Interaction of Photons With Matter

General Stuff

Objectives

- To review three principal interactions of photons with matter.
- To examine the factors affecting the probability of photon interactions.
- To introduce the linear and mass attenuation coefficients as useful measures of the probability of interaction.

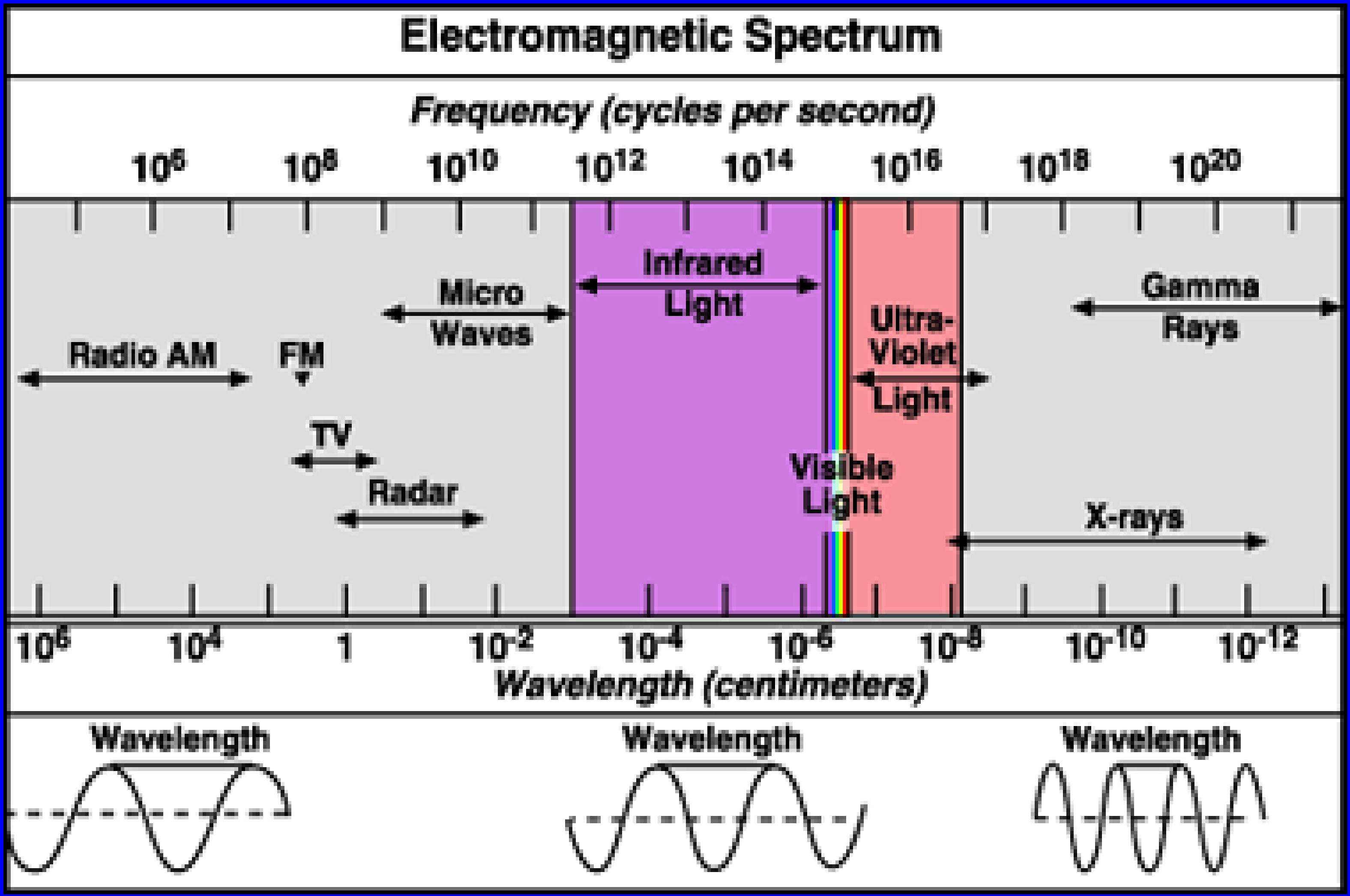
Introduction

- Understanding how radiation interacts with matter is essential to understanding:
  - How instruments detect radiation
  - How dose is delivered to tissue
  - How to design an effective shield

Properties of Photons

- A photon is a “packet” of electromagnetic energy.

- It has no mass, no charge, and travels in a straight line at the speed of light.


Electromagnetic Spectrum
Frequency (cycles per second)
10^6
10^8
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10^{12}
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10^{16}
10^{18}
10^{20}
Infrared Light
Micro Waves
Radio AM
FM
TV
Radar
Ultra-Violet Light
Visible Light
Gamma Rays
X-rays
10^6
10^4
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Wavelength (centimeters)
Wavelength
Wavelength
Wavelength

Properties of Photons (cont'd)

This discussion is limited to photons with enough energy to ionize matter:

- X-rays: characteristic x-rays
  bremsstrahlung
- gamma rays
- annihilation radiation (511 keV)

Photon Interactions

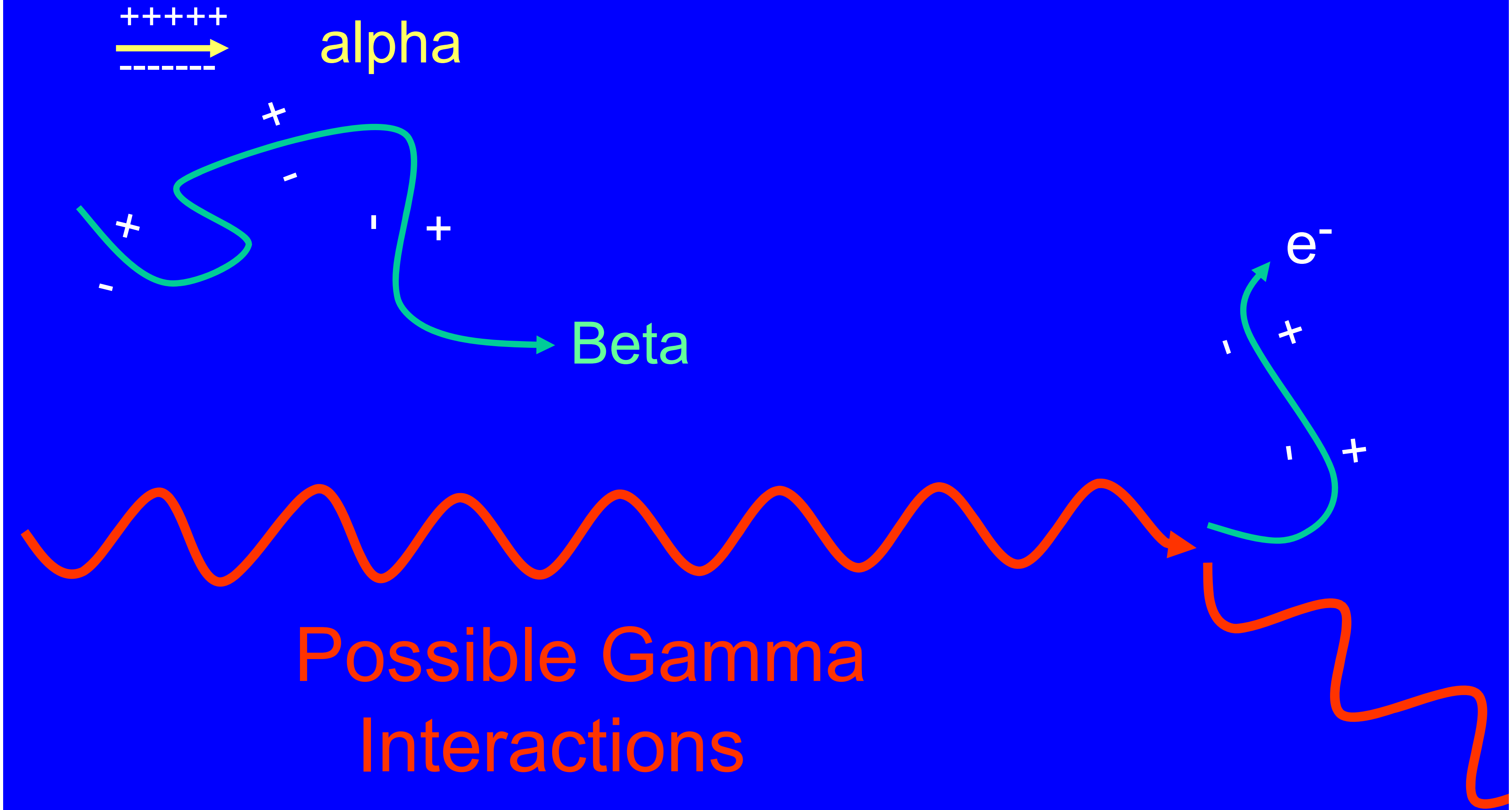
- Photons interact differently in matter than charged particles because photons have no electrical charge.

- In contrast to charged particles, photons do not continuously lose energy when they travel through matter.

Photon Interactions (cont'd)

- When photons interact, they transfer energy to charged particles (usually electrons) and the charged particles give up their energy via secondary interactions (mostly ionization).

- The interaction of photons with matter is probabilistic, while the interaction of charged particles is certain.


+++++
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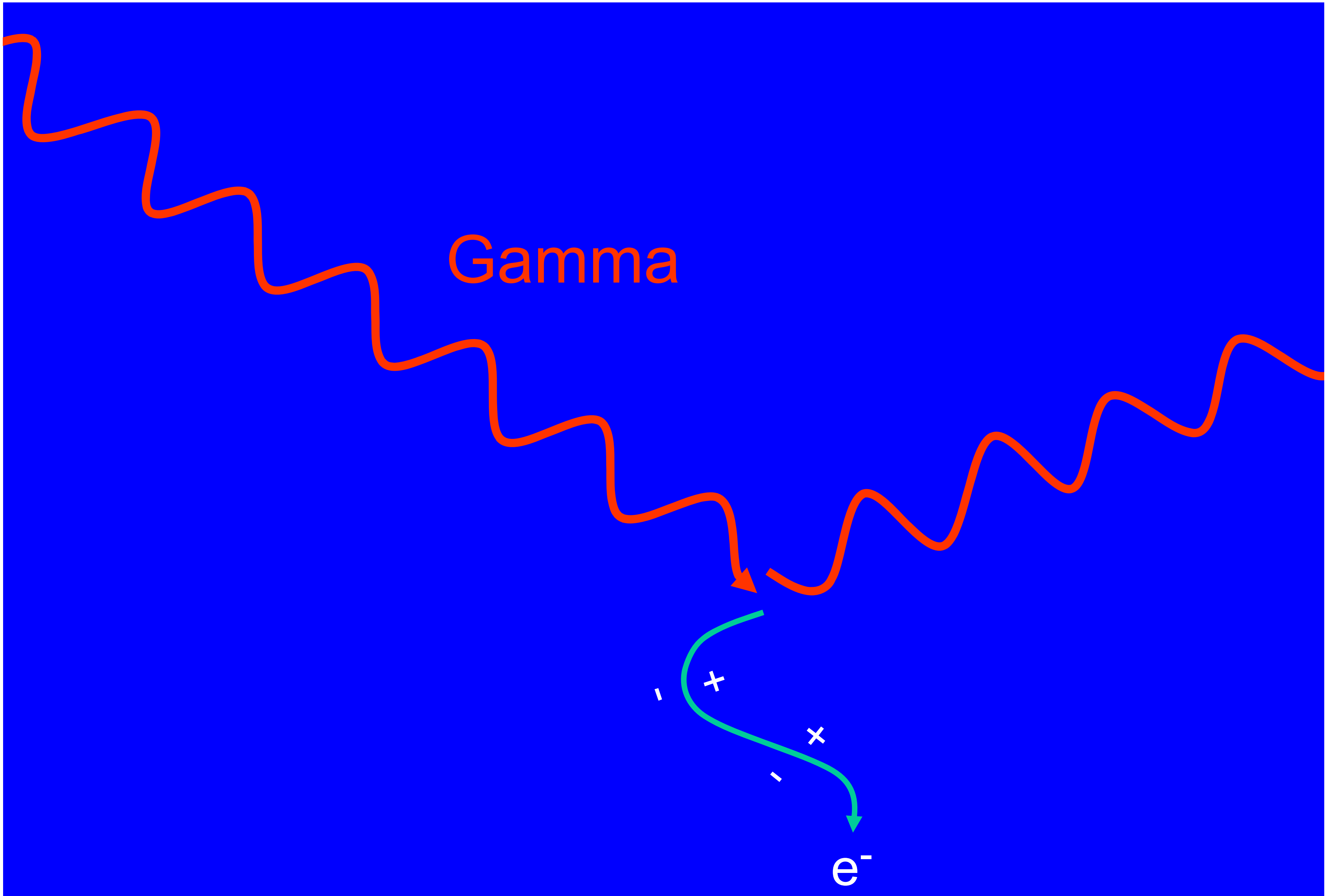
alpha
Beta
e-
Possible Gamma
Interactions


Gamma
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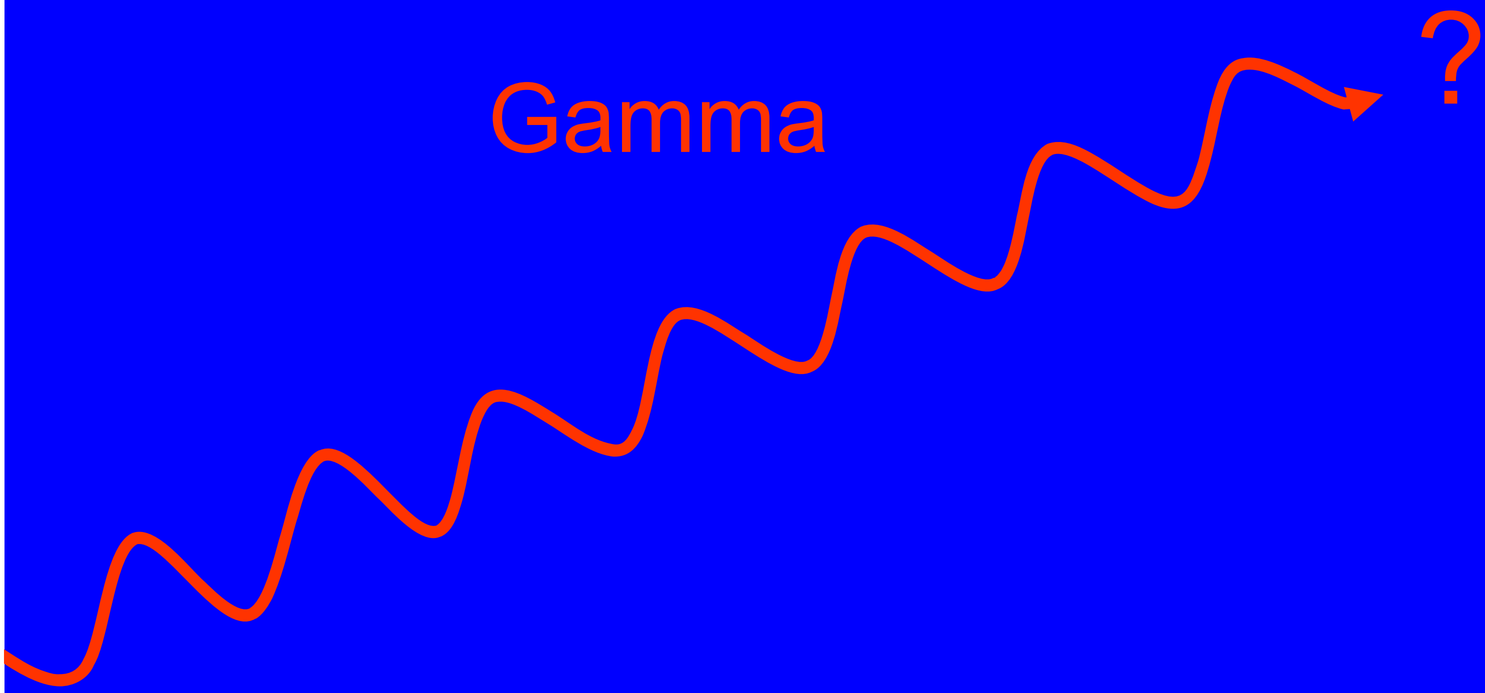
Gamma
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Photon Interactions (cont'd)

- The probability of a photon interacting depends upon:
  - The photon energy
  - The atomic number and density of the material (electron density of the absorbing matter).

