METHODOLOGY FOR THE DEVELOPMENT OF TECHNICAL THINKING OF STUDENTS OF ACADEMIC LYCEUMS IN THE FIELD OF PHYSICS

Umirov Habibullo Bakhodirovich
Teacher at Academic Lyceum under Karshi EEI
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Abstract. *In this work, the Zeeman effect. Simple and complex. The electron moves in the atom. Since this motion is not rectilinear, the electron has an angular momentum (in classical physics, the angular momentum of particle relative to some origin is determined by the vector product of its radius vector and momentum, here m - the mass of the particle, v - its velocity, r - the radius vector). This formula is considered inapplicable for microparticles, since the radius and velocity cannot be determined simultaneously (See to the uncertainty relation). The moment of momentum because of the movement in space is called orbital. According to quantum theory, the modulus of the orbital momentum vector are equal, here l - the number of orbital quantum which takes the values 0, 1, 2, ... Thus, the angular momentum of the electron L, like the energy, is quantized, namely, takes discrete values.*

Keywords: *Zeeman effect, electron, formula, space, quantum theory.*

One more important conclusion follows from quantum theory: the projection of the angular momentum of the electron onto some given direction in space z (for example, onto the direction of the lines of force of the magnetic or electric field) is also quantized according to the following rule:

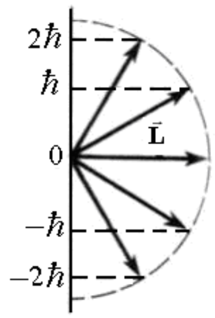

Figure 1. The electron which moves around the nucleus is considered the elementary circular electric current.

Experimental data indicated that the electron in the 1s state (orbital quantum number l = 0, and, therefore, L = 0) has a nonzero angular momentum S, which is not associated with the movement of the particle as a whole. This angular momentum was called spin (spin is in English spin, its meaning is rotation). When the concept of "Spin" was introduced, it was assumed that the electron can be considered as a "rotating top", and its Spin is considered as the characteristic of such rotation. The modulus of the spin moment and its projection satisfy the expressions

$$|\vec{\mathbf{S}}| = \hbar\sqrt{\mathbf{s}(\mathbf{s}+1)} \qquad \mathbf{S}_z = \hbar \mathbf{m}_s \quad (1)$$

The spin quantum number for the electron is equal to s = 1/2. The quantum number of the projection $\mathbf{m}_s = \pm 1/2$. Namely, there are only two projections.

The total angular momentum J for the electron in an atom is taking shape from the orbital and spin moments, and according to the rule of moment addition, the quantum number of the total angular momentum has two values:

$$\vec{J} = \vec{L} + \vec{S}, \quad J = L + \frac{1}{2}, L - \frac{1}{2} \quad (2)$$

The presence of spin and magnetic moment in the electron made it possible to explain the previously observed splitting of spectral lines. If grains of table salt fall into the flame of the gas stove, a yellow glow is seen: excited sodium atoms pass from the 3p state to the 3s state. But, if we observe this radiation with the good spectrometer, we will find that the yellow line of sodium doubles: two close lines with wavelengths of 589.0 and 589.6 nm and for most of the other lines. This phenomenon is called the "fine structure" of atomic spectra.

The reason for the bifurcation is that the electron has its own magnetic moment μs, which interacts with the magnetic field BL which is created by the orbital motion in the atom.

$$E = -\frac{me^4}{8\varepsilon_0^2 h^2}\frac{1}{n^2} - (\vec{\mu}_s \vec{B}_L) \quad (3)$$

The interaction energy of the object with magnetic moment μ with the external magnetic field B is equal to

$$U_m = -(\vec{\mu}\vec{B}) \quad (4)$$

This energy must be added to the energy of the Coulomb interaction of the electron with the nucleus. For example, the energy of the atom for a hydrogen atom is equal to

Taking into account expressions (1) and (2), the scalar product of the vectors of the intrinsic magnetic moment of the electron μs and the induction BL can be written as $(\vec{\mu}_s \vec{B}_L) = const(\vec{s}\vec{L})$ Since the electron magnetic moment μs has two projection values, the expression in parentheses also has two meanings. The spin-orbit interaction leads to the splitting of the energy level into two sublevels. In the sodium atom, the energies of the 3p3/2 and 3p1/2 states are slightly different, and we observe two lines with close wavelengths in transition to the 3s1/2 state. Back in 1896, the Dutch physicist P. Zeeman discovered that when the light source is placed in a magnetic field, spectral lines undergo splitting. The effect is quite subtle: the difference in wavelengths is hundredths of nm at the induction of a magnetic field of 1 Tl. Distinguish between simple and complex Zeeman effects.

We start with a simple explanation.

