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Influence of Magnetic Fields with Induction of 7 T on Physical and Chemical Properties of Aqueous NaCl Solutions

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Abstract: The physicochemical properties of NaCl aqueous solutions in a wide range of concentrations were studied. We determined that constant magnetic fields with an induction of up to 7 T had a significant effect on the physicochemical properties of these solutions. First, we detected a decrease in pH that was dependent on the magnetic field strength both in water and in NaCl solutions. This effect was not associated with the presence of sodium cations or chlorine anions in water. Secondly, with an increase in magnetic field induction the redox potential of aqueous solutions also increased. Magnetic fields did not cause any changes in the concentration of dissolved molecular oxygen in deionized water. In this case, in aqueous solutions of NaCl under the action of a magnetic field, a concentration-dependent tendency to a decrease in the concentration of dissolved molecular oxygen is observed. Third, it was shown that under the action of a magnetic field on a NaCl solution, the rate of hydrogen peroxide generation increased with increasing NaCl concentration. Fourth, the essential role of the primary state of aqueous solutions in relation to the gas composition and gas equilibrium under magnetic influence was established. The work also evaluated the contribution of flow-mixing during sample preparation on the physicochemical properties of the solutions.

Keywords: magnetic fields; physical and chemical properties of water; aqueous NaCl solutions; reactive oxygen species

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1. Introduction

Water is the most common chemical compound of any living organism, including humans. This can constitute 75% body weight in infants and 55% in the elderly [1–3]. What is more, we need to provide the body with a constant supply of water in order to renew it. Approximately 2/3 of all water in the body is intracellular and 1/3 extracellular [4]. Extracellular water is needed to transport nutrients to all cells in the body and to eliminate waste products [5]. Intracellular water is a medium for biochemical reactions and is also directly involved in them [6]. It is well known that the main physicochemical properties of water can significantly affect the rate of reactions, especially enzymatic, taking place in it [7]. The physicochemical properties of water undergo changes when chemicals are dissolved in it or it is exposed to physical factors [8–12]. This may have important implications in medicine, pharmaceuticals, agriculture, the food industry, and a number of related fields.

