Interaction of Charged Particles With Matter

3/1/2011

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Objectives

Qualitative

- Ionization
- Excitation
- Bremsstrahlung
- Cerenkov radiation

Objectives

Quantitative

To review the following measures of energy loss:

- W Value
- Specific Ionization
- Stopping Power/Linear Energy Transfer
- Mass Stopping Power

Introduction

Introduction

General

- “The interaction of charged particles with matter” concerns the transfer of energy from the charged particles to the material through which they travel.

- The “charged particles” considered here are:

  - Alpha particles (+2 charge)

  - Beta particles (+ or -1 charge) or electrons

- Photons and neutrons, which have no charge, interact very differently.

Introduction

General

- Charged particles passing through matter continuously interact with the electrons and nuclei of the surrounding atoms.
- In other words, alpha and beta particles are continually slowing down as they travel through matter.
- The interactions involve the electromagnetic forces of attraction or repulsion between the alpha or beta particles and the surrounding electrons and nuclei.

Introduction

Force of the Interaction

- The force associated with these interactions can be described by Coulomb's equation:

$$F = \frac{k\,q_1\,q_2}{r^2}$$

k is a constant = 9 x 10^9 N-m^2/C^2.

q_1 is the charge on the incident particle in Coulombs.

q_2 is the charge on the "struck" particle.

r is the distance between the particles in meters.

Introduction

Force of the Interaction

Things to notice about the equation:

- The force increases as the charge increases
- The force increases as the distance decreases (it quadruples if the distance is cut in half)
- The force can be positive or negative (attractive or repulsive)

$$F = \frac{k\ q_1\ q_2}{r^2}$$

Introduction

Four Types of Charged Particle Interactions

- The four types of interactions are:
  - Ionization (alphas and betas)
  - Excitation (alphas and betas)
  - Bremsstrahlung (primarily betas)
  - Cerenkov radiation (primarily betas)
- Ionization is almost always the primary mechanism of energy loss.

Ionization

Ionization

General

- A charged particle (alpha or beta particle) exerts sufficient force of attraction or repulsion to completely remove one or more electrons from an atom.
- The energy imparted to the electron must exceed the binding energy of the electron.
- Ionization is most likely to involve atoms near the charged particle's trajectory.
- Each ionization event reduces the charged particle's velocity, i.e., the alpha or beta particles loses kinetic energy.

Ionization

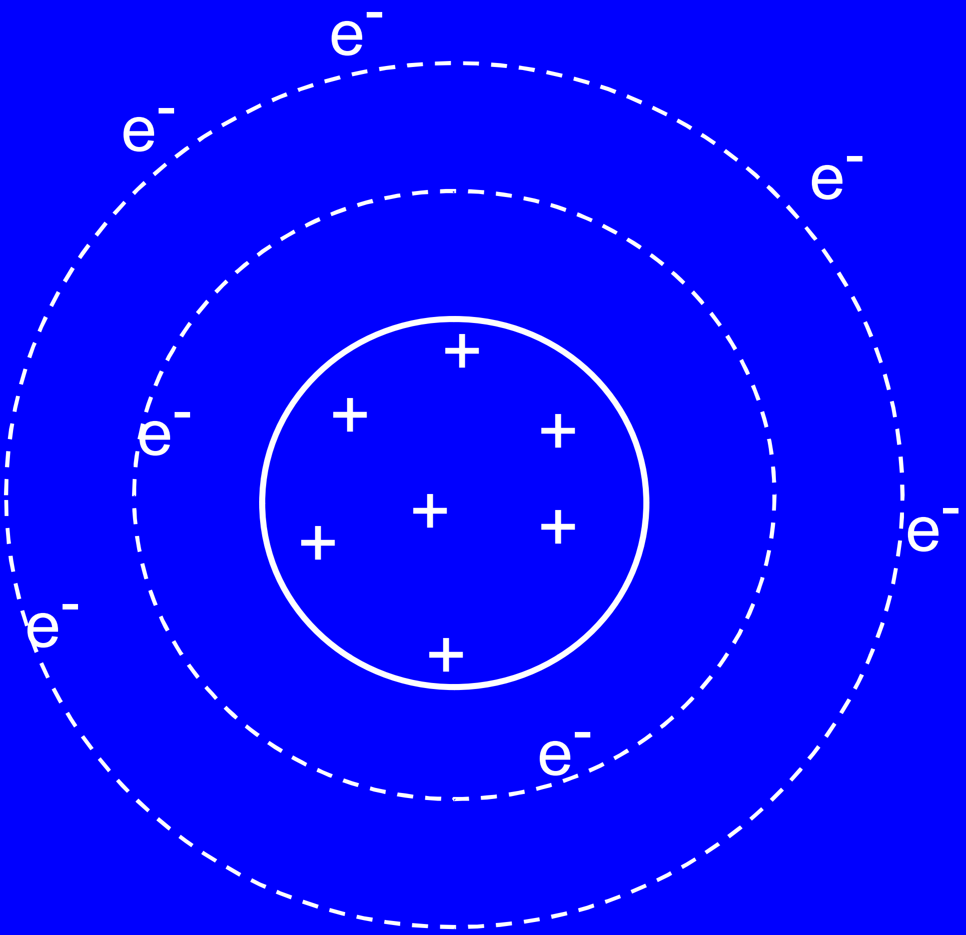
Ion Pairs

- Ionization turns a neutral atom into an ion pair.
- The electron stripped away from the atom is the negative member of the ion pair.

  It is known as a secondary electron.

  The secondary electron has some, but not much, kinetic energy - usually less than 100 eV.

  Sometimes it has enough energy to ionize additional atoms. Then it is referred to as a delta ray.
- The atom , now with a vacancy in one of its electron shells, is the positive member of the ion pair.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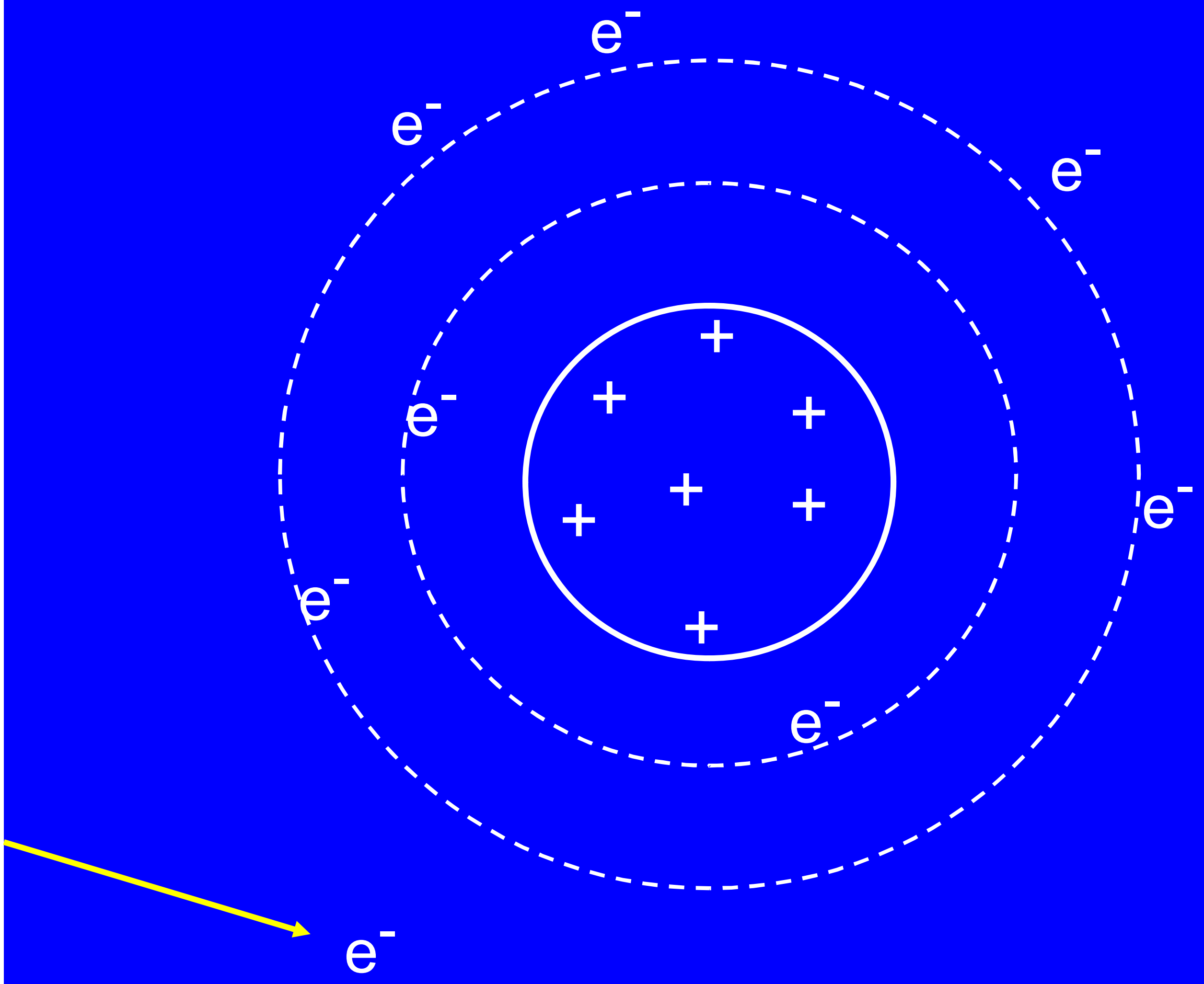
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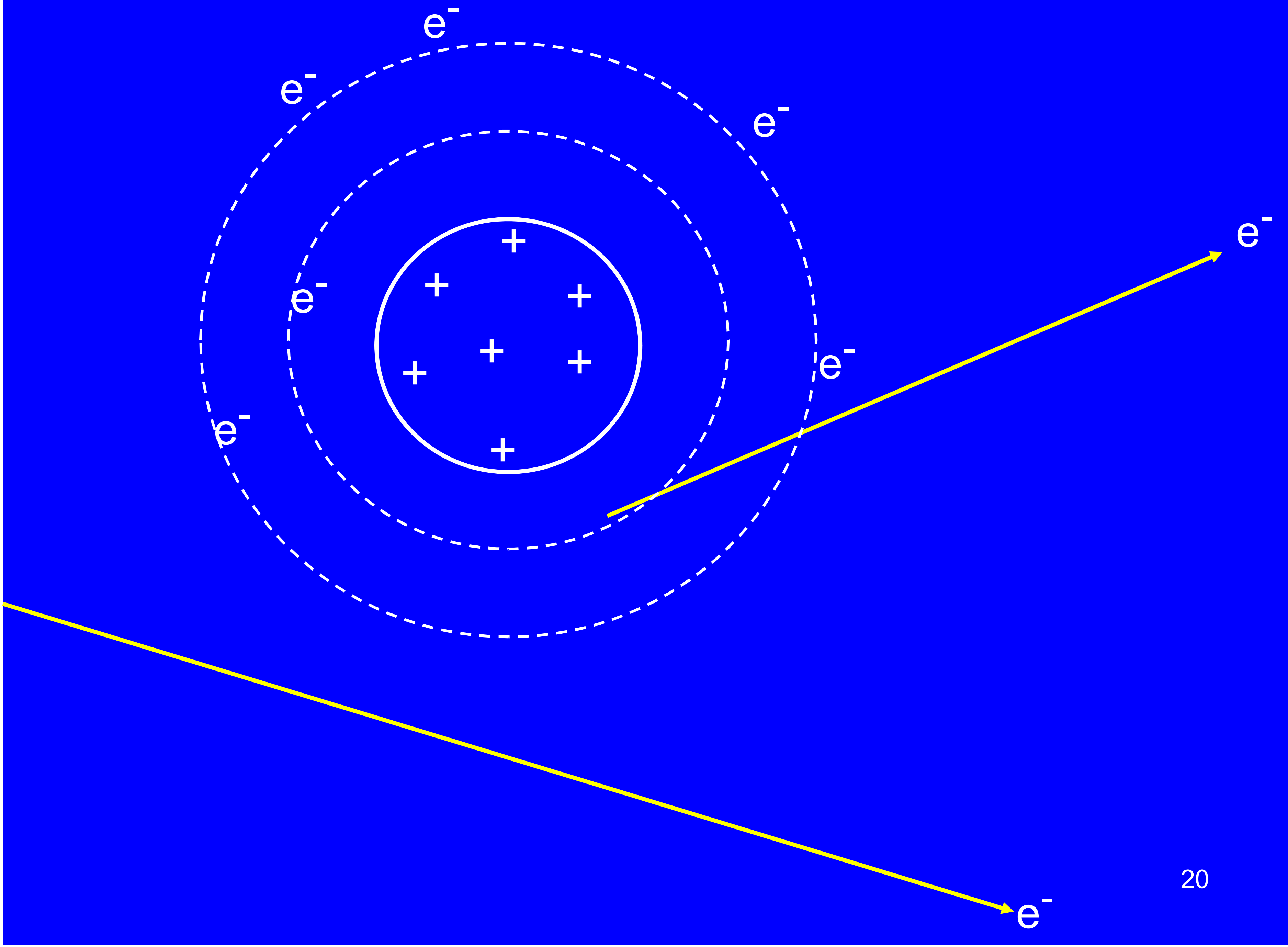
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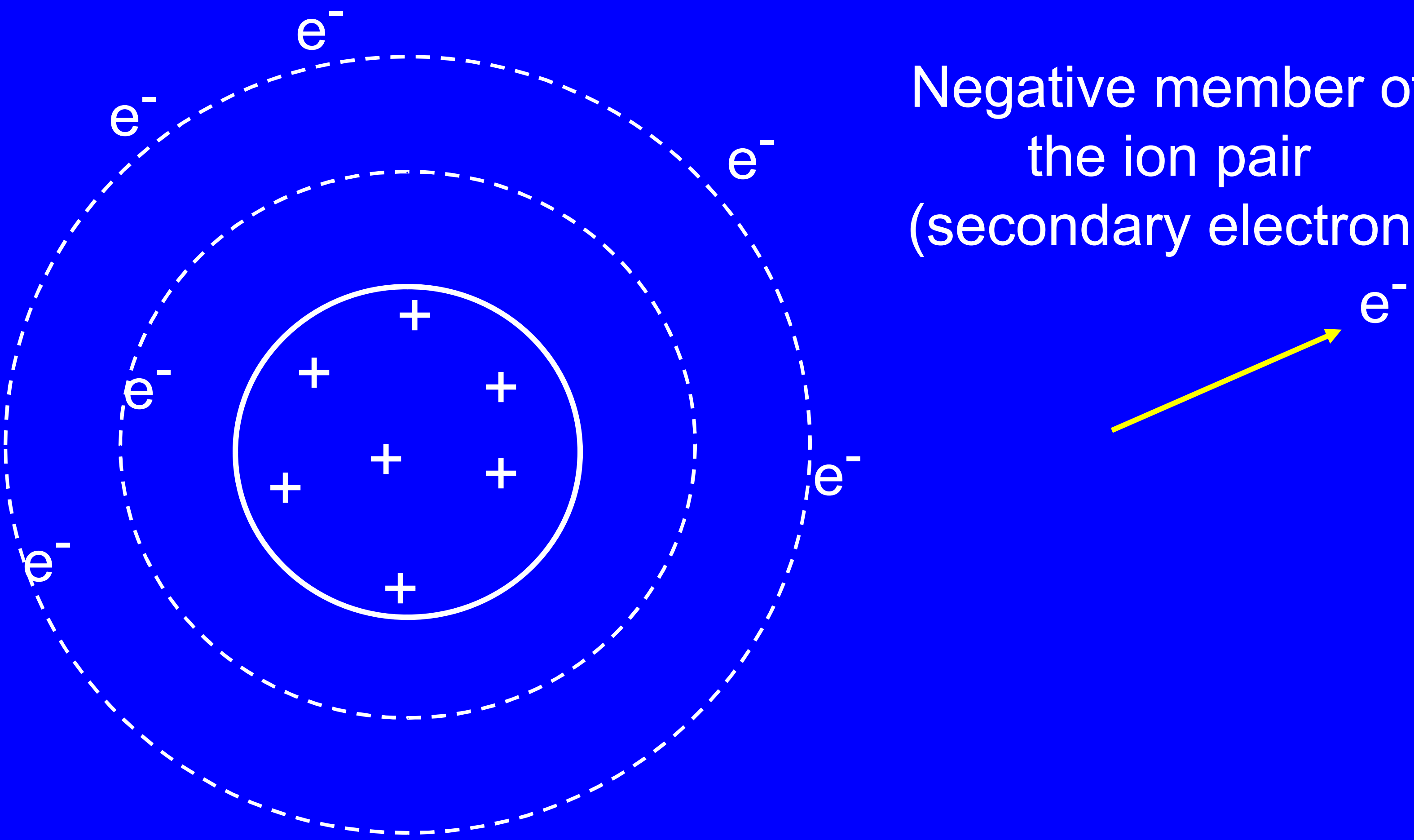
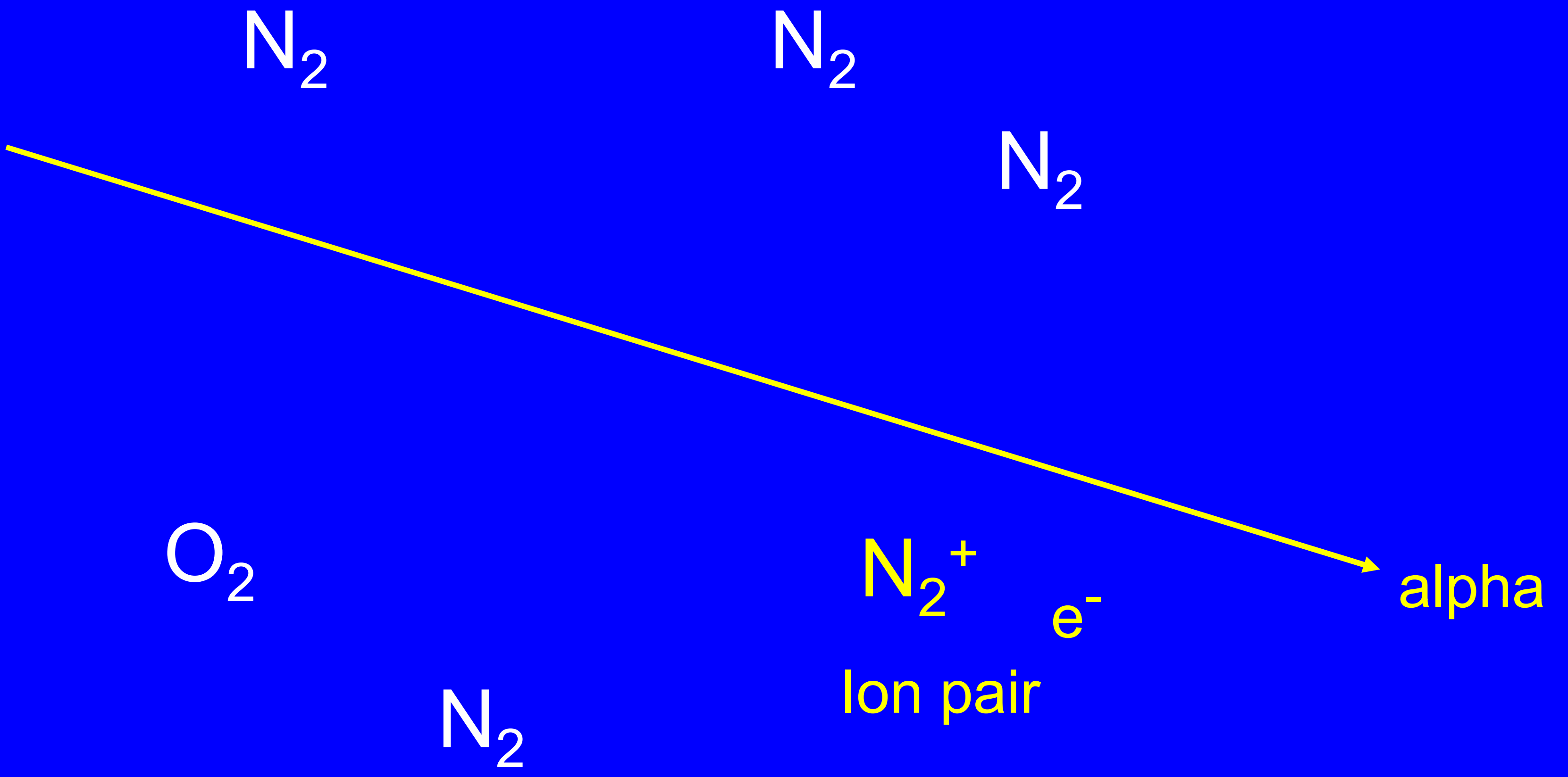


