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Effect of magnetic field of light on refractive index*

Zhang Tao(张 涛)†

Key Laboratory of Beam Technology and Material Modification of Ministry of Education, Institute of Low Energy Nuclear Physics, Beijing Radiation Centre, Beijing Normal University, Beijing 100875, *China*

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Light refraction in a medium results from energy exchange between the medium and the magnetic field of the light. Formulas of refractive index, that is, the ratio of light speed in vacuum to light speed in the medium, were derived with the inductor model of electron cloud and the law of energy conservation. Refractive indices of several media were calculated using the formulas derived, and the calculated results are in agreement with the results measured. The anisotropy and the nonlinearity of the refractive index are explained with the theory described in this work.

Keywords: refractive index, light speed, medium
PACC: 7820B, 4110H

1. Introduction

Recently, many researches on the measurement or application of refractive index have been conducted.[1–5] It is well known that the speed and direction of a light will generally change when it enters a medium from vacuum. This phenomenon is called light refraction. Refractive index is a very important property of a medium. Lorentz's theory believes that electrons in the medium are forced to vibrate in the alternating electric field of the light, and derives the relation between refractive index and light frequency. Lorentz's theory indicates that the refractive index increases as the light frequency increases when it is far from the resonant frequency of the medium, and decreases as the light frequency increases when it lies in the resonant frequency zone of the medium. Lorentz's theory deals with the effect of electric field of light on the refraction. Generally, light has a lower speed in a medium than in vacuum. This phenomenon has not been well explained for a long time. In this paper, we study the effect of the magnetic field of a light on the refraction when the light frequency is far from the resonant frequency of the medium, and try to understand the refraction phenomenon further.

2. Theory

When the light meets an isotropic transparent medium, some part of the light is reflected, some enters the medium. The latter includes three parts: the part absorbed, the part scattered, and the part refracted by the medium.[6] All of these parts of the light have interactions with the molecules of the medium. If the light is not strong, these interactions do not make the electrons in the molecules deviate evidently from their ground states, and the energies of the four parts of the light (reflected, absorbed, scattered, and refracted) are independent of each other. Suppose that the light is composed of the above four parts both in vacuum and after it meets the medium. It is the refracted part that is finally received for the measurement of refractive index of light in the medium. We imagine to have separated the refracted part from the other parts of the light and only consider this part of light by denoting it as 'the light' in the following text.

2.1. The average exchange energy density in the medium

Suppose that the light is a plane monochroic electromagnetic wave, and that the magnetic and electric fields of the light at a point in the medium are ex-

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†E-mail: taozhang@bnu.edu.cn

pressed as

$$H_{\mathrm{M}} = H_{\mathrm{M0}} \cos \omega t,$$
$$E_{\mathrm{M}} = E_{\mathrm{M0}} \cos \omega t, \quad (1)$$

where H_{M0} (in A/m) and E_{M0} (in V/m) are amplitudes of the magnetic field and the electric field intensities of the light in the medium; ω (in rad/s) is the angular speed, and t, in second, is time. For clearness, H and B stand for the magnetic field intensity and the magnetic induction of the light in vacuum, $B = \mu_0 H$ (μ_0 is vacuum permeability, $\mu_0 = 4\pi \times 10^{-7}$H/m); H_{M} and B_{M} stand for the magnetic field intensity and the magnetic induction of the light in the medium; H_0 and B_0 are the amplitudes of H and B, with $B_0 = \mu_0 H_0$; H_{M0} and B_{M0} are the amplitudes of H_{M} and B_{M} respectively. For most transparent media, the absolute value of the magnetic susceptibility χ is much less than 1. Thus the magnetic field of the light in the medium is almost equal to that in vacuum, i.e. $H_{\mathrm{M}} \approx H$, $B_{\mathrm{M}} \approx B$, $H_{\mathrm{M0}} \approx H_0$, $B_{\mathrm{M0}} \approx B_0$.

The electrons and nuclei of the molecules in the medium interact with the electric and magnetic fields of the light. According to Lorentz's theory, the interaction between the medium and the electric field of the light contributes little to the refraction of the light in the medium when the light frequency is far from the resonant frequency of the medium.[7,8] So the effect of the electric field of the light on the refraction can be neglected in this case.