Photon Interactions (cont'd)

- The three principal types of photon interactions are:
  - Photoelectric effect
  - Compton scattering (incoherent scattering)
  - Pair production

Photon Interactions (cont'd)

- There are a number of less important mechanisms by which photons interact with matter. The most important of the unimportant photon interactions are:
  - Rayleigh scattering (coherent scattering)
  - Thomson scattering (coherent scattering)
  - Photonuclear reactions

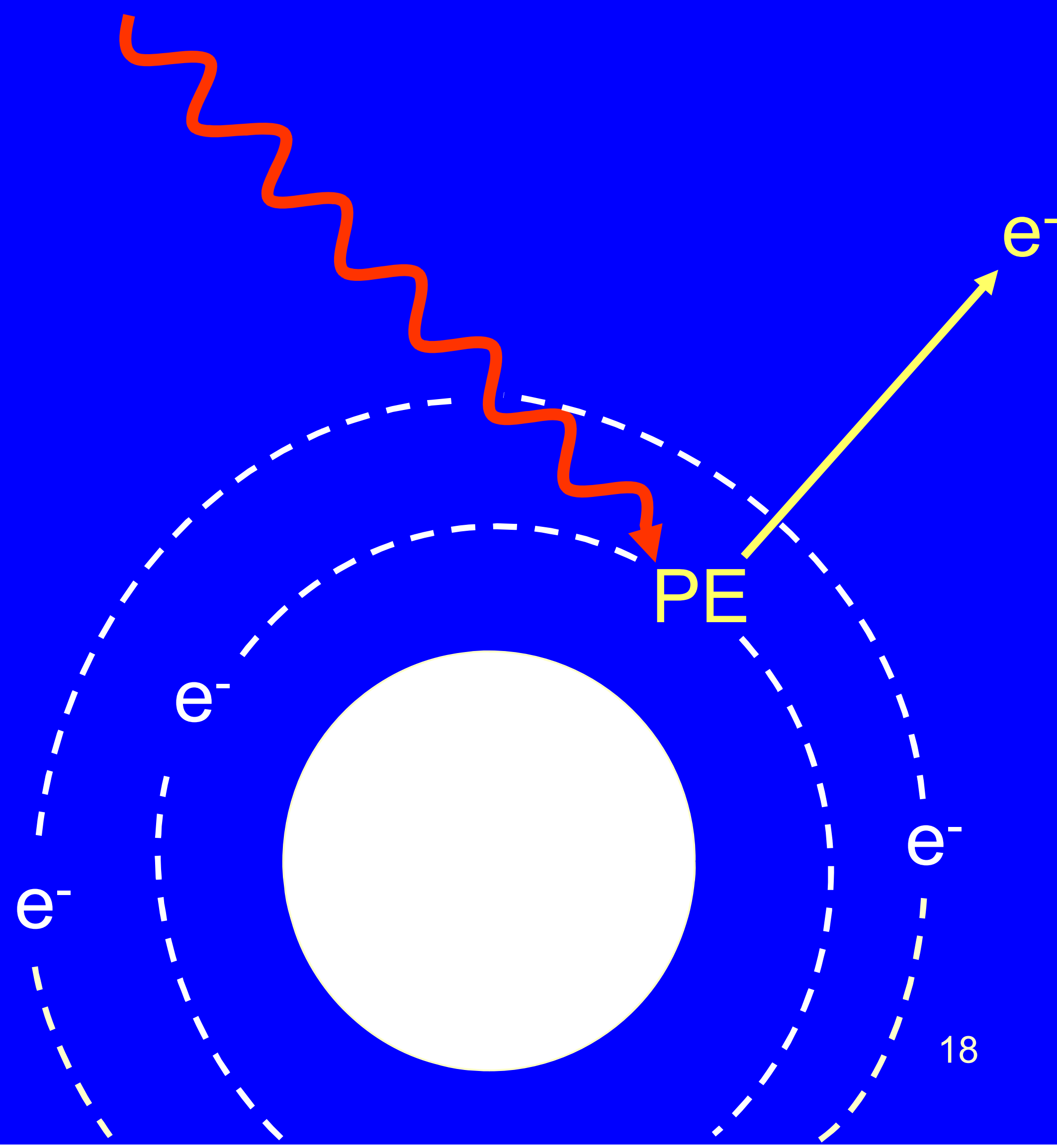
Photoelectric Interaction

Photoelectric Interaction

- In the photoelectric (PE) interaction, the photon is absorbed by an inner shell (e.g., K shell) electron of an atom.
- All the photon energy is transferred to the electron so that the photon disappears.
- The electron is ejected from the atom. This leaves a vacancy in the shell that the electron originally occupied.

Photoelectric Interaction

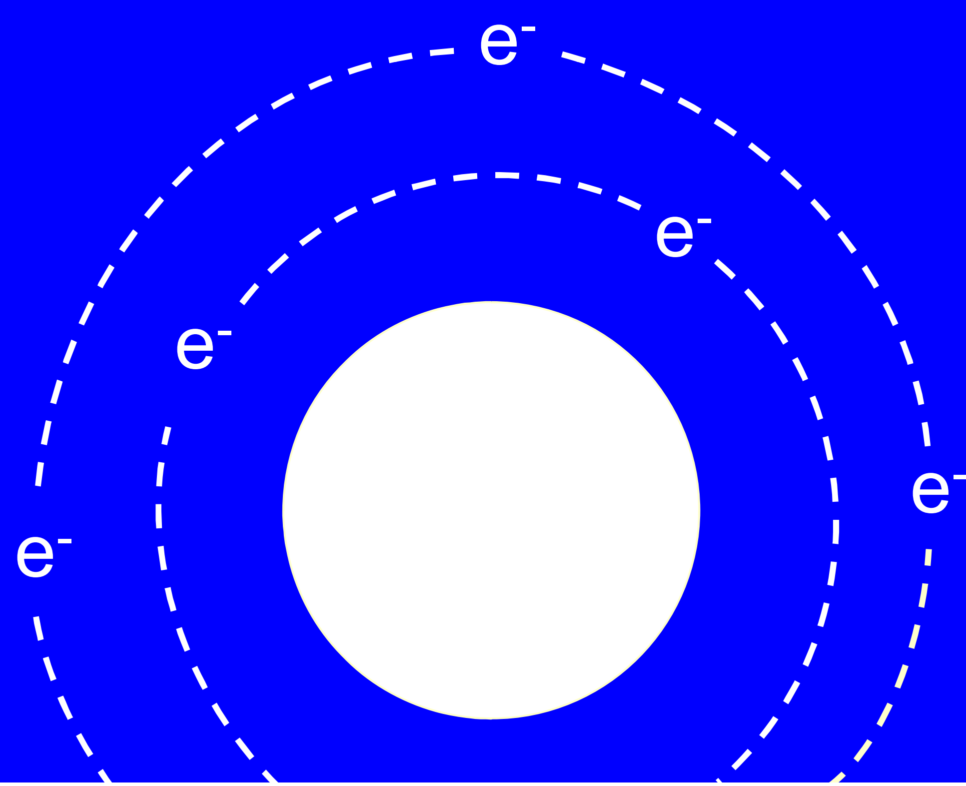
- Some of the photon's energy is used to overcome the binding energy of the electron
- The rest of its energy is given to the electron as kinetic energy



Photoelectric Interaction

- The vacancy created in the electron shell is then filled by an electron falling from a higher energy shell

- When this happens, either a characteristic x-ray or an auger electron is emitted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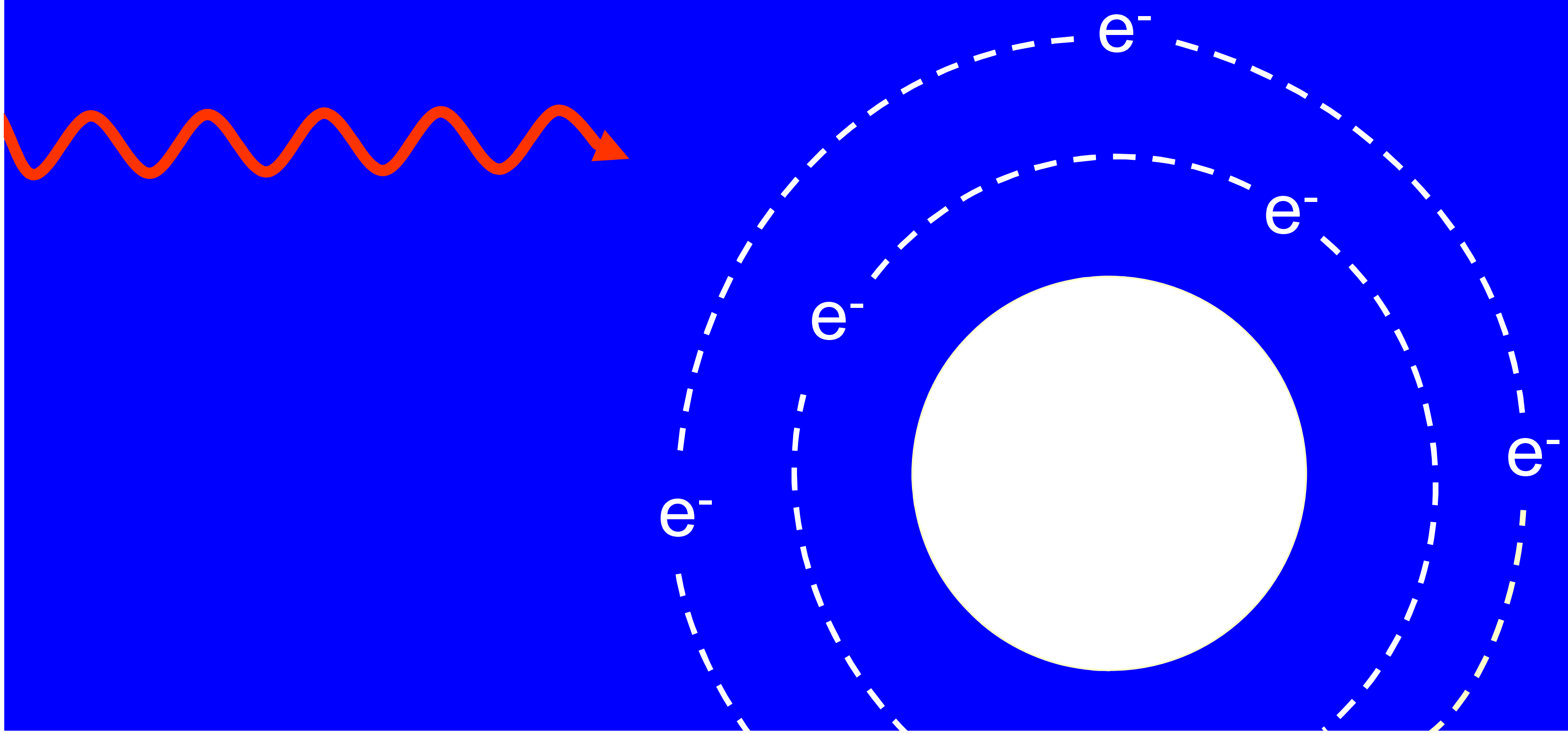
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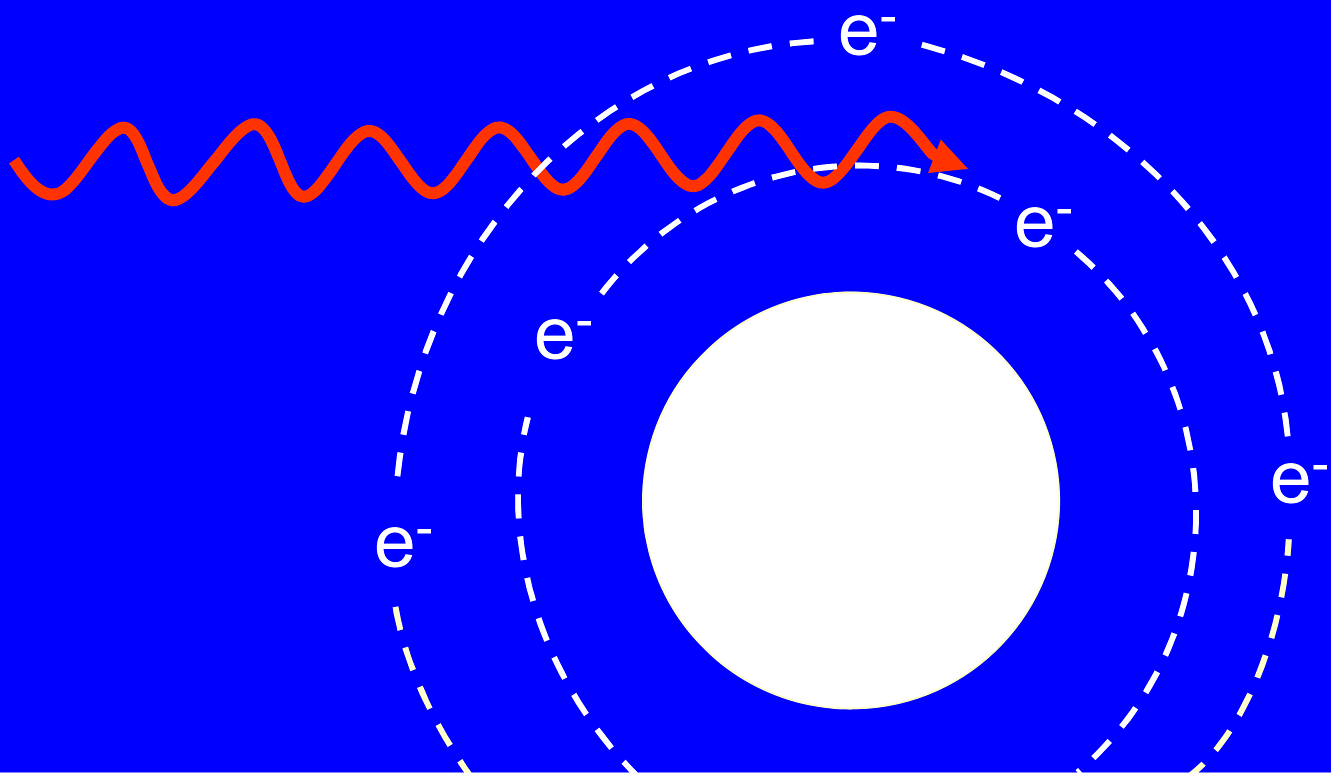

