University Fundamental Physics (Vol 2)

张三慧 编著
Zhang Sanhui

清华大学出版社

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A BRIEF INTRODUCTION TO THE CONTENT

The content of this volume includes three parts: electromagnetism, wave and optics, and fundamentals of quantum physics. In the part of electromagnetism, the fundamental concepts and principles, as electric field, magnetic field, and electromagnetic induction, are explained explicitly. In the part of wave and optics, the basic characteristics of vibration and wave, and the basic principles of wave optics and geometric optics, are introduced. In the part of fundamentals of quantum physics, the basic concepts as wave-particle quality, probability wave, uncertainty relation and energy quantization, and the regulations about the states of electrons in atoms and solids are given. At last, a short statement about the nucleus physics including radioactivity, is introduced.

Volume 2 and Volume 1 cover all the pedagogic requirements of physics course in colleges and universities and hence can be used as textbooks of physics. They can also be used as pedagogic references by high-school teachers or as self-learning materials by other readers.

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FOREWORD

This English edition of the *University Fundamental Physics* is written for Bilingual pedagogy of physics. The physics contents include mechanics, heat, electromagnetism, optics, and fundamental quantum physics. All these branches satisfy the kernel fundamental requirements declared by the Physics Pedagogic Directing Committee of Ministry of Education. So this book can be used as a reference book for the physics course given to non-physics-majored students in universities. The writer really thinks that there are surely many defects and errors in this work both in language and in explanations of physical principles. He waits and welcomes heartily your comments and corrections.

Zhang Sanhui
In Tsinghua Yuan
May 2010

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PART 3

ELECTROMAGNETISM

Electromagnetism is a branch of physics studying the laws of electric and magnetic phenomena. In the West, the record about the observation of such phenomena may be traced back to Greek philosopher Thales who found a piece of amber rubbed with cloth could attract light chips. In China, similar records has also be found in acient books, such as "慈石召铁, kind stones (magnetite) attract iron", "顿牟缀芥, amber picks up chips". It was Gilbert who first (16 century) introduced the word ηλεκτρον (meaning amber originally then electricity) to describe the state of amber attracting chips. In our country, the word "电" was first found in the engraved writing left during the Zhou Dynasty to record the lightning in the sky. The systematic and quantitative study of electricity may be considered as beginning with the research of the interaction between electric charges by Coulomb in 1785. Then the electrostatic theory was established. In 1780 Galvani discovered electric current by accident. In 1820, Oersted found the effect on a magnetic needle by an electric current. Then the theory about electric current and its magnetic effect was formed gradually in 1830's, Faraday did his famous purposeful experiments about electromagnetic induction, revealed further the relation between electricity and magnetism. Based on all these discoveries and his own contribution, a complete and beautiful macroscopic theory of electromagnetics was established by Maxwell in 1865. This theory is now called as the classical theory of electromagnetism. This achievement has been considered as the most important theoretical fruit after Newton's classical mechanics.

CHAPTER 11

ELECTROSTATIC FIELD

As the starting chapter of electromagnetism, we first discuss the ideas and laws about the interaction between stationary charges. The definition of Electric field is given and Coulomb's law is intruduced to calculate the electric field. Then Gauss's law and its application to the calculation of electric field is introduced.

11.1 Electric Charges

All electromagnetic phenomena are now attributed to the electric charge (or simply called charge) at rest or moving. The fundamental properties of electric charges having been found are:

1. Two varieties of electric charges. There are two classes of charges, similar charges repel each other and dissimilar charges attract each other. It was Benjemin Franklin who named the two classes as positive and negative respectively.

The amount of electricity carried by a body is denoted by Q or q called the electric charge (or simply the charge) and is measured in SI unit coulomb with the symbol C. When the dimension of a charged body is much smaller than the distances involved in a problem, such charged body is called a **"point Charge"**.

2. Conservation of electric charge. When there is no charge moving through the boundary of a system, the algebraic sum of charges in it remains constant. There may be production or destruction of charge in some process in the system. But as the positive and negative charges are always produced or vanish with just the same amount, the total charge in the system is still kept unchanged.

3. Quantization of electric charge. In nature, electric charge comes in units of magnitude only. That megnitude is called the elementary charge, equal to the charge carried by a proton or an electron, and is always denoted by e. In SI, we have

$$e = 1.6 \times 10^{-19} \mathrm{C}$$

4. Invariance of electric charge. The charge on a body is independent of the speed of the body. Since the speed of a body is different relative to different frames of reference. This invariance is also called relativistic invariance.