Negative member of
the ion pair
(secondary electron)

Positive member of the ion pair
(e.g., N_2^+)

This is an ion pair



N_2 N_2

N_2

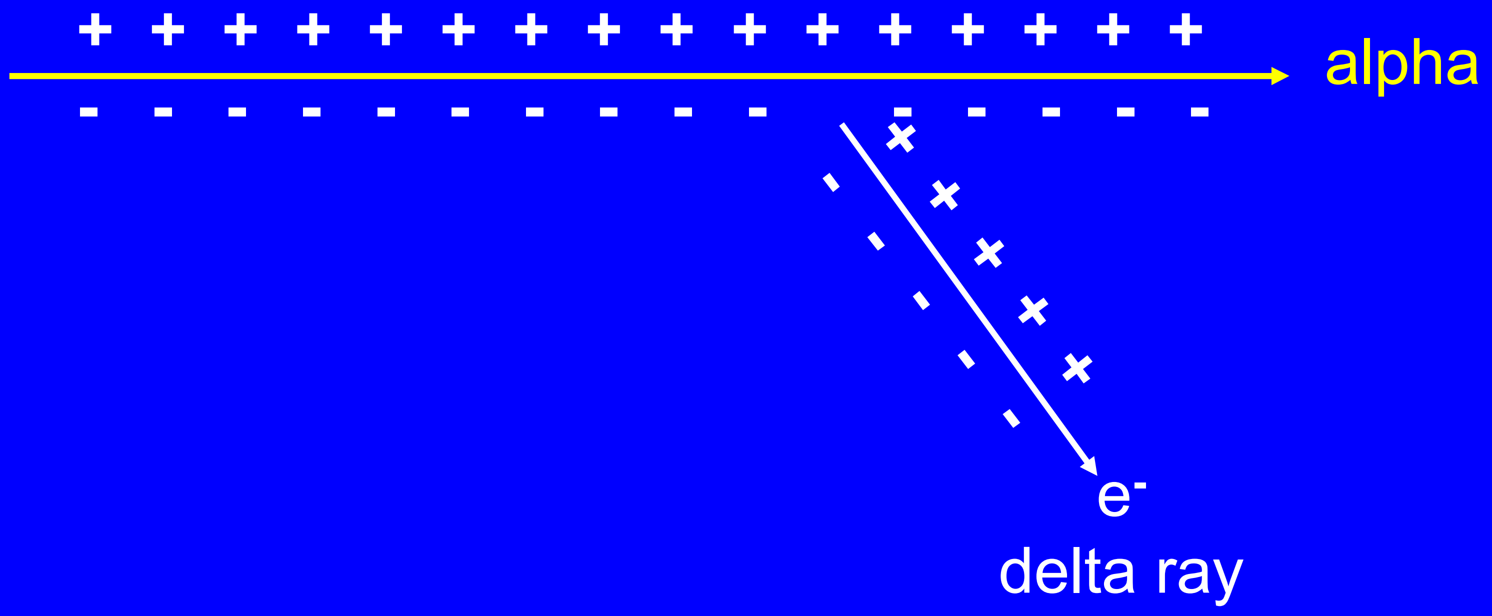
O_2 N_2^+ e^- alpha

Ion pair

N_2

Ionization

Delta Ray



A delta ray is a secondary electron (negative member of an ion pair) that has sufficient kinetic energy to cause additional ionization.

Excitation

Excitation

General

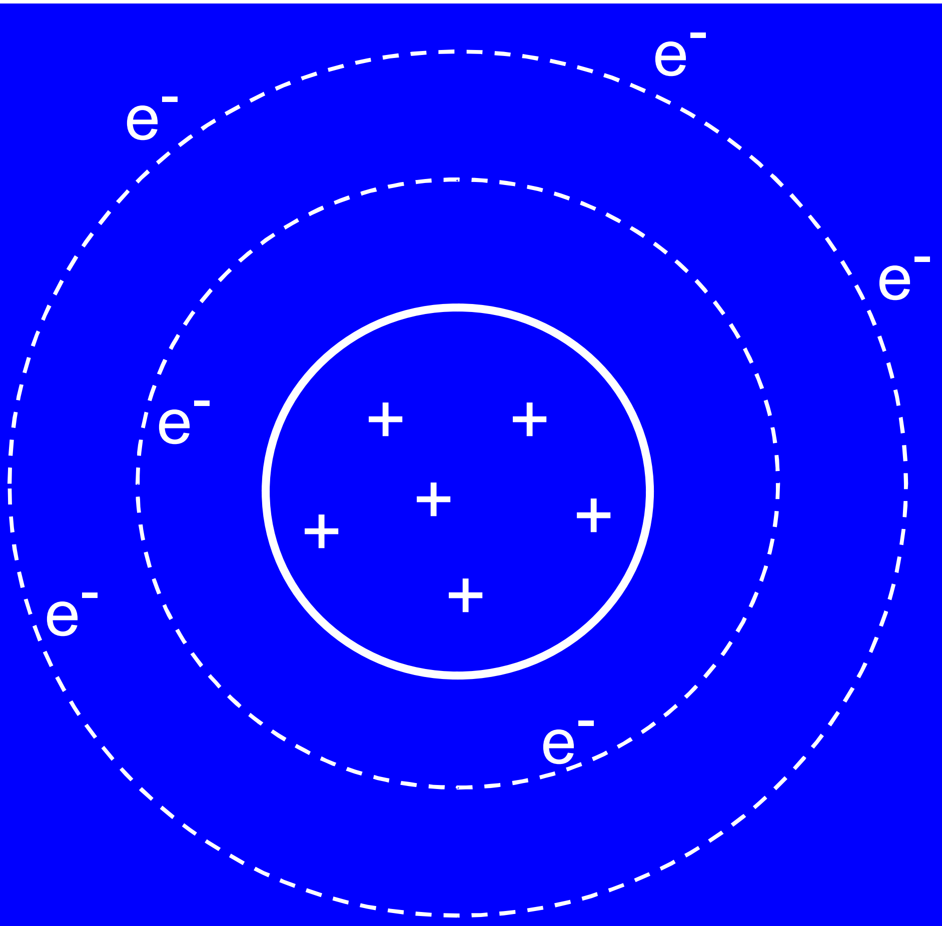
- The charged particle (alpha or beta particle) exerts just enough force to promote one of the atom’s electrons to a higher energy state (shell).