Each electron in the molecules appears within a certain space and forms an electron cloud of a certain shape. The electron cloud of each electron can be considered as a conductor. The conductors of different electron clouds are independent of each other because each of the electrons is confined within its space in the molecule. When the alternating magnetic field of the light exists in the electron cloud conductor, $\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t$ of the light causes a whirling electric field in the conductor. Thus an induced electromotance forms in the electron cloud conductor (so it is an electron cloud inductor also), and there exists an induced current on the surface of the electron cloud conductor. The induced current is actually a statistical result of the electron's directional motion, which is an additive motion superposed on the original motion of the electron in the atom. Thus the electron cloud acts as a coil with a certain inductance, and the electron cloud inductor exchanges energy with $\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t$ of the light when they interact with each other (Fig.1). When H_{M} changes from H_{M0} to 0, $|\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t|$ of the light increases. Hence, the induced current increases and the electron cloud inductor gains energy from the light. When H_{M} changes from 0 to H_{M0}, $|\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t|$ of the light decreases, and the induced current decreases and the electron cloud inductor returns energy to the light.

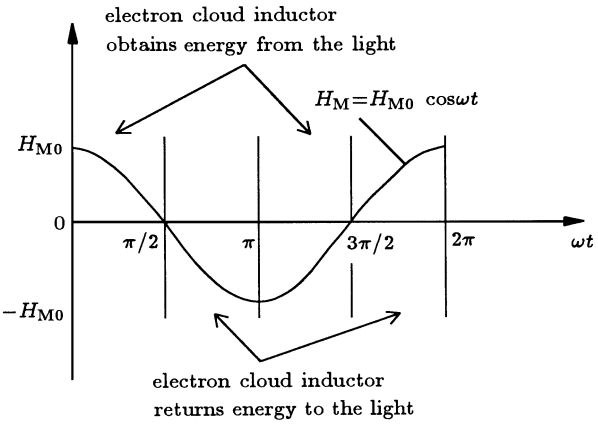


Fig.1. Waveform of the magnetic field $H_{\mathrm{M}} = H_{\mathrm{M0}} \cos \omega t$ of the light at a point in the medium and the energy exchanging process between the light and the electron cloud inductor. H_{M0} is the amplitude of the magnetic field of the light.

The alternating electric field of the light causes a whirling magnetic field in the electron cloud conductor. But the whirling magnetic field does not cause induced electromotance in it.

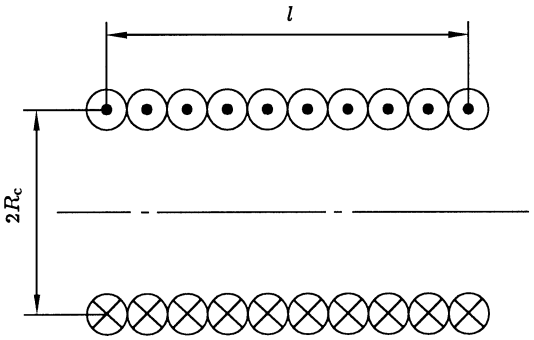


Fig.2. Schematic drawing of the coil. l is the length and R_{C} is the radius of the coil.

The inductance L_{C} of the coil shown in Fig.2 is[9]

$$L_{\mathrm{C}} = \mu n_{\mathrm{C}}^2 V_{\mathrm{C}} \left[\sqrt{1 + \left(\frac{R_{\mathrm{C}}}{l} \right)^2} - \left(\frac{R_{\mathrm{C}}}{l} \right) \right], \quad (2)$$

where μ is permeability, n_{C} is the number of turns per metre of the coil, V_{C} is the volume of the coil, R_{C} is the radius and l is the length of the coil. Inductance of the coil is related to the shape of the coil. Likewise,

the inductance L of the electron cloud inductor, which is considered as a coil, is

$$L = \mu_0 n_{\mathrm{E}}^2 V g, \tag{3}$$

where the unit of L is H; n_{E} is the number of turns per metre on the electron cloud inductor which is considered as a coil; V, in m^3, is the volume of the electron cloud inductor, or in other words, V is the equivalent volume of the electron cloud which is considered as a coil; g is a factor like the term in square bracket of Eq.(2), which is related to the shape and also the direction of the electron cloud relative to the magnetic field of the light, as shown in Fig.3, with $0 < g \leq 1$. We call g the shape and direction factor of the electron cloud.

