to this graph, for a fraction of energy equal to 0.368, we’re looking at a relative probability per energy interval of about 1.09. The curve is relatively flat here and somewhat insensitive to energy in this range.

That’s why we weren’t worried about how many decimal places we have in the energy. Notice, it’s pretty flat and roughly the relative probability per energy interval is about 1.09.
Example

- Multiply this probability by the fractional energy interval (0.2 parts in 19)
  
  \[ 1.09 \times 0.2/19 = 0.0115 \]

- So the number of positrons generated is given by
  
  \[ 3.96 \times 10^3 \times 0.0115 = 45 \text{ positrons} \]

We have to multiply this probability times the fractional energy interval. The fractional energy interval is 0.2 MeV out of 19 MeV, or 0.2 parts out of 19. So the probability is 0.0115. Multiply this probability by the total number of positrons to give us 45 positrons in this energy interval that are generated via pair production.
After pair production

- Positrons and electrons transfer energy to target atoms – ionization and excitation
- Positron comes to rest
- Annihilates with electron
- Generates two photons
  - 0.511 MeV energies
  - Ejected 180° to each other
- Significant applications in imaging – PET imaging

What happens after pair production takes place. The positrons and electrons transfer energy to the target. We will see that described in the next few lectures. Through the processes of ionization and excitation, the positron deposits energy and eventually comes to rest. At that time it annihilates with an electron generating 2 photons of 0.511 MeV energy ejected at 180° to one another. We have already seen the applications of positrons to imaging, although the energy of a positron involved in pair production may be much higher than those energies we see in imaging.
Another process that we need to be aware of is called triplet production. It occurs when pair production occurs in the vicinity of an electron rather than a nucleus. In triplet production a positron-electron pair is generated and also the electron is ejected. The threshold energy for triplet production is 2.04 MeV, 1.022 MeV to create the pair, and 1.022 MeV to conserve momentum and energy.
The attenuation coefficient for triplet production is approximately 1/6 that as for pair production, but it is usually included in calculated attenuation coefficients for pair production. So generally we are not going to worry so much about triplet production when we look at these interactions. We are going to focus mainly on pair production at the higher energies.
What can we say about the various dependences of the pair production attenuation coefficient? This graph plots the pair production electronic attenuation coefficient as a function of photon energy. Notice that it is on a log-log plot.
Two very important observations can be made. One is the threshold energy at 1.022 MeV. If the photon energy is less than the threshold 1.022 MeV, pair production will simply not occur. Notice, however, that for energies above the threshold relative increase in attenuation coefficient as a function of energy is relatively flat, meaning that the attenuation coefficient is relatively independent of energy.

In summary, we have a threshold of 1.022 MeV, a dramatic increase in attenuation coefficient just above the threshold, and rather flat energy dependence at higher energies.
The other thing we need to look at is the Z dependence of the attenuation coefficient. Pair production occurs in the force field of a nucleus, so a larger nuclear mass means a higher probability of interaction. The nuclear mass is roughly 2Z, consequently, the mass attenuation coefficient is roughly proportional to Z.

Note that earlier in the lecture I said that the atomic attenuation coefficient is proportional to $Z^2$. In going from atomic attenuation coefficient to mass attenuation coefficient, we divide by Z, so the mass attenuation coefficient is proportional to Z.
In summary, we can say the following: When pair production occurs, a photon interacts in the vicinity of the nucleus creating an electron-positron pair. Pair production has an energy threshold of 1.022 MeV required to produce the pair, with the remaining energy shared by the electron and the positron. On the average each of the two gets half of the energy.

**Summary**

- Photon interacts in vicinity of nucleus, creating electron-positron pair
- Threshold energy is 1.022 MeV
- Energy shared by electron and positron
  - On average, each gets half the energy
Summary

- Triplet production also occurs
  - Usually included with pair production
- Mass attenuation coefficient proportional to Z
- Attenuation coefficient increases rapidly with energy immediately above threshold, levels off at higher energies
- 2 annihilation photons produced, each with energy 0.511 MeV

Triplet production also occurs. But it is usually included in consideration with pair production.

The mass attenuation coefficient for pair production is roughly proportional to Z. The attenuation coefficient increases with energy immediately above the threshold and then levels off at higher energies. Eventually, two annihilations of photons are produced. Each photon has energy of 0.511 MeV. These annihilation photons can cause ionization elsewhere at some distance from the location of the interaction.
Let us now tie everything together, take a step backward, and look at all the attenuation coefficients.

The total attenuation coefficient is the sum of the individual attenuation coefficients for each interaction, the attenuation coefficient for the photoelectric effect, plus the attenuation coefficient for coherent scatter, plus the attenuation coefficient for Compton scatter, plus the attenuation coefficient for pair production. In addition we can write similar expressions for the mass attenuation coefficient, the electronic attenuation coefficient, and the atomic attenuation coefficient. Moreover, there will be similar expressions for energy transfer coefficients and energy absorption coefficients.