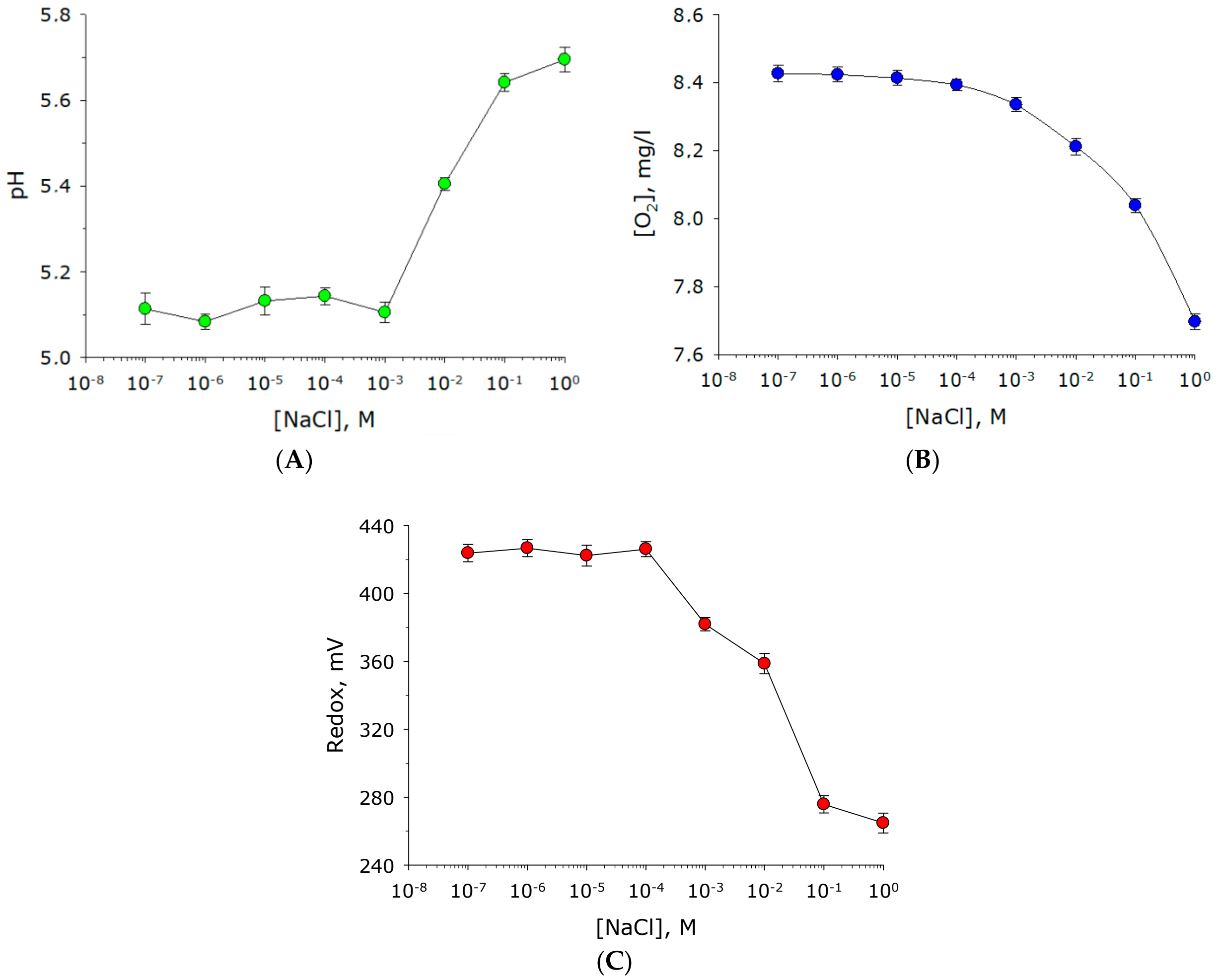
From the point of view of experimental science, water cannot be represented only by a set of identical H_2O molecules. Water almost always contains dissolved gases and trace amounts of molecules, ions, and associates. What we call 'water' is almost always an aqueous solution—a complex heterogeneous formation. In this paper we will utilize two concepts: an aqueous solution, and deionized water—an object that has been purified of any inclusions and impurities to the best possible standard. Below we list the most well-known experimental facts about long-term changes in the physicochemical properties of water and aqueous solutions after exposure to a constant magnetic field. One of the most studied properties of aqueous solutions is the hydrogen index (pH). Changes in pH after exposure to a magnetic field were first identified by Joshi and Kamat in 1966. They found that when distilled water passed through a magnetic field with an induction of up to 0.5 T, the pH of water increased by more than 0.5 units [13]. This experiment was repeated several years later using bidistilled water and a magnetic field with an induction of up to 2.4 T and a much lower fluid flow rate [14]. The measurements were carried out away from the magnet. Such a significant effect on pH value was not reproduced. Subsequently, when using more accurate and modern measurement methods, no significant changes in the pH value of water or aqueous solutions were found after exposure to magnetic fields with an induction of up to 3 T [15]. Introduction of instruments that generate magnetic fields made it possible to register a large number of magnetic field effects on water and other liquids, including post-effects. For example, data were obtained on the effect of a constant magnetic field on the concentration of molecular oxygen dissolved in distilled water [16]. Changes in some optical properties [17], in evaporation rate [18], and in a number of other physical and chemical characteristics were detected. Moreover, in experiments using aqueous solutions of salts, the effects were often more pronounced, and sometimes qualitatively different. For example, it was shown that a magnetic field with a relatively weak induction of up to 0.7 T can reduce the pH value of an aqueous saline solution by almost 0.25 units [19]. It was found that the conductivity of an aqueous solution of $CaCl_2$ after exposure to a magnetic field can increase or decrease relative to the control, depending on the salt concentration [20]. The presence of cations and anions can also significantly affect many other physicochemical characteristics of aqueous solutions [21–23].

