

# Short introduction to electrodynamics

February 11, 2023

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# 1 Introduction

Welcome to the exciting world of Electrodynamics - a branch of physics that deals with the interaction between electrically charged particles and electromagnetic fields. This comprehensive book delves into the fundamental principles and advanced concepts of Electrodynamics, exploring a wide range of topics that are essential to understanding the behavior of electrical and magnetic fields.

The contents of this book will cover a diverse array of subjects including Coulomb's Law, electric potential, Gauss' Law, Faraday's Law of Induction, Maxwell's equations, the electromagnetic spectrum, electromagnetic waves in matter, and electromagnetic interactions in particle physics. The book will also delve into the properties of conductors, insulators, and semiconductors, as well as the dielectric constant, permittivity, magnetic susceptibility, and permeability.

Whether you are a student, researcher, or a professional in the field of physics, this book provides a comprehensive overview of Electrodynamics that is both accessible and engaging. By the end of this book, you will have a deeper understanding of the fundamental principles of Electrodynamics and how they apply to a wide range of physical phenomena. So get ready to explore the world of Electrodynamics and expand your knowledge of the fascinating interaction between electricity and magnetism.

## 2 Electric fields

### 2.1 Coulomb's law and electric forces

Coulomb's law is a fundamental law in electromagnetism that describes the interaction between electrically charged particles. It states that the force between two point charges is proportional to the product of the charges and inversely proportional to the square of the distance between them. Mathematically, Coulomb's law can be expressed as:

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

where  $F$  is the force between the two charges,  $q_1$  and  $q_2$  are the magnitudes of the charges,  $r$  is the distance between the charges, and  $k$  is the Coulomb constant. The direction of the force is along the line connecting the two charges and can be either attractive (if the charges have opposite sign) or repulsive (if the charges have the same sign).

Electric forces play a crucial role in many physical and biological phenomena, ranging from the behavior of charged particles in electric and magnetic fields to the interactions between charged proteins and other molecules in living systems. Understanding the behavior of electric forces is therefore essential for a wide range of scientific and engineering disciplines, including physics, chemistry, biology, and electrical engineering.

### 2.2 Electric potential and potential energy

Electric potential, also known as voltage, is a measure of the electric potential energy per unit charge at a given point in space. It is defined as the amount of work required to move a unit charge from a reference point to a given point, and is usually denoted by the symbol  $V$ . The electric potential difference between two points is equal to the work done by the electric field on a unit charge as it moves from one point to the other.

Potential energy is a scalar quantity that describes the amount of energy stored in a system due to its configuration or arrangement. In the context of electromagnetism, electric potential energy is the energy stored in an electric field due to the presence of charged particles. The electric potential energy of a system of charges is proportional to the magnitude of the charges and the electric potential difference between them.

In electric circuits, electric potential energy is often stored in capacitors, which are electrical components that store energy in an electric field. When a charged capacitor is connected to a circuit, the electric potential energy stored in its electric field can be converted into other forms of energy, such as kinetic energy or thermal energy. Understanding the relationship between electric potential, potential energy, and the behavior of charged particles in electric fields is important for a wide range of applications, including the design of electrical devices and the analysis of electrical circuits.

### 2.3 Electric field in various configurations

The electric field is a vector field that describes the force experienced by a charged particle in a given location. It is defined as the force per unit charge, and its direction is that of the force on a positive test charge. The electric field produced by a single point charge is proportional to the charge and inversely proportional to the

square of the distance from the charge. The electric field due to a point charge can be represented by radial vectors pointing away from the charge for positive charges and towards the charge for negative charges.

For electric dipoles, the electric field is proportional to the separation of the charges and the strength of the dipole moment. Electric dipoles have a net charge of zero, but have a separation of positive and negative charges. The electric field due to an electric dipole points from the positive charge to the negative charge and its magnitude decreases as the inverse square of the distance from the dipole.