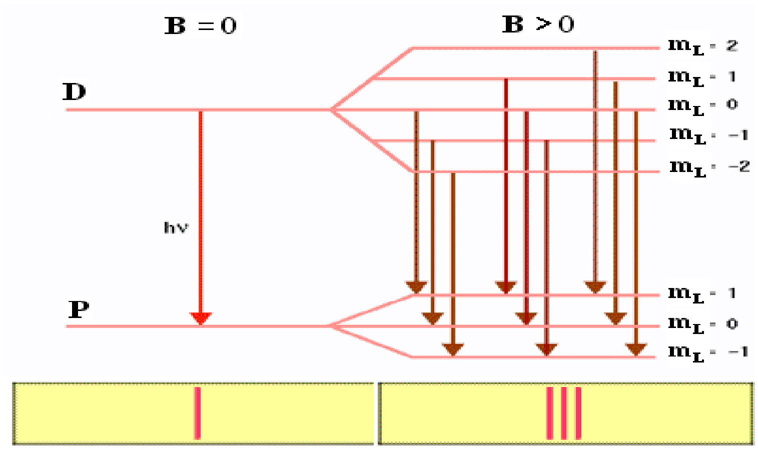

Figure 2

We consider the atom which the sum of the electron spin moments S is equal to zero. Only the orbital angular momentum and the magnetic moment proportional to it are not equal to zero. In the external magnetic field B, the interaction energy of the magnetic moment (the direction of the z axis coincides with the induction vector):

$$U = -(\vec{\mu}_L \vec{B}) = \mu_z B = \frac{e}{2m} L_z B = \frac{e\hbar}{2m} B m_L = \mu_Б B m_L \quad (5)$$

In this expression, the constant μБ = 0.927·10-23 J/T is the Bohr magneton, m is the electron mass, mL = 0, ± 1, ..., ± L is the magnetic quantum number which determines the possible values of the projections of the orbital momentum on the given magnetic field direction. This energy must be added to the energy of the atom. The additional energy in the magnetic field has (2L+1) equidistant values: ΔU = μБB. It is necessary to take into account the selection rules ΔmL = 0, ± 1 in order to correctly display possible transitions of an electron from excited states. The figure shows that the level which corresponds to the P-state (L = 1) is split into 3 sublevels in the magnetic field, and there are 5 sublevels for the D-state (L = 2). The figure also shows all the transitions allowed by the selection rules. There are 9 transitions, but sublevels are equally spaced, different frequencies are only 3. The radiation is polarized. If we look perpendicular to the magnetic field, then all 3 lines are visible, if they are in common, then they are only 2 extreme ones.

Complex (anomalous) Zeeman effect

Now we consider more complicated case, when the orbital L and spin S moments of the atom are not equal to zero. These mechanical moments correspond to magnetic ones, which also add up

$$\vec{J} = \vec{L} + \vec{S} \quad и \quad \vec{\mu}_J = \vec{\mu}_L + \vec{\mu}_S \quad (6)$$

Magnetic moments are proportional to mechanical moments

$$\vec{\mu}_L = \frac{e}{2m}\vec{L} = g_L \frac{e}{2m}\vec{L}, \quad \vec{\mu}_S = \frac{e}{m}\vec{S} = g_S \frac{e}{2m}\vec{S} \quad (7)$$

The introduced proportionality coefficient g is called the gyromagnetic ratio (or the Lange factor by the name of the physicist who proposed it). gL=1 is for orbital motion, gS=2 is for spin motion. It is this difference in the values of the gyromagnetic ratios which causes the complex Zeeman effect.

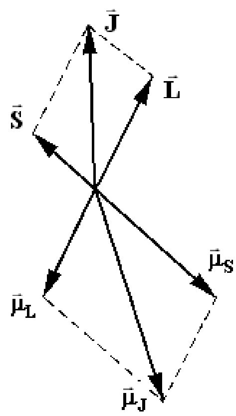

Figure 3. We consider the vector model of the atom which is shown in the figure on the right

Since the electron charge is negative, the vectors of the magnetic moments are directed opposite to the corresponding angular momenta. The scale is chosen so that the lengths of the segments which represent the vectors L and μL are the same. Under this condition, the vector μS will be represented by a segment twice as long as S, in this case gS=2. Obviously, the vector of the total angular momentum μJ will not lie on the same straight line with the vector of the total angular momentum J. In the absence of the external field, the vector J is conserved in magnitude and direction, and its components L and S retain only their lengths. The vectors L and S precess around the constant vector J. The corresponding magnetic moments μL, μS and their sum μJ will precess with the same angular velocity. Because of the high speed of this precession, only the projection of the magnetic moment vector μJ onto the direction of the vector J - μ || (we can get distracted from the presence of perpendicular component). The parallel component can be written as. Here, the gyromagnetic ratio (the Lange factor) is g