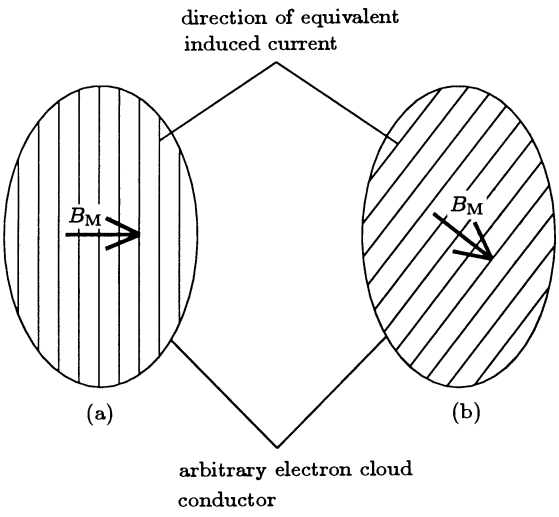


Fig.3. The electron cloud of an electron, which is not in ball shape, has different shape and direction factors when the electron cloud has different directions relative to the magnetic field B_{M} of the light, i.e. $g_{\mathrm{a}} \neq g_{\mathrm{b}}$, where g_{a} is the shape and direction factor of the electron cloud shown in (a) and g_{b} is in (b).

The wavelength of the light is usually much larger than the size of a molecule. So $\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t$ of the light is almost of the same value everywhere in each electron cloud of the molecule at some instant. The induced electromotance, which is produced by $\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t$ in the electron cloud inductor, is (Fig.4)

$$U = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -\int S_{\mathrm{E}} \frac{\mathrm{d}B_{\mathrm{M}}}{\mathrm{d}t} n_{\mathrm{E}} \mathrm{d}x = -V n_{\mathrm{E}} \frac{\mathrm{d}B_{\mathrm{M}}}{\mathrm{d}t}, \tag{4}$$

where the unit of U is volt; Φ, in Weber-turns, is the flux linkage; S_{E}, in square metres, is the cross section area of the electron cloud inductor at position x; and B_{M} is in tesla. The induced current I in the coil of the electron cloud inductor is

$$I = \frac{U}{\sqrt{R^2 + (2\pi f L)^2}} = \frac{U}{2\pi f L} = -\frac{1}{2\pi f \mu_0 n_{\mathrm{E}} g} \frac{\mathrm{d}B_M}{\mathrm{d}t}, \tag{5}$$

where I is in ampere, R is the resistance of the coil of the electron cloud inductor, f is the frequency of the light. Equation (5) shows that R=0 because the electron is not scattered when it moves within an atom. Thus the electron cloud inductor is equivalent to a pure inductor with zero resistance.

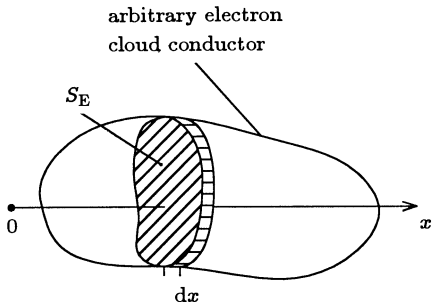


Fig.4. An electron cloud conductor and its induced electromotance produced by $\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t$ of the light. Magnetic field B_{M} of the light and the x-axis are in the same direction.

Part of the energy of the light and the energy stored in the electron cloud inductor transfer into each other continuously when the light is refracted in the medium. The energy stored in the electron cloud inductor is

$$\begin{aligned} W_{\mathrm{E}} = \frac{1}{2} L I^2 &= \frac{V}{2\omega^2 \mu_0 g} \left(\frac{\mathrm{d}B_{\mathrm{M}}}{\mathrm{d}t} \right)^2 \\ &= \frac{V}{2\mu_0 g} B_{\mathrm{M0}}^2 \sin^2 \omega t, \end{aligned} \tag{6}$$

where $B_{\mathrm{M}} = B_{\mathrm{M0}} \cos \omega t$, $\omega = 2\pi f$. W_{E} is the energy that the electron cloud inductor receives from the light. For convenience, we call the induced current energy, which is stored in the medium due to $\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t$ of the light and is exchanged between the light and the medium, the exchange energy. So W_{E} is a kind of exchange energy. The time average exchange energy of one electron is

$$< W_{\mathrm{E}} >= \frac{1}{2\pi} \int_0^{2\pi} W_{\mathrm{E}} \mathrm{d}\theta = \frac{V B_{\mathrm{M0}}^2}{4\mu_0 g}, \tag{7}$$

where $\theta = \omega t$. Equation (7) indicates that the average exchange energy of one electron is proportional to the equivalent volume of the electron cloud of this electron. A similar result can be derived for the nuclei in the molecules. Because the volumes of the nuclei are much smaller than those of the electron clouds,

the exchange energy that the nuclei receives from the dB_M/dt of the light is very small. The interactions of the nuclei with both the electric field and the magnetic field of the light are very weak, so the nuclei's contribution to refraction can be neglected.