For continuous charge distributions, such as a uniformly charged sphere or a charged ring, the electric field can be calculated using Gauss's law. Gauss's law states that the total electric flux through a closed surface is proportional to the charge enclosed by the surface. This allows for the calculation of the electric field produced by extended charge distributions, such as those found in many electrical and electronic devices.

In all of these configurations, the electric field produced by the charged particles has important implications for a wide range of physical and biological systems. Understanding the behavior of electric fields is therefore essential for many scientific and engineering disciplines, including physics, chemistry, biology, and electrical engineering.

## 2.4 Gauss's law and its applications

Gauss's law is a fundamental law in electromagnetism that relates the distribution of electric charge to the electric field it produces. It states that the total electric flux through any closed surface is proportional to the total charge enclosed within that surface. Mathematically, Gauss's law can be expressed as:

$$\int \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0}$$

where  $E$  is the electric field,  $d\vec{A}$  is an infinitesimal element of the closed surface,  $Q$  is the total charge enclosed within the surface, and  $\epsilon_0$  is the vacuum permittivity.

One of the key applications of Gauss's law is to calculate the electric field produced by a continuous charge distribution. By dividing the charge distribution into small elements and applying Gauss's law to each element, it is possible to determine the electric field produced by the entire distribution. This can be especially useful for solving problems involving extended charge distributions, such as those found in many electrical and electronic devices.

Another important application of Gauss's law is in the design of electrical shielding and containment systems. By carefully controlling the distribution of electric charge on the surface of a conductive material, it is possible to create an electric field that cancels out external electric fields, effectively shielding the interior from external electric fields. This can be used, for example, to protect delicate electronic components from external electromagnetic interference.

Gauss's law also has important implications for our understanding of the behavior of electric fields in a variety of physical and biological systems. For example, it can be used to calculate the electric field inside a charged conductor, or to determine the distribution of charge on the surface of a dielectric material in the presence of an external electric field.

In conclusion, Gauss's law is a powerful tool for understanding and analyzing the behavior of electric fields in a wide range of physical and biological systems, and is an essential part of the study of electromagnetism.

## 3 Magnetic fields

### 3.1 Biot-Savart law and Ampere's law

Biot-Savart law and Ampere's law are two important laws in electromagnetism that describe the relationship between magnetic fields and electric currents.

Biot-Savart law is a fundamental law that describes the magnetic field produced by an electric current. It states that the magnetic field at any point in space is proportional to the product of the current and the vector cross product of the distance from the point to the current and the direction of the current. Mathematically, the Biot-Savart law can be expressed as:

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \vec{r}}{r^3}$$

where  $d\vec{B}$  is an infinitesimal element of magnetic field,  $I$  is the current,  $d\vec{l}$  is an infinitesimal element of current,  $\vec{r}$  is the vector from the current to the point of interest,  $r$  is the distance from the current to the point of interest, and  $\mu_0$  is the vacuum permeability.

Ampere's law, on the other hand, relates the magnetic field to the electric current that produces it. It states that the line integral of the magnetic field around a closed loop is proportional to the current enclosed within the loop. Mathematically, Ampere's law can be expressed as:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$$

where  $\vec{B}$  is the magnetic field,  $d\vec{l}$  is an infinitesimal element of the closed loop, and  $I_{enc}$  is the current enclosed within the loop.

Both Biot-Savart law and Ampere's law are essential tools for understanding the behavior of magnetic fields and electric currents, and have important applications in a wide range of scientific and engineering disciplines, including physics, electrical engineering, and materials science.

### 3.2 Magnetic field due to current-carrying wires

The magnetic field due to a current-carrying wire is a fundamental concept in electromagnetism that describes the magnetic field produced by an electric current flowing through a wire.

According to the Biot-Savart law, the magnetic field at a point in space due to a current-carrying wire is proportional to the current in the wire, the distance from the wire to the point, and the tangent to the wire at that point. The direction of the magnetic field is perpendicular to both the direction of the current and the direction from the wire to the point.