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \quad (8)$$

We place the atom in homogeneous magnetic field B. And this field will be "weak", less than BL. Then the spin-orbit interaction remains in force, the total moment μ|| will be oriented in the magnetic field. In the absence of the field E0,

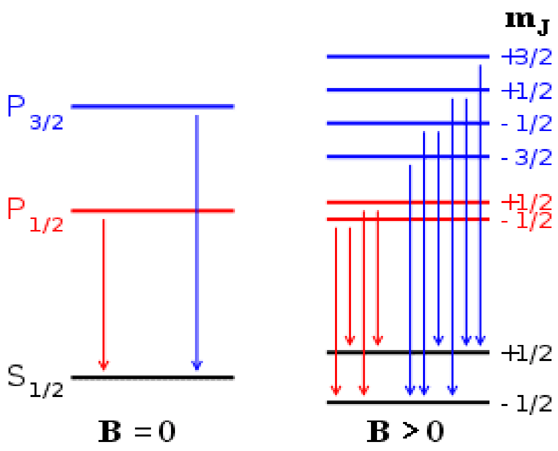

Figure 5. the energy of interaction of the magnetic moment of the atom with the external field is added

$$E = E_0 - (\vec{\mu}\vec{B}) = E_0 + g\mu_B B m_J, \quad (9)$$

here the magnetic quantum number takes on a series of values mJ=J, J-1, ..., -J (there are 2J+1 in total). This formula shows what energy levels each level of the atom splits into the magnetic field. It is necessary to take into account the selection rules ΔmJ=0, ±1 in order to imagine which lines will appear in the radiation spectrum.

The figure on the right shows the splitting of the 3S1/2, 3P1/2, and 3P3/2 levels of sodium in a magnetic field and shows all possible transitions. The 589.6 nm line and its splitting are shown in red, and the 589.0 nm line is shown in blue. Since the factor g is different in magnitude for different states (gS=2, for states 3P1/2 and 3P3/2 its magnitude is 2/3 and 4/3, respectively), the wavelengths of all transitions are different. All of 10 are visible!

The radiation is polarized. The splitting pattern essentially depends on the direction of observation with respect to the direction of the magnetic field. In this regard, a distinction is made between the longitudinal and transverse Zeeman effects. When observed perpendicular to the magnetic field (the transverse Zeeman effect), all components of the spectral lines are linearly polarized: some of them are parallel to the field B (π-components), some of them are perpendicular (σ-components). When observed along the field (longitudinal Zeeman effect), only the σ-components remain visible, but their linear polarization is replaced by circular polarization. The historical names "normal" for a simple effect and "anomalous" for a complex effect turned out to be unfortunate, namely, a complex effect is overwhelmingly common, and a simple effect is a special case of complex effect. The Zeeman effect is used in spectroscopy, in quantum electronics devices, in particular for measuring the strengths of weak magnetic fields in laboratory conditions. The Zeeman effect later found a very useful application in astronomy, since the splitting of lines in the radiation spectrum of celestial bodies can be used to judge the strength of their magnetic fields. For example, it was precisely from the Zeeman effect which astrophysicists were able to establish that spots on the Sun are considered a consequence of the disturbance of powerful magnetic fields near its surface - solar magnetic storms.

In strong magnetic fields, the connection between the spin and orbital magnetic moments is torn, they are independently oriented in the magnetic field. Splitting into three lines is observed as in the simple Zeeman effect (Paschen-Buck effect, 1912).

If we place a substance which emits or absorbs light into the external magnetic field, then important optical phenomena arise: the emission and absorption spectra of the substance, the polarization characteristics of light, the speed of its propagation, and others change. The spectral lines are split into several components in the emission and absorption spectra. The phenomenon is called with the name of the discoverer as the Zeeman effect.

The installation for studying the Zeeman effect consists of a magnet (1) among the poles which the light source is located, an ideal spectrometer (2), a lens system (3), a polaroid (4), a photodetector (5), and a spectrometer eyepiece (6).

We investigate the line of the spectrum with a wavelength of 579.0 nm, caused by the transition between the states 6^1D_2 and 6^1P_1.