  Insufficient energy was transferred to ionize the atom.

- Excitation usually occurs farther away from the charged particle's trajectory than ionization.

- The excited atom will de-excite and emit a low energy ultraviolet photon.

- Each excitation event reduces the charged particle's velocity.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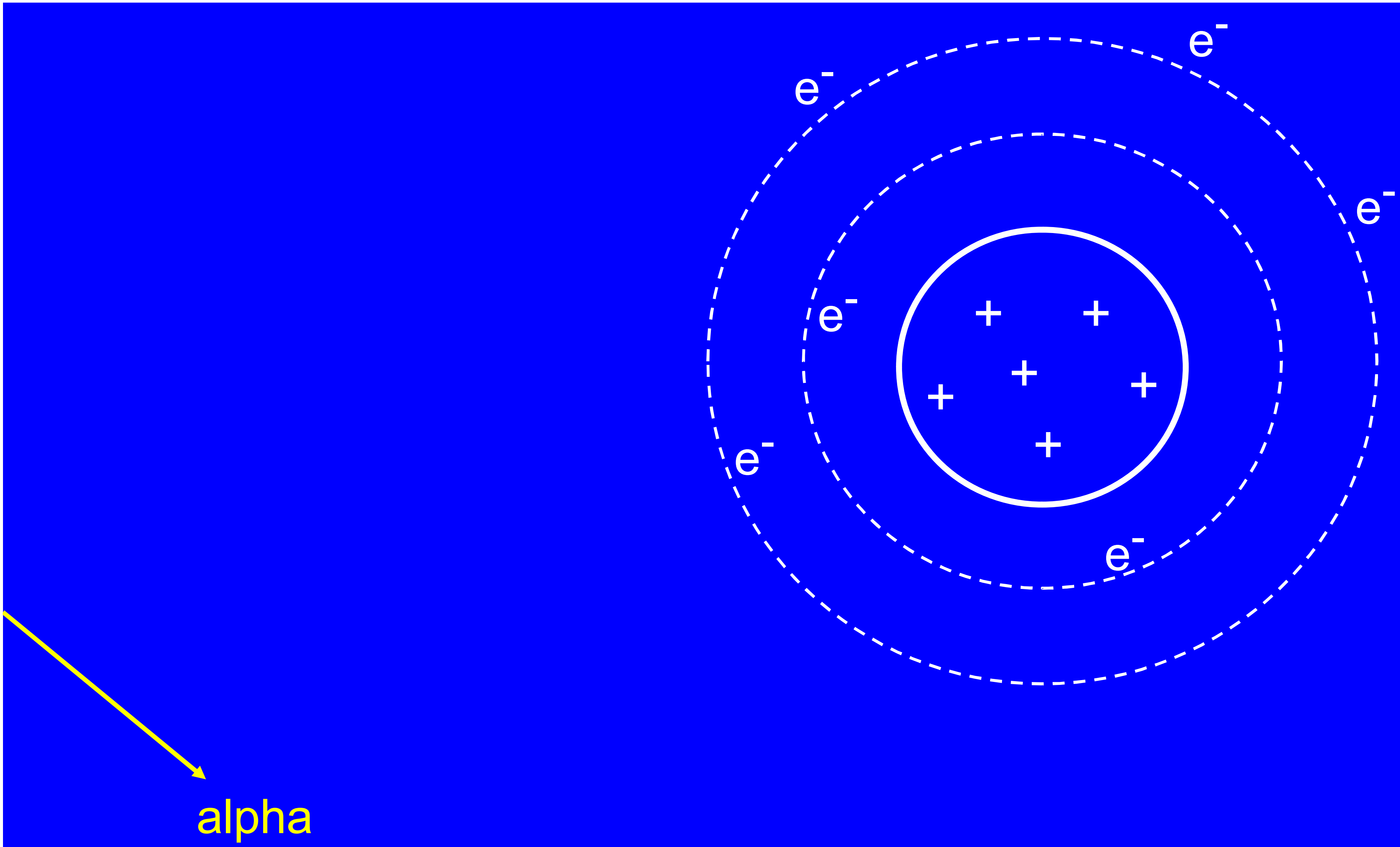
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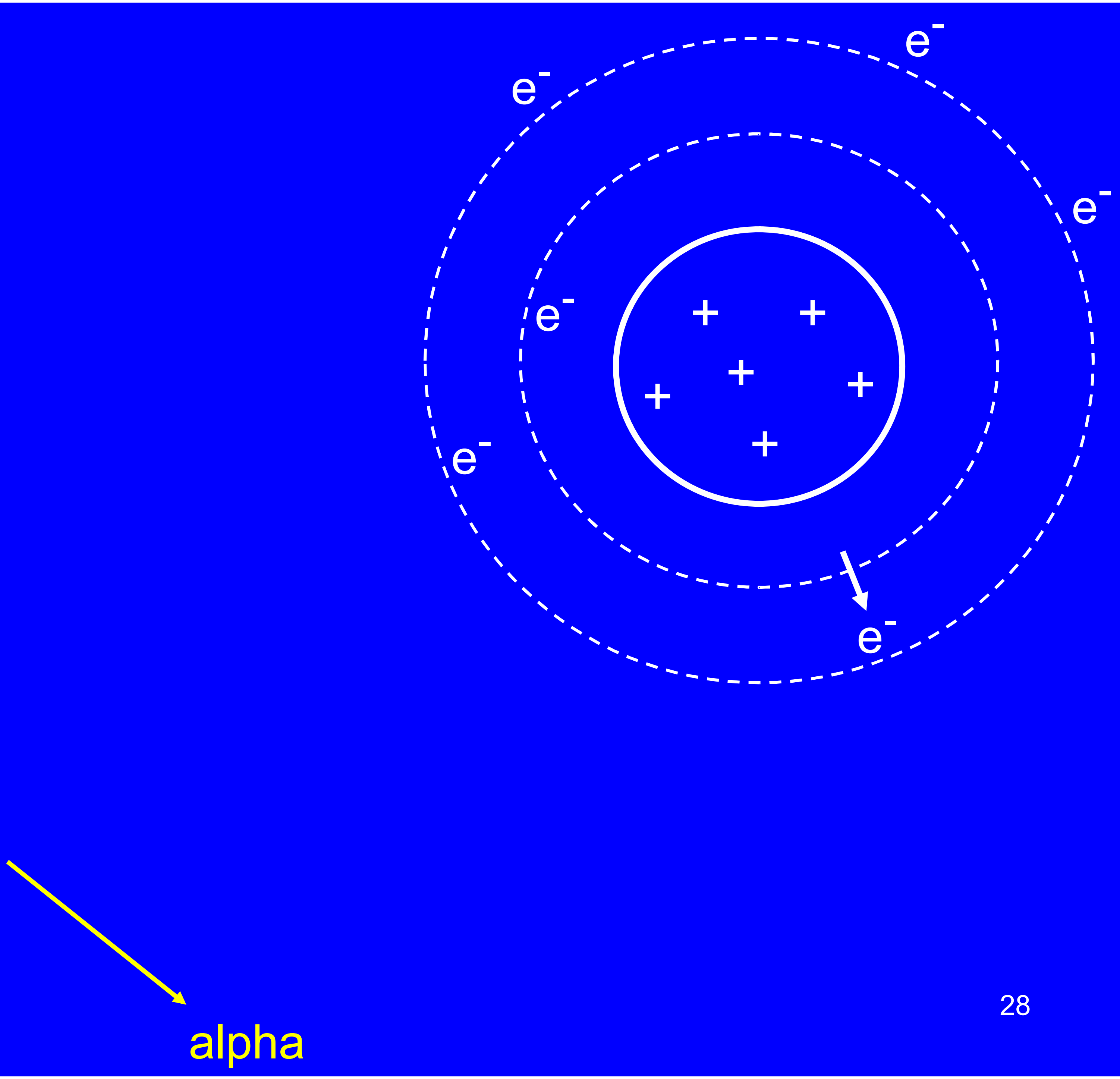
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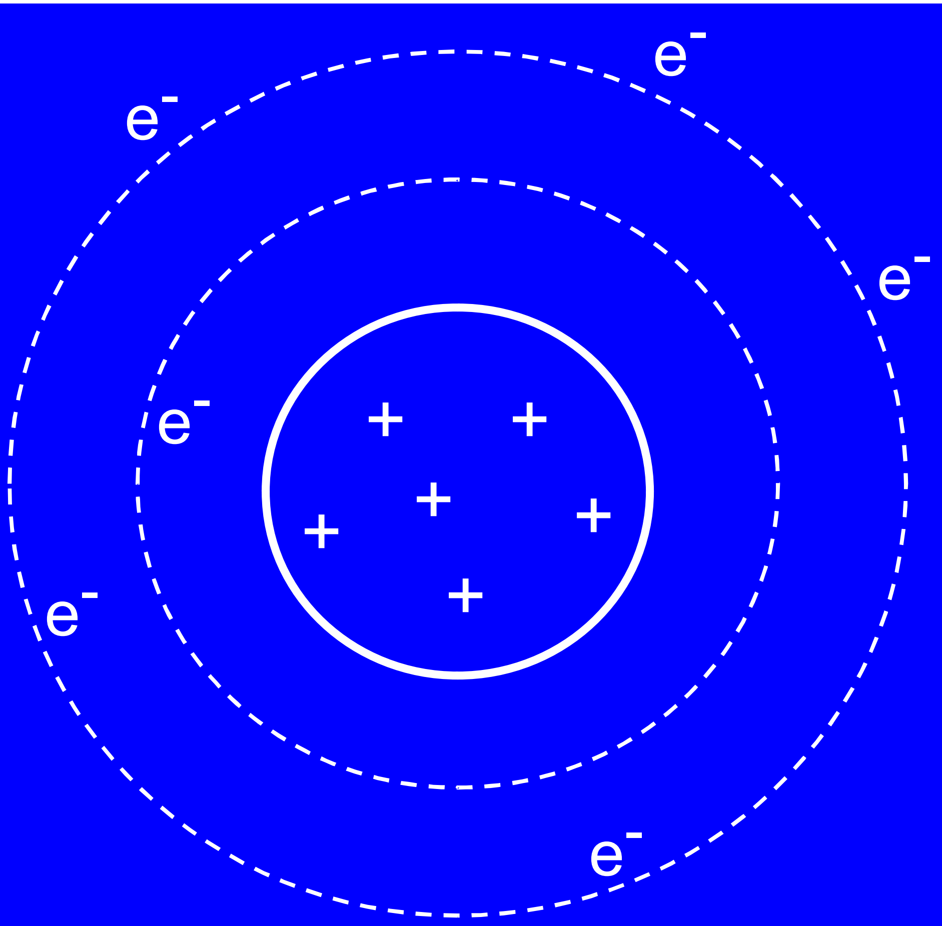