For a long, straight wire, the magnetic field at a point perpendicular to the wire is proportional to the current in the wire and inversely proportional to the distance from the wire. The magnetic field is directed perpendicular to both the wire and the line connecting the point to the wire, and is strongest near the wire.

For a current-carrying loop, the magnetic field is proportional to the current in the loop and the number of turns in the loop. The magnetic field is strongest at the center of the loop and is directed perpendicular to the plane of the loop.

The magnetic field due to a current-carrying wire has important applications in many areas of science and technology, including electric motors, generators, transformers, and magnetic storage devices. Understanding the behavior of the magnetic field due to a current-carrying wire is essential for the design and operation of these and many other electrical and electronic devices.

### 3.3 Faraday's law of induction

Faraday's law of induction is a fundamental law of electromagnetism that describes the relationship between magnetic fields and electric currents. The law states that a changing magnetic field generates an electric field (also known as an electromotive force or "EMF"). This electric field, in turn, induces an electric current in a conductor.

Mathematically, Faraday's law can be expressed as:

$$\frac{d\Phi_B}{dt} = -\frac{d\mathcal{E}}{dt}$$

where  $\frac{d\Phi_B}{dt}$  is the rate of change of the magnetic flux through a loop ( $\Phi_B$ ), and  $-\frac{d\mathcal{E}}{dt}$  is the induced electromotive force (EMF) in the loop.

Faraday's law is an important principle in the operation of many electrical and electronic devices, including generators, transformers, and inductors. It provides a fundamental explanation of how energy can be transformed from one form to another, and is a cornerstone of our understanding of electromagnetic phenomena.

Faraday's law of induction is also closely related to Lenz's law, which states that the direction of the induced current is such that it opposes the change in magnetic flux that caused it. This relationship between magnetic fields and electric currents forms the basis of electromagnetic induction and has numerous applications in a wide range of scientific and engineering disciplines.

### 3.4 Inductance and magnetic energy

Inductance is a measure of the ability of a coil of wire to store energy in a magnetic field. It is defined as the ratio of the magnetic flux through the coil to the current flowing in the coil. The unit of inductance is the henry (H), which is the amount of inductance that will induce an electromotive force (EMF) of one volt in a coil when the current in the coil changes at a rate of one ampere per second.

The magnetic energy stored in a coil with inductance  $L$  and current  $I$  can be calculated using the formula:

$$U = \frac{1}{2}LI^2$$

where  $U$  is the magnetic energy,  $L$  is the inductance, and  $I$  is the current.

This equation shows that the magnetic energy stored in a coil is proportional to the square of the current and the inductance. This relationship is important in the operation of devices such as transformers and inductors, where energy is stored in magnetic fields and then transferred from one circuit to another.

Inductance is a key concept in the study of electromagnetism and is closely related to Faraday's law of induction and Lenz's law. The ability of a coil to store energy in a magnetic field is an important principle in many electrical and electronic devices and has numerous applications in a wide range of scientific and engineering disciplines.

## 4 Electromagnetic waves

### 4.1 Maxwell's equations and the wave equation

Maxwell's equations are a set of four partial differential equations that describe the behavior of the electric and magnetic fields in a given region of space. The equations are:

1. Gauss's law:

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

where  $\vec{E}$  is the electric field,  $\rho$  is the charge density, and  $\epsilon_0$  is the vacuum permittivity.

2. Gauss's law for magnetism:

$$\nabla \cdot \vec{B} = 0$$

where  $\vec{B}$  is the magnetic field.

3. Faraday's law of induction:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

where  $\vec{E}$  is the electric field and  $\vec{B}$  is the magnetic field.

4. Ampere's law:

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

where  $\vec{B}$  is the magnetic field,  $\vec{J}$  is the current density,  $\mu_0$  is the vacuum permeability, and  $\epsilon_0$  is the vacuum permittivity.