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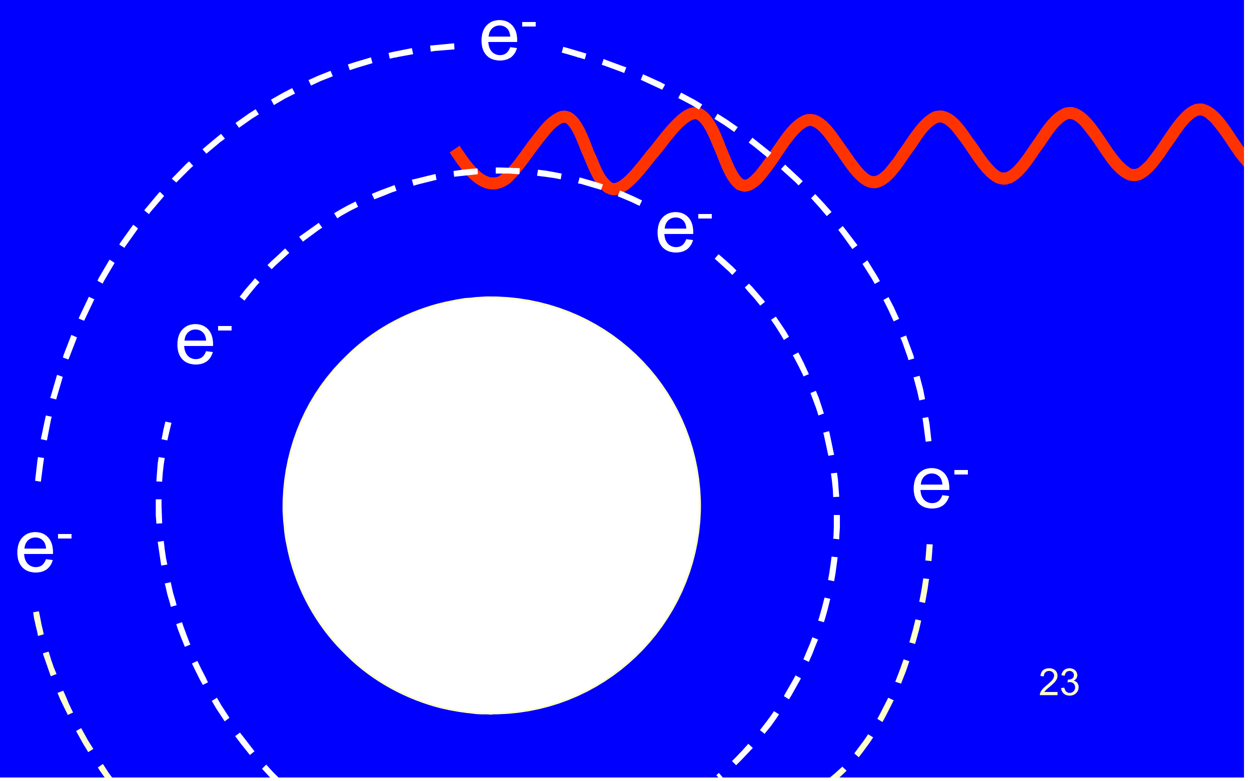
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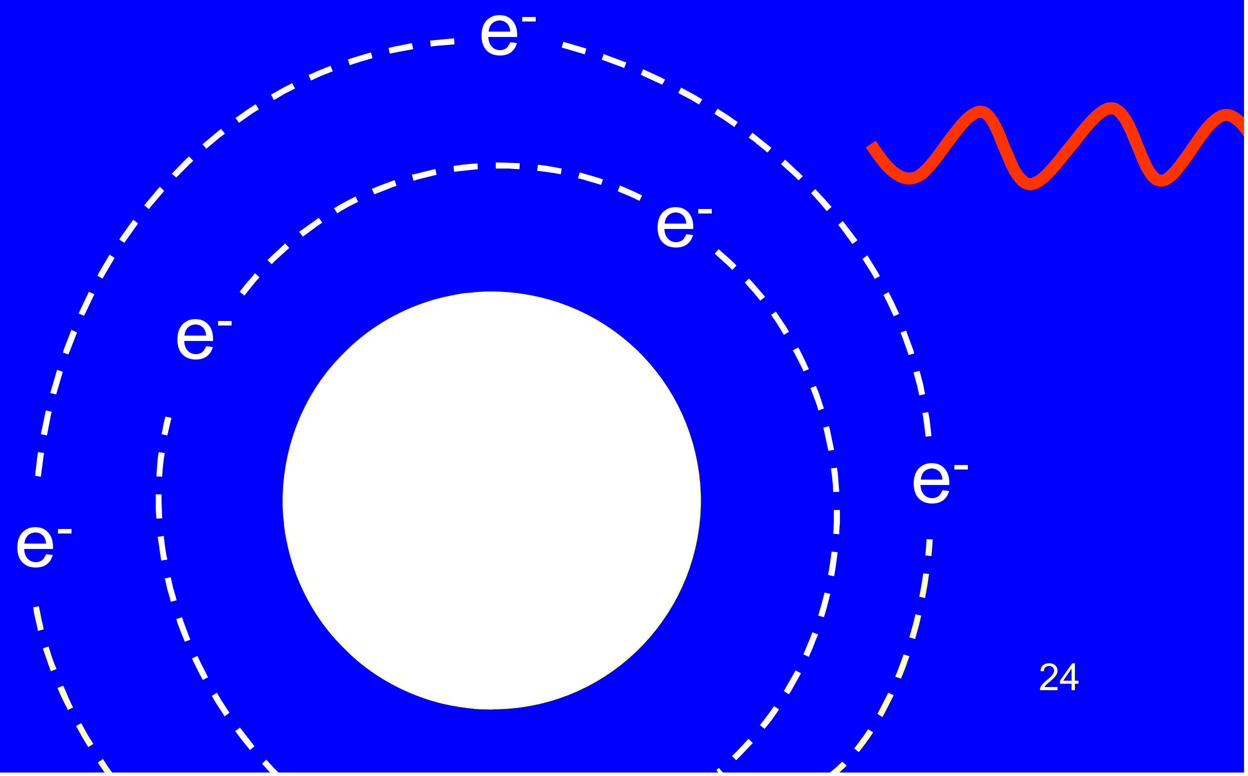
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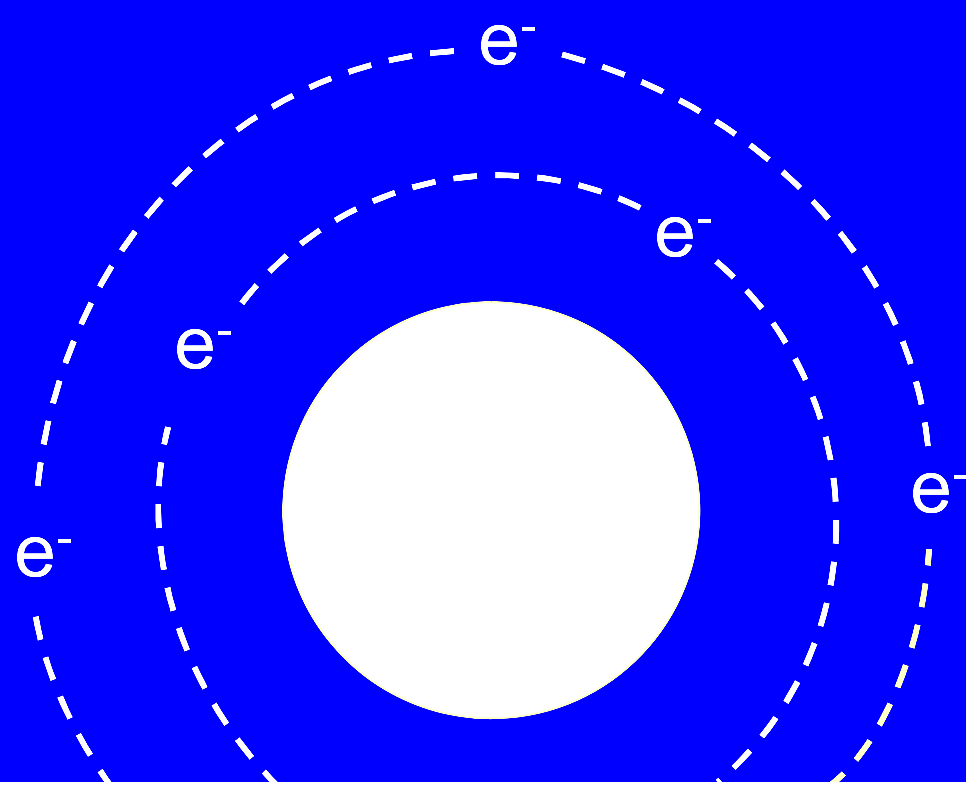
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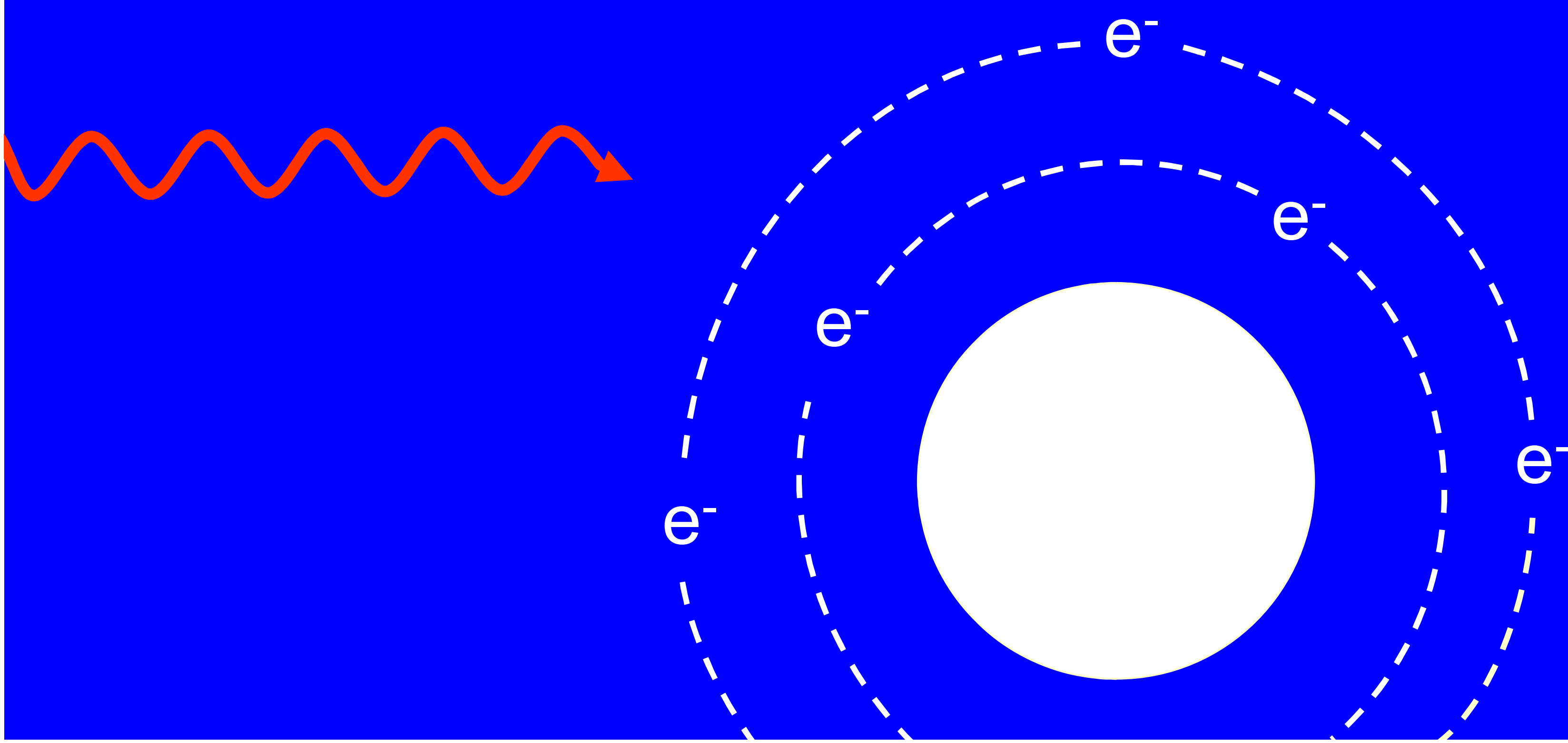
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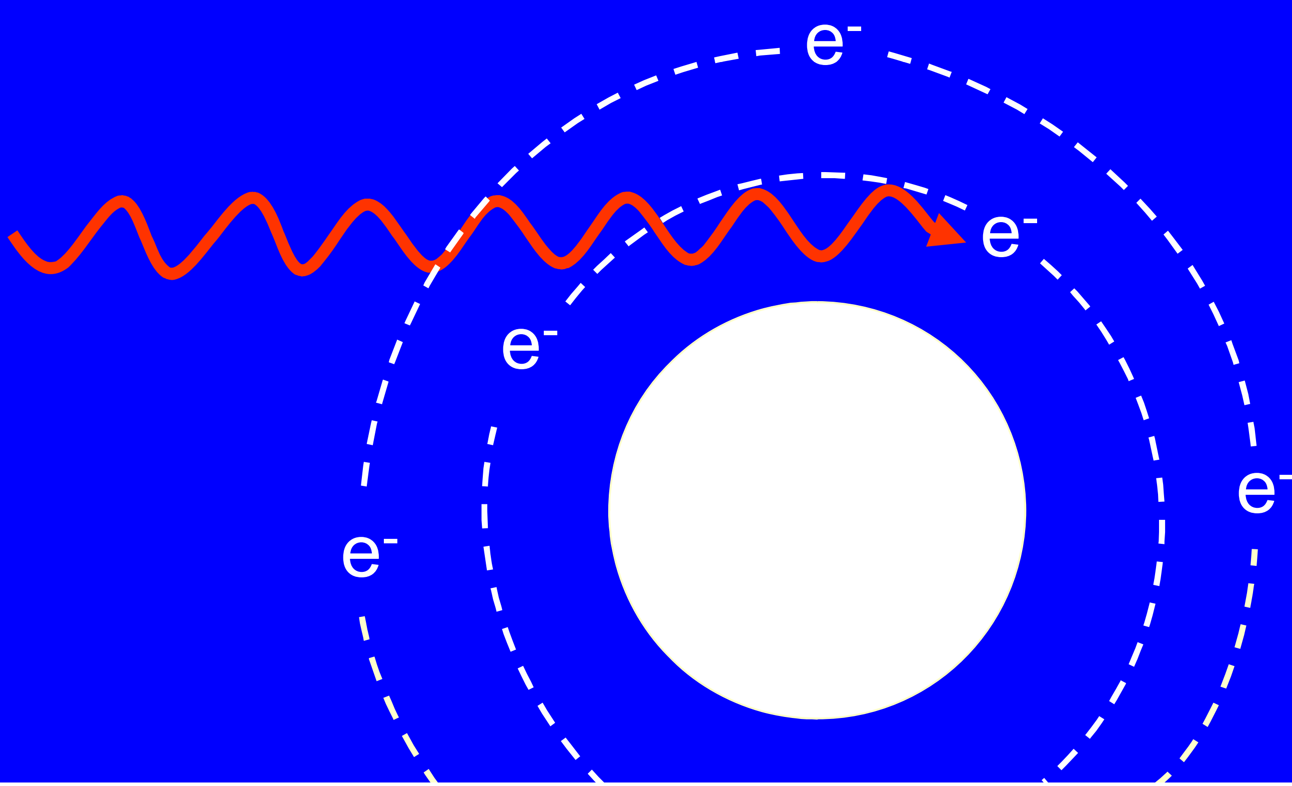

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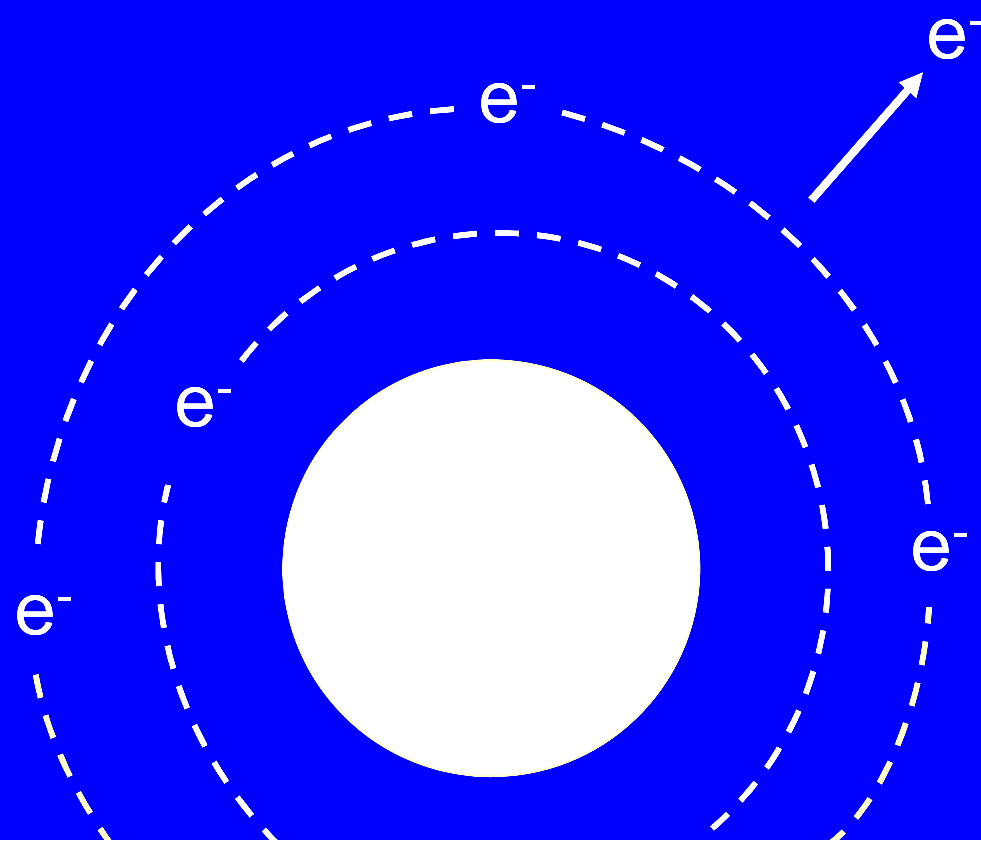