When neglecting the effects of electric field of the light and the nuclei on the refraction, the average exchange energy W_A stored in one molecule of the medium is the sum of all the electron clouds' $< W_E >$ in the molecule, i.e.

$$W_A = \sum_{i=1}^{z} < W_E >_i = \frac{B_{M0}^2}{4\mu_0} \sum_{i=1}^{z} \left(\frac{V}{g}\right)_i, \qquad (8)$$

where i stands for electron i in the molecule, z is the number of electrons in the molecule. The average exchange energy stored in the medium of unit volume, i.e. the average exchange energy density in the medium when the light runs in the medium, is

$$W_{ex} = \rho W_A = \frac{\rho B_{M0}^2}{4\mu_0} \sum_{i=1}^{z} \left(\frac{V}{g}\right)_i \approx \frac{\rho B_0^2}{4\mu_0} \sum_{i=1}^{z} \left(\frac{V}{g}\right)_i, \qquad (9)$$

where ρ (in m^{-3}) is the molecule density of the medium. And

$$W_{ex} = \sum (\rho W_A)_j, \qquad (10)$$

when there exist j kinds of molecules in the medium.

2.2. The average energy densities of the light in vacuum and in the medium

The above text indicates that a part of the energy of the light becomes the exchange energy stored in the electron cloud inductors when the light is in the medium. According to Eq.(6), the exchange energy is directly proportional to $\sin^2 \omega t$. The energy of the light in the medium is directly proportional to $H_M^2 \propto \cos^2 \omega t$. The exchange energy stored in the electron cloud inductor is of opposite phase to the energy of the light. So the exchange energy is not a part of the energy of the light itself, although the exchange energy stems from the light. As a result, the light itself has less energy in the medium than in vacuum so as to keep energy conservation in the light-medium system. When a light block (Fig.5) goes into the medium from vacuum, this light block itself either has a lower energy density, or has a smaller volume in the medium than in vacuum, to give out part of the energy of the light block to the electron cloud inductors in the medium.

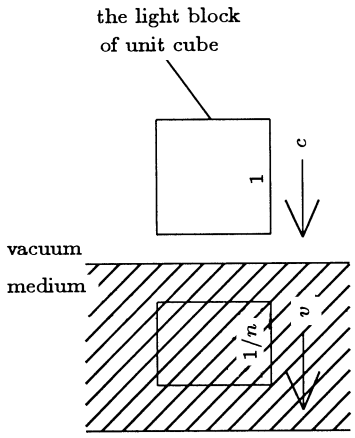


Fig.5. The light block taken from the continuous light flux is a unit cube when it is in vacuum. The dimension of the light block in the direction of the speed is $1/n$, so the volume of the light block is $1/n$ that of the original when it goes into the isotropic medium from vacuum. The light speed is $v = c/n$ in the medium.

It is well known that the time-average energy density of the light in vacuum is

$$W_v = \frac{1}{2\mu_0} B_0^2, \qquad (11)$$

while that of the light in the medium with $\mu \approx \mu_0$ is

$$W_m = \frac{1}{2\mu} B_{M0}^2 \approx \frac{1}{2\mu_0} B_0^2 = W_v, \qquad (12)$$

where μ is the permeability of the medium. Equation (12) indicates that the light has almost the same average energy density in the medium as in vacuum when the medium has $\mu \approx \mu_0$. So the light block will decrease its volume when it goes into the medium from vacuum (Fig.5); in other words, the dimensions of the light block will shrink. Suppose that the shrinkage of dimensions is in the speed direction of the light block, then the light block must have a lower speed in the medium than in vacuum when it goes into the medium (Fig.5). The light decreases its speed in the medium due to the exchange energy stored in the medium. Suppose that the speed of the light is v in the medium. The light block decreases its dimension in its speed direction from 1 to $1/n$ when the light block goes into the medium from vacuum, where $n = c/v$, n being the refractive index of the medium and c the light speed in vacuum with $c > v$.