These equations describe how electric and magnetic fields interact with charges and currents in a given region of space. They are fundamental to the understanding of the behavior of electromagnetic fields and are widely used in a range of scientific and engineering disciplines.

In addition to Maxwell's equations, the wave equation is also a key concept in electromagnetism. The wave equation describes how an electric field will propagate through space over time:

$$\frac{\partial^2 \vec{E}}{\partial t^2} = c^2 \nabla^2 \vec{E}$$

where  $\vec{E}$  is the electric field,  $t$  is time,  $c$  is the speed of light, and  $\nabla^2$  is the Laplacian operator. The wave equation is used to study the behavior of electromagnetic waves, including light, radio waves, and microwaves, among others.

### 4.2 Electromagnetic wave properties

Electromagnetic waves are transverse waves that consist of oscillating electric and magnetic fields. The properties of an electromagnetic wave are related to its velocity, frequency, and wavelength. Here are some key concepts:

1. Velocity: The velocity of an electromagnetic wave is equal to the speed of light, which is approximately 299,792,458 meters per second in a vacuum. In a medium with a refractive index other than 1, the velocity of the wave will be reduced.

2. Frequency: The frequency of an electromagnetic wave is the number of cycles of the wave that occur per second. It is measured in Hertz (Hz) and is related to the wavelength and velocity of the wave.
3. Wavelength: The wavelength of an electromagnetic wave is the distance between two consecutive peaks of the wave. It is related to the velocity and frequency of the wave and is typically measured in meters.

The relationship between the velocity, frequency, and wavelength of an electromagnetic wave can be described by the following equation:

$$v = \lambda f$$

where  $v$  is the velocity,  $\lambda$  is the wavelength, and  $f$  is the frequency of the wave.

The properties of an electromagnetic wave are important for a range of applications, including communication, medical imaging, and remote sensing, among others. Understanding these properties is essential for the design and development of new technologies that utilize electromagnetic waves.

### 4.3 Polarization and reflection/refraction of electromagnetic waves

Polarization and reflection/refraction are two important properties of electromagnetic waves.

Polarization refers to the direction of the electric field in an electromagnetic wave. The electric field in an electromagnetic wave can be polarized in any direction, but it is most often polarized in a single direction, either vertically or horizontally. When the electric field is polarized in a single direction, it is said to be linearly polarized. When the electric field is polarized in multiple directions, it is said to be circularly polarized. The polarization of an electromagnetic wave affects how it interacts with matter and how it is affected by certain devices, such as polarizing filters.

Reflection and refraction are two related phenomena that occur when an electromagnetic wave encounters an interface between two different materials, such as air and glass. Reflection occurs when an electromagnetic wave is reflected back into the same material it came from, while refraction occurs when an electromagnetic wave changes direction as it passes from one material to another. The amount of reflection and refraction that occurs depends on the properties of the two materials and the angle of incidence of the wave.

Both polarization and reflection/refraction play important roles in many areas of science and technology, including optics, telecommunications, and remote sensing. Understanding these properties is critical for designing and improving a wide range of technologies and for making accurate predictions about how electromagnetic waves will behave in different situations.

## 5 Electromagnetic radiation

### 5.1 Electromagnetic spectrum

The electromagnetic spectrum refers to the full range of electromagnetic radiation, from low-frequency radio waves to high-frequency gamma rays. The different types of electromagnetic radiation in the spectrum are characterized by their wavelength, frequency, and energy. Here is an overview of some of the main types of electromagnetic radiation in the spectrum:

1. Radio Waves: Radio waves have the longest wavelength and lowest frequency in the electromagnetic spectrum. They are used for a range of communication technologies, including broadcast radio, television, and wireless communication.
2. Microwaves: Microwaves have a slightly shorter wavelength and higher frequency than radio waves. They are used for a range of applications, including microwave ovens, GPS, and radar.
3. Infrared: Infrared radiation has a shorter wavelength and higher frequency than microwaves. It is emitted by warm objects and is used for sensing temperature changes and remote control.
4. Visible Light: Visible light is the part of the electromagnetic spectrum that can be seen by the human eye. It has a relatively short wavelength and high frequency and is responsible for our sense of sight.
5. Ultraviolet: Ultraviolet radiation has a shorter wavelength and higher frequency than visible light. It is responsible for sunburn and is used for sterilization and black light effects.
6. X-rays: X-rays have a shorter wavelength and higher frequency than ultraviolet radiation. They are used for medical imaging and for penetrating materials to reveal their internal structure.

7. Gamma Rays: Gamma rays have the shortest wavelength and highest frequency in the electromagnetic spectrum. They are emitted by radioactive materials and are used in cancer treatment.

The different types of electromagnetic radiation in the spectrum have different properties and uses, and understanding the electromagnetic spectrum is important for a wide range of scientific and technological applications.

## 5.2 Properties of electromagnetic radiation

The properties of electromagnetic radiation, such as absorption, emission, and scattering, play important roles in a wide range of natural and technological processes.

Absorption is the process by which electromagnetic radiation is absorbed by a material, reducing the intensity of the radiation. Absorption occurs when the energy of the electromagnetic radiation is transferred to the atoms and molecules in a material, causing them to become excited and eventually return to their ground state, releasing the absorbed energy as heat or other forms of radiation. Absorption can be selective, meaning that certain frequencies of electromagnetic radiation are absorbed more or less than others, depending on the properties of the material. This is the basis for many spectroscopic techniques, such as infrared spectroscopy and ultraviolet-visible spectroscopy.

Emission is the process by which electromagnetic radiation is released by a material. Emission can occur when excited atoms and molecules return to their ground state, releasing energy in the form of electromagnetic radiation. This is the basis for many light-emitting technologies, such as light-emitting diodes (LEDs) and fluorescent lights.

Scattering is the process by which electromagnetic radiation is redirected or dispersed as it passes through a material. Scattering occurs when the electromagnetic radiation interacts with the atoms and molecules in a material, causing it to change direction. Scattering can cause the radiation to become diffuse, reducing the intensity and clarity of the image, or it can cause the radiation to be reflected in specific directions, producing a pattern known as Rayleigh scattering.

These properties are important for a wide range of scientific and technological applications, including remote sensing, medical imaging, and lighting technology. Understanding the properties of electromagnetic radiation is critical for developing and improving these technologies and for making accurate predictions about how electromagnetic radiation will behave in different situations.

## 6 Electromagnetic properties of materials

### 6.1 Conductors, insulators, and semiconductors

Conductors, insulators, and semiconductors are different types of materials that have different electromagnetic properties.

Conductors are materials that allow electric charge to flow freely through them. Metals, such as copper and aluminum, are good conductors. This makes them useful in many electrical and electronic applications, such as in electrical wires, conductors in electrical circuits, and in electrical components.

Insulators are materials that do not allow electric charge to flow through them easily. Glass, air, rubber, and some plastics are good insulators. This makes them useful in many electrical and electronic applications, such as in electrical insulation, protective coatings, and in electrical insulators.

Semiconductors are materials that have electrical conductivity between that of conductors and insulators. Silicon and germanium are two examples of semiconductors. Semiconductors are useful in many electronic devices, such as transistors and diodes, because of their unique electronic properties that allow them to be used to control and manipulate the flow of electric charge.

The conductivity, or ability to conduct electric charge, of a material is dependent on the type and number of electrons available in its atomic structure. By controlling the number of electrons in a material, it is possible to change its conductivity and make it into a conductor, insulator, or semiconductor. This makes it possible to create many different types of electronic devices and to customize their properties for specific applications.