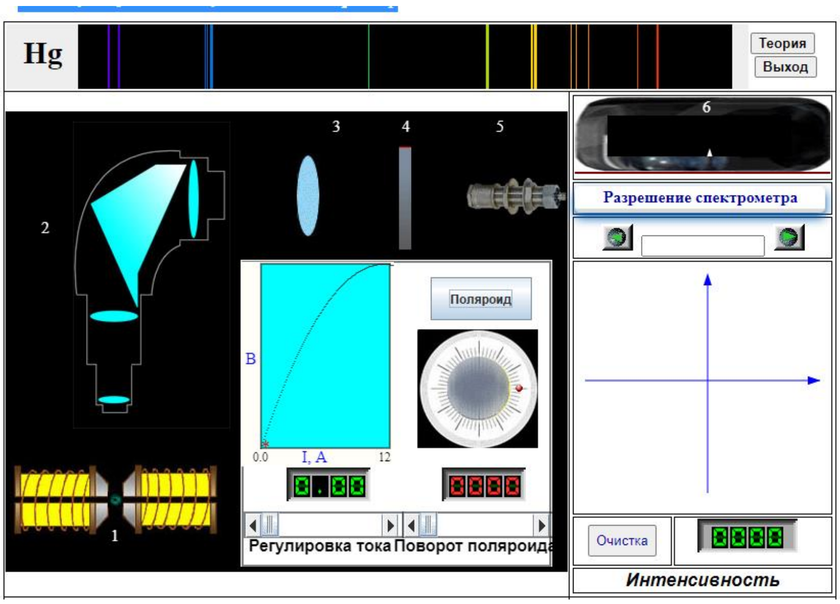

Figure 6. In this work, the mercury lamp serves as the source.

TASK 1. Light the spectral lamp by pressing the "Start" button. Find a line suitable for studying (yellow mercury 579 nm) in appeared spectrum. Several successive presses of the "Spectrometer resolution" button increase it. In this case, it is worth looking at the level diagram and the transition between them, which give this line in the absence of the external magnetic field (the button "Go to the level diagram" of displaying of this diagram is used in order to do this).

Then, it is need to move the pointer under this line (the indicator will show the wavelength).

Qualitatively investigate the dependence of the splitting of the spectral line on the magnitude of the magnetic induction by adjusting the magnitude of the current flowing through the magnet winding.

If the splitting of the line in the magnetic field is not seen, the resolution must be further increased by pressing the "Spectrometer resolution" button again (Do not overdo it, otherwise, return to the initial low resolution). Find the formula which is connecting the number of sublevels which are formed in the magnetic field and the quantum number of the total angular momentum of the atom.

Describe the observed results of the experiment.

Complex (anomalous) Zeeman effect If we place a substance which emits or absorbs the light into the external magnetic field, then important optical phenomena arise: the emission and absorption spectra of the substance, the polarization characteristics of light, the speed of its propagation, and others change. The spectral lines are split into several components in the emission and absorption spectra. The phenomenon is called with the name of the discoverer as the Zeeman effect.

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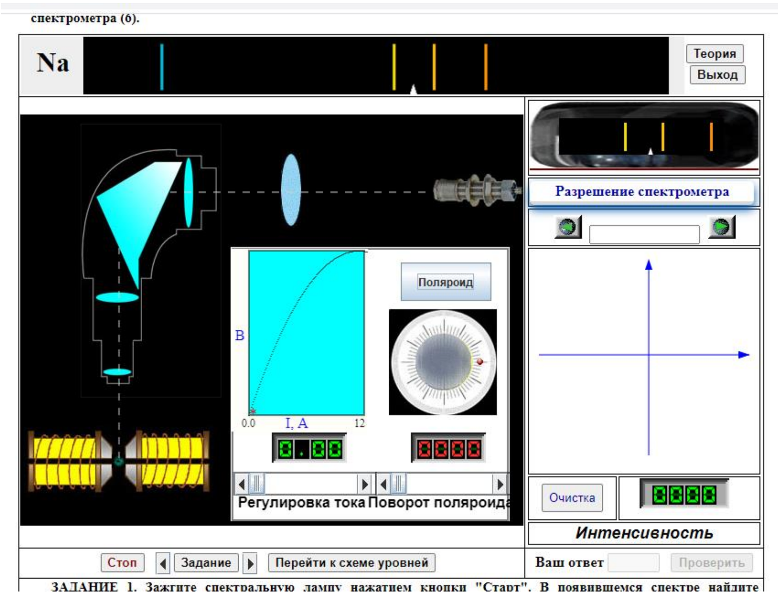

Figure 7

TASK 2. Light the spectral lamp by pressing the "Start" button. Find a suitable line for studying (yellow sodium 589 nm) in appeared spectrum. Several successive presses of the "Spectrometer resolution" button will allow us to see that the sodium yellow line doubles. In this case, it is worth looking at the level diagram and the transitions between them, which give this doublet in the absence of the external magnetic field (the button "Go to the level diagram" of displaying of this diagram is used in order to do this).

Then it is need to select one of the lines of the doublet. The indicator will show the wavelength for the selected line.

Qualitatively investigate the dependence of the splitting of the spectral line on the magnitude of the magnetic induction by adjusting the magnitude of the current flowing through the magnet winding.

If the splitting of the line in the magnetic field is not seen, the resolution must be further increased by pressing the "Spectrometer resolution" button again (Do not overdo it, otherwise, return to the initial low resolution). Find the formula which is connecting the number of sublevels which are formed in the magnetic field and the quantum number of the total angular momentum of the atom.

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