11.2 Electric Field and Electric Field Intensity

Modern physics thinks that the interaction between charges is mediated by a field. The field which can exert force on charge at rest is called **electric field.** To study the electric field associated with (or produced by) charge Q (called the **source charge** in this case), we put a point positive charge q (called the **test charge**) at some point P (called field point) around Q and keep it stationary. Observation shows that the direction of the electric field force $\boldsymbol{F}$ on q for positive charge is definite and the magnitude of the force F is proportional to the charge amount q of the test charge, or F/q is constant for point P. Similar tests at other field points show the same, only that the const. ratio F/q are different for different points. Then the ratio $\boldsymbol{F}/q$ can be used to express the characteristics of every point of the electric field. We define $\boldsymbol{F}/q$ as the **electric field intensity** and denote it with $\boldsymbol{E}$, then by definition

$$\boldsymbol{E} = \boldsymbol{F}/q \ (q \text{ at rest}) \tag{11.1}$$

that is, the electric field intensity at some point is equal to the force on unit charge at rest at that point in magnitude and its direction is the same as the force on a positive charge. One in the case when the source charges are stationary, their electric field is called **electrostatic field** which is expressed as a vector function of coordinates mathmetically.

When the source charge is composed of many charges. The force $\boldsymbol{F}$ on test charge q is the resultant of the forces $\boldsymbol{F}_i$ on q by each source charge alone, that is

$$\boldsymbol{F} = \sum \boldsymbol{F}_i$$

Then the definition equation (11.1) gives

$$\boldsymbol{E} = \frac{\boldsymbol{F}}{q} = \sum \frac{\boldsymbol{F}_i}{q}$$

As $\boldsymbol{F}_i/q = \boldsymbol{E}_i$ is the electric field intensity produced by the i-th source charge alone, we have finally

$$\boldsymbol{E} = \sum \boldsymbol{E}_i \tag{11.2}$$

This equation means that in the electric field produced by many charges, the electric field in tensity at every point is equal to the vector sum of the electric field intensities at that point produced by each source charge individually. This conclusion is called the **superposition principle of electric field.**

11.3 Coulomb's Law and Calculating Electrostatic Field

In the last section we have given the definition of electric field intensity, With which we can find the electric force on a charge provided the field intensity is known. Now let us go to the electric field intensity distribution around some source charges. For electrostatic field distribution, the basic law is Coulomb's law which says: **In vacuum, the direction of electric force F between two point charges at rest is along the line joining them, the magnitude of the force is proportional to both the charge amount q_1 and q_2 and inversely proportional to the square of the distance r between them.** Mathematically, in SI units, we have

$$F = \frac{kq_1 q_2}{r^2} \tag{11.3}$$

where the coefficient k is called electrostatic force constant and has the following value in calculation

$$k = 9 \times 10^9 \mathrm{N \cdot m^2/C^2} \tag{11.4}$$

For simplicity in the expression in electromagnetism and calculation, we introduce another constant ε_0 with the value

$$\varepsilon_0 = \frac{1}{4\pi k} = 8.85 \times 10^{-12} \mathrm{C^2/(N \cdot m^2)} \tag{11.5}$$

which is called the **electric permittivity of vacuum.**

Substituting k with this ε_0 in Eq. (11.3) yields

$$F = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2} \tag{11.6}$$

In this equation, if q_2 is taken as a test charge, F is then the electric field force on q_2 in the electric field of q_1. By the definition equation Eq. (11.1), $F/q_2 = \frac{q_1}{4\pi\varepsilon_0 r^2}$ is the electric field intensity of the electric field produced by q_1 at the location of q_2. Dropping the subscript 1 of q_1, we obtain generally: the magnitude of the electric field intensity of the electric field produced by a point charge q at rest in vacuum is

$$E = \frac{q}{4\pi\varepsilon_0 r^2} \tag{11.7}$$

where r is the distance from the charge q to the field point. The direction of the electric field intensity (or simply field) can be found with a positive test charge, as Fig. 11.1 shows. For a positive source charge q, its field $\boldsymbol{E}$ points away from the charge q, and for a negative source charge, its field $\boldsymbol{E}$ points to the charge q.

Considering both the direction and magnitude, the electric field $\boldsymbol{E}$ at distance r from the source point charge q can be expressed as

$$\boldsymbol{E} = \frac{q}{4\pi\varepsilon_0 r^2}\boldsymbol{e}_r \tag{11.8}$$

where $\boldsymbol{e}_r$ is the unit vector from the source charge to the field point.

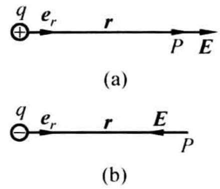

Fig. 11.1 The direction of $\boldsymbol{E}$ of point charge q

As Eq. (11.8) shows that $\boldsymbol{E}$ is related to the radius vector only, the electric field of a point charge in vacuum has a spherically symmetrical distribution about the charge as the center.

Eq. (11.8) is the expression for the electric field of a single point charge. By the principle of superposition, we can find the field distribution of a system of point charges $q_1, q_2, \cdots, q_n$ as

$$\boldsymbol{E} = \sum_{i=1}^{n} \frac{q_i}{4\pi\varepsilon_0 r_i^2}\boldsymbol{e}_{ri} \tag{11.9}$$

where r_i is the distance from q_i to the field point and $\boldsymbol{e}_{ri}$ is the unit vector directed from q_i to the field point.