### 6.2 Dielectric constant and permittivity

The dielectric constant and permittivity are related concepts in electromagnetism that describe the ability of a material to store electrical energy in an electric field.

The dielectric constant, also known as the relative permittivity, is a dimensionless constant that describes the ratio of the electrical energy stored in a material to the energy stored in a vacuum. The dielectric constant

of a material is a measure of its electrical polarization, or the ability of its electrons to be re-arranged in response to an electric field.

The permittivity, also known as the electric constant, is a measure of the ability of a material to store electrical energy in an electric field. It is a measure of the electric field strength required to produce a unit charge density in a material. The permittivity is related to the dielectric constant by the formula:

$$\epsilon = \epsilon_0 \kappa$$

where  $\epsilon_0$  is the permittivity of free space, which has a value of approximately  $8.85 \times 10^{-12}$  farads per meter, and  $\kappa$  is the dielectric constant of the material.

The dielectric constant and permittivity are important parameters in many electrical and electronic applications, including capacitors, electric power transmission, and in the design of electrical insulation materials. They are also used to describe the behavior of materials in electric fields, including the amount of energy that is stored in a material in response to an electric field, and the efficiency with which a material can store and release electrical energy.

### 6.3 Magnetic susceptibility and permeability

The magnetic susceptibility of a material refers to how susceptible it is to being magnetized in the presence of a magnetic field. It is a dimensionless scalar quantity that is defined as the ratio of the magnetic induction produced in a material to the magnetic field strength applied to it. The magnetic permeability of a material is a measure of its ability to support the formation of a magnetic field within it. It is a scalar value that is usually represented as a relative permeability, which is the ratio of the magnetic induction produced in a material to the magnetic field strength applied to it.

Together, the magnetic susceptibility and magnetic permeability of a material determine how the material will respond to magnetic fields. For example, magnetic materials such as iron have high magnetic susceptibility and permeability, and they are therefore able to support strong magnetic fields. On the other hand, materials with low magnetic susceptibility and permeability, such as copper and aluminum, are not very susceptible to being magnetized and cannot support strong magnetic fields.

## 7 Electrodynamic phenomena

### 7.1 Electric circuits

Electric circuits refer to networks of electrical components that are connected together to perform a specific task, such as the transmission or transformation of electrical energy. In the context of electromagnetism, electric circuits can be used to study and understand a variety of electromagnetic phenomena.

Resistors are electrical components that are designed to resist the flow of electric current, and they are often used to control the amount of current in a circuit. Capacitors are components that store electrical energy in an electric field, and they are used in circuits to smooth out fluctuations in current. Inductors are components that store energy in a magnetic field, and they play a key role in circuits that involve alternating current (AC).

AC circuits are circuits that involve the use of AC current, which is a type of current that alternates in direction. AC circuits are used in a variety of applications, such as power transmission and the operation of electrical motors. On the other hand, DC circuits are circuits that involve the use of direct current, which is a type of current that flows in one direction. DC circuits are commonly used in batteries and in applications that require a constant voltage.

In electric circuits, the interplay between resistors, capacitors, and inductors can result in a variety of interesting and useful phenomena, such as oscillations, filtering, and the creation of AC waveforms. The study of electric circuits and their behavior is an important part of electromagnetism and electrical engineering.

### 7.2 Electromagnetic waves in matter

In the context of electromagnetics, electromagnetic waves in matter refers to the behavior of electromagnetic waves when they propagate through different types of media, such as plasmas, waveguides, and resonators.

Plasmas are a type of matter composed of ions and free electrons, and they exhibit unique behavior when subjected to electromagnetic fields. For example, plasmas can support certain types of electromagnetic waves that cannot exist in other types of media.

Waveguides are structures that are designed to confine and guide electromagnetic waves, often over long distances. They have a variety of applications, such as in microwave communication systems, where they are used to transmit signals between antennas.