2.3. Energy conservation

The light resumes its speed in vacuum when it leaves the medium and goes back to vacuum. So the refraction process should obey the law of energy conservation. The energy in the light block in vacuum, which is a unit cube (Fig.5), is $1 \times W_v = W_v$. The light block has the same average energy density in the

medium as in vacuum, but the volume of the block becomes $1/n$ in the medium and part of the energy of the light transfers to the exchange energy that is stored in the electron cloud inductors in the medium. The average density of the exchange energy stored in the medium is $W_{\rm ex}$ (Eq.10). According to the law of energy conservation, the energy in unit volume of the light block in vacuum is equal to the sum of the energy of the light and the exchange energy in the $1/n$ volume which is occupied by the light block in the medium, that is

$$W_{\rm v} = (W_{\rm m} + W_{\rm ex})/n \tag{13}$$

for the refracted part of light, where $W_{\rm ex}$, $W_{\rm v}$ and $W_{\rm m}$ are in J/m^3. Suppose that there is one type of molecule in the medium. With Eqs.(13), (12), (11) and (9), we have

$$\frac{B_0^2}{2\mu_0} = \frac{1}{n}\frac{\rho B_0^2}{4\mu_0}\sum_{i=1}^{z}\left(\frac{V}{g}\right)_i + \frac{1}{n}\frac{B_0^2}{2\mu_0}, \tag{14}$$

and

$$n = 1 + \frac{1}{2}\rho\sum_{i=1}^{z}\left(\frac{V}{g}\right)_i. \tag{15}$$

Equation (15) shows that all the molecules in the medium are arranged in the same direction relative to the magnetic field of the light. If this condition is not met, then

$$n = 1 + \frac{1}{2}\rho\sum_{i=1}^{z}\left(\frac{V}{< g >}\right)_i, \tag{16}$$

where $< g >$ is the average value (in solid angle) of g of electron i in all the molecules in the medium. And then we have

$$n = 1 + \frac{1}{2}\sum\left[\rho\sum_{i=1}^{z}\left(\frac{V}{< g >}\right)_i\right]_j, \tag{17}$$

when there are j kinds of molecules in the medium. ρ is in m^{-3} and V is in m^3, so the right hand sides of Eqs.(15)–(17) are dimensionless quantities. According to these equations, the refractive index n increases as ρ or V increases. When the electron cloud of one electron is not in ball shape, the g of this electron is anisotropic. This is the main reason for the anisotropy of refractive index of an anisotropic medium. If the directions of the electron clouds that are not in ball shape are disorderly arranged in the medium, the medium does not show macroscopic anisotropy in the refractive index. Otherwise, the medium shows macroscopic anisotropy in the refractive index.

3. Tests and discussions

Under the standard condition (273K, $\sim 10^5$Pa) and Na incident light (wavelength λ=589.3nm in vacuum), the measured refractive index of He gas $n_{\rm He}$=1.000035.[10] The density of He gas is 2.686×10^{25} atoms/m^3. Na light frequency is far different from the resonant frequency of inert gas.[11] There are two 1s electrons in He atom and their electron clouds are in ball shape. These electron clouds coincide in space. Suppose that these two electron clouds have the same volume when the electrons in He atoms are in ground state. Then the term in the square brackets of Eq.(2) is 2/3 for a coil in ball shape.[12] So $< g >= g = 2/3$, and g is isotropic for the electron cloud in ball shape. With the above data, the equivalent volume of each electron cloud in He atom by Eq.(15) is V=0.8687×10^{-30}m^3. So the equivalent radius of each electron cloud in He atom is $r_{\rm He}$=$(3V/4\pi)^{1/3}$=0.592×10^{-10}m. Helium gas does not have inherent magnetic moment and is a diamagnetic medium. Langevin magnetic susceptibility is[13]

