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SACCHARIDE SOLUTIONS UNDER THE MAGNETIC FIELD ACTION

Fluctuations in the intensity of light scattering in a 5-% aqueous solution of glucose under the action of a magnetic field are registered. The effect is shown to result from the emergence of the turbulent motion in the solution.
Keywords: aqueous glucose solution, magnetic field, turbulence.

1. Introduction

One of the challenging problems in modern medical physics is an issue concerning the physical mechanism of interaction between human organism and a magnetic field. It is known that the magnetic field can considerably affect the state of organism. However, from the physical viewpoint, this fact remains unclear, because almost all bioorganic substances belong to the class of diamagnetic media.

It is possible to come closer to the understanding of complicated processes occurring in organism under the action of magnetic field by studying this action on simpler physical systems, which organism consists of. For instance, these are solutions. We will focus our attention on glucose solutions with regard for their important role in the functioning of human organism.

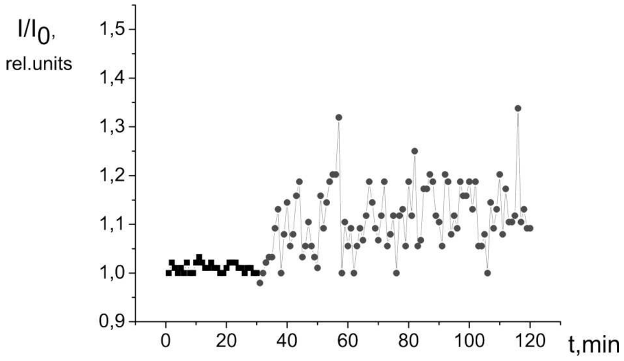
Opposite opinions are expressed in the literature concerning the influence of magnetic fields on the physical properties of solutions. Some scientists reject this influence altogether, referring, as it was in the case of organism as a whole, to the diamagnetism of aqueous solutions (see, e.g., work [1]). On the other hand, there are a number of experimental data that bring us to a conclusion that the magnetic field does affect the properties of aqueous solutions (see, e.g., work [2]). At present, no convincing molecular model, which would substantiate this influence, has been proposed. There are only speculations at the qualitative level.

This work was aimed at studying the action of a magnetic field on aqueous saccharide solutions.

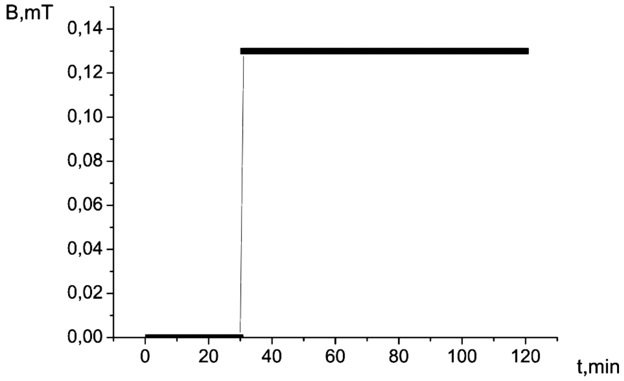
2. Experiment and Its Discussion. Phenomenon Model

To fulfil the task, the light scattering in the aqueous glucose solution is studied. A cylindrical cuvette was filled with the analyzed liquid and arranged in the Helmholtz coil. The measurements were carried out with the help of a nephelometer NFM-4. The dependences of the light scattering intensity on the time were obtained. A typical dependence is depicted in Fig. 1, *b*, where $\alpha = I/I_0$ is the relative scattering intensity, I_0 is the scattering intensity at the time moment $t = 0$ (the measurement start), and I the scattering intensity at the time moment $t > 0$. Figure 1, *a* demonstrates the time dependence of the magnetic field induction B in the given experiment.

It is seen that, before the magnetic field had been applied, the scattering intensity remains constant within experimental error. However, from the time moment of the field application, the light scattering intensity increases. Moreover, it demonstrates fluctuations that substantially exceeded random deviations



a



b

Fig. 1. Dependences of the magnetic induction B (a) and the relative scattering intensity (b) on the time t in the 5-% aqueous solution of glucose

associated with possible experimental errors. In our opinion, this result unambiguously evidences the existence of the magnetic field action on the solution structure.

Now, having convinced that the magnetic field effect does exist, let us consider a probable mechanism of observed scattering intensity fluctuations arising when the magnetic field is switched on. Let $\mathbf{H}$ designate the strength of an external magnetic field. Being switched on, this field gives rise to the substance magnetization, which is characterized by a vector $\mathbf{P}$. It is known (see, e.g., work [3]) that the both vectors are related by the relation

$$\mathbf{P} = \boldsymbol{\chi} \cdot \mathbf{H}, \tag{1}$$

where $\boldsymbol{\chi}$ is the tensor of magnetic susceptibility.