Remember how we go from linear attenuation coefficient to energy transfer coefficient to energy absorption coefficient. To obtain the energy transfer coefficient we take the amount of energy transferred to kinetic energy of charged particles, divide it by the energy of the incident photon, and multiply it by the appropriate linear attenuation coefficient. Of course in each attenuation process the energy transferred to kinetic energy of the charged particles is going to be a different value depending on the particular process. To obtain the energy absorption coefficient, we need to know what fraction of that energy transferred to charged particles is absorbed versus what fraction is reradiated in the form of Bremsstrahlung. So that’s how we’re going from one coefficient to another coefficient.
This is really a neat graph. It summarizes all the attenuation coefficients for oxygen.

The dotted line is Rayleigh scatter. Notice it tails off pretty quickly with energy and at no point is it the predominant interaction coefficient.

Photoelectric effect starts off as the predominant interaction coefficient and drops off very rapidly with energy. We know that the dependence on energy is roughly energy to the minus 3rd power.

Compton scatter starts off low and then flattens off and then tails off with higher energy; remember it’s roughly 2 orders of magnitude change in attenuation coefficient for 5 orders of magnitude of energy.

Pair production starts off at the threshold energy of 1.02 MeV and increases gradually with energy.

So here is the sum of all of them. On this same graph we see the total attenuation coefficient for tin. Notice we have this little blip here for the absorption edge because of the binding energy of tin electrons.
Let’s summarize. Rayleigh, or coherent, scatter never has the largest attenuation coefficient. The attenuation coefficient for Rayleigh scatter is greater than that for Compton scatter at low energies. The attenuation coefficient for Rayleigh scatter becomes greater than that for the photoelectric effect near about 100 keV, but by that time Compton scatter has taken over. Finally, when Rayleigh scatter occurs, there’s no energy lost in the medium.
Photoelectric absorption is the dominant interaction at low photon energies and for high-Z materials. The probability of photoelectric absorption falls off very rapidly with increasing energy. This probability is inversely proportional to $E^3$.

- Increases dramatically with increasing $Z$  
  - Proportional to $Z^3$

Photoelectric absorption is the dominant interaction at low photon energies and for high-Z materials. The probability of photoelectric absorption falls off very rapidly with increasing energy. This probability is inversely proportional to the $E^3$ power. This probability increases dramatically with increasing $Z$. In particular, it is approximately proportional to $Z^3$. 
The probability of absorption increases very sharply when the energy of the photon matches the binding energy of an orbital electron. These are demonstrated as photoelectric absorption edges. Finally, photoelectric absorption is a very efficient energy transfer process because all the photon energy with the exception of the amount of energy required to overcome the binding energy of the photoelectron gets transferred to the electron. We don’t lose any energy to scattered photons or anything like that.
Compton scatter

- Dominant interaction in soft tissue in the photon energy range for radiation therapy
- Very little change in probability with energy (less than 2 orders of magnitude from 1 keV to 100 MeV)
- Maximum attenuation near 100 keV

Compton scatter is the dominant interaction in soft tissue in the photon energy range used in radiation therapy. There is very little change in absorption probability with energy. We notice less than 2 orders of magnitude decrease in probability as we go from 1 keV to 100 MeV, which is 5 orders of magnitude, with the maximum attenuation occurring around 100 keV.
Compton scatter

- Not a good energy transfer mechanism at low energies (approaches classical limit – no energy transfer)
- Better energy transfer mechanism at higher energies
- Attenuation coefficient virtually independent of Z or energy

Compton scatter is not a good energy transfer mechanism at low energies. Remember that Compton scatter approaches the classical limit where there is no energy transfer. Compton scatter is a more efficient energy transfer mechanism at higher energies.

The mass attenuation coefficient for Compton scatter is virtually independent of atomic number and virtually independent of energy.
And finally we have pair production. Pair production exhibits a threshold energy at 1.022 MeV. The probability of attenuation increases rapidly at energies above the threshold but the probability of attenuation levels off at higher energies. The energy is shared by the electron/positron pair. Either can have any energy from 0 to the available energy which is the energy of the incident photon minus 1.022 MeV. On the average the electron and positron have the same energy.
When the positron comes to rest, two annihilation photons are created, each with energy of 0.511 MeV and ejected at 180°; consequently, we can have additional ionization going on at a distance from the original interaction site. Pair production is an efficient energy transfer process because once you overcome that 1.022 MeV to produce the electron/positron pair, all the kinetic energy goes into the pair of charged particles.
Here’s a nice table of energy transfer and energy absorption that also illustrates what we have been saying about energy transfer and energy absorption. Notice the percentage of interactions by each process and the fraction of energy that’s transferred by each process.

We start with coherent scatter and we see that the fraction of interactions reaches a maximum at about 30 keV, but even at that energy, it’s nowhere near being the predominant interaction. And, of course, there is no energy transfer in coherent scatter.

We see here the energy dependence of the photoelectric effect, starting from its being the predominant effect at low energies, and its probability going to zero above 200 keV. Notice that, in general, the fraction of energy transferred via the photoelectric effect is greater than the fraction of interactions that take place via the photoelectric effect. The reason why this occurs is that almost all the energy of the incident photon is transferred to the photoelectron, whereas for other processes, the energy transfer is not as efficient.