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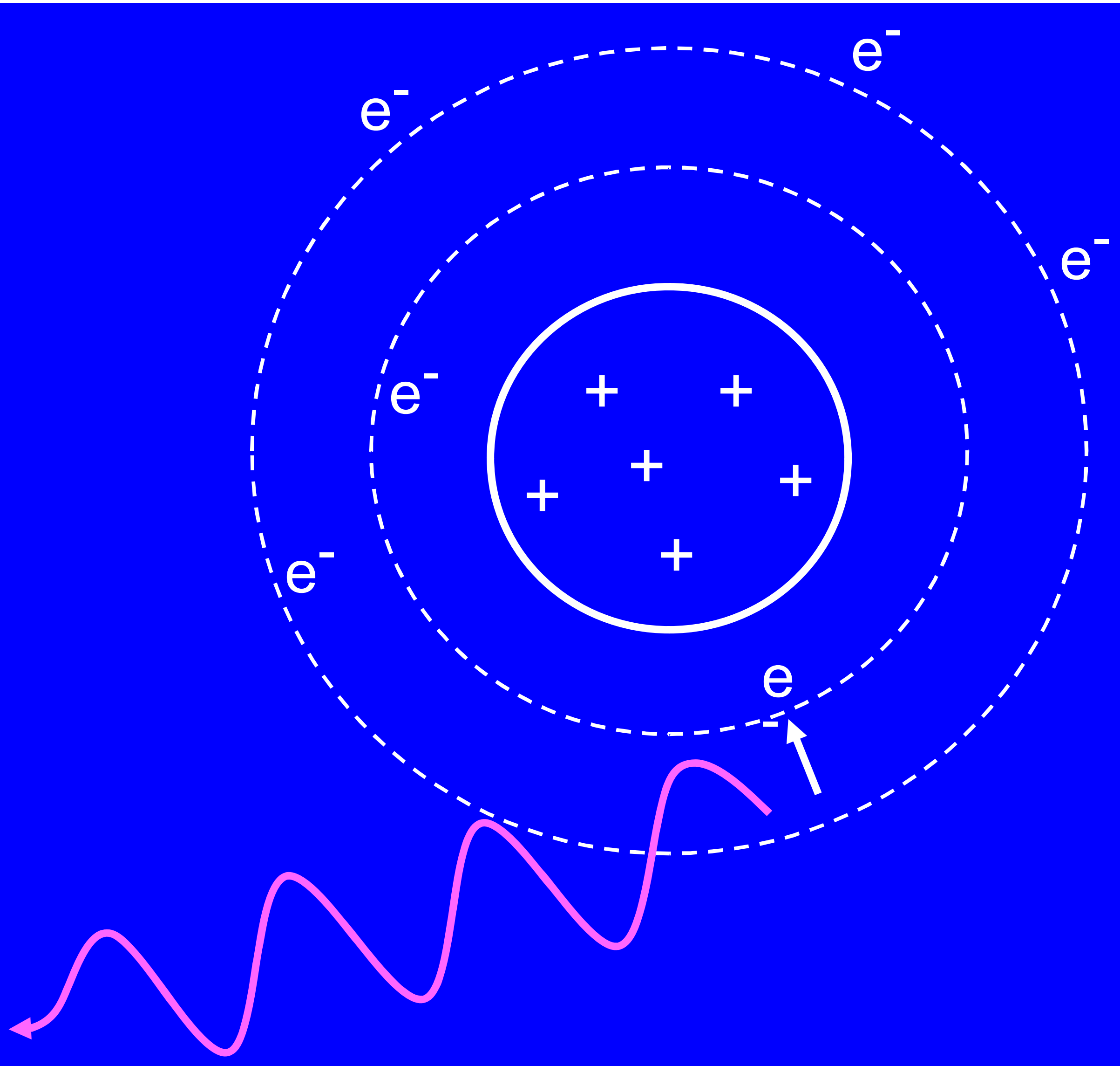


Ultra violet photon

Bremsstrahlung

Bremsstrahlung

General

- Bremsstrahlung radiation is electromagnetic radiation that is produced when charged particles are deflected (decelerated) while traveling near an atomic nucleus.

- Bremsstrahlung is almost exclusively associated with electrons (beta particles) because the latter are easily deflected.

- Large particles (e.g., alpha particles) do not produce significant bremsstrahlung because they travel in straight lines. Since they aren't deflected to any real extent, bremsstrahlung production is inconsequential.

Bremsstrahlung

General

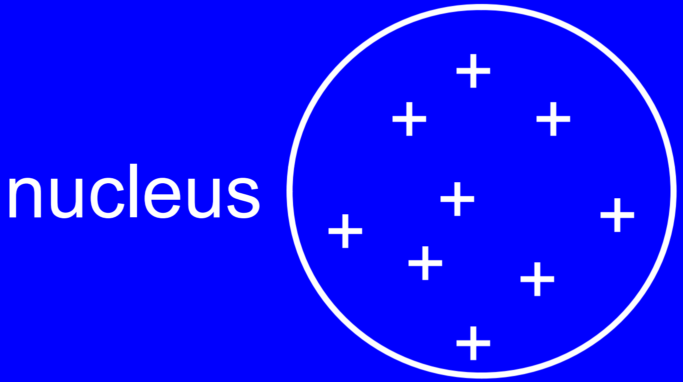
- Bremsstrahlung photons may have any energy up to the energy of the incident particle.

  For example, the bremsstrahlung photons produced by P-32 betas have a range of energies up to 1.7 MeV, the maximum energy of the P-32 alphas.

- Bremmstrahlung is most intense when:

  - The beta particles or electrons have high energies

  - The material has a high atomic number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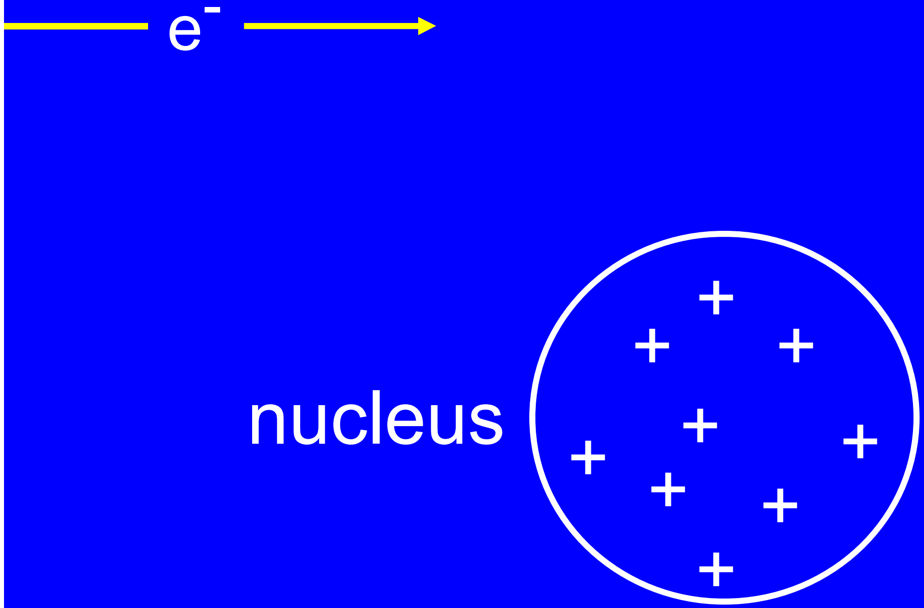
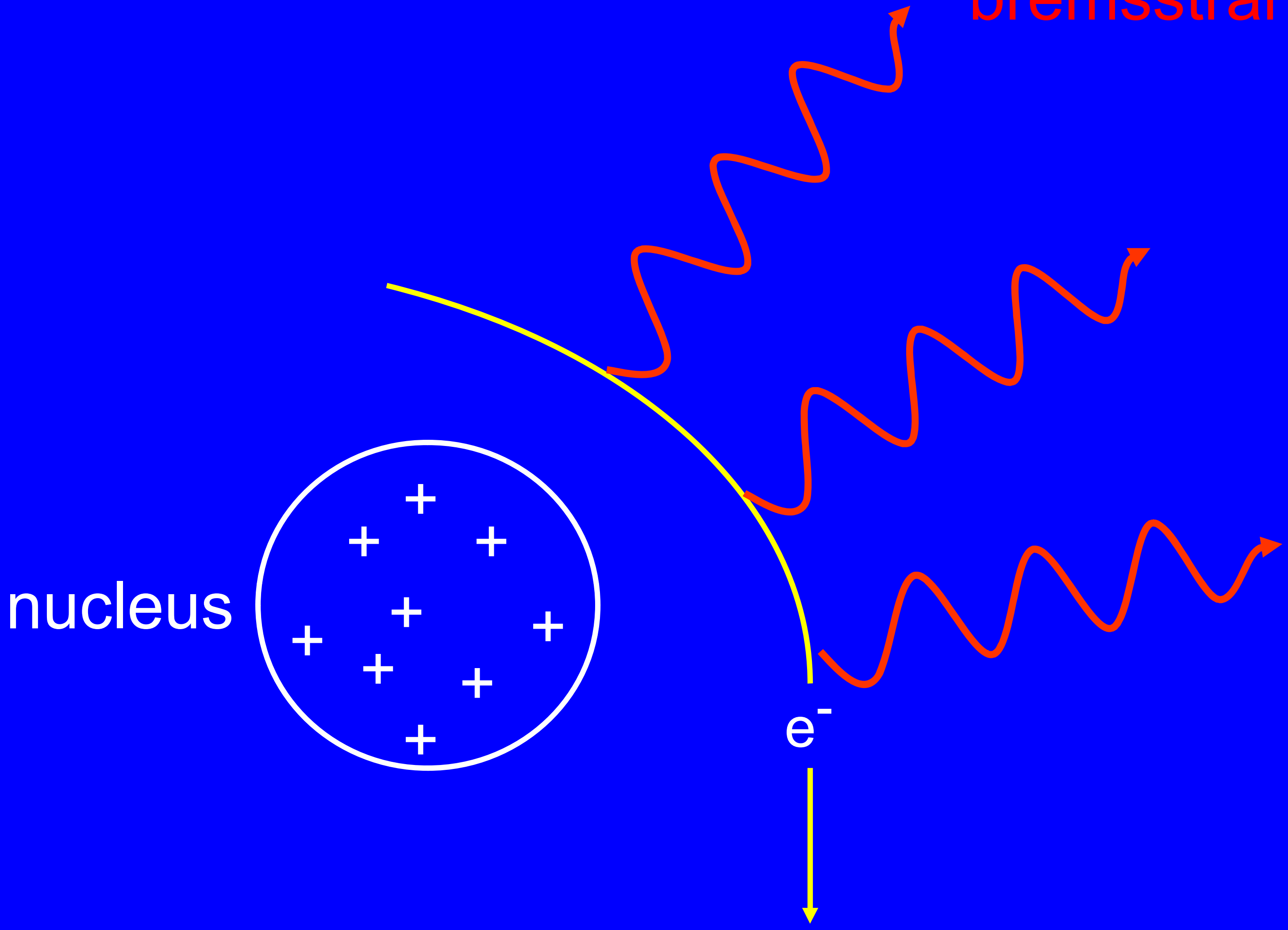
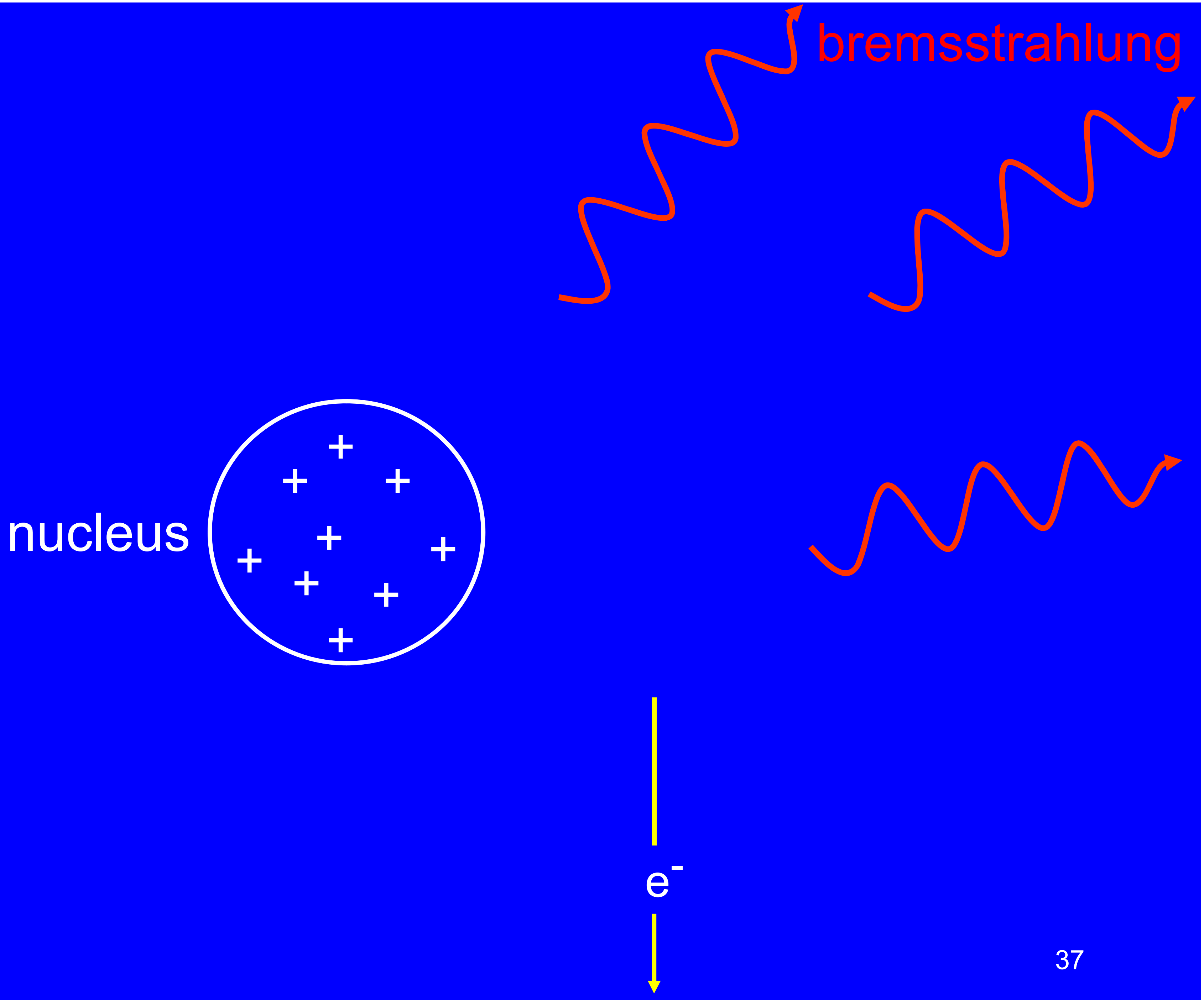
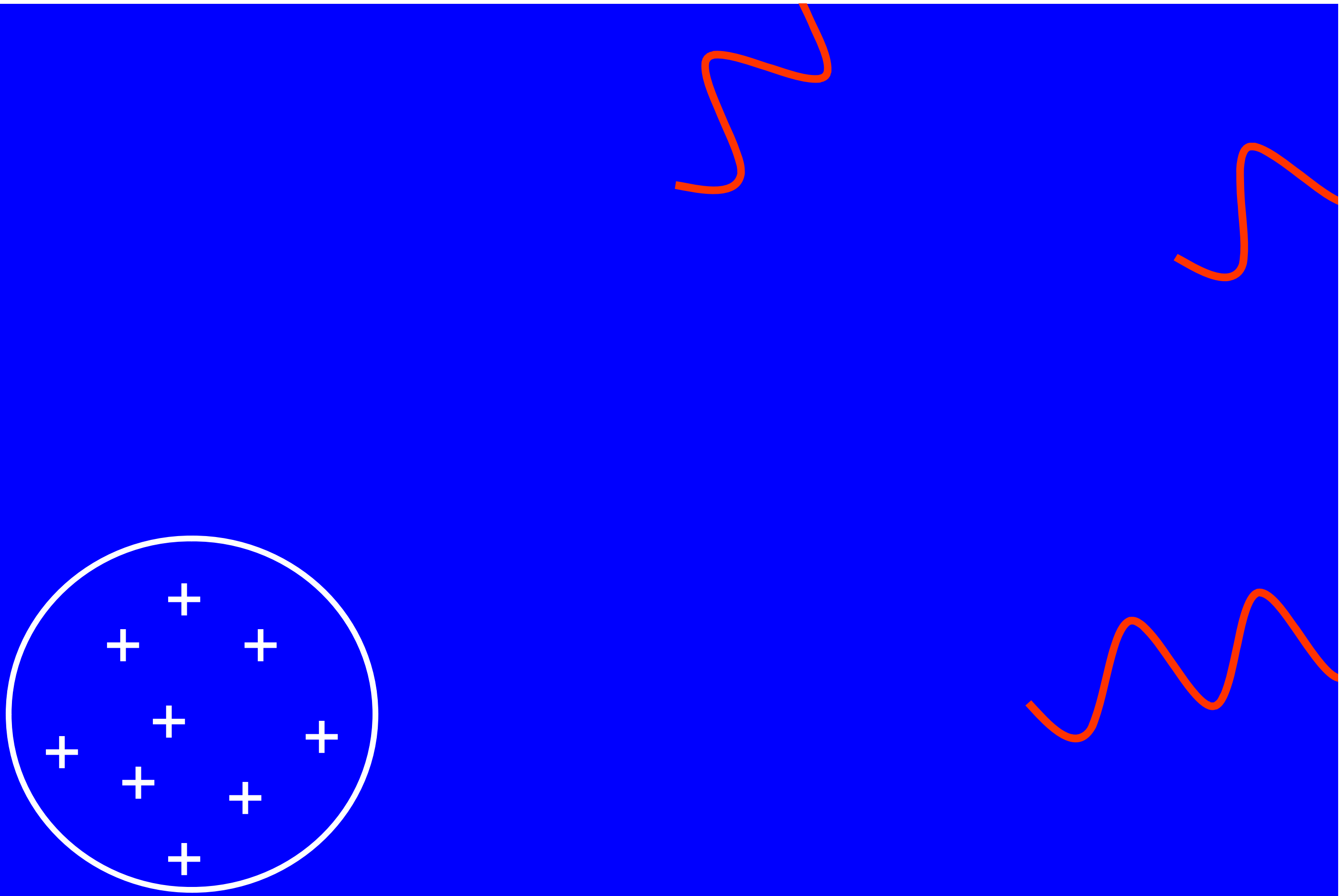