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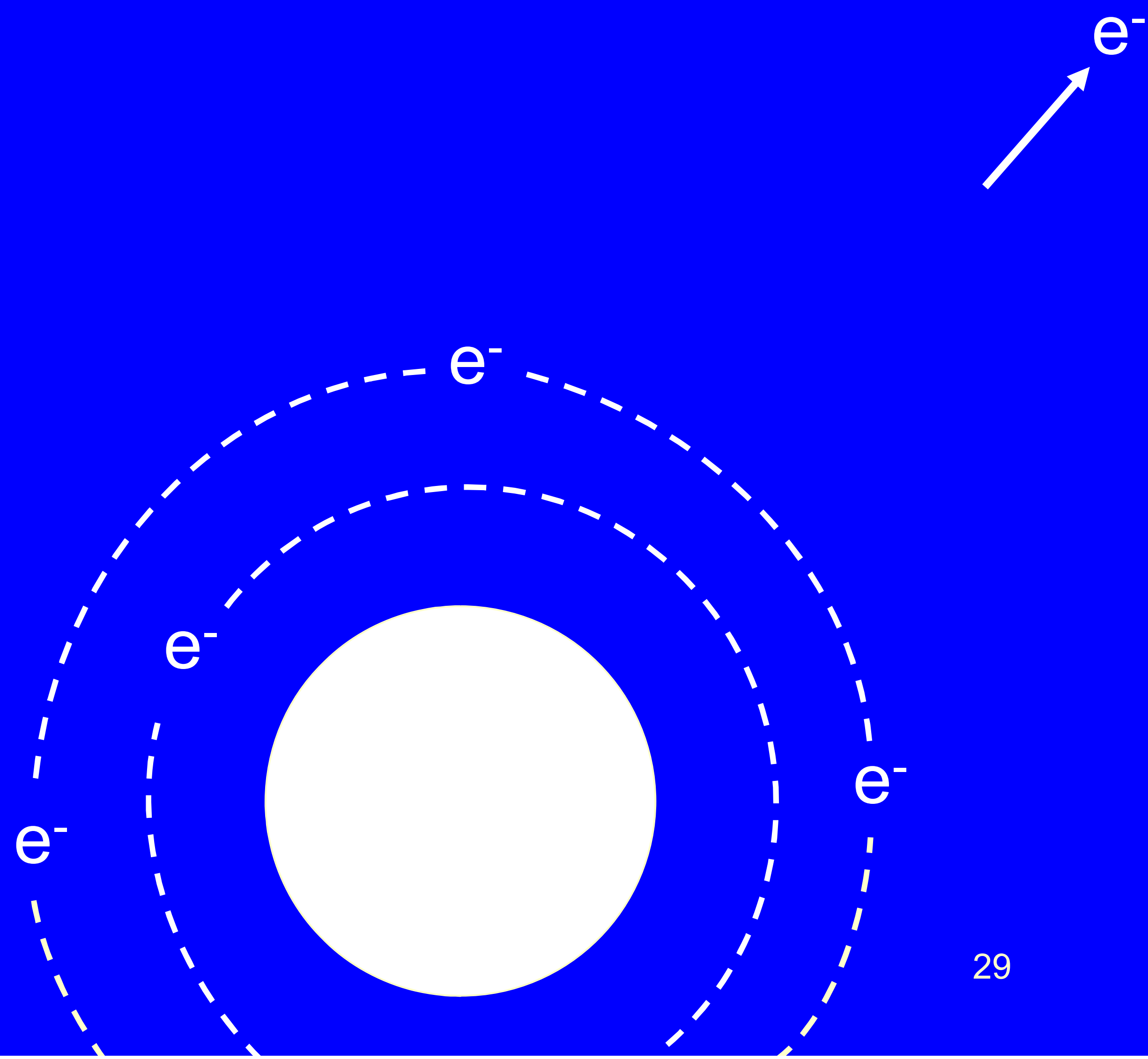
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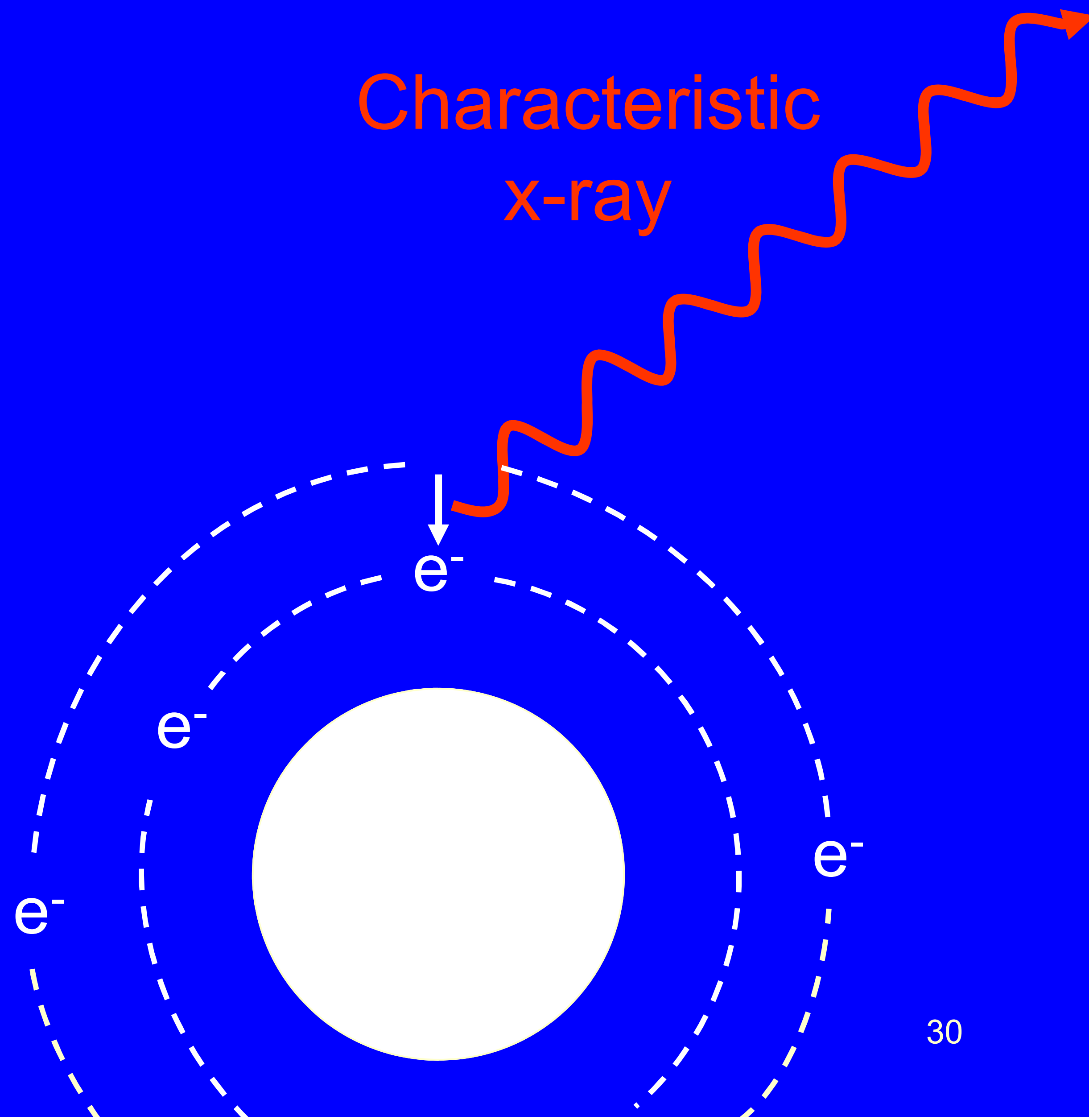
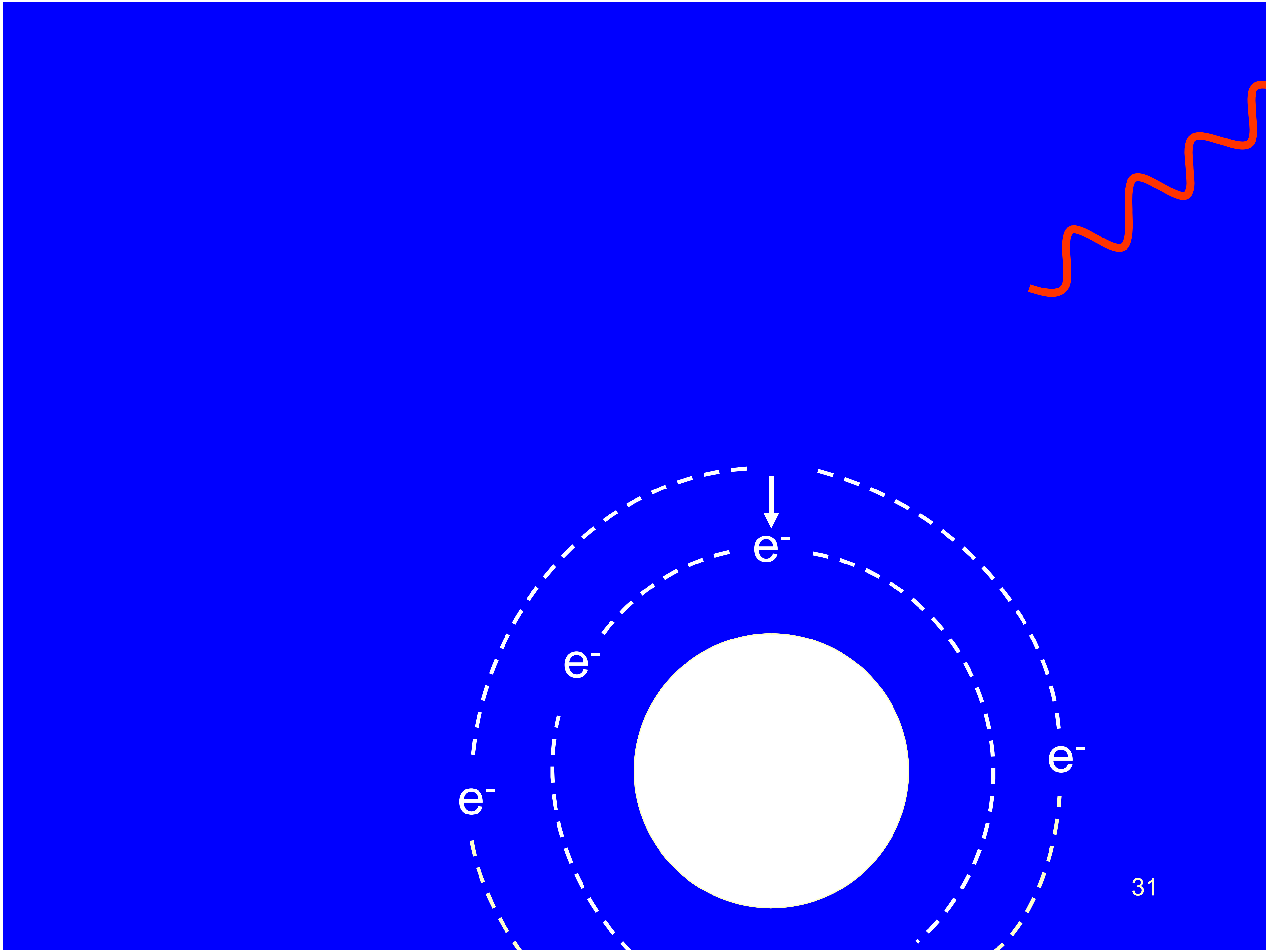

Characteristic
x-ray
e-
e-
e-
e-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Photoelectric Interaction

- PE interactions are desirable in shields for photons since the photons are completely absorbed.

- On the other hand, PE interactions are not desirable from the standpoint of absorbed dose to human tissue.

Photoelectric Interaction

- The PE interaction is most probable for:
  - Low energy photons (as long as the photon energy exceeds the electron's binding energy)
  - High atomic number and high density materials (i.e., high electron density)

Photoelectric Interaction

- Lead is widely used for shielding gamma rays and x-rays because it has a high atomic number (Z = 82) and it is inexpensive.

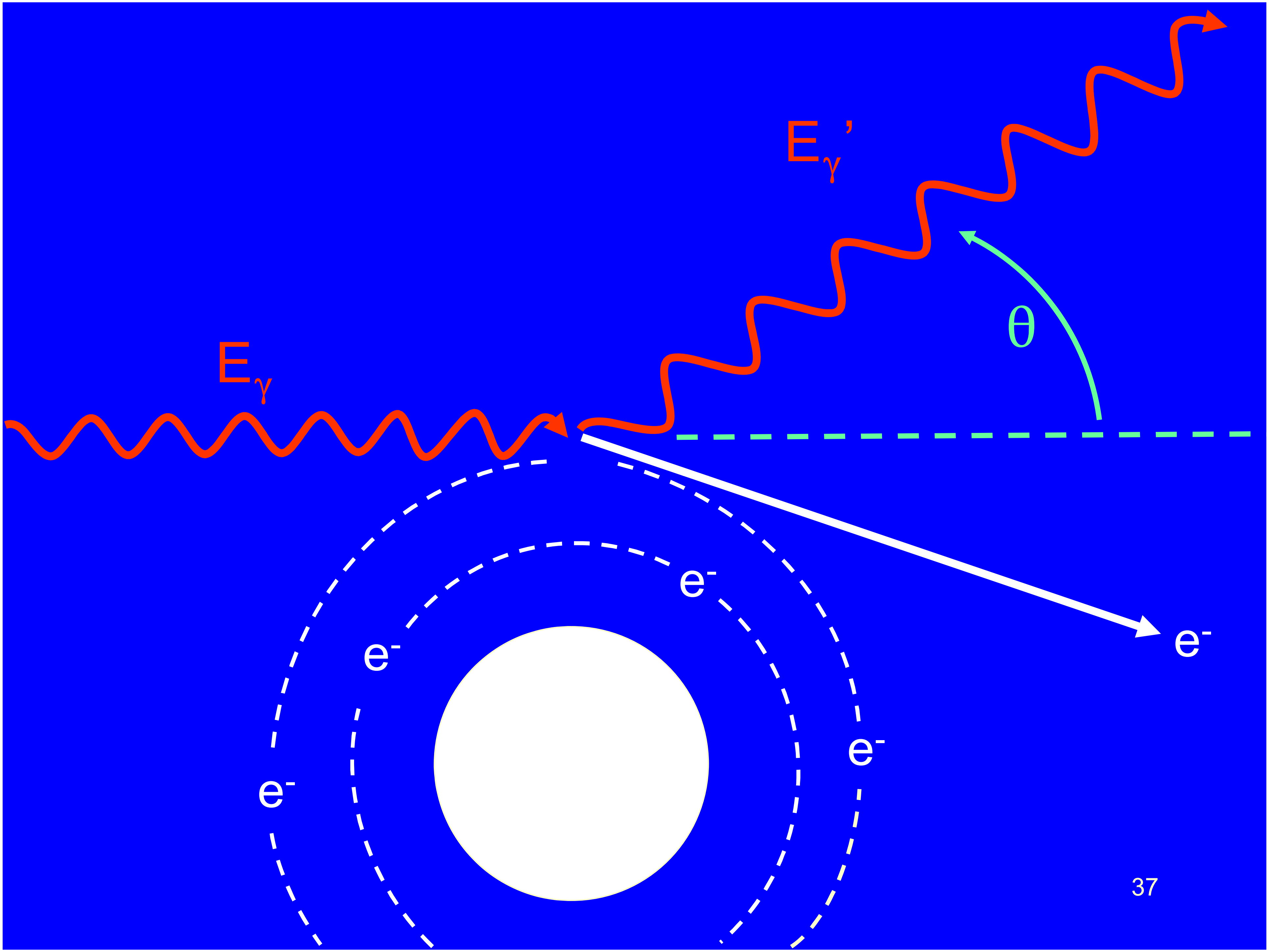
- Tungsten has a lower atomic number (Z = 74) but is a better shield because it has a much higher density (18-19 g/cm^3) than lead (11 g/cm^3)

- Uranium can be an even better shield. Its atomic number is 92 and its density is 18 g/cm^3

Compton Scattering

Compton Scattering

- In Compton scattering, a photon transfers a portion of its energy to a loosely bound outer shell electron of an atom (the binding energy of the electron is considered negligible)
- The photon loses energy and changes direction. This is known as incoherent scattering.



E_γ
E_γ'
θ
e⁻
e⁻
e⁻
e⁻
e⁻
e⁻

Compton Scattering

- The following equation is used to calculate the energy of the scattered photon (E'_{γ})

$$E'_{\gamma} = \frac{E_{\gamma}}{1 + \left(\frac{E_{\gamma}}{511\,keV}\right)(1 - \cos\theta)}$$

Compton Scattering

- The following equation is then used to calculate the energy of the scattered electron (E_e)

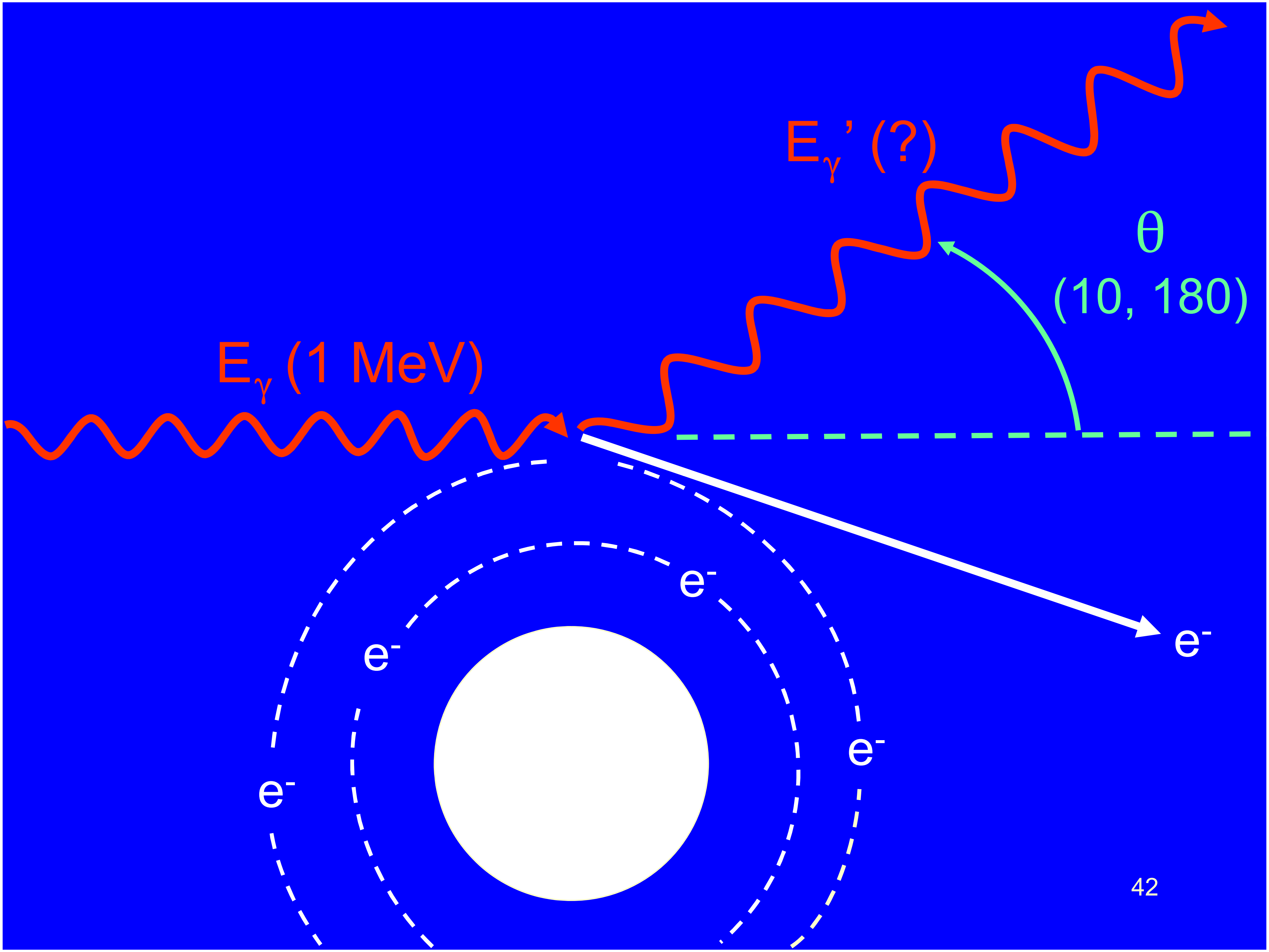
$$E_e = E_\gamma - E_\gamma^{'}$$

Compton Scattering

- The division of energy between the electron and scattered photon depends on the angle of scatter (θ)
- The photon loses the least amount of its energy when θ is small
- The photon loses the largest amount of its energy when θ is 180 degrees

Compton Scattering

- For example, lets calculate the energy of the scattered photon (E'_γ) when a 1 MeV photon (E_γ) scatters at an angle of:
  - 10 º
  - 180 º



Eγ (1 MeV)
Eγ' (?)
θ
(10, 180)
e-
e-
e-
e-
e-

Compton Scattering

$$E_{\gamma}^{'} = \frac{E_{\gamma}}{1 + \left(\frac{E_{\gamma}}{511\, keV}\right)(1 - \cos\theta)}$$

E = 1 MeV, and

θ = 10º and 180º

10 Degree Scattering Angle

$$E_{\gamma}^{'} = \frac{1\,MeV}{1 + \left(\frac{1\,MeV}{0.511\,MeV}\right)\left(1 - \cos 10^{\circ}\right)}$$

$$E_{\gamma}^{'} = \frac{1\,MeV}{1 + \left(\frac{1\,MeV}{0.511\,MeV}\right)\left(1 - 0.985\right)}$$

$$E_{\gamma}^{'} = 0.97\,MeV$$

180 Degree Scattering Angle

$$E_{\gamma}^{'} = \frac{1\,MeV}{1+\left(\frac{1\,MeV}{0.511\,MeV}\right)\left(1-\cos 180^{\circ}\right)}$$

$$E_{\gamma}^{'} = \frac{1\,MeV}{1+\left(\frac{1\,MeV}{0.511\,MeV}\right)\left(1-(-1)\right)}$$

$$E_{\gamma}^{'} = 0.20\,MeV$$

Bonus calculation! We will now calculate the energy of 2 MeV photons scattered at 180º

$$E_\gamma' = \frac{2\,MeV}{1 + \left(\frac{2\,MeV}{0.511\,MeV}\right)\left(1 - \cos 180^\circ\right)}$$

$$E_\gamma' = \frac{2\,MeV}{1 + \left(\frac{2\,MeV}{0.511\,MeV}\right)\left(1 - (-1)\right)}$$

$$E_\gamma' = 0.227\,MeV$$

Compton Scattering

- In most situations, the energy of gamma rays scattered at 180 º is close to 200 keV.

- As the energy of the original photons decrease, the energy of the scattered photons decrease.