By its physical sense, the magnetization $\mathbf{P}$ equals the magnetic moment per unit volume. In other words, $\mathbf{P}$ is a macroscopic parameter. This means that $\mathbf{P}$ characterizes a certain region, in which a local equilibrium takes place. Conventionally (see, e.g., work [3]), this region is defined as a physically infinitesimal volume. For brevity, let us call it the block. Every block is characterized by its χ-value and, accordingly, the value of the quantity $\mathbf{P}$. This circumstance can be expressed by introducing the functions $\chi(\mathbf{x})$ and $\mathbf{P}(\mathbf{x})$, where $\mathbf{x}$ is the radius vector of block's center of inertia. Then the magnetic moment of the block equals

$$\mathbf{m}(\mathbf{x}) = \mathbf{P}(\mathbf{x})w(\mathbf{x}), \tag{2}$$

where $w(\mathbf{x})$ is the block volume. According to formula (1), we have

$$\mathbf{m}(\mathbf{x}) = \chi(\mathbf{x}) \cdot \mathbf{H}w(\mathbf{x}). \tag{3}$$

Let us distinguish between isotropic and anisotropic blocks. The quantity χ is a zero-rank tensor (a scalar) for the former and a second-rank tensor for the latter. Below, the anisotropic block will be referred to as a cluster.

When the magnetic field is switched on, the cluster is subjected to the action the external mechanical momentum

$$\mathbf{M_m}(\mathbf{x}) = \mathbf{m}(\mathbf{x}) \cdot \mathbf{H}. \tag{4}$$

For the isotropic block, this momentum is evidently absent.

Let the cluster be axially symmetric. Let us designate the principal values of the tensor χ as $\chi_\parallel$ and $\chi_\perp$, and the angle between the vector $\mathbf{H}$ and the tensor axis that corresponds to the principal value $\chi_\parallel$ as φ. According to formula (4), we have

$$|\mathbf{M_m}(\varphi)| = \chi_\mathbf{a} H^2 w \cos\varphi \sin\varphi, \tag{5}$$

where $\chi_\mathbf{a} = \chi_\parallel - \chi_\perp$. As we see, the switching-on of the magnetic field gives rise to the emergence of mechanical momenta in the liquid. Accordingly, if the liquid was at rest before the field is switched-on, those momenta should induce a motion in the liquid. What character has this motion?

Let us use the continuous approximation and consider the block as a mathematically infinitesimal volume $d\mathbf{x}$, i.e., a vicinity of the point $\mathbf{x}$. In this approximation, the cluster becomes a point singularity, the concentrated momentum. Such a singularity is conventionally called the rotation center (see, e.g., work

[4]). The concentration $\rho_{\mathbf{m}}$ of rotation centers is described by the expression

$$\rho_{\mathbf{m}} = \sum_J \mathbf{M}_{\mathbf{m}}(\phi^{(J)})\delta(\mathbf{x} - \mathbf{X}^{(J)}), \tag{6}$$

where $\delta\left(\mathbf{x} - \mathbf{X}^{(J)}\right)$ is the delta-function, and $\mathbf{X}^{(J)}$ the radius vector of the j-th rotation center. If the system includes such centers, the determination of the character of the motion induced by them is reduced to the solution of the equation of motion for those centers in a viscous liquid and looks like

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \operatorname{div} \sigma + \rho_f, \tag{7}$$

where ρ is the density, $\mathbf{v}$ the velocity, p the pressure, σ the viscous stress tensor, and ρ_f the bulk force density.

Designating the value of ρ_f at $\mathbf{x} = \mathbf{X}^{(J)}$ as $\mathbf{f}^{(J)}$, we obtain the following expression for this quantity:

$$d(\mathbf{M}_{\mathbf{m}}(\phi^{(J)})\delta(\mathbf{x} - \mathbf{X}^{(J)})) = d\mathbf{x} \times \mathbf{f}^{(J)}. \tag{8}$$

Problems similar to that formulated above are met in the theory of polymeric solutions and in the theory of suspensions. In those domains, the rigorous solution of such problems is considered to be unsolvable; instead, the Ozeen approximation method is applied (see, e.g., work [3]). The main role in this method is played by the Ozeen tensor $\mathbf{T}(\mathbf{x}, \mathbf{x}')$, which connects the velocity perturbation $\mathbf{v}'$ at the point $\mathbf{x}$ with the force $\mathbf{F}$ at the point $\mathbf{x}'$:

$$\mathbf{v}'(\mathbf{x}) = \mathbf{T}(\mathbf{x}, \mathbf{x}')\mathbf{F}(\mathbf{x}'). \tag{9}$$

As a result of this perturbation, an additional force acts on the center located at the point $\mathbf{x}$. This force is called the hydrodynamic interaction force. In our case, a similar relation looks like

$$\boldsymbol{\omega}'(\mathbf{x}) = \mathbf{S}(\mathbf{x}, \mathbf{X}')\mathbf{M}(\mathbf{X}'). \tag{10}$$

It defines the tensor $\mathbf{S}(\mathbf{x}, \mathbf{X}')$, which describes the perturbation of the angular velocity $\boldsymbol{\omega}'(\mathbf{x})$ created at the point $\mathbf{x}$ by the force moment $\mathbf{M}(\mathbf{X}')$ acting at the point $\mathbf{X}'$.