e^-
nucleus

bremsstrahlung




bremsstrahlung
nucleus
+
e^-



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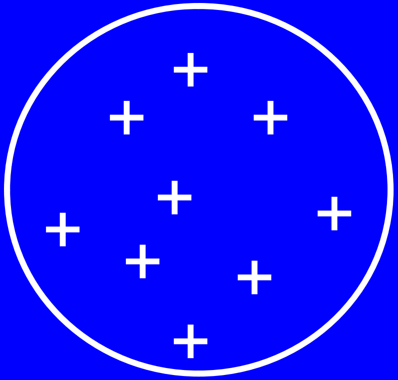

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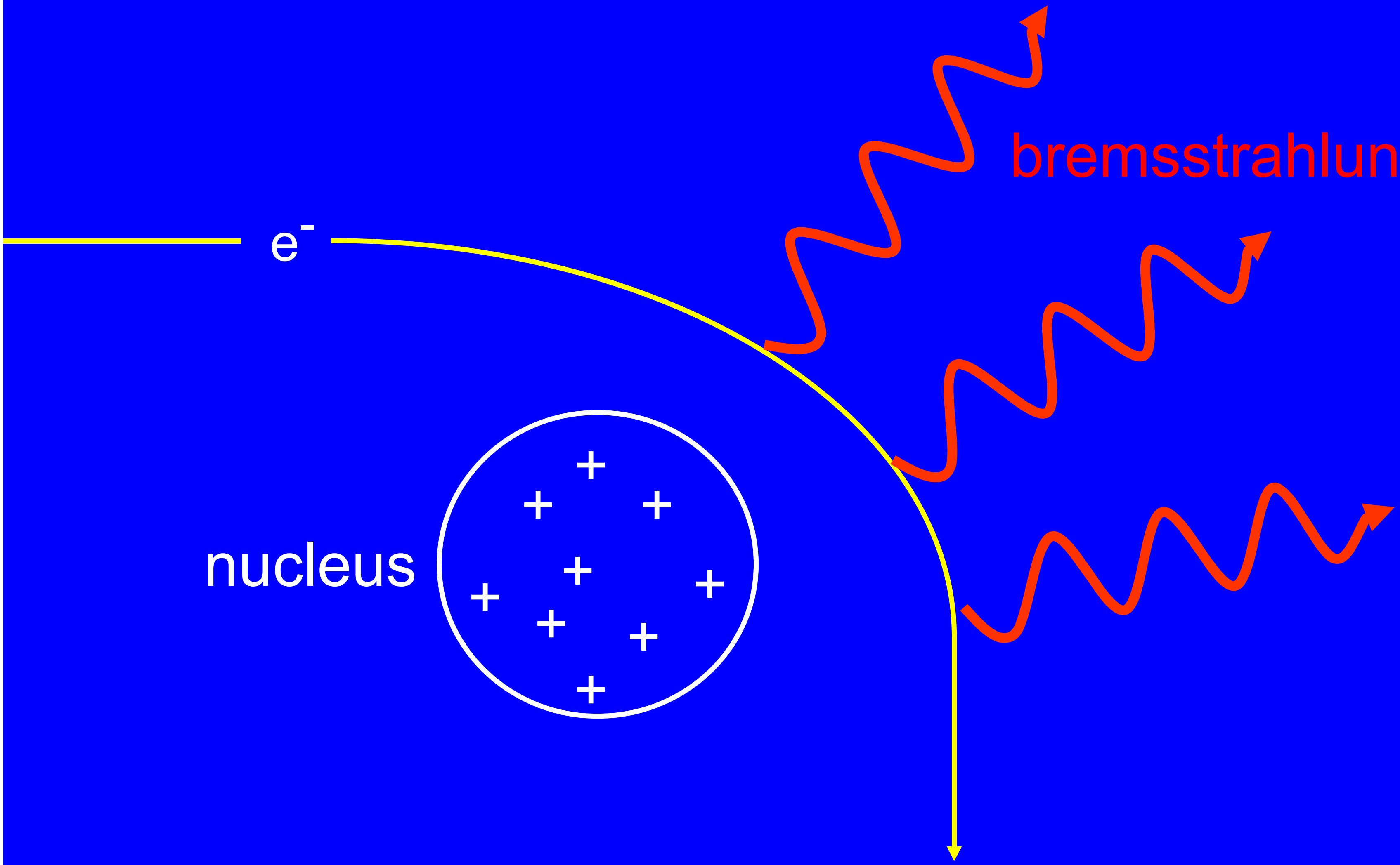


The greater the charge in the nucleus (atomic number), the greater the deflection of the electrons and the greater the intensity of the bremsstrahlung

Bremsstrahlung

Intensity of Bremsstrahlung – Monoenergetic Electrons

- According to Evans, the fraction of the energy of monoenergetic electrons that is converted to bremsstrahlung (f) can be calculated as follows

$$f = 0.0007\,Z\,E$$

Z is the atomic number of the material

E is the kinetic energy of the electron (MeV)

Bremsstrahlung

Intensity of Bremsstrahlung – Monoenergetic Electrons

- Turner gives slightly different equation for the fraction of the energy of monoenergetic electrons that is converted to bremsstrahlung:

$$f = \frac{(6\,x\,10^{-4})\,Z\,E}{1 + (6\,x\,10^{-4})\,Z\,E}$$

Z is the atomic number of the material

E is the kinetic energy of the electrons (MeV)

Bremsstrahlung

Intensity of Bremsstrahlung – Beta Particles

- The following equation (Evans) estimates the fraction of beta particle energy converted to bremsstrahlung (f).

  Beta particles are emitted with a range of energies up to some maximum value (E_{max}).

$$f = \frac{Z\ E_{\max}}{3000}$$

  Z is the atomic number of the material

  E_{max} is the maximum energy of the beta particles (MeV)

Bremsstrahlung

Intensity of Bremsstrahlung – Beta Particles

- The beta energy rate (MeV/s) is the activity of the beta emitter multiplied by the average energy of the beta particles:

Beta energy rate = Activity x Average beta energy
(MeV/s) (dps) (MeV)

- This is multiplied by the fraction (f) to determine the bremsstrahlung energy emission rate in MeV/s.

Bremsstrahlung energy rate = Beta energy rate x f
(MeV/s) (MeV/s)

Bremsstrahlung

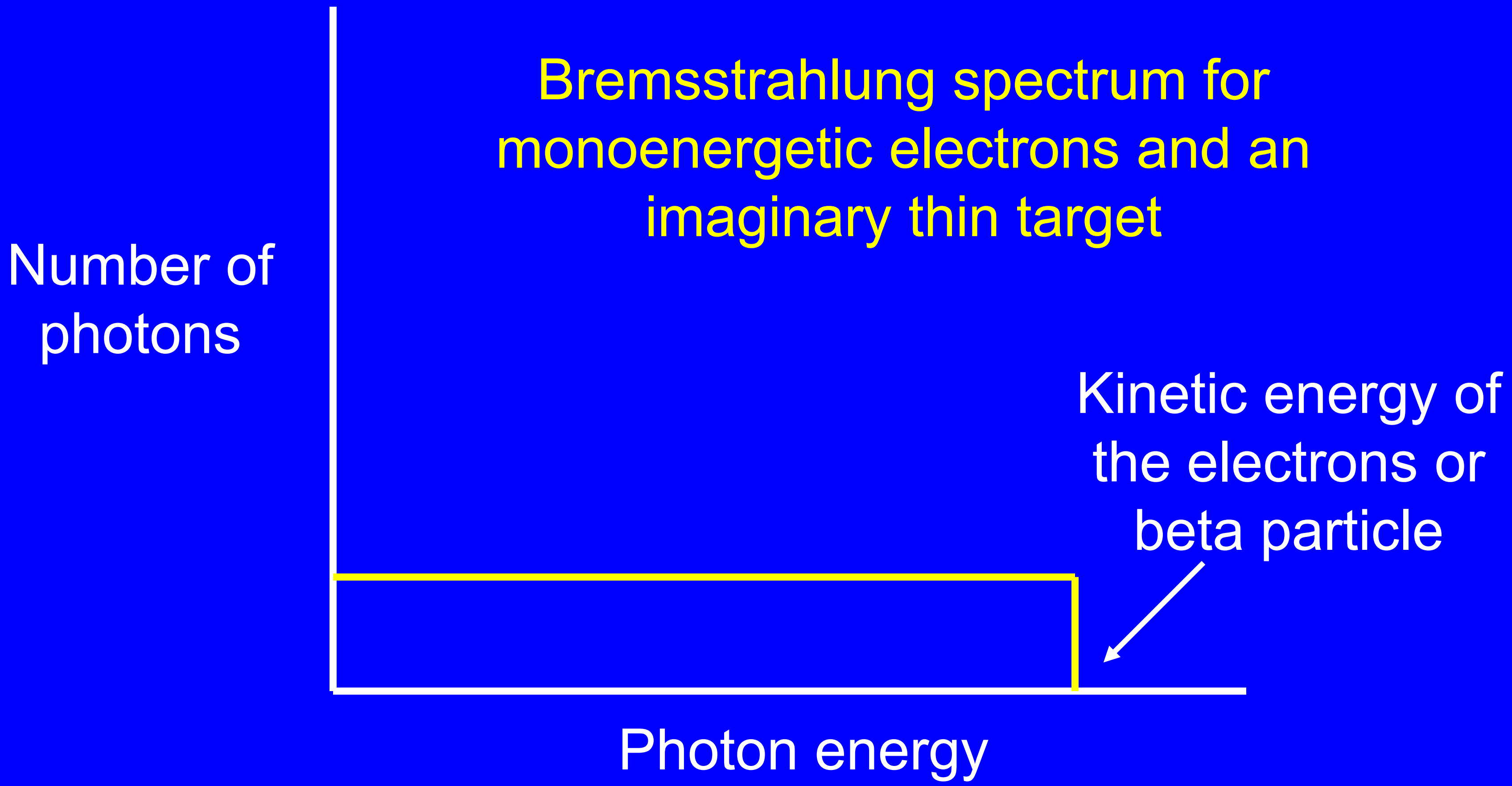
Bremsstrahlung Spectra

- The following discussion tries to explain the shape of a bremsstrahlung spectrum (e.g., that produced in the target of an x-ray tube)
- Bremsstrahlung photons have a range of energies up to the maximum energy of the electrons/beta particles.
- When monoenergetic electrons lose energy in an extremely thin target, the bremsstrahlung spectrum is flat up to the maximum energy of the electrons.