$$\chi = -\frac{N_{\rm A}e^2}{6mc^2}\sum_{i=1}^{z} < R^2 >_i. \tag{18}$$

All the notations in Eq.(18) are in centimetre-gram-second (cgs) units. χ is in cm^3/mol, N_A is Avogadro's constant, e is electron charge, m is electron static mass, $< R^2 >_i$ is average value of R^2, R is the distance from electron to nucleus, i stands for electron i in the atom. Both the diamagnetic susceptibility and the refractive index are mainly caused by the interaction between the magnetic field and the electrons in the molecules of the medium. For He atom, if letting $R = r_{\rm He}$=0.592×10^{-8}cm, then with Eq.(18) we can calculate the magnetic susceptibility of He $\chi'_{\rm He} = -1.977\times10^{-6}$cm^3/mol (cgs). The measured magnetic susceptibility of He is $\chi_{\rm He}$=-1.88 -2.02×10^{-6}cm^3/mol (cgs).[14,15] $\chi'_{\rm He}$ is within the range of $\chi_{\rm He}$. This indicates that Eq.(15) and the result of $r_{\rm He}$=0.592×10^{-10}m are reasonable.

Electron density of H_2 gas is almost the same as that of He gas under standard condition. Their measured refractive indices are $n_{\rm He}$=1.000035 and $n_{\rm H2}$=1.000140.[10] Each electron in H_2 appears in the space of about two H atoms. The volume of each electron cloud in H_2 is larger than that in He. This explains $n_{\rm H2} > n_{\rm He}$.

The O_2 and N_2 gases have almost the same atomic density under the standard condition. Oxygen atom has one more electron than nitrogen atom does. It

seems that the refractive indices of O_2 should be larger than that of N_2. But the measured refractive indices are n_{O2}=1.000272 for O_2 gas and n_{N2}=1.000297 for N_2 gas.[10] According to the periodic law, the radius of N atom is larger than that of O atom. This makes $n_{O_2} < n_{N_2}$.

The main composition of air is N_2 78.1%, O_2 21% and Ar 0.9% (in volume percentage).[16] The measured refractive index of air n_{air}=1.000292 under the conditions of 273K, $\sim 10^5$ Pa and Na light.[10] We have calculated the refractive indices of air to test Eq.(17). The measured refractive indices of O_2, N_2 and Ar gases are n_{O2}=1.000272, n_{N2}=1.000297 and n_{Ar}=1.000283.[10] Let $0.5\rho\sum(V/ < g >)_i = D$. The D values of O_2, N_2 and Ar gases under the standard condition are D_{O2}=0.000272, D_{N2}=0.000297 and D_{Ar}=0.000283 by using Eq.(17). When N_2, O_2 and Ar are mixed to form air, the electron clouds in N_2, O_2 and Ar molecules do not change their shape and size because the interaction between gas molecules is very weak. So $\sum(V/ < g >)_i$ values keep constants for all the molecules of N_2, O_2 and Ar. Only the densities of N_2, O_2 and Ar change when N_2, O_2 and Ar are mixed to form air. So the refractive index of air calculated using Eq.(17) is

$$\begin{aligned} n'_{air} &= 1 + 0.21D_{O2} + 0.781D_{N2} + 0.009D_{Ar} \\ &= 1.0002915. \end{aligned} \tag{19}$$

Here n'_{air} is close to n_{air}.

Expected values of radius for electron shells in inert gas atoms by Hartree-Fock method are listed in Table 1. The s, p and d electron shells are in closed ball shape for inert gas atoms, in which the s electron shell is equivalent to two conductors in ball shape, as mentioned above. The p electron shell has three pairs of electrons and each electron cloud of the p electron is not in ball shape. These three pairs of electrons occupy different spaces of p electron shell and in collective effects they make the p electron shell in ball shape. Everywhere in the p electron shell exists the electron cloud that is formed by two p electrons. So p electron shell is equivalent to two conductors in ball shape for inert gas atoms. The same result can be gained for d electron shell for inert gas atoms. The sequence of the contribution of one electron to the refraction is s>p>d electron when these electron shells have nearly the same radius.