Below, the behavior of a separate cluster will be analyzed. The corresponding equation of motion is written in the form

$$I \frac{d^2\varphi}{dt^2} = \mathbf{M}, \tag{11}$$

where I is the cluster moment of inertia, and $\mathbf{M}$ the mechanical moment acting on the cluster. The mechanical moment is written as the sum

$$\mathbf{M} = \mathbf{M}_{\mathbf{N}H} + \mathbf{M}_{\mathbf{H}}. \tag{12}$$

Here, the first term, $\mathbf{M}_{\mathbf{N}H}$, is not connected with the hydrodynamic interaction, whereas the second one, $\mathbf{M}_{\mathbf{H}}$, is. For convenience, the first component will be referred to as the own moment, and the second one as the interaction moment.

For the own moment, we have the expression

$$\mathbf{M}_{\mathbf{N}H} = \mathbf{M}_{\mathbf{m}} + \mathbf{M}_{\mathbf{E}} + \mathbf{M}_{\mathbf{V}}, \tag{13}$$

where $\mathbf{M}_{\mathbf{E}}$ and $\mathbf{M}_{\mathbf{V}}$ are the moments induced by the elastic and viscous, respectively, responses of the environment. Assuming the angle φ to be small, let us expand function (5) in a power series of φ and confine the expansion to the first-order term,

$$\mathbf{M}_{\mathbf{m}} = \chi_{\mathbf{a}} H^2 \varphi. \tag{14}$$

For the moment $\mathbf{M}_{\mathbf{E}}$ induced by the elastic response of the environment, we have

$$\mathbf{M}_{\mathbf{E}} = -\alpha\varphi, \tag{15}$$

where α is the effective coefficient of elasticity. By definition, the moment $\mathbf{M}_{\mathbf{V}}$ induced by the viscous response of the environment is an odd function of $\frac{d\varphi}{dt}$. Therefore, expanding this function in a series in $\frac{d\varphi}{dt}$ to the first two terms, we obtain

$$\mathbf{M}_{\mathbf{V}} = -\beta \frac{d\varphi}{dt} - \gamma \frac{d\varphi}{dt}\frac{d\varphi}{dt}\frac{d\varphi}{dt}, \tag{16}$$

where β and γ are the effective coefficients of internal friction of the first and third, respectively, orders. Keeping the second term in expansion (16), we assign a dissipative nonlinearity to the system. Finally, the interaction moment is presented in the form

$$\mathbf{M}_{\mathbf{H}}(\mathbf{X}^{(p)}) = -\beta\boldsymbol{\omega}'(\mathbf{X}^{(p)}). \tag{17}$$

Substituting expression (10) into formula (17), we obtain

$$\mathbf{M}_{\mathbf{H}}(\mathbf{X}^{(p)}) = -\beta \sum_{j \neq p} \mathbf{S}(\mathbf{X}^{(p)}, \mathbf{X}^{(j)})\mathbf{M}_{\mathbf{N}H}(\mathbf{X}^{(j)}). \tag{18}$$

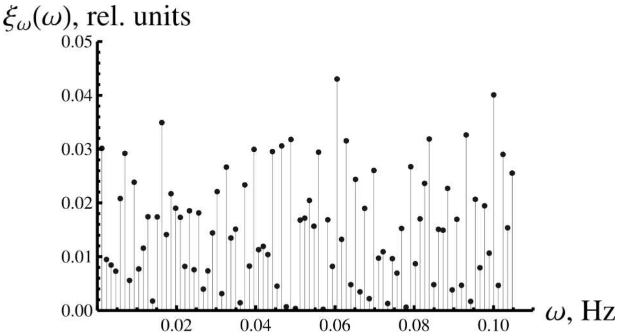


Fig. 2. Fourier spectrum of the scattered light intensity in the 5-% aqueous solution of glucose under the action of the 0.13-mT magnetic field