  Imaginary targets like this are not found in the real world.

Bremsstrahlung

Bremsstrahlung Spectra



Bremsstrahlung spectrum for monoenergetic electrons and an imaginary thin target

Number of photons

Kinetic energy of the electrons or beta particle

Photon energy

Bremsstrahlung

Bremsstrahlung Spectra

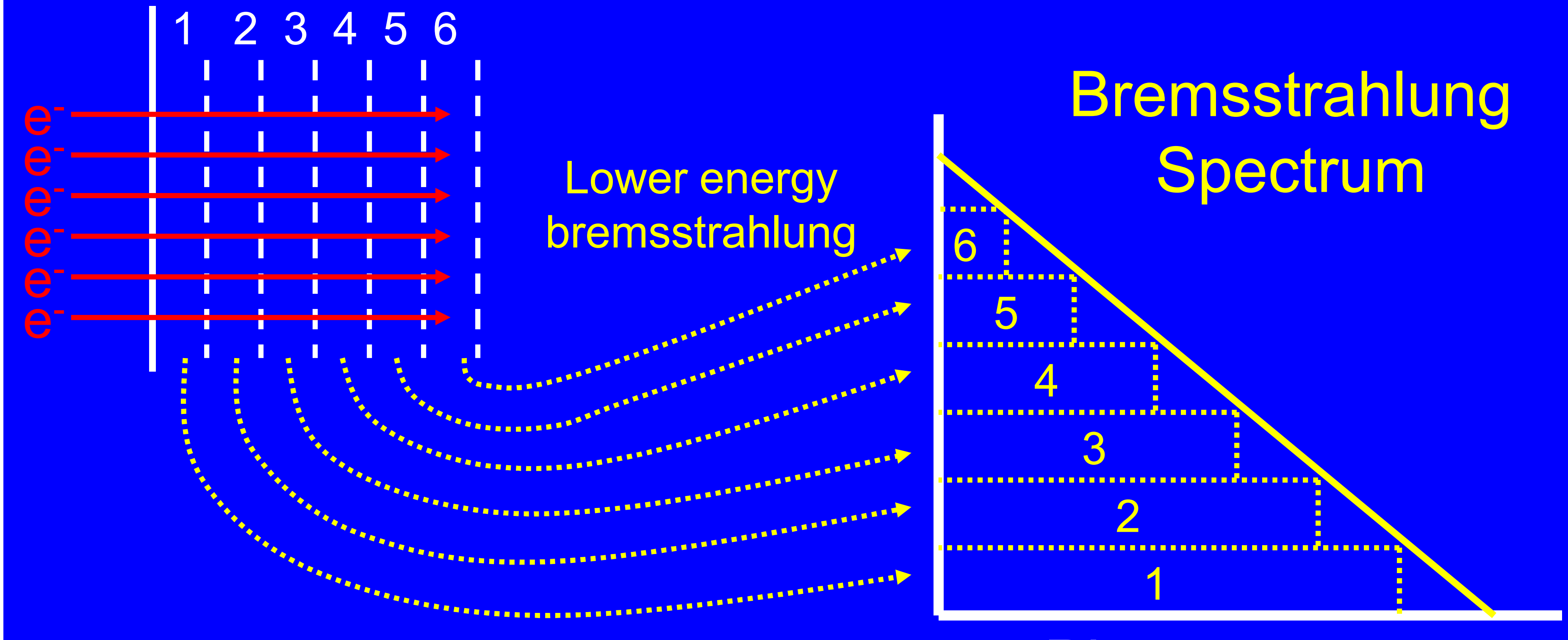
- Monoenergetic electrons losing energy in a thick (real world) target can be considered to interact in a series of thin sections (targets).
- The deeper into the target a given section is, the lower the energy of the electrons, and the lower the maximum energy of the bremsstrahlung produced there.

  The bremsstrahlung produced in the deeper sections by the lower energy electrons contributes to the low energy end of the overall bremsstrahlung spectrum:
- Bremsstrahlung produced in the shallow sections of the target where the electron energies are higher contributes to the high energy portion of the spectrum.

Bremsstrahlung

Bremsstrahlung Spectra

Target consisting of
six thin sections



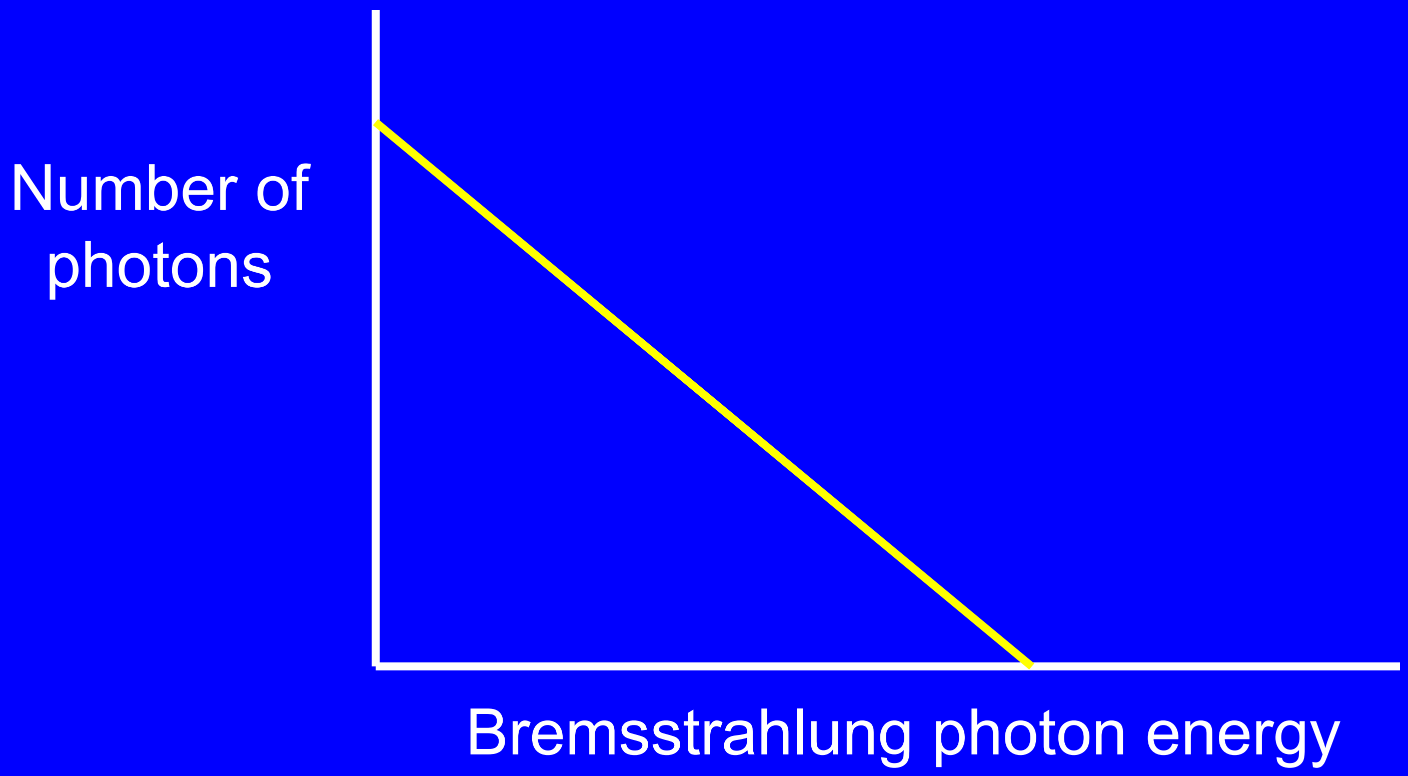
Higher energy bremsstrahlung

Photon energy

Bremsstrahlung

Bremsstrahlung Spectra

- As a result, the bremsstrahlung spectrum produced with a real world (thick) target looks something like this:



Bremsstrahlung

Bremsstrahlung Spectra

- There is always some shielding/filtration between the source of the bremsstrahlung and the point of interest.

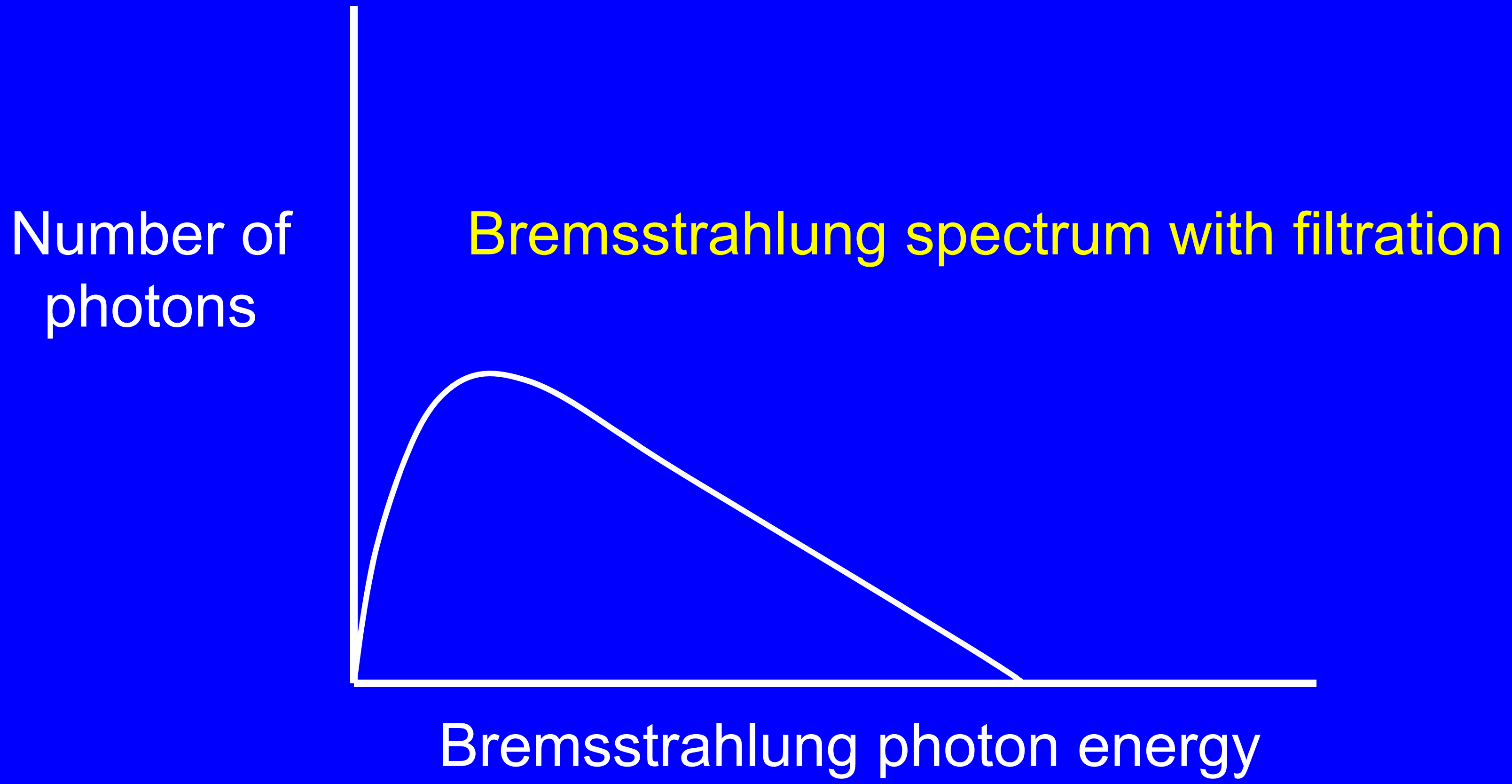
- For example, the glass wall of an x-ray tube will shield the bremsstrahlung generated in the target (anode) as would a filter intentionally placed in front of the tube.

- This shielding primarily reduces the intensity of the low energy bremsstrahlung.

- As such, a “real world” bremsstrahlung spectrum looks more like that on the next slide.

Bremsstrahlung

Bremsstrahlung Spectra



Cerenkov Radiation

Cerenkov Radiation Production

General

- Cerenkov radiation is the blue light emitted by charged particles that travel through a transparent medium (e.g., water) faster than the speed of light in that medium.

- Just as a plane going faster than sound produces a cone of sound (a sonic boom), a charged particle going faster than light produces a cone of light (Cerenkov radiation)

- The production of Cerenkov radiation is essentially limited to high energy (i.e., fast) beta particles and electrons.