Compton Scattering

- Compton scattering occurs at all photon energies and in all materials.
- The potential for Compton scattering is always present.
- It is usually the most probable type of interaction

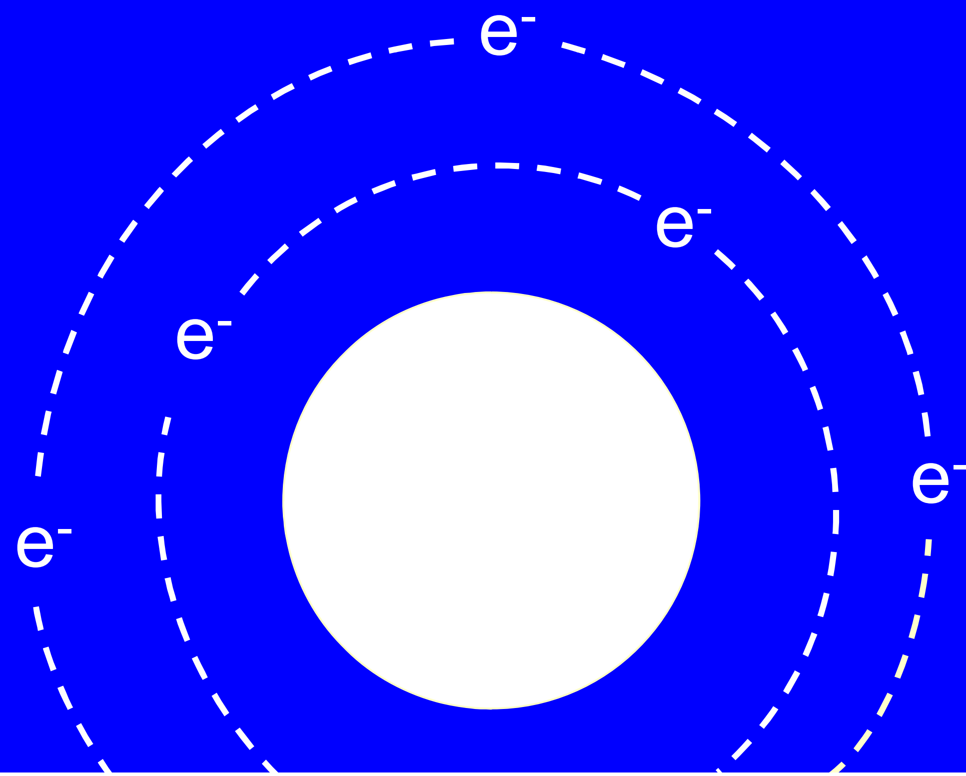
Compton Scattering

- The photons are scattered in all directions by the scattering object.
- The more energetic the incident photon, the more forward the scatter (smaller θ)
- Lower energy photons are more likely to scatter at an angle of 90º or higher.

Compton Scattering

– The photon loses the greatest amount of energy when $\theta = 180°$.

– The scattered electron has the greatest amount of energy when $\theta = 180°$.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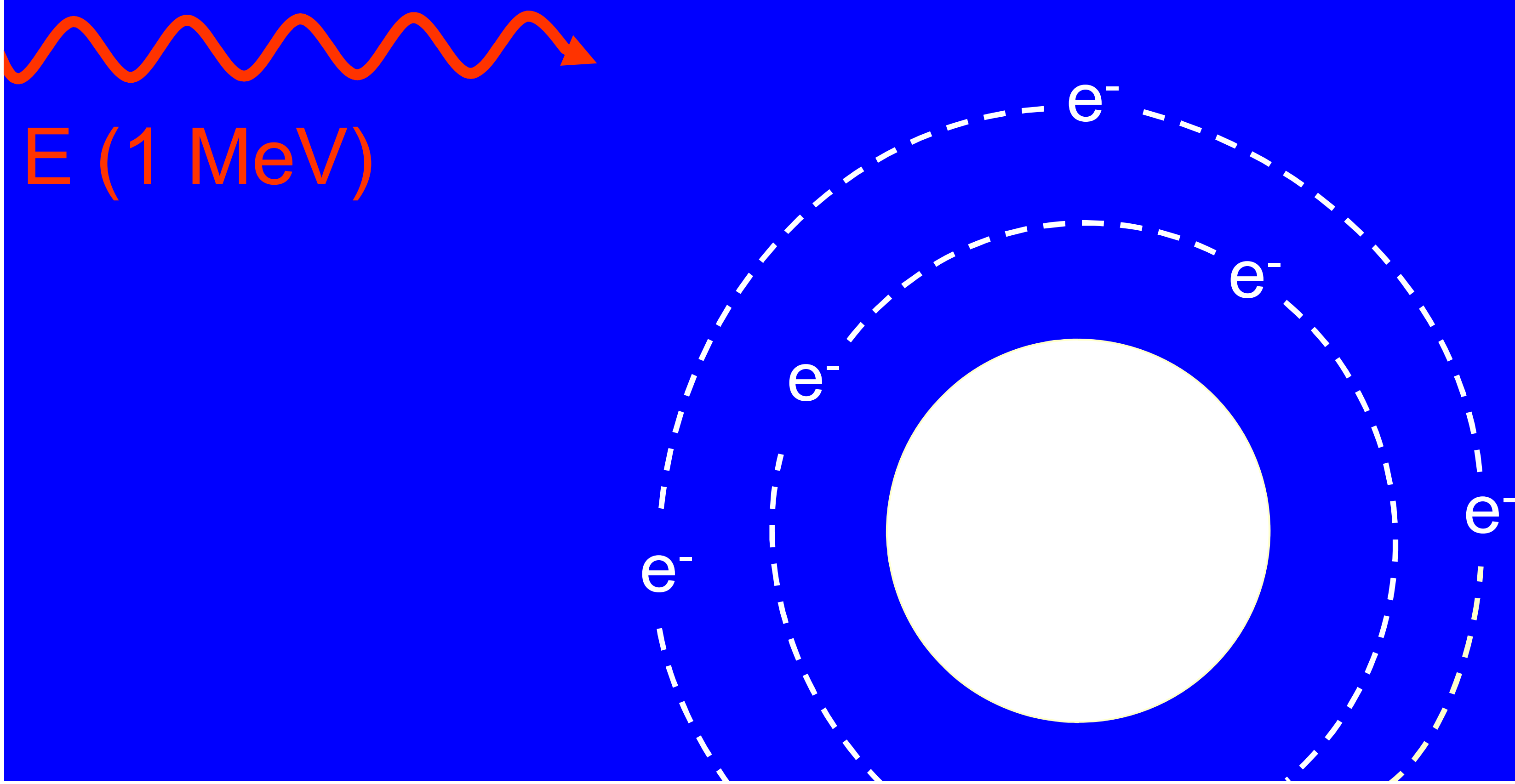
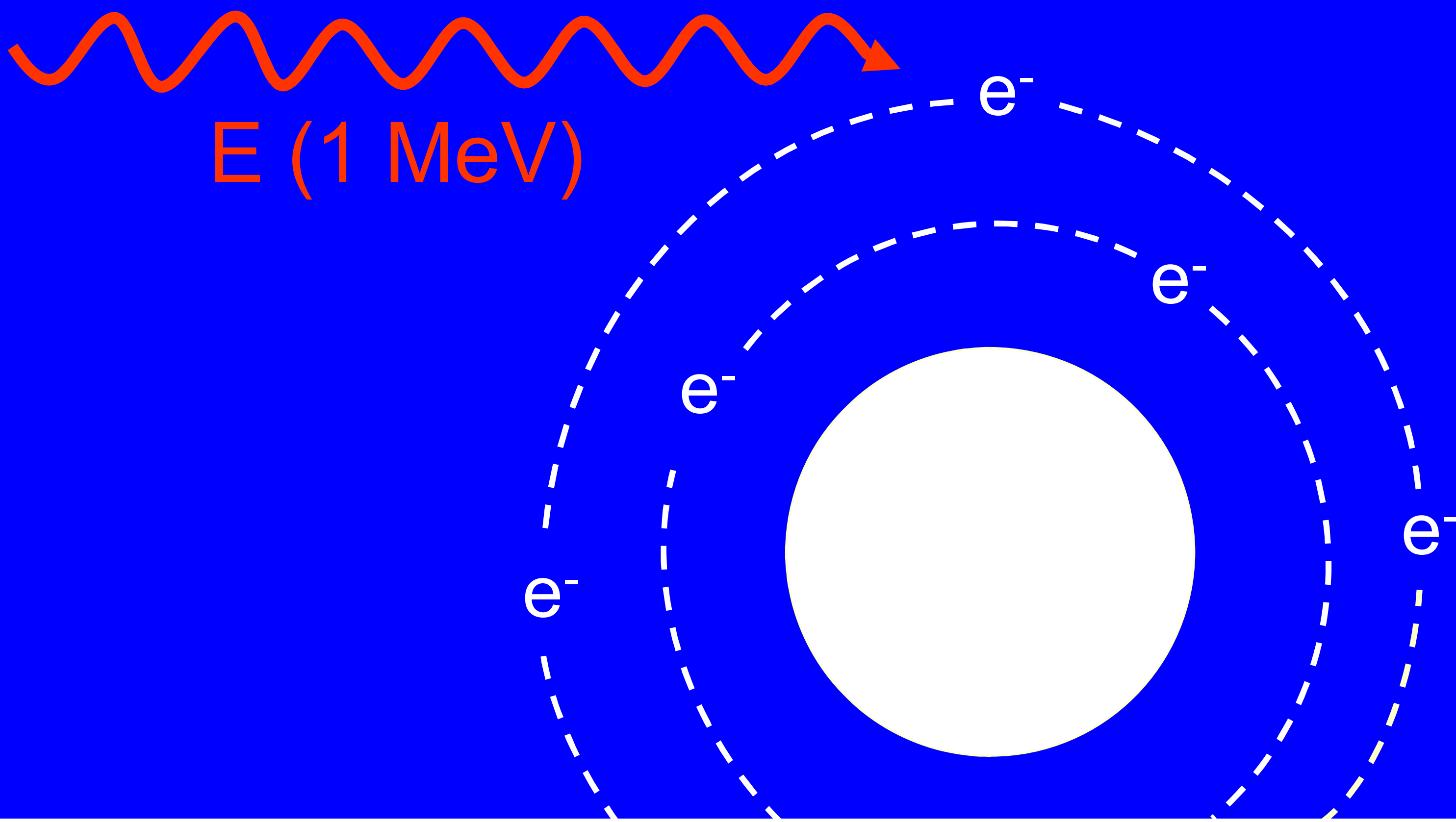

E (1 MeV)
e-
e-
e-
e-
e-


E (1 MeV)
e⁻
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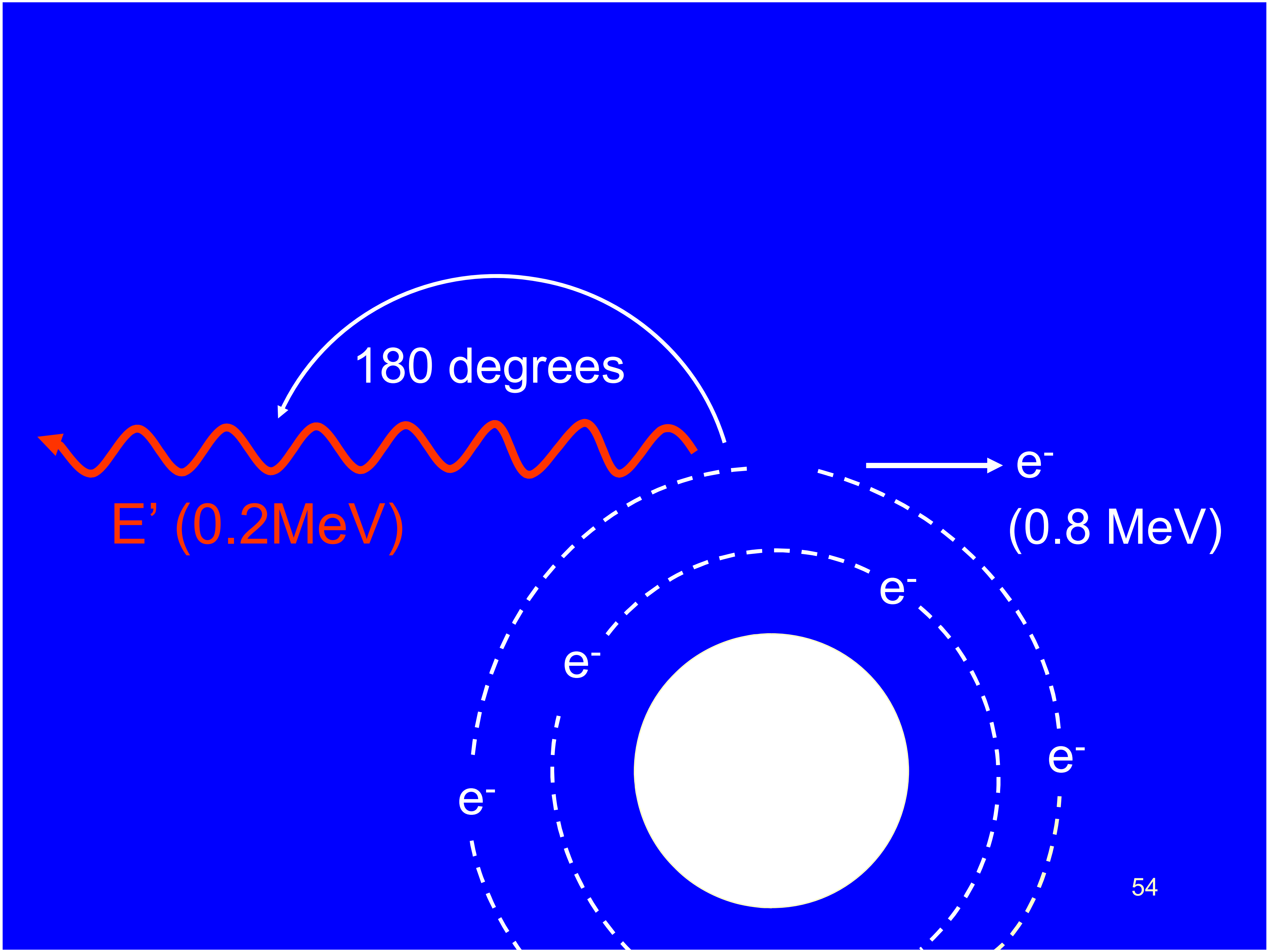

180 degrees
E' (0.2MeV)
e-
(0.8 MeV)
e-
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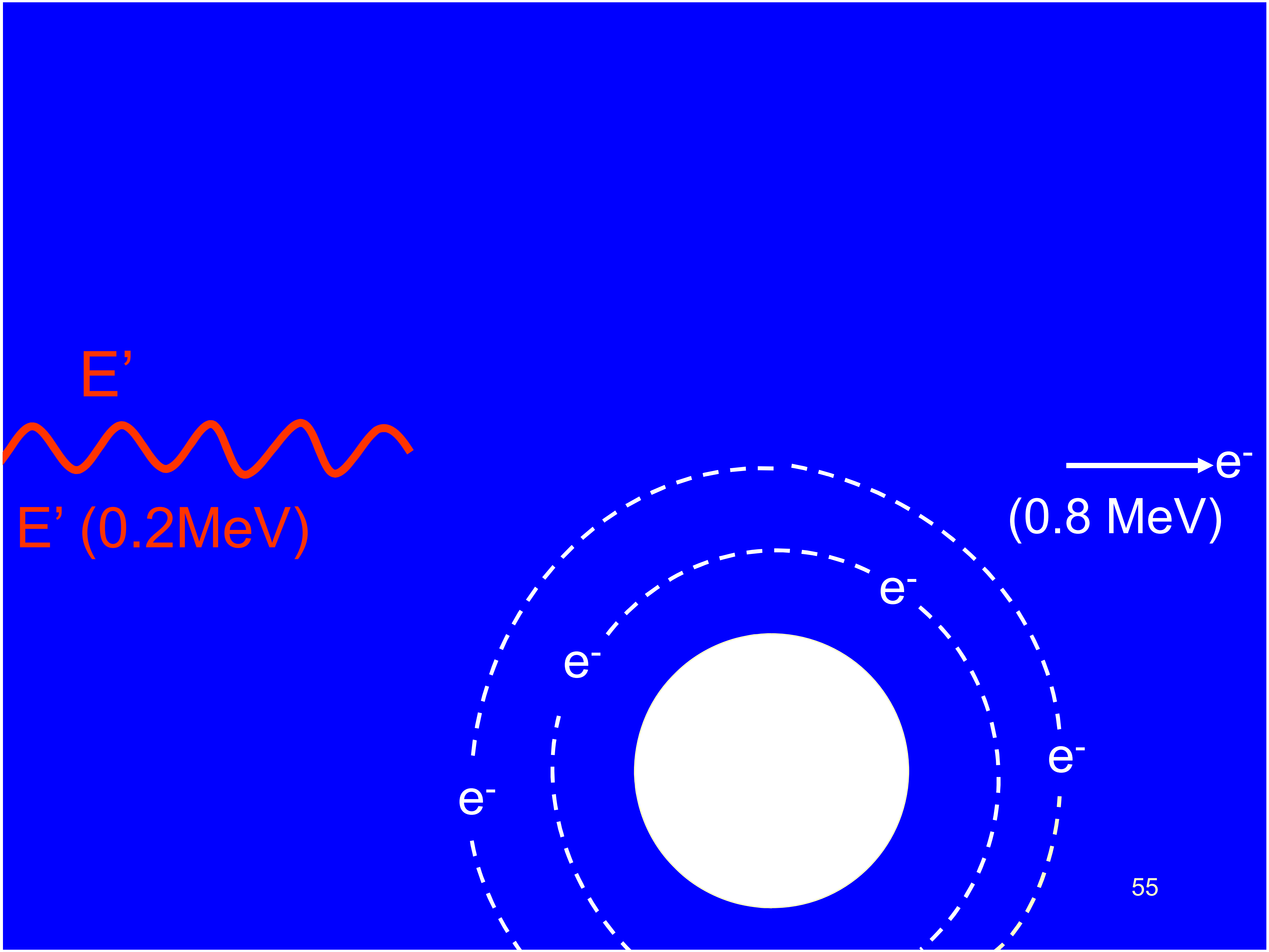
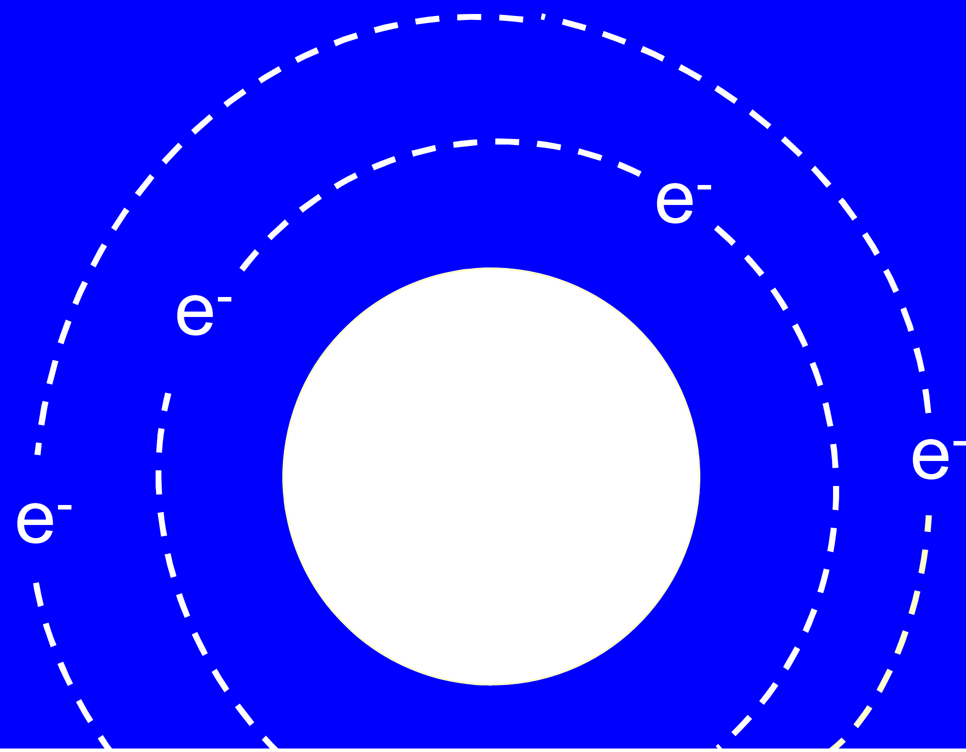

E’
E’ (0.2MeV)
e-
(0.8 MeV)
e-
e-
e-
e-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Compton Scattering

- In some radiation safety applications the exposure to Compton scattered photons can be a significant source of exposure, for example, to medical personnel present during radiological procedures.