After substituting the corresponding expressions for the moments into the equation of motion (11), the latter reads

$$I\frac{d^2\varphi(\mathbf{X}^{(p)})}{dt^2} = -\alpha\varphi(\mathbf{X}^{(p)}) + \chi_\mathbf{a}H^2\varphi(\mathbf{X}^{(p)}) -$$

$$-\beta\frac{d\varphi(\mathbf{X}^{(p)})}{dt} - \gamma\frac{d\varphi(\mathbf{X}^{(p)})}{dt}\frac{d\varphi(\mathbf{X}^{(p)})}{dt}\frac{d\varphi(\mathbf{X}^{(p)})}{dt} +$$

$$+\beta\sum_{j\neq p}\mathbf{S}(\mathbf{X}^{(p)},\mathbf{X}^{(j)})\{\alpha\varphi(\mathbf{X}^{(j)}) - \chi_\mathbf{a}H^2\varphi(\mathbf{X}^{(j)}) +$$

$$+\beta\frac{d\varphi(\mathbf{X}^{(j)})}{dt} + \gamma\frac{d\varphi(\mathbf{X}^{(j)})}{dt}\frac{d\varphi(\mathbf{X}^{(j)})}{dt}\frac{d\varphi(\mathbf{X}^{(j)})}{dt}. \quad (19)$$

Formulas (11) and (19) allow qualitative conclusions to be made about the character of motion excited in the system by the magnetic field. In particular, at $\mathbf{M_H} = 0$, i.e. in the absence of hydrodynamic interaction, nonlinear damped oscillations are realized in the system. After some time, an equilibrium state is established in the system. This state corresponds to $\varphi = 0$, when all magnetic moments are oriented in the direction of the external field. In other words, a laminar motion is realized in the system at $\mathbf{M_H} = 0$.

Those formulas also demonstrate that the terms, which are identical by form, have different signs under the sum sign $\mathbf{S}(\mathbf{X}^{(p)}, \mathbf{X}^{(j)})$ and outside it. For example, the term $\beta\frac{d\varphi(\mathbf{X}^{(j)})}{dt}$ has the sign "+" under the sum sign. This means that the corresponding energy, instead of being absorbed by the thermostat, is transferred to the j-th cluster by other clusters by means of the hydrodynamic interaction. In other words, the hydrodynamic interaction provides a feedback in the system.

What character will the motion obtain, if the hydrodynamic interaction is taken into account? The answer to the question depends on the ratio between the own and interaction moments. If the ratio between them is such that the inequality $\mathrm{Re} < \mathrm{Re}_{cr}$ is satisfied, where Re_{cr} is the Reynolds number that is critical for the given system, the motion remains laminar. A small excess of Re over the critical value results in the appearance of a periodic motion; namely, there arise undamped self-oscillations in the system of clusters.

If the Reynolds number increases further, new and new unstable oscillation modes emerge in the system, and the motion transforms into a multiperiodic one. In the scenario of turbulence emergence proposed by L.D. Landau [3], this motion is identified with the turbulent one.

The magnetic anisotropy of clusters is accompanied by their dielectric anisotropy. Accordingly, the mentioned motion of clusters stimulates the appearance of anisotropy fluctuations, which comprises an origin of the chaotic behavior of the light scattering intensity observed experimentally. In the framework of this scenario, a typical attribute of the latter is the presence of incommensurate frequencies in the Fourier spectrum of the mentioned motion.

There are also other scenarios of turbulence [3]. In particular, this is a scenario associated with the frequency doubling. In order to check, to which scenario the dependence exhibited in Fig. 1, *b* belongs, the Fourier spectrum of this function was calculated. The calculation result is depicted in Fig. 2. One can see that the frequency doubling is out of the question, which gives preference to L.D. Landau's scenario.

3. Conclusions

According to our experiment, the turbulence arises at low magnetic inductions of an order of 10^{-4} T. In other words, the laminar motion is practically absent under the action of the magnetic field, i.e. the parameter $\mathrm{Re_{cr}}$ has a small value in this case. How can this fact be explained?

The turbulence is known to start with the formation of vortices. However, the rotation centers, which were discussed above, are, by definition, those elementary vortices that excite the liquid and prohibit it from the formation of a laminar motion. Therefore, it is quite reasonable that the turbulization of the liquid occurs practically without passing through the stage of laminar motion.

Our research enables us to assert that the application of the magnetic field gives rise to the formation of a turbulent motion in the solution. In our opinion, it is reasonable to call this effect the magnetohydrodynamic instability. It results in an increase of the scattered light intensity in the solutions subjected to the action of a magnetic field.

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РОЗЧИНИ САХАРИДІВ
ПІД ДІЄЮ МАГНІТНОГО ПОЛЯ

Р е з ю м е

Встановлено факт виникнення флуктуації інтенсивності розсіяння світла в водному розчині глюкози концентрацією 5% при дії магнітного поля. Показано, що цей ефект є наслідком виникнення в розчині турбулентного руху.