We observe that from 30 keV to 30 MeV, Compton scatter is the predominant interaction. Those are two good numbers to remember, 30 keV – 30 MeV, as the energy range in which Compton scatter is the predominant interaction in soft tissue.
Pair production only starts to be a significant component here about 15 MeV and becomes the predominant interaction past 30 MeV, and notice again, that the fraction of energy transferred via pair production is greater than the fraction of interactions occurring. Analogous to what happens in the photoelectric effect, when pair production occurs, a fixed amount of energy goes into overcoming an energy barrier, with the rest of the energy being transferred to kinetic energy of charged particles.

We finally look at the fraction of energy lost to Bremsstrahlung and see that at low to moderate energies, very little energy is lost to Bremsstrahlung; that is, most of the energy is absorbed by the charged particles, but at high energies, some of the energy is re-radiated as Bremsstrahlung.

We need to know all of this if we are going to try to derive energy transfer coefficients or energy absorption coefficients, or if we want to go from fluence to dose, which is energy absorbed, which is ultimately going to be our goal. We are going to be revisiting a lot of this later in the course when we talk about cavity theory.

### Energy transfer and energy absorption

<table>
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<th>E (keV)</th>
<th>% interactions by each process</th>
<th>% energy transferred</th>
<th>% energy lost to Brems</th>
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<td></td>
<td>Coh</td>
<td>Compt</td>
<td>Photo</td>
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Let us conclude this lecture by examining some of the implications of all of this information.

First of all, let’s look at implications in imaging. In the energies used in diagnostic x-ray, much of the beam is in the energy range where photoelectric absorption is the predominant interaction. Therefore, contrast, which is the difference in absorption, is caused by differences in atomic number as well as in density giving rise to high-contrast images. In particular, the differentiation between bone and soft tissue, which corresponds to a difference of about 50% in atomic number, is greatly magnified by the fact that attenuation goes as the cube of the atomic number. This is why imaging works so well at low energies. This differential absorption giving rise to contrast is so dependent on Z.

Contrast media such as barium have K-edges near the energies of the diagnostic x-rays, giving rise to further enhancement of absorption.
In the x-ray energy region used in radiation therapy, much of the beam interacts by Compton scatter, so when we image using photons at therapy energies, contrast is caused only by differences in density giving rise to lower contrast images.

Implications in imaging

- In the therapy x-ray region, much of the beam is in the Compton scatter range, so contrast is caused only by differences in density giving rise to lower contrast images.
We also need to look at the radiation that reaches the image receptor when we image using radiation that interacts with the target.

When photoelectric absorption occurs, the radiation that is emitted is an electron with a very short range. Consequently, the only radiation reaching a detector is radiation that has not been involved in an interaction.
Implications in imaging

- The radiation emitted from Compton scatter includes a photon, which can reach the detector. Because this radiation does not contain information as to the point of interaction, it adds noise to the image produced at the image plane.

For higher energy photons that interact via Compton scatter, we could eject a photon, which can also reach a detector. The problem is that this radiation carries no information about where it came from. Consequently, it adds noise to the image that’s produced at the image receptor. When Compton interactions occur, not only do we have poor contrast because of differences in absorption but we also have more noise because of the presence of scattered radiation.

These are some implications of the different energy ranges and the different interactions in imaging.
Implications in shielding

- In the diagnostic range (photoelectric), the attenuation is highly dependent on Z, so we use lead, which has the highest Z of stable isotopes.
- In the therapy range (Compton), all materials have the same attenuation per unit mass, so we use materials with the best construction capabilities, e.g. concrete.

What about implications of these interactions in shielding? In the diagnostic energy range, the attenuation is highly dependent on Z, remember attenuation goes as $Z^3$. What do we use for shielding material in this energy range? The most effective shield in the diagnostic energy range is a material with high Z. In fact, we use lead, which has the highest Z of all stable isotopes.

But in the therapy energy range, in which Compton scatter is the predominant interaction, all materials have the same attenuation per unit mass. Another way of saying this is that equal masses attenuate equal amounts. We do not get any advantage with high-Z material. As a consequence, we normally use standard construction materials for shielding. We shield our therapy rooms with several feet of concrete, because it’s easier to use several feet of concrete that using several inches of lead.

Equal masses shield equal amounts.
Finally, what are the implications of the various interactions in radiation therapy? If we are trying to treat with radiation in the orthovoltage energy range, that is around 100-250 kVp, a large fraction of the interactions are in the photoelectric regime. Absorption of energy is highly dependent on Z. Consequently for a given amount of radiation, bone, a higher-Z material, absorbs much more energy than an equal mass of soft tissue. However, when we are in the megavoltage range of energies, where Compton scatter is the predominant interaction, the differences in energy absorption (remember energy per unit mass) among the various forms of tissue are negligible. Equal masses absorb equal amounts. An equal mass of bone absorbs the same amount of radiation as an equal mass of soft tissue. Consequently the dose delivered to bone equals the dose delivered to soft tissue to a very good approximation.

I hope you keep in mind a lot of the implications of these different interactions. That’s all very important especially when we go into Med Phys 2 and Med Phys 3 and we learn about these applications to both imaging and therapy.