Compton Scattering

- In most applications Compton scattering is undesirable, e.g.,
  - Gamma spectroscopy
  - Diagnostic x-ray imaging
- However, the absorbed dose to a tumor from photons in radiation therapy is actually delivered by the Compton scattered electrons.

Pair Production

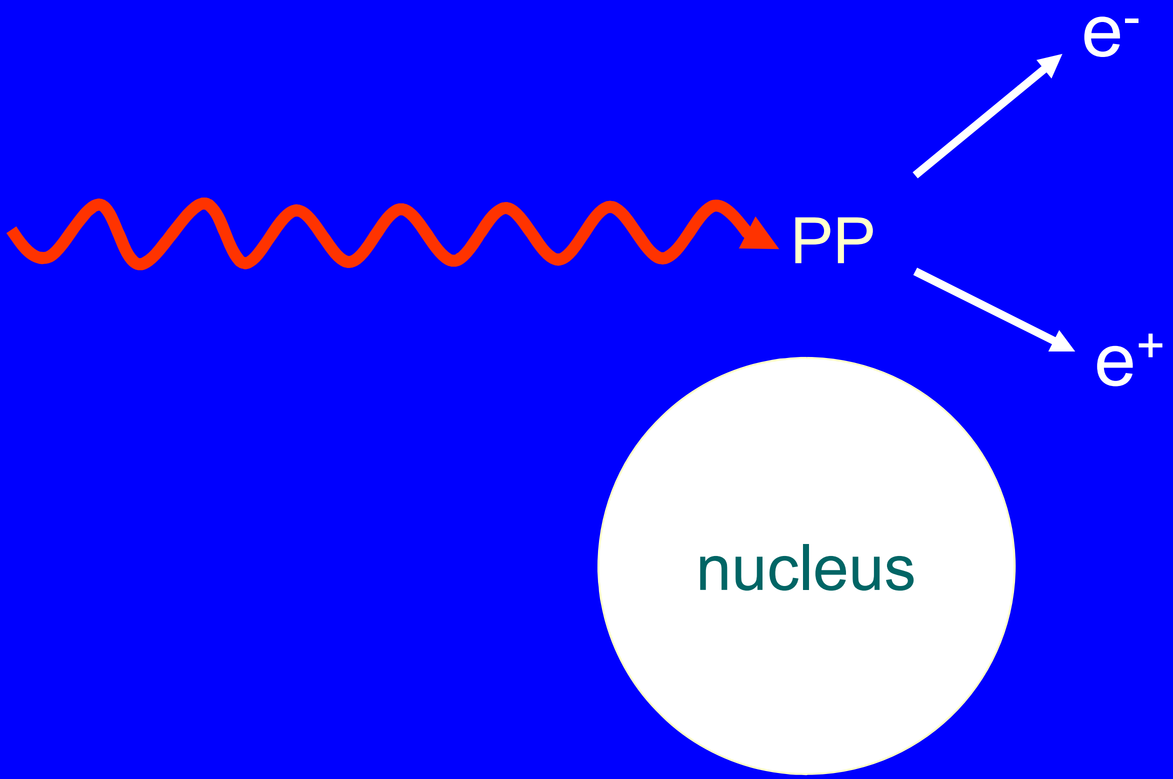
Pair Production

- In pair production, a photon interacts with the electric field of the nucleus of an atom.

- The photon completely disappears while an electron and a positron are produced.

Pair Production

- Since the electron and positron each have an energy equivalence of 511 keV, the incoming photon must have an energy of at least 1022 keV for pair production to take place.

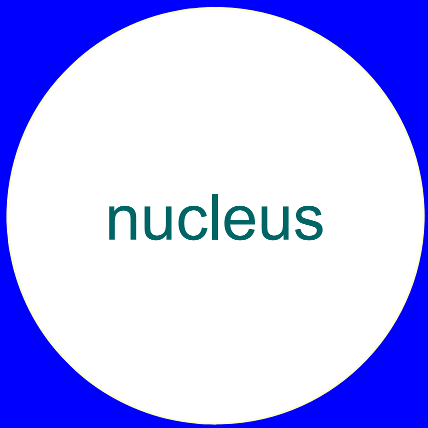


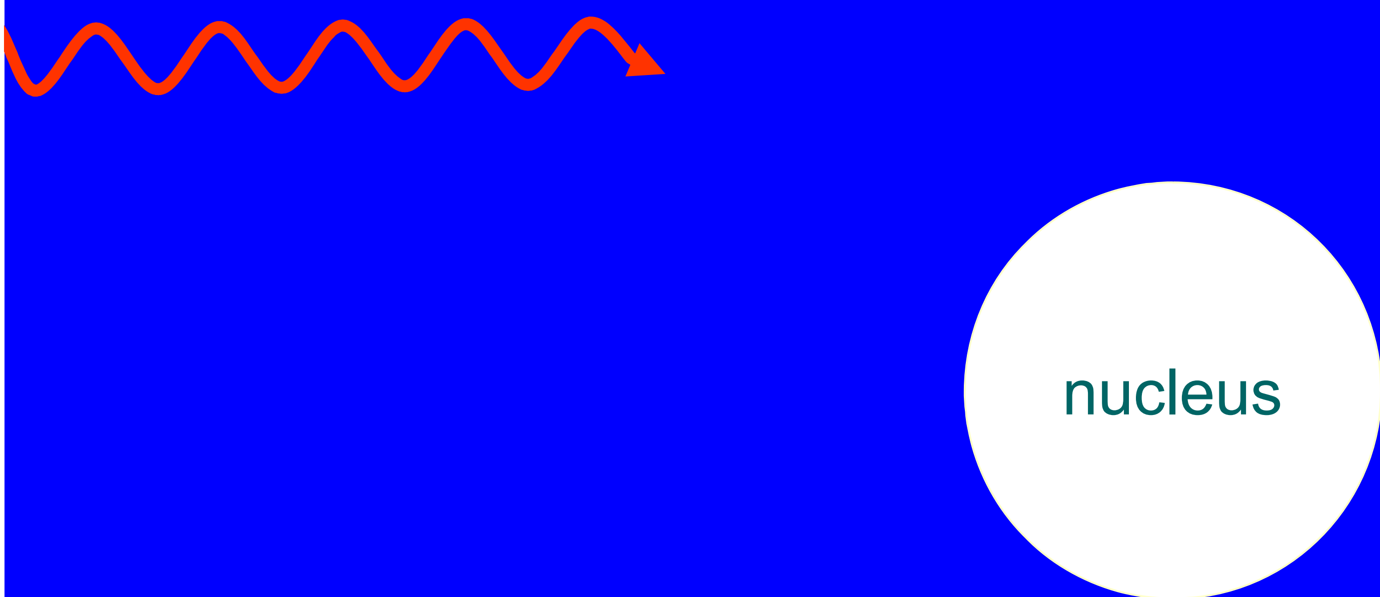
Pair Production

- Any additional photon energy above 1022 keV is given to the positron and the electron as kinetic energy.
- The kinetic energy of the electron and the positron are not necessarily the same.
- PP is most likely to occur with relatively high photon energies and high atomic number materials (larger nuclei).

Pair Production

- The electron and positron will give up their kinetic energy via ionization, excitation and/or bremsstrahlung.
- Ultimately, the positron will annihilate itself and an electron, most likely after it has given up all of its kinetic energy. The result is the production of two 511 keV annihilation photons.
- If the positron comes to rest before its annihilation (the most probable case), the two photons will be emitted 180 degrees from each other.


nucleus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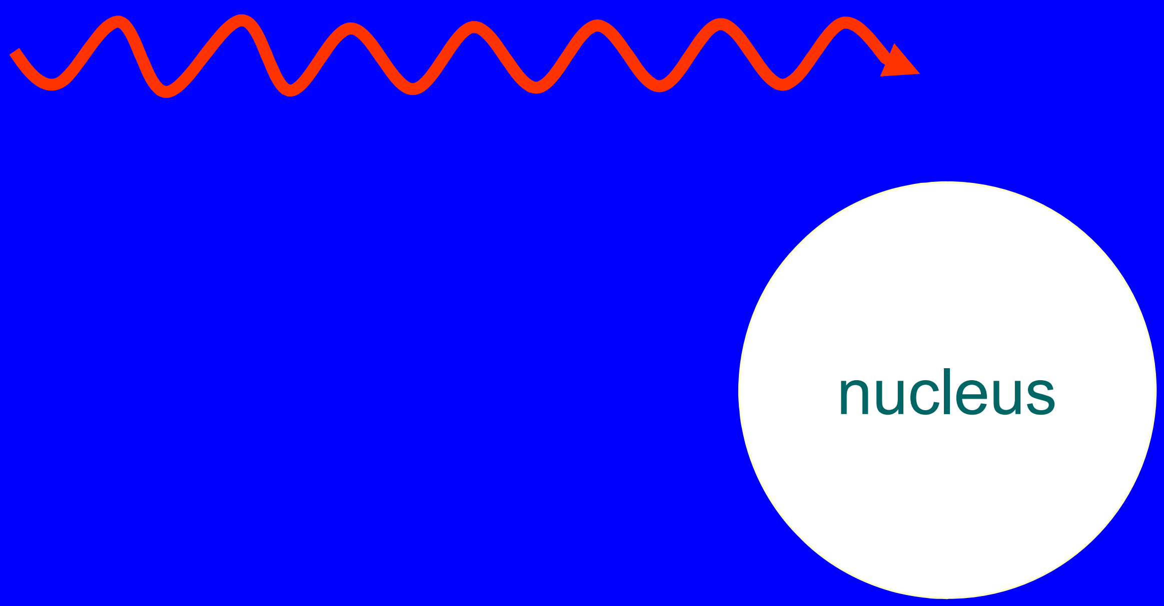
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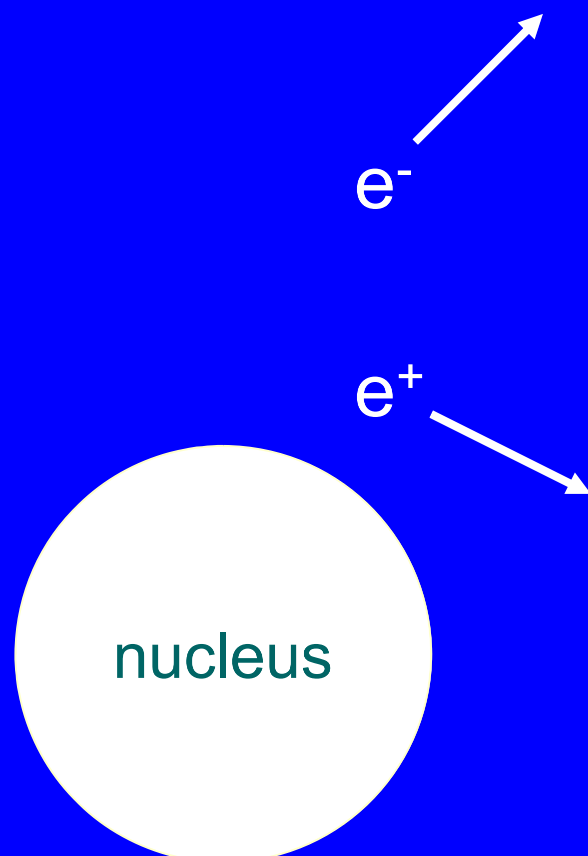
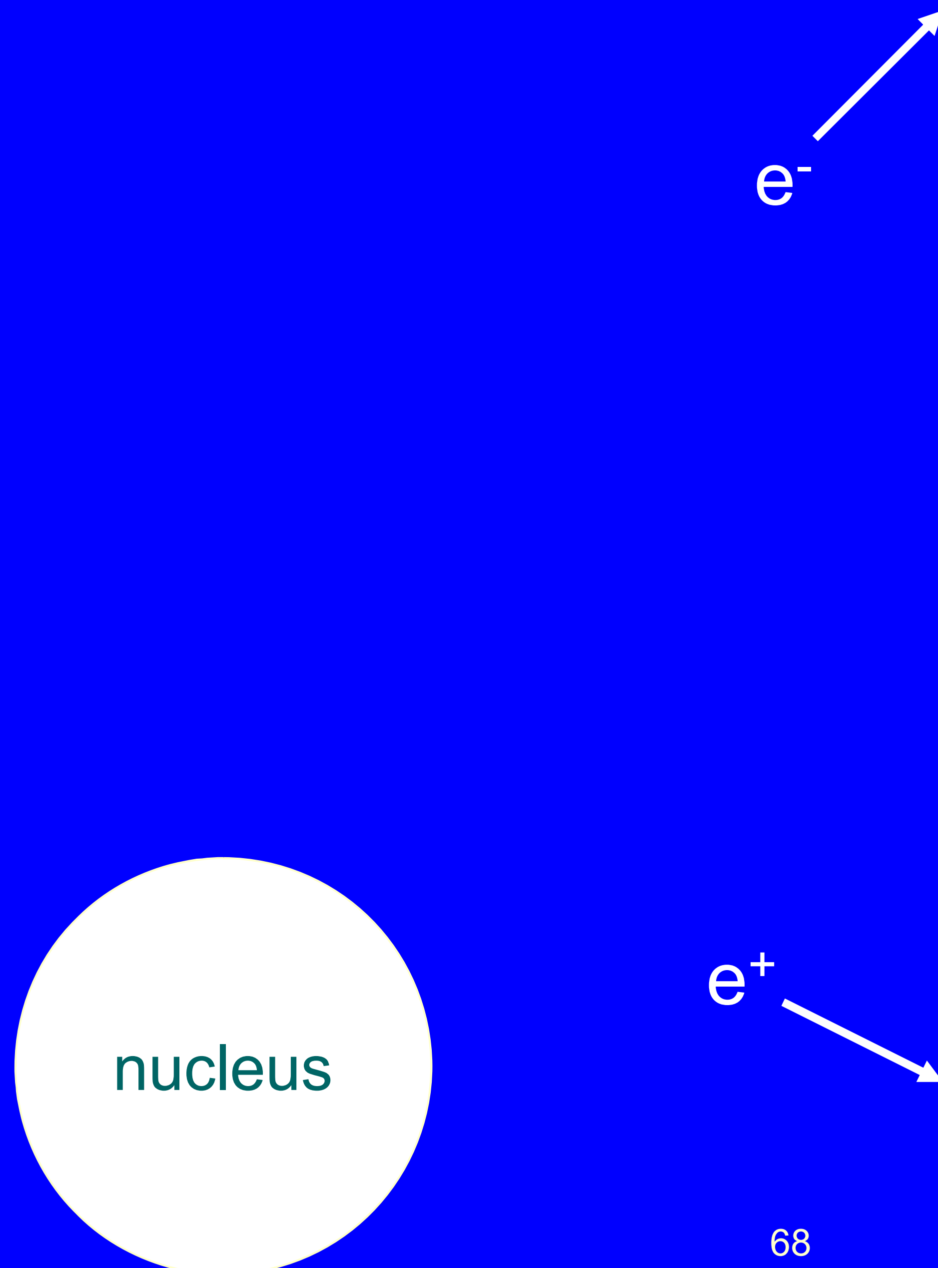

e-
e+
nucleus


e-
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e^+

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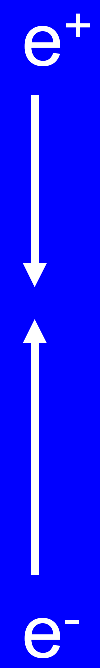
Innocent bystander