Cerenkov Radiation Production

General

- Cerenkov radiation is often associated with reactor fuel pools or nuclear criticality accidents.
- It is possible to quantify beta emitters by measuring the intensity of their Cerenkov radiation (Cerenkov counting)

Quantitative Measures of Energy Loss

Quantitative Measures of Energy Loss

General

The four most common measures of energy loss by charged particles:

1. W Value
2. Specific Ionization
3. Stopping power or Linear Energy Transfer
4. Mass Stopping Power

Quantitative Measures of Energy Loss

W Value

- W is the average energy lost by a charged particle per ion pair produced.

- It depends on: the type of charged particle

  material that is being ionized

- W doesn't change much with the energy of the particle, but it does increase at low energies (< 0.2 MeV) for protons and alpha particles.

Quantitative Measures of Energy Loss

W Value

- Beta particles lose an average of 34 eV per ion pair produced in air.
- Alpha particles lose an average of 36 eV per ion pair produced in air.
- Alpha particles and beta particles (or electrons) lose an average of approximately 22 eV per ion pair produced in water (Turner p. 140, 161)

Quantitative Measures of Energy Loss

Specific Ionization

- Specific ionization is the average number of ion pairs produced per unit distance traveled in a material by a charged particle.
- It depends on: the type of charged particle,
  the energy of the charged particle
  the material through which it travels.
- Alpha particles produce 20,000 to 60,000 ion pairs per centimeter (cm) in air.
- Beta particles might produce 100 ion pairs per cm in air.

Quantitative Measures of Energy Loss

Stopping Power and Linear Energy Transfer

- There is no practical difference between stopping power and linear energy transfer.

- The stopping power or the linear energy transfer is the average energy lost by a charged particle per unit distance traveled.

- Typical units: MeV/cm or eV/um

Quantitative Measures of Energy Loss

Stopping Power and Linear Energy Transfer

- When a distinction is made:

  Stopping power is used to describe the total energy lost by the charged particle.

  Linear energy transfer (LET) is used to describe the energy lost by the charged particle that is locally absorbed in the material the particle is traveling through.

- In this sense, stopping power is akin to kerma while LET is akin to absorbed dose

Quantitative Measures of Energy Loss

Stopping Power and Linear Energy Transfer

- LET is sometimes referred to as the restricted stopping power.

  It describes the energy lost by charged particles in low energy interactions.

  The assumption is that the secondary electrons produced in these low energy interactions don’t travel outside the volume of interest and deposit their energy locally.

  This would exclude interactions producing delta rays or bremsstrahlung.

Quantitative Measures of Energy Loss

Stopping Power and Linear Energy Transfer

- The maximum energy that can be transferred in these interactions is sometimes indicated with a subscript, e.g., $\mathrm{LET}_{1\ \mathrm{keV}}$, $\mathrm{LET}_{5\ \mathrm{keV}}$
- The greater the energy cutoff, the larger the LET,

  e.g., $\mathrm{LET}_{5\ \mathrm{keV}} > \mathrm{LET}_{1\ \mathrm{keV}}$
- If no restriction is placed on the energy of the interactions, the unrestricted LET is indicated as LET_{∞}
- LET_{∞} is the same as stopping power.

Quantitative Measures of Energy Loss

Mass Stopping Power

- The mass stopping power can be more convenient to use than the stopping power.
- It is the stopping power (e.g., MeV/cm) divided by the density (g/cm^3) of the material.
- The units of the mass stopping power are usually MeV cm^2 g^{-1} (MeV per g/cm^2)
- It is the average energy lost by a charged particle per unit distance traveled where the distance is expressed as an aerial density (g/cm^2)

Alpha Particles

Alpha Particles

General

- The principal types of interactions for alpha particles are:
  - Ionization
  - Excitation
- Usually have energies from 4 to 8 MeV
- High specific ionization
  (because of their +2 charge and low velocity)
- High LET radiation - lose their energy very quickly as they travel through matter.

Alpha Particles

General

- Easy to shield – can be stopped by a piece of paper
- Not an external hazard – cannot penetrate the dead layer of skin on the surface of the body
- Potential internal hazard – the large radiation weighting factor for alpha particles (20) means that the consequence of a given alpha particle dose is greater than that for other types of radiation.

Alpha Particles

Alpha Tracks

Alpha particle tracks are short and straight.

From Turner, James. Atoms, Radiation, and Radiation Protection, 1st edition. 1986, pg. 74.

Alpha Particles

Range

- The range of an alpha particle is short:

  - approximately 5 cm in air.

  - 20 to 70 um in tissue (one, two or three cells)

- The survey instrument must be close (e.g., < 1 cm) to a contaminated surface if alpha emitting radionuclides are to be detected.

  It is best if the contaminated surface is dry and clean - dust or moisture could attenuate the alphas.

Alpha Particles

Range in Air

- Alphas with energies of 4 to 8 MeV (almost all alpha emitters):

$$R\ (\text{cm}) = 1.24\,E - 2.62$$

- Alphas with energies below 4 MeV:

$$R\ (\text{cm}) = 0.56\,E$$

E is the alpha energy in MeV

Alpha Particles

Approximate Data for 5 MeV Alphas

	Air (ρ=0.001293 g/cm^3)	Water (ρ=1 g/cm^3)
W (eV/ip)	36	22
Stopping Power/LET (MeV/cm)	1.23	950
Mass Stopping Power (MeV cm^2 g^{-1})	950	950
Specific Ionization (Ion pairs per cm)	34,000	4.3 x 10^7
Range (g/cm^2)	5 x 10^{-3}	3 x 10^{-3}
Range (cm)	4	3 x 10^{-3} (30 um)

Beta Particles

Beta Particles

General

- Beta particles (or electrons) interact by all of the following mechanisms:
  - Ionization
  - Excitation
  - Bremsstrahlung
  - Cerenkov radiation *(relatively unimportant)*

For betas above 150 eV, roughly 95% of the particle's energy loss in water is due to ionization.

Beta Particles

General

- Not as intensely ionizing as alphas (because they have higher velocities and one half the charge).
- Low specific ionization (ca. 100 ion pairs per cm in air)
- Low stopping powers (low LET radiation)
- Betas might produce (the specific ionization) in air.

Beta Particles

Range

- Much greater range than alphas (except for the lowest energy betas):
  - Approximately 3 meters in air for a 1 MeV beta
  - A few millimeters in tissue (water)
- The atomic number of the material is not a major factor. In fact, the range of beta particles under 20 MeV is greater in lead than in water!
- The next slide shows two empirical equations relating the range of a beta particle to its energy.

Beta Particles

Range (as a density thickness)

- The range of a beta particle can be determined if the energy is known:

$$R = 0.412\,E^{1.27 - 0.0954 \ln E}$$

- The energy of a beta particle can be determined if the range is known:

$$\ln E = 6.63 - 3.2376\sqrt{10.2146 - \ln R}$$

R is the range in mg/cm^2

E is the maximum beta energy in MeV

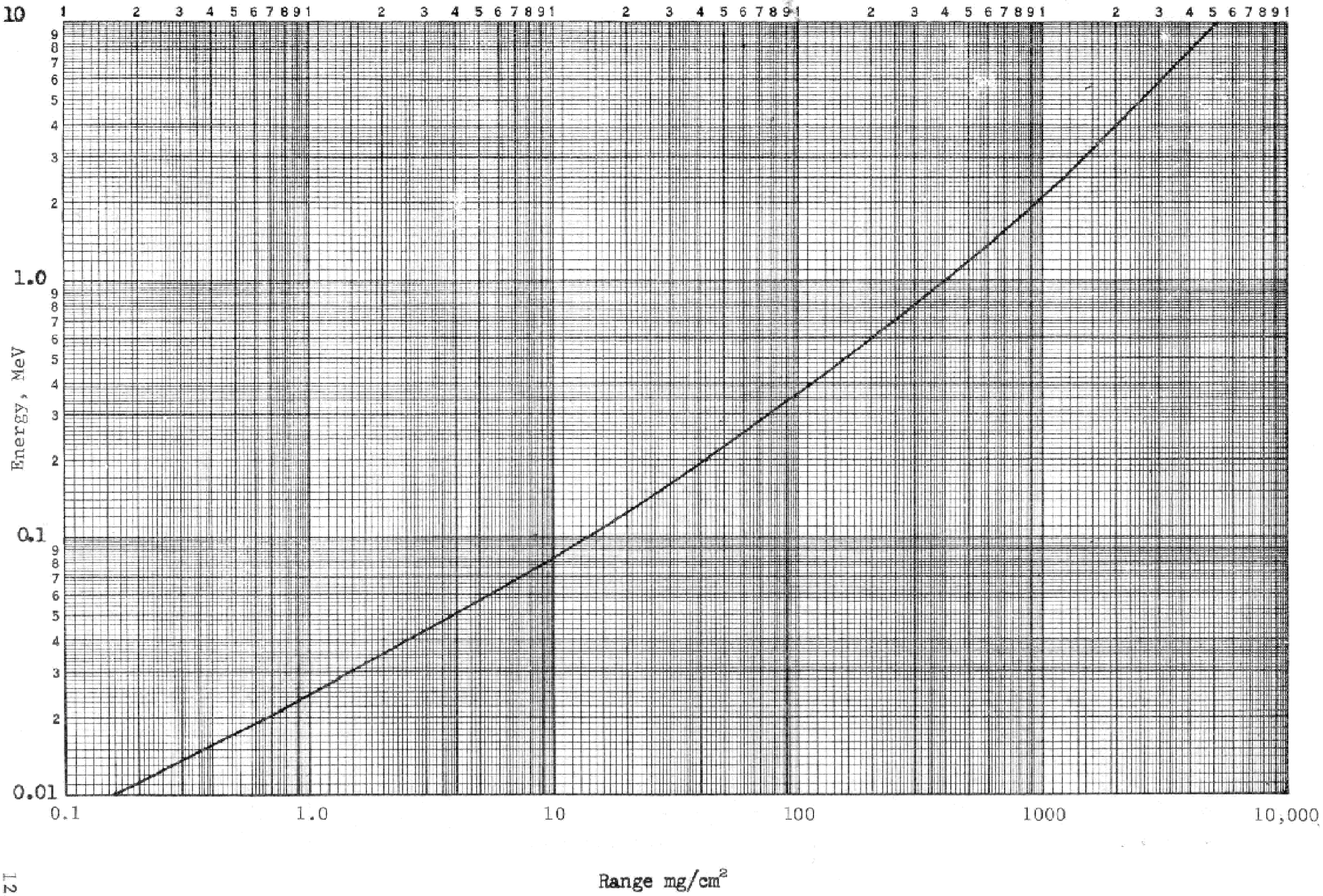
Beta Particles

Range (as a density thickness)

- The easiest way to determine the range of a beta particle is to use a curve similar to that on the next slide.

  A more readable version can be found on page 163 of PTP's Rad Health Handbook.

BETA PARTICLE
RANGE ENERGY CURVE



Beta Particles

Range and Penetration

- Beta particles (and electrons) travel in convoluted paths.
- They do not travel in a straight line.
- The “range” of a beta particle usually refers to the total path length.
- The range is greater than the distance between the beginning and the end of the path followed by the particle (the penetration thickness).

  In other words, the range of a beta particle is greater than the thickness of a material that can be penetrated.

Beta Particles

Range and Penetration

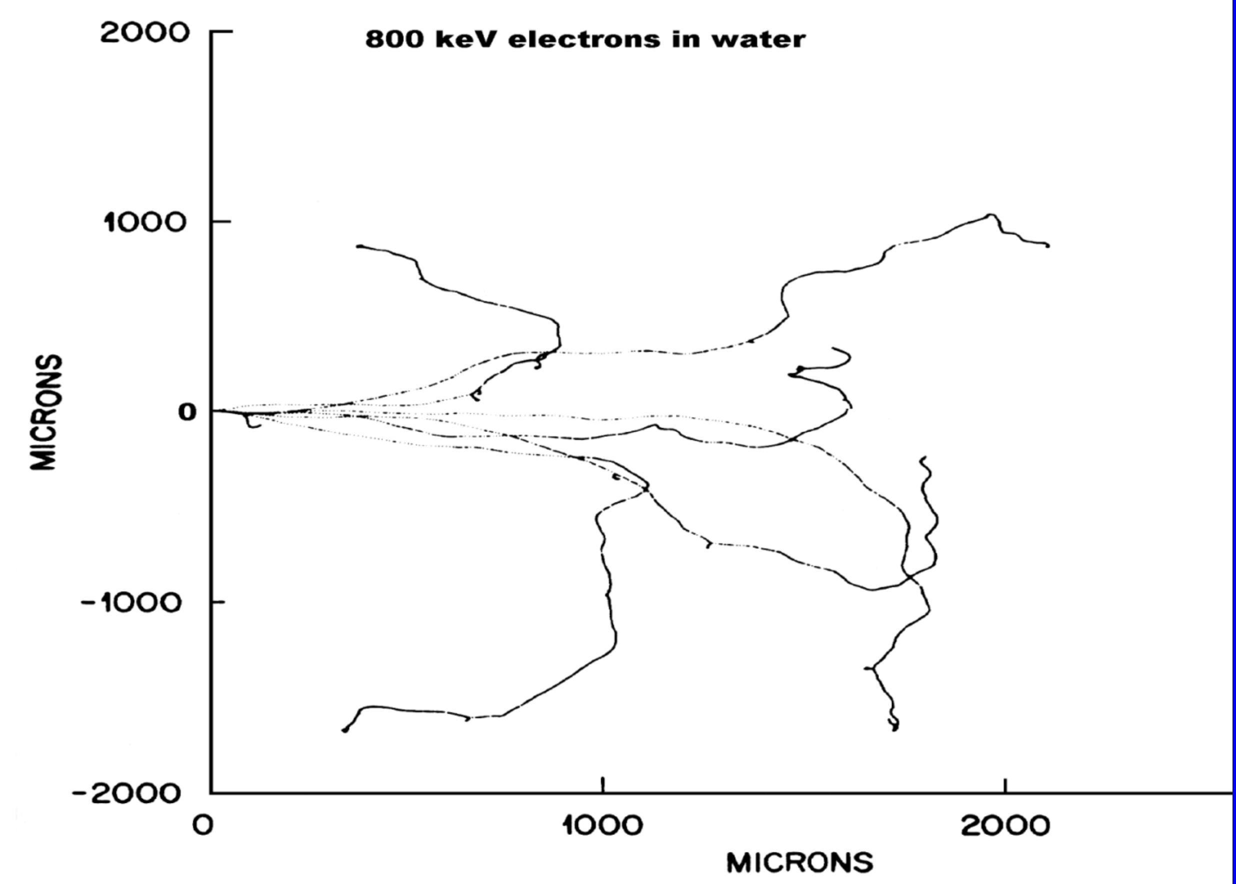
- The following slide shows the predicted paths of 800 keV beta particles in water.