When the charge on a body is continuously distributed, we can consider that the charge is composed of many infinitesimal charge elements $\mathrm{d}q$ and every charge element can be treated as a point charge. Assuming the field produced by any charge element $\mathrm{d}q$ to be $\mathrm{d}\boldsymbol{E}$, then by Eq. (11.8), we obtain

$$\mathrm{d}\boldsymbol{E} = \frac{\mathrm{d}q}{4\pi\varepsilon_0 r^2}\boldsymbol{e}_r$$

where r is the distance from $\mathrm{d}q$ to the field point, and $\boldsymbol{e}_r$ the unit vector along that direction. The electric field produced by all the charges on the body at the field point P can then be calculated by integration as

$$\boldsymbol{E} = \int \mathrm{d}\boldsymbol{E} = \int \frac{\mathrm{d}q}{4\pi\varepsilon_0 r^2}\boldsymbol{e}_r \tag{11.10}$$

With Eq. (11.9) or Eq. (11.10), we can find the electric field distribution produced by a given charge distribution at rest. Be careful that the two equations are both vector equations. Some examples are given below.

Example 11.1 A pair of equal but opposite charges $+q$ and $-q$ with separation $\boldsymbol{l}$ constitute an **electric dipole**. Find the electric field at a point on the bisecting line of an electric dipole and far from it ($r \gg l$).

Solution: As shown in Fig. 11.2, the radius vectors from $+q$ and $-q$ to the field point P on the bisecting line are $\boldsymbol{r}_+$ and $\boldsymbol{r}_-$ with $r_+ = r_-$ respectively. From Eq. (11.8), the fields produced by $+q$ and $-q$ at P are

$$\boldsymbol{E}_+ = \frac{q\boldsymbol{r}_+}{4\pi\varepsilon_0 r_+^3}, \quad \boldsymbol{E}_- = \frac{-q\boldsymbol{r}_-}{4\pi\varepsilon_0 r_-^3}$$

respectively. Let r be the distance from the middle point of the dipole to field point P, then

$$r_+ = r_- = \sqrt{r^2 + \frac{l^2}{4}} = r\sqrt{1 + \frac{l^2}{4r^2}} = r\left(1 + \frac{l^2}{8r^2} + \cdots\right)$$

Since $r \gg l$. Take first order approximation, we have $r_+ = r_- = r$. The net electric field at P becomes now

$$\boldsymbol{E} = \boldsymbol{E}_+ + \boldsymbol{E}_- = \frac{q}{4\pi\varepsilon_0 r^3}(\boldsymbol{r}_+ - \boldsymbol{r}_-)$$

Since $\boldsymbol{r}_+ - \boldsymbol{r}_- = -\boldsymbol{l}$, this equation reduced to

$$\boldsymbol{E} = \frac{-q\boldsymbol{l}}{4\pi\varepsilon_0 r^3}$$

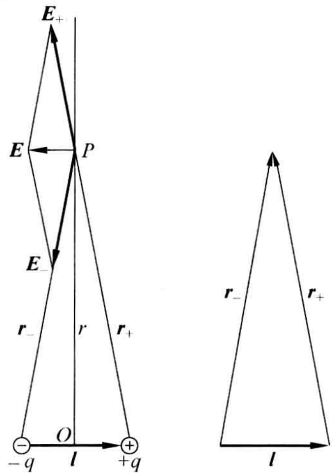

Fig. 11.2 Example 11.1

Define $\boldsymbol{p} = q\boldsymbol{l}$ as the electric dipole moment, we have

$$\boldsymbol{E} = \frac{-\boldsymbol{p}}{4\pi\varepsilon_0 r^3} \tag{11.11}$$

which shows that at far points on the bisecting line of an electric dipole, the electric field intensity is proportional to its electric dipole moment, inversely proportional to the cube of the distance from the center of the dipole to the field point and opposite in direction to the dipole.

Example 11.2 A straight line of lenght L is uniformly charged with a linear density λ(C/m). Find the field at a point on the bisecting plane of the line.

Solution: Let line Ox on the bisecting plane be taken as the x axis and the charged line itself lie on the y axis (Fig. 11.3). Consider a charge element $dq = \lambda dl$ on a length element dl. Denote the field produced by dq at point P by $d\boldsymbol{E}$. After resolving $d\boldsymbol{E}$ along x and y axes, we find, due to the symmetric distribution of the charge with respect to the line OP, the y components of the fields produced by all the charge elements on L sum to zero. Then the resultant field at P is simply the sum of the x components,

$$E = \int dE_x = \int dE \cdot \cos\theta = \int_{-L/2}^{+L/2} \frac{\lambda x\, dl}{4\pi\varepsilon_0 r^3}$$

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