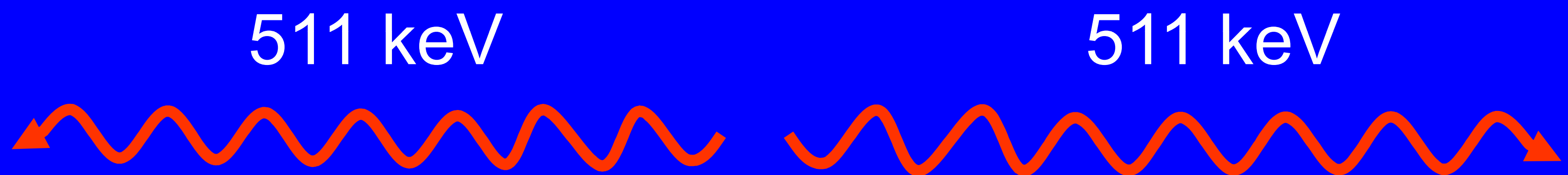
e^+

e^-

Innocent bystander



Innocent bystander

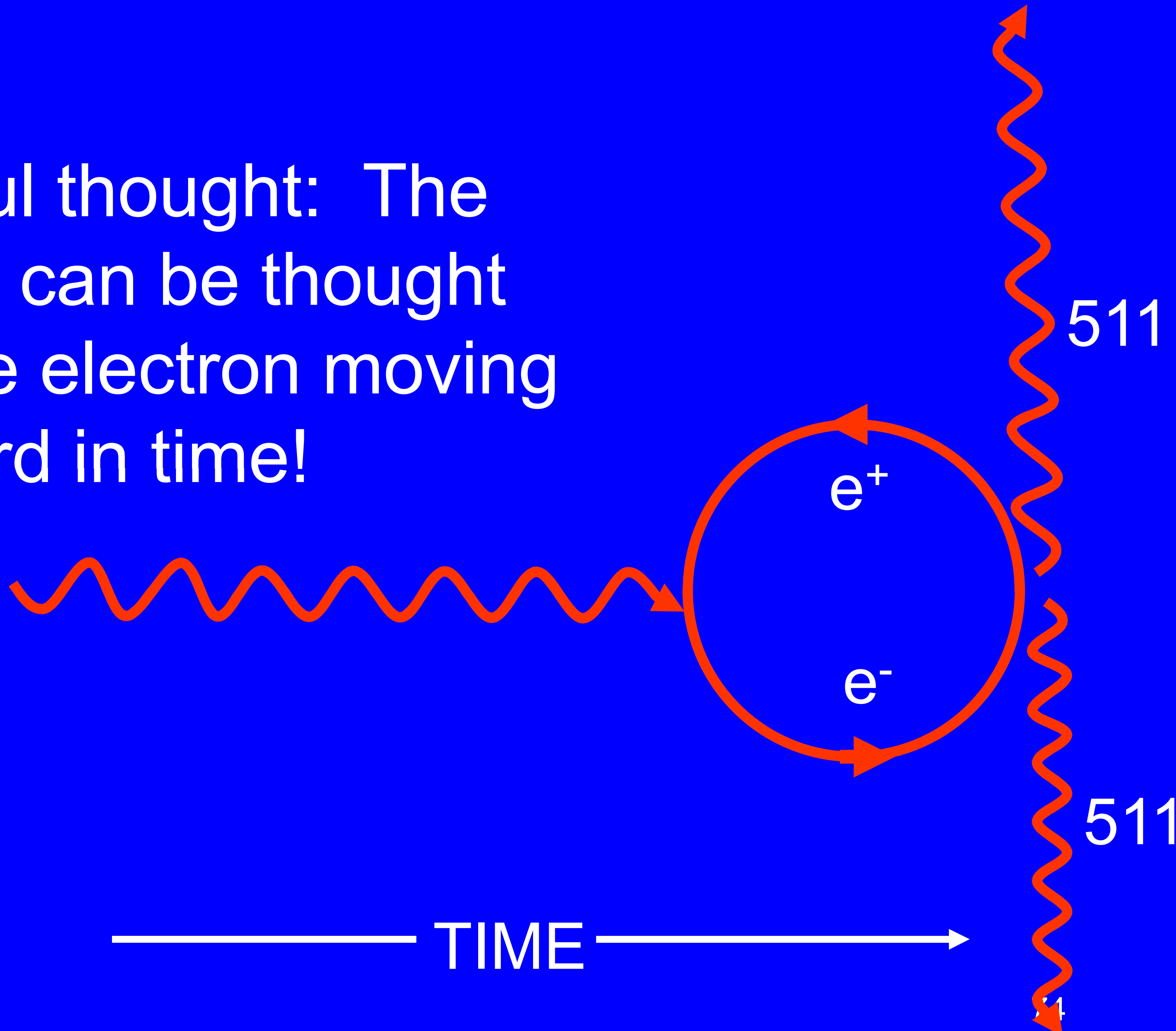

511 keV
511 keV

Pair Production

- In shielding, spectroscopy, or dosimetry applications, the two 511 keV photons created after pair production must always be considered.

Pair Production

- A fanciful thought: The positron can be thought of as the electron moving backward in time!



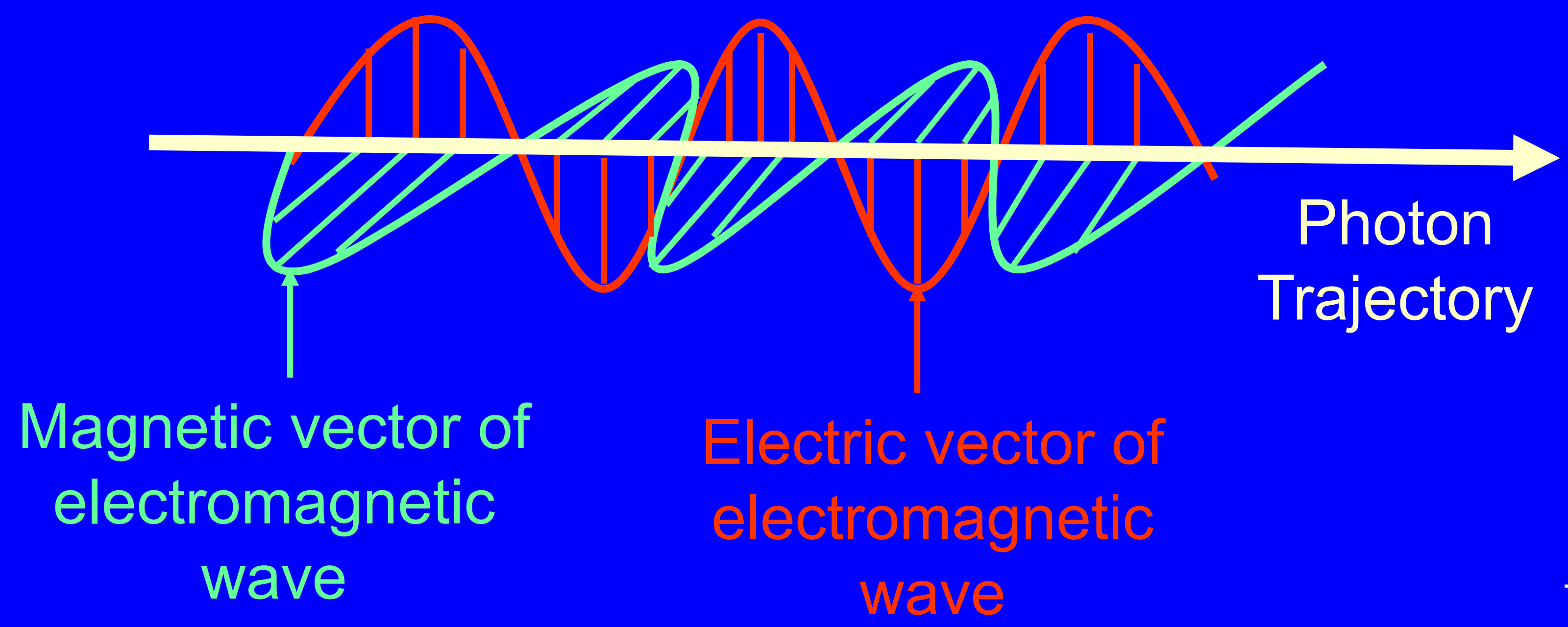
The Most Important of the Unimportant Photon Interactions with Matter

Raleigh Scattering

- Raleigh scattering is a type of coherent scattering whereas Compton scattering is incoherent.
- With coherent scattering, the photon changes direction but does not lose energy. Its wavelength is unaffected.
- Because it can be explained in terms of a wave–particle interaction, it is sometimes referred to as "classical scattering." The photon is the wave and the electron is the particle.

Raleigh Scattering

- The photon is viewed as electric and magnetic waves oscillating in two planes at right angles to each other. The intersection of the two planes is defined by the trajectory of the photon.



Raleigh Scattering

- The electric field of the passing photon causes the electrons of an atom to oscillate. These vibrating electrons emit their own electromagnetic radiation and return to their original undisturbed state. The electromagnetic emissions of the atom’s electrons to combine to produce a photon (electromagnetic wave) that leaves in a direction different from that of the incident photon.

- Raleigh scattering is most important when the photon energy is low and the atomic number is high. In such a case, the binding energy of the outer electrons is high compared to the photon energy - this limits the probability of Compton scattering.

Raleigh Scattering

- In the case of lead, Raleigh scattering can be more probable than Compton scattering at energies up to 100 keV or so. In water, this is true up to about 10 keV. At these low energies, the photoelectric effect is far more probable than either type of scattering.

- The scattering angle is quite small.

- The net effect of coherent scattering (in shielding, x-ray imaging, etc.) is essentially the same as Compton scattering at shallow angles where little energy is lost by the photon.

Thomson Scattering

- Thomson scattering is another type of coherent scattering. It is of even less interest than Raleigh scattering.
- In Thomson scattering, only a single “free” electron is involved rather than all the electrons of the atom as was the case with Raleigh scattering.
- Once again, the electromagnetic wave of the photon causes the vibration of the electron. Note, this is not a case of “excitation” where the electron is moved to a higher energy level.
- The original photon disappears and a new photon of the same energy is emitted in a different direction.

Photonuclear Reactions

- In photonuclear reactions, the photon is absorbed by the nucleus of the atom and a nuclear particle (neutron, proton, alpha) is ejected. Photon induced fission would be an extreme example. Of these, photo-neutron reactions are the most common.
- For these reactions to occur, the photon energy must exceed the binding energy of the particle.
- Usually this threshold energy is on the order of 7 – 15 MeV. There are exceptions however.

Probability of Interactions

Probability of Interactions

- Charged particles (e.g., alphas and betas) continuously interact with the material they travel through. Photons occasionally interact.

- We will now consider the factors that affect the probability of photon interactions (photoelectric effect, compton scattering, pair production)

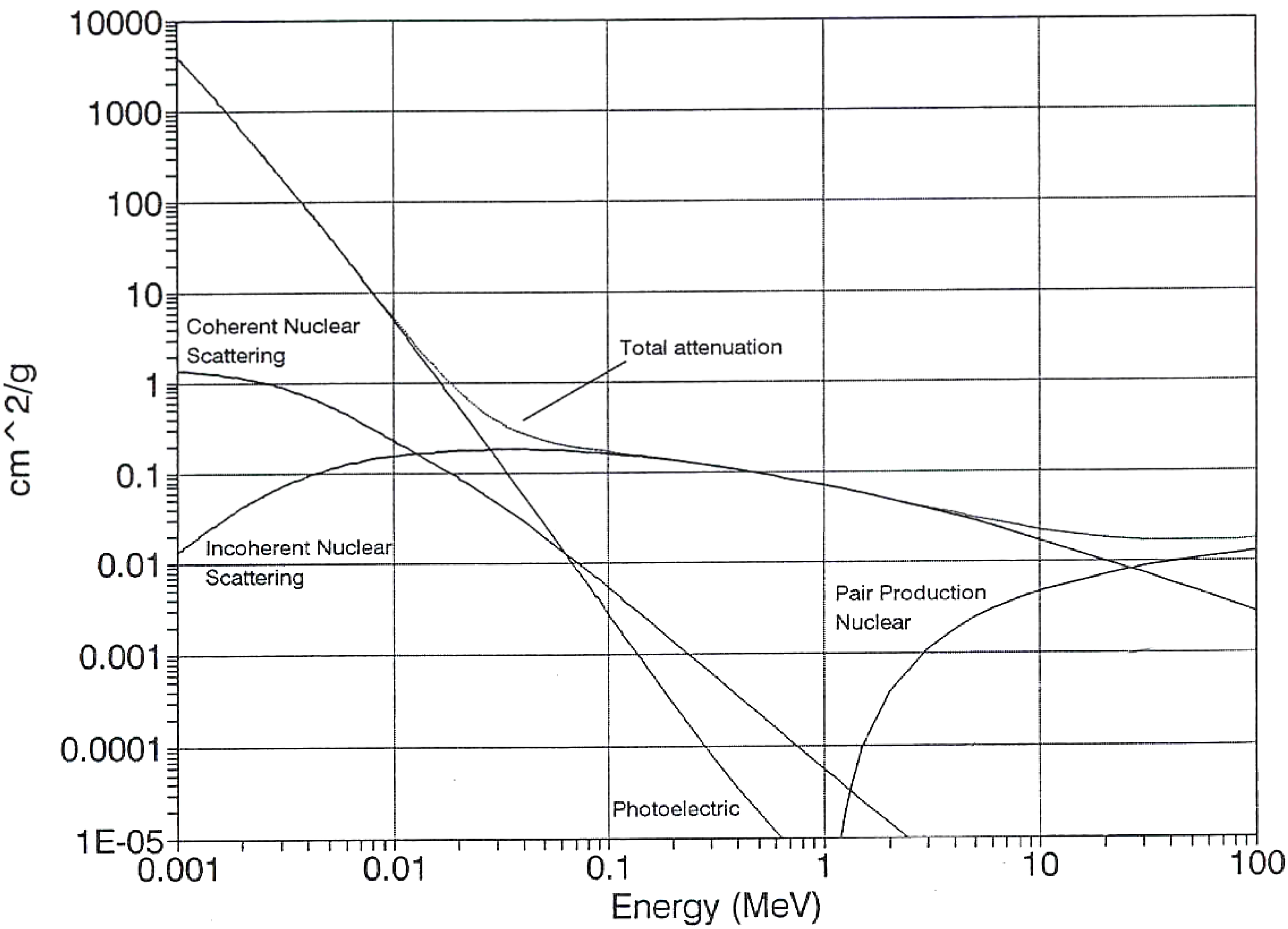
Probability of Interactions

- The two most important factors influencing the probability of a given type of interaction are:
  - the energy of the photon (E)
  - the atomic number (Z) and density of the material (i.e., the electron density)

Probability of Interactions

- The next slide shows the probability of an interaction as a function of the photon energy in a low-Z material (water).

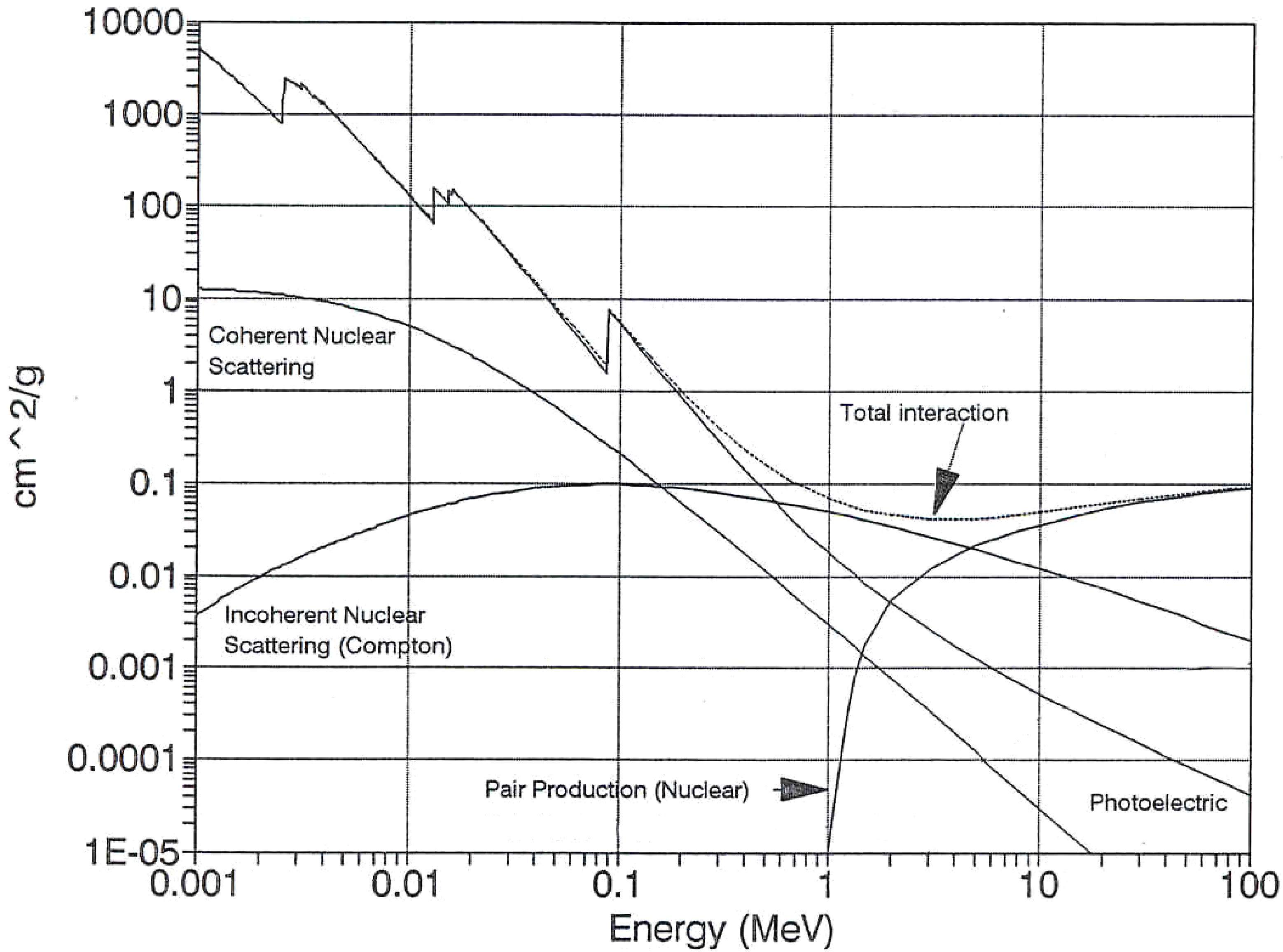
- Note that the probability of the photoelectric effect decreases dramatically as the the photon energy increases.



Mass Attenuation Coefficients for Photons in Water

Probability of Interactions

- The next slide shows the probability of an interaction as a function of the photon energy for a high-Z material (lead).
- Again, look at the probability of the photoelectric effect.