The average penetration thickness: 1500 um

The average range (path length): 3500 um.

Beta Particles

Range and Penetration

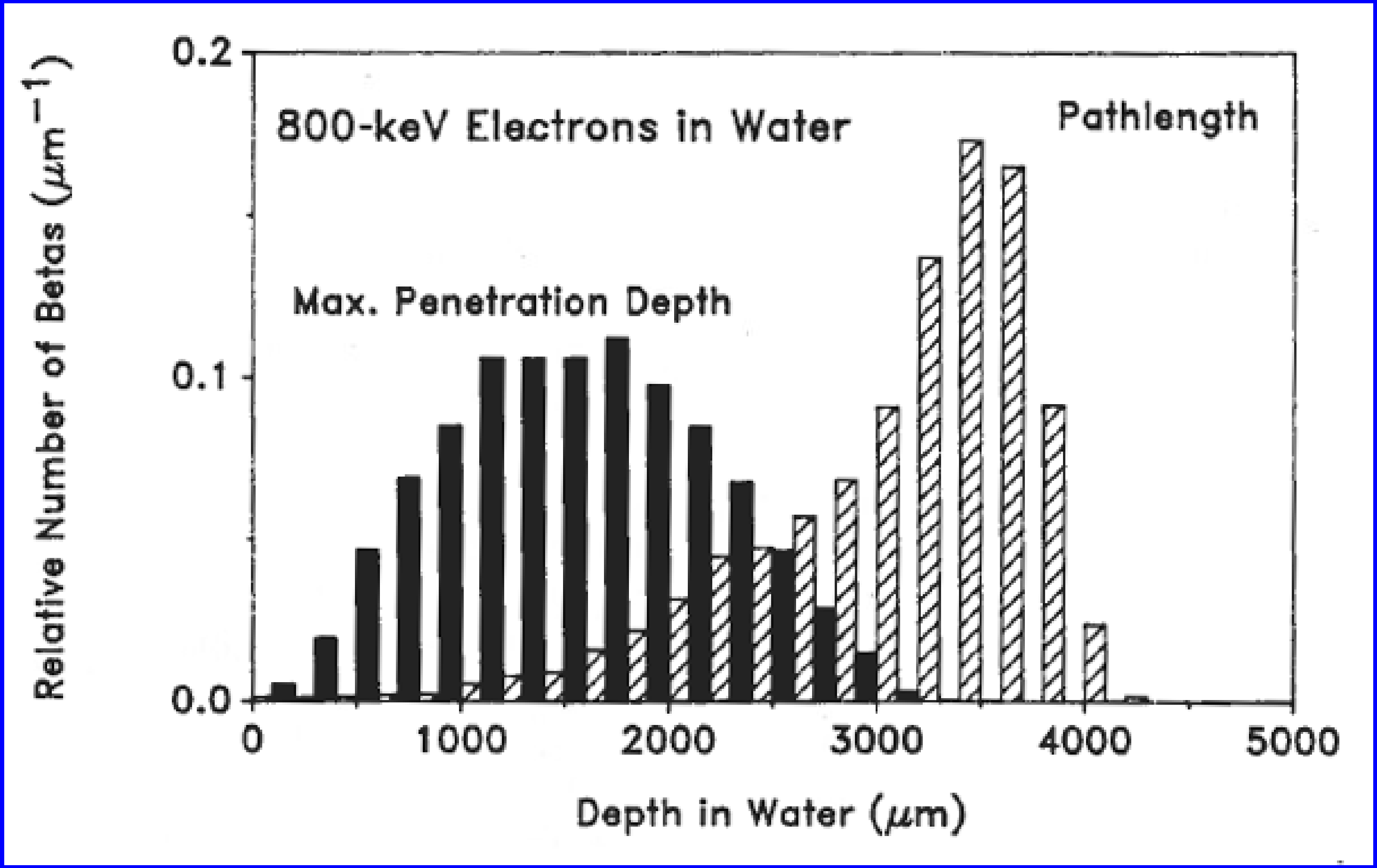


Beta particle tracks are convoluted.

From Turner, James. Atoms, Radiation, and Radiation Protection, 2nd edition. 1995, pg. 151.

Beta Particles

Range and Penetration



From Turner, James. Atoms, Radiation, and Radiation Protection, 2nd edition. 1995, pg. 151.

Beta Particles

Bremsstrahlung

- Bremsstrahlung is most significant for high energy beta emitters such as P-32 and Sr-90.
- The presence of bremsstrahlung is often interpreted as a indication that high energy beta emitters are present.
- Nevertheless, bremsstrahlung can be detected when low energy beta emitters (e.g., tritium) are present in high enough activities (e.g., a tritium exit sign).

Beta Particles

Bremsstrahlung

- To minimize the production of unwanted bremsstrahlung, beta sources should be shielded with a low atomic number material.

  For example, high energy beta emitters are commonly shielded with plastic.

Beta Particles

Bremsstrahlung

- Shielding a high energy beta source with lead could increase the production of bremsstrahlung.

  Nevertheless, if the lead is thick enough, it will also stop the bremsstrahlung.

- Sometimes a beta shield has two layers:
  - plastic nearest the source to stop any betas
  - lead outside the plastic to stop any bremsstrahlung.

Beta Particles

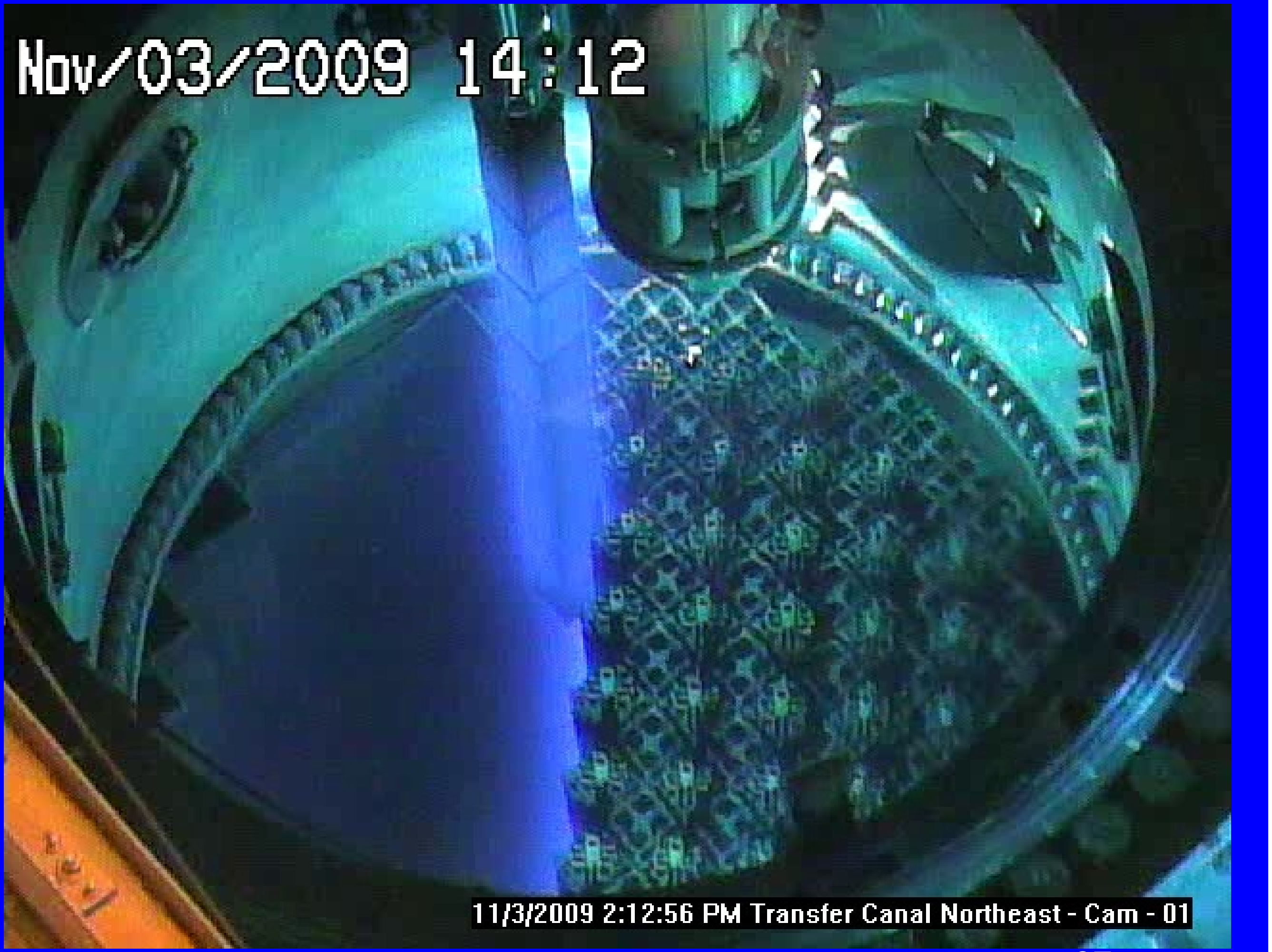
Cerenkov Radiation

- The emission of Cerenkov radiation is an interesting, but relatively unimportant, type of beta particle (or electron) interaction.
- Cerenkov radiation is the blue glow that often seen in a reactor's spent fuel pool.
- The Cerenkov radiation primarily is due to the high energy Compton scattered electrons produced by gamma emissions from the fuel.

Beta Particles

Cerenkov Radiation

Fuel assemblies being removed from the reactor vessel at TMI's operating unit.



Beta Particles

Approximate Data for 1 MeV Beta Particles

	Air (ρ=0.001293 g/cm^3)	Water (ρ=1 g/cm^3)
W (eV/ip)	34	22
Stopping Power/LET (MeV/cm)	3.3×10^{-3}	1.89
Mass Stopping Power (MeV cm^2 g^{-1})	2.6	1.89
Specific Ionization (Ion pairs per cm)	100	86,000
Range (g/cm^2)	0.4	0.5
Range (cm)	300	0.5

Summary

Summary

Types of Interactions

- Charged particles continuously interact as they travel through matter - it is not a matter of probability.
- The major type of interactions: ionization
- The other types of interactions: excitation
  bremsstrahlung
  Cerenkov radiation
- Bremsstrahlung production is sometimes an important concern with beta particles.
- Cerenkov radiation is interesting but rarely important.

Summary

Alpha Particles

- High specific ionization
- High LET (aka stopping power)
- Travel in straight lines
- Short range: a few cm in air
  a couple of cells in the body
- Potential internal hazard but not an external hazard

Summary

Beta Particles

- Low specific ionization
- Low LET radiation (i.e., low stopping power)
- Convoluted path
- Large range: a few hundred cm in air
  several mm in the body
- Penetration distance is less than the range

Summary

Beta Particles

- Produce bremsstrahlung photons when they change direction.
- Maximum energy of the bremsstrahung photons is the same as the maximum energy of the beta particles.
- The higher the atomic number of the material, the greater the fraction of the beta particle energy that will be emitted as bremsstrahlung
- The higher the energy of the beta particle (or electron) the greater the fraction of the energy that will be emitted as bremsstrahlung.

Summary

Beta Particles

- Bremsstrahlung complicates radiation protection, sample counting, shielding, and dosimetry.

- Bremsstrahlung production can be minimized by shielding beta sources with a low Z material such as plastic.

References

References

- Evans, R. The Atomic Nucleus. McGraw-Hill. 1955.
- Turner, James. Atoms, Radiation, and Radiation Protection, 2nd edition. John Wiley and Sons, Inc., 1995.