Resonators are structures that are designed to store electromagnetic energy and provide it in a controlled manner. They are used in many different applications, such as in microwave and millimeter-wave filters, where they are used to pass desired signals and reject unwanted ones.

In each of these examples, the behavior of electromagnetic waves is influenced by the properties of the medium in which they are propagating, and this can affect the wave's velocity, frequency, wavelength, and other properties.

### 7.3 Electromagnetic fields in moving media

In the context of electromagnetic properties of materials, Electromagnetic fields in moving media refer to the behavior of electromagnetic fields in media that are in motion relative to an observer. This involves studying the transformation of electromagnetic fields under Lorentz transformations, which describe the change in space and time coordinates between two observers in relative motion.

The study of electromagnetic fields in moving media is also known as relativistic electrodynamics, which is a branch of electrodynamics that takes into account the effects of special relativity on electromagnetic fields. In this context, the theory of special relativity is applied to the equations of electromagnetism, resulting in a more accurate and complete description of the behavior of electromagnetic fields in moving media.

### 7.4 Electromagnetic interactions in particle physics

In particle physics, electromagnetic interactions refer to the way charged particles interact with electromagnetic fields. This is one of the four fundamental forces in the universe, along with the strong force, weak force, and gravitational force. Electromagnetic interactions play a crucial role in many processes, including the behavior of electrons in atoms and the interactions between charged particles in nuclear systems. Some examples of electromagnetic interactions in particle physics include:

1. The electromagnetic force between two charged particles, which can be described by Coulomb's law.
2. The energy levels and spectral lines of atoms, which are due to the interaction between electrons and the electromagnetic field produced by the nucleus.
3. The scattering of charged particles by electromagnetic fields, which is important in many particle physics experiments.
4. The production and decay of particles through electromagnetic processes, such as the electromagnetic decay of a meson into a photon and two electrons.

In general, the study of electromagnetic interactions in particle physics helps us to understand the behavior of charged particles on a small scale and to gain insight into the fundamental forces of nature.

## 8 Formulary

1. Coulomb's Law:

$$\vec{F} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \hat{r}$$

2. Electric Field Intensity:

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2} \hat{r}$$

3. Gauss's Law:

$$\frac{1}{\epsilon_0} \oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}$$

4. Electric Potential:

$$V = -\frac{1}{4\pi\epsilon_0} \int \frac{Q}{r} dr$$

5. Biot-Savart Law:

$$\vec{B} = \frac{\mu_0}{4\pi} \int \frac{I d\vec{l} \times \vec{r}}{r^2}$$

6. Ampere's Law:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enc}}$$

7. Faraday's Law of Induction:

$$\frac{d\phi}{dt} = -\frac{d\vec{A}}{dt} = -\frac{\partial \vec{B}}{\partial t}$$

8. Inductance:

$$L = \frac{\phi}{I}$$

9. Magnetic Energy:

$$W = \frac{1}{2} LI^2$$

10. Maxwell's Equations:

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad \nabla \cdot \vec{B} = 0 \quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \nabla \times \vec{B} = \mu_0 \left( \vec{J} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right)$$

11. Electromagnetic Wave Equation:

$$\frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = \nabla^2 \vec{E}$$

12. Electromagnetic Waves Velocity:

$$v = \frac{\lambda}{T} = c$$

13. Electromagnetic Waves Frequency:

$$f = \frac{1}{T}$$

14. Electromagnetic Waves Wavelength:

$$\lambda = \frac{c}{f}$$

15. Dielectric Constant:

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}$$

16. Permittivity:

$$\epsilon = \epsilon_0 \epsilon_r$$

17. Magnetic Susceptibility:

$$\chi = \frac{\mu}{\mu_0}$$

18. Permeability:

$$\mu = \mu_0 \chi$$

19. Ohm's Law:

$$V = IR$$

20. Power:

$$P = IV = \frac{V^2}{R} = I^2 R$$