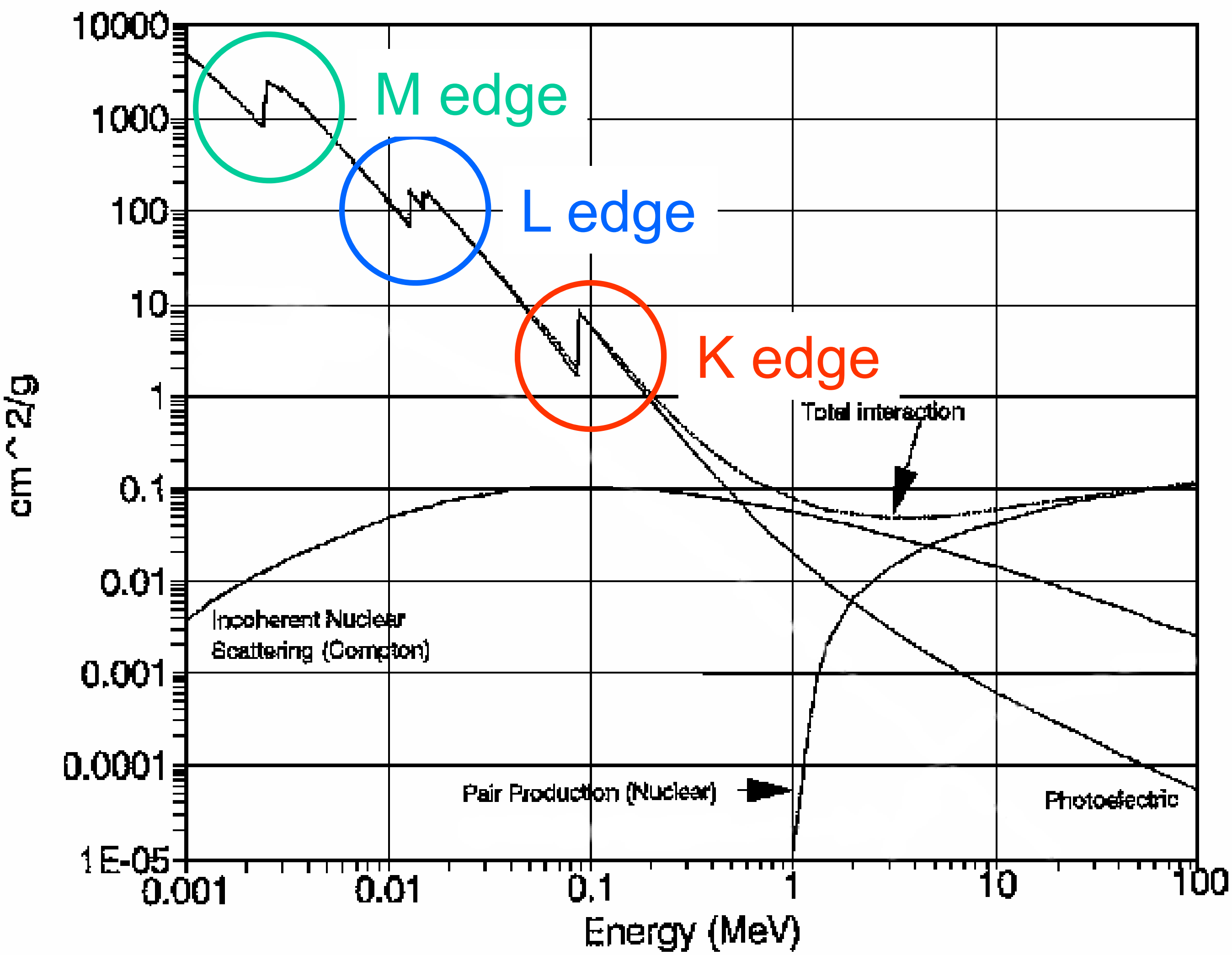
Mass Attenuation Coefficients for Photons in Lead

Probability of Interactions

- In general, the curves for water and lead have the same shape: as the photon energy increases, the probability of a PE interaction decreases.
- But, on the curve for lead, there are three sudden increases (or decreases depending on how you look at it) in the probability of a PE interaction.

Probability of Interactions

- The “spikes” or sudden increases in the probability of PE interactions are called the K, L and M edges.
- Going from lower to higher energies, there are sudden increases in the probability of interaction because the photon “gains” enough energy to eject the M, L and K shell electrons, respectively.
- The electron binding energies are approximately 3 keV (M shell), 15 keV (L shell) and 88 keV (K shell).



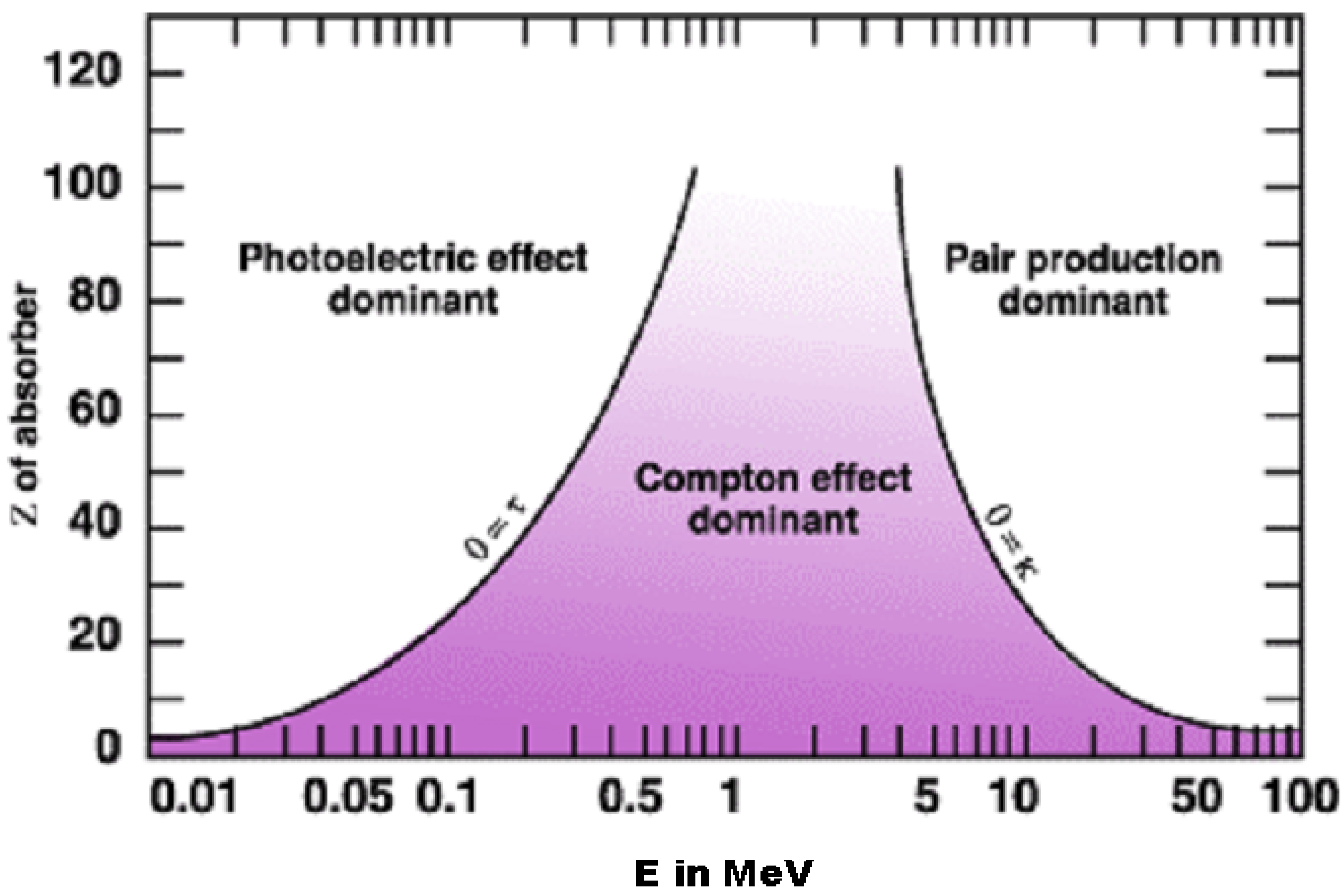
Mass Attenuation Coefficients for Photons in Lead (Based on data from Berger and Hubbell, 1987)

Probability of Interactions

- It is sometimes said that an element is transparent to its own radiation. This means is that a material is somewhat more effective at absorbing photon energies below and above the energies of its own characteristic x-rays.

- For example, the energy of lead's K_{α} x-ray is 75 keV. As indicated in the previous figure, absorption by lead increases as the photon energy decreases below 75 keV. At the same time, absorption increases when the photon energy exceeds 88 keV (at the K-edge).

- This effect of increasing energy is somewhat short-lived. Absorption is greater at 75 keV than at energies above 120 keV or so.


Photoelectric effect dominant
Compton effect dominant
Pair production dominant
Z of absorber
E in MeV
120
100
80
60
40
20
0
0.01
0.05
0.1
0.5
1
5
10
50
100

Probability of Interactions

- The previous slide shows how the photoelectric effect is dominant at low energies in high Z materials.

- Compton scattering occurs at all energies in all materials, but is the dominant interaction in the medium energy range.

- Pair production only occurs at energies above 1.022 MeV. Pair production becomes more probable as the photon energy and the atomic number of the material increase.

Probability of Interactions

- There are two common quantities used to describe the probabilities of these interactions:

  linear attenuation coefficient (μ).

  mass attenuation coefficient (μ/ρ).

Probability of Interactions

- The linear attenuation coefficient (μ) is the probability of an interaction per linear distance traveled by the photon.

- It is actually the sum of the probabilities of the photoelectric effect (τ), compton scattering (σ) and pair production (κ)

$$\mu = \tau + \sigma + \kappa$$

Probability of Interactions

- The greater the number of atoms encountered per centimeter traveled, the larger the value of μ and the more probable a given type of interaction.

- The units of μ are cm^{-1}.

Probability of Interactions

- μ is the sum of the individual attenuation coefficients for the photoelectric effect, Compton scattering, and pair production.
- The value of μ depends on photon energy and type and the atomic number (and density) of the material.
- Values of μ can be hard to find in the literature.

Probability of Interactions

- A more common quantity for expressing the probability of an interaction is the mass attenuation coefficient (μ/ρ)

- It is equal to the linear attenuation coefficient (μ), divided by the density of the material (ρ). The units of μ/ρ are cm^2/g.

Probability of Interactions

- The mass attenuation coefficient can be thought of as the fraction of the photons interacting per unit density thickness
- Values of μ/ρ are found in:

  PTP's Radiological Health Handbook (beginning on page 90)
  http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html

MASS ATTENUATION COEFFICIENTS--Continued

Photon Energy	Ar	K	Ca	Fe	Cu	Mo	Sn	I	W	Pb
keV										
10	64.5	80.9	96.5	173.	224.	86.2	141.	161.	95.5+	133.+
15	19.9	25.0	30.1	56.4	74.2	28.2	47.0	55.2	142.	115.+
20	8.53	10.8	13.0	25.5	33.5	81.7*	21.3*	26.0	67.0	85.7
30	2.62	3.30	3.99	8.13	10.9	28.8	41.3	8.67*	23.0	29.7
40	1.20	1.49	1.78	3.62	4.89	13.3	19.4	22.7	10.7	14.0
50	0.687	0.843	0.998	1.94	2.62	7.20	10.7	12.6	5.91	7.81
60	.460	.560	.648	1.20	1.62	4.41	6.53	7.78	3.65*	4.87
80	.275	.324	.365	0.595	0.772	2.02	3.02	3.65	7.89	2.33*
100	.204	.233	.256	.370	.461	1.11	1.68	2.00	4.43	5.40
150	.143	.158	.168	.196	.223	0.428	0.614	0.714	1.57	1.97
200	.121	.132	.138	.146	.157	.245	.328	.372	0.777	0.991
300	.0996	.108	.112	.110	.112	.139	.164	.178	.320	.404
400	.0878	.0949	.0979	.0940	.0941	.105	.116	.122	.190	.231
500	.0795	.0859	.0885	.0840	.0836	.0883	.0946	.0976	.136	.161
600	.0733	.0792	.0814	.0769	.0762	.0788	.0816	.0835	.108	.125
800	.0641	.0692	.0712	.0669	.0660	.0661	.0669	.0676	.0799	.0885
MeV										
1.0	.0576	.0621	.0639	.0599	.0589	.0583	.0578	.0581	.0654	.0708
1.5	.0470	.0506	.0520	.0488	.0480	.0470	.0463	.0464	.0497	.0517
2.0	.0407	.0439	.0453	.0425	.0420	.0415	.0410	.0411	.0437	.0455
3.0	.0338	.0366	.0378	.0362	.0360	.0366	.0367	.0370	.0402	.0418

MASS ATTENUATION COEFFICIENTS--Continued

Photon Energy	Ar	K	Ca	Fe	Cu	Mo	Sn	I	W	Pb
keV										
10	64.5	80.9	96.5	173.	224.	86.2	141.	161.	95.5 +	133. +
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MeV										
1.0	.0576	.0621	.0639	.0599	.0589	.0583	.0578	.0581	.0654	.0708
1.5	.0470	.0506	.0520	.0488	.0480	.0470	.0463	.0464	.0497	.0517
2.0	.0407	.0439	.0453	.0425	.0420	.0415	.0410	.0411	.0437	.0455
3.0	.0338	.0366	.0378	.0362	.0360	.0366	.0367	.0370	.0402	.0418

Probability of Interactions

- Should it be necessary to convert from μ / ρ to μ, the densities of common materials can found in PTP's Radiological Health Handbook on page 5 and the RHH pg. 65, or the HHPRH pp. 5-50—5-51.

Probability of Interactions

- Photoelectric effect

The probability varies approximately with Z^4

The probability varies approximately with $1/E^3$

Probability of Interactions

- Compton Scattering

The probability per atom varies approximately with Z

The probability varies approximately with 1/E

Probability of Interactions

- Pair Production

The probability per atom varies approximately with Z^2

The probability varies approximately with the natural log of E

Probability of Interactions

- A related quantity is the mass energy absorption coefficient (μ_{en}/ρ). The units are the same as those of the mass attenuation coefficient (cm^2/g).

- The mass energy absorption coefficient can be thought of as the fraction of the photon energy that is absorbed per unit density thickness

Probability of Interactions

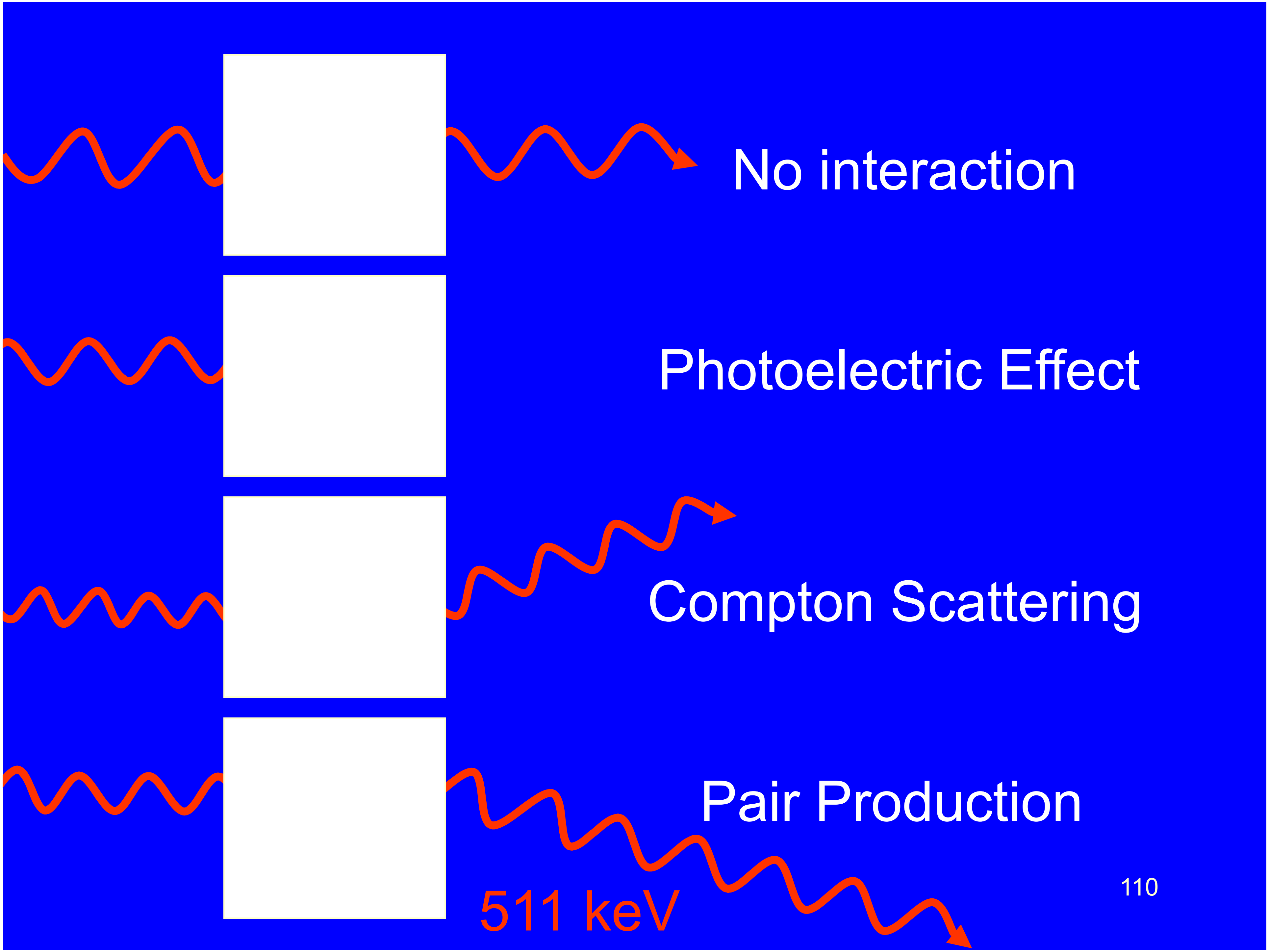
- The mass energy absorption coefficient (μ_{en}/ρ) is smaller than the mass attenuation coefficient (μ/ρ)

- Values of μ_{en}/ρ are found in:

  PTP's Radiological Health Handbook
  (beginning on page 90)
  http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html

Probability of Interactions

- The mass attenuation coefficient (μ/ρ) is normally used in shielding calculations
- The mass energy absorption coefficient (μ_{en}/ρ) is normally used in dosimetry calculations


No interaction
Photoelectric Effect
Compton Scattering
Pair Production
511 keV