Table 1. Expectation radii of electron shells for inert gas atom $< r >_{nl}$.[17]

	He	Ne	Ar	Kr	Xe
	$< r >_{nl}/10^{-10}$m				
1s	0.93	0.16	0.09	0.04	0.03
2s		0.89	0.41	0.19	0.12
2p		0.96	0.38	0.16	0.10
3s			1.42	0.54	0.32
3p			1.66	0.54	0.31
3d				0.55	0.28
4s				1.63	0.75
4p				1.95	0.78
4d					0.87
5s					1.98
5p					2.34

We have $r_{He}/ < r >_{nl}$=0.592/0.93=0.6366 for He. Thus the $< r >_{nl}$ of He in Table 1 can be changed into the equivalent radius of the electron shell conductor by multiplying it by 0.6366. In estimation, the other data in Table 1 can be changed into the equivalent radii of the electron shell conductors by multiplying them by 0.6366. Now we can estimate the refractive indices of inert gas elements under standard condition using Eq.(15):

$$\begin{aligned} n &= 1 + \frac{1}{2}\rho\sum\left(\frac{V}{g}\right)_i \\ &= 1 + \frac{1}{2g}\rho\frac{4\pi}{3}2\sum(0.6366\times < r >_{nl})^3, \end{aligned} \tag{20}$$

where g=2/3 for the ball-shaped electron shell. With Eq.(20) and the data in Table 1, the refractive indices have been calculated and listed in Table 2. The measured refractive indices are also listed in Table 2. The calculated refractive index of Ne is close to the measured value. The calculated refractive indices show certain deviations for Ar, Kr and Xe. The Hartree–Fock method has good accuracy for small atoms, but poor accuracy for large atoms.[18] This may be one of the origins for these deviations.

Table 2. Calculated and measured refractive indices of inert gas.

	He	Ne	Ar	Kr	Xe
Measured n[10]	1.000035	1.000069	1.000283	1.000427	1.000702
Calculated n'	1.000035	1.0000693	1.000329	1.000532	1.000967
$(n'-n)/n$		2.99×10^{-7}	4.60×10^{-5}	1.05×10^{-4}	2.65×10^{-4}

Conditions: 273K, $\sim 10^5$Pa, Na light.

Equations (15)–(17) are derived under the conditions that the electrons in the medium do not deviate obviously from their ground states and that the absolute value of the magnetic susceptibility χ of the medium is far less than 1. Equations (15)–(17) indicate that the refractive index n is not related to the magnetic field, the electric field and the frequency of the light. $\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t$ of the light causes a whirling electric field E_{s} in the electron cloud conductor. We have $E_{\mathrm{s}} \propto |\mathrm{d}B_{\mathrm{M}}/\mathrm{d}t| = \omega B_{\mathrm{M0}}|\sin \omega t|$. If the magnetic field, the electric field or the frequency of the light is so high that the electrons in the medium are strongly disturbed, then these electrons will deviate obviously from their ground states. Thus the shapes, directions or sizes of these electron clouds change obviously, so that the refractive index of the medium changes accordingly. This results in the nonlinearity of the refractive index. The shape and direction factor g and the equivalent volume V of the electron clouds are no longer constants in this case. They can be expressed as $g = g(H_0,\ E_0,\ \omega)$ and $V = V(H_0,\ E_0,\ \omega)$. When the light frequency $f = \omega/2\pi$ is close to the resonant frequency of the medium, the interaction between the electric field of the light and the medium cannot be neglected. This will further make a complicated relation between the refractive index of the medium and the light frequency.

When the wavelength of the x-rays is close to the size of the electron cloud, there exist simultaneously the negative and positive magnetic flux linkages of the x-ray in the electron cloud space at most of or all the time, and these magnetic flux linkages counteract each other. Hence the absolute value of the sum of $\mathrm{d}\Phi/\mathrm{d}t$ in the electron cloud is decreased, and the exchange energy held by the electron is small. This explains why the refractive index of x-rays is close to 1.

4. Conclusions

The interaction between the light and the medium under the condition that the light frequency is far from the resonant frequency of the medium has been studied, and the result shows that the slowdown effect of the light in the medium is caused by the energy exchange between the light and the medium. The exchange energy results from the electromagnetic induction between the magnetic field of the light and the charged particles of the medium, and the interaction between $\mathrm{d}B/\mathrm{d}t$ of the light and the electron clouds in the medium makes main contribution to the exchange energy. This is still valid when the electrons in the medium are evidently disturbed. We have tested the formulas of the refractive index derived in this work using several media and by Langevin diamagnetic magnetic susceptibility of helium; and the results are in good agreement with the measured data. The anisotropy and the nonlinearity of the refractive index are explained with the theory developed in this work. Research on the interaction between the light and the medium when the light frequency is in the resonant frequency zone of the medium is under way. It would increase our knowledge of light behaviour in the medium.

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