Currently, the only time that an average person would undergo magnetic fields with an induction of more than 1 T is during magnetic resonance imaging (MRI). This requires a strong and uniform magnetic field accurate to a few ppm over the entire scan volume. Most MRI machines operate at a magnetic field strength of about 1.5 T, while there are commercial systems available with a field strength of 7 T [24]. The inductance of a magnetic field in the range of 7.0 T is not achievable in most tomographs, while inductance an order of magnitude lower is capable of influencing biophysical and biochemical processes in biological objects [25,26]. It has been previously shown that under the influence of a static magnetic field with an induction of 0.5 T in stem cells, the expression of CD49d, CD54 and CD73 decreases, changes associated with differentiation and division occur, while there are no changes in DNA integrity [27]. A static magnetic field was shown to affect the proliferation, adhesion, and differentiation of various types of cells, making it a helpful tool for regenerative medicine [28]. With an increase in the inductance of the magnetic field, its effect on biological objects increases. Thus, with an inductance of 7 T, there is a 20–40% decrease in the viability of cells of the lines HTB 63 (melanoma), HTB 77 IP3 (ovarian carcinoma), and CCL 86 (lymphoma) [29].

Consequently, a large number of phenomena have been established to date that occur in aqueous solutions when exposed to a constant magnetic field. Moreover, all these phenomena are observed during direct action of a magnetic field on an object. The post-effects of magnetic field exposure are most pronounced in the presence of ions. In this case, the presence of cations and anions in the aqueous phase can have a significant effect on the measured values, both quantitatively and qualitatively. The nature of this effect is still not fully understood. In the current study we assessed a number of physicochemical properties of aqueous NaCl solutions using high-precision measuring instruments, namely: the concentration of hydrogen peroxide, the concentration of dissolved molecular oxygen, pH, and redox potential. The experimental conditions included varying NaCl concentrations and magnetic field induction. We demonstrated that both the concentration of NaCl and the magnetic field strength have a significant effect on the basic physicochemical properties of aqueous solutions. The impact of flow-mixing during sample preparation on the physicochemical properties of the solutions was also evaluated.

2. Results

We observed changes in a number of physicochemical parameters upon dilution of a NaCl solution with deionized water. First, we investigated the effect of diluting a NaCl solution with deionized water on pH value (Figure 1A). Deionized water had a pH of approximately 5.1 and the pH of a 1 M NaCl solution was 5.7. When the NaCl solution was diluted to a concentration of 1 mM, the pH value decreased to 5.1. Further dilution had no significant effect on the pH of the NaCl solution.



(**A**) (**B**)

(**C**)

Figure 1. Change in pH (**A**), redox potential (**B**) and molecular oxygen concentration (**C**) when diluting a sodium chloride solution with deionized water. Data are presented as means and standard errors of the mean (n = 6–12).

Second, we studied the change in the redox potential of a NaCl solution upon dilution with deionized water (Figure 1B). We determined that the redox potential of a 1 M NaCl solution was 265 mV, for a 1 mM NaCl solution it was 380 mV, and a 0.1 mM solution 425 mV. The latter roughly corresponds to the redox potential of deionized water. No significant changes in the redox potential were registered after further dilution of the NaCl solution.

Third, we measured molecular oxygen concentration in NaCl solutions upon dilution with deionized water (Figure 1C). The concentration of molecular oxygen in a 1 M NaCl solution was 7.7 mg/L. After dilution of the 1 M sodium chloride solution, the concentration of molecular oxygen increased. When the concentration of NaCl reached 10^{-5} M, the molecular oxygen concentration stopped increasing. The molecular oxygen concentration remained unchanged after the NaCl solution was diluted further.

It should be noted that the intensive shaking and stirring performed when mixing and preparing samples of the solutions to the required concentration have a significant effect on the concentration of dissolved molecular oxygen (Figure 2). It is known that in water saturated with atmospheric gases, the concentration of molecular oxygen reaches 8.7 mg/L at 22 °C [30]. In this case, the concentration of molecular oxygen in water can easily be reduced by passing atomic nitrogen through the water [31]. As can be seen from Figure 2, after shaking oxygen-depleted water for 1 min in the presence of atmospheric gases, the concentration of molecular oxygen in the water significantly increased due to transfer from the air. At the same time, after mechanical action on water containing the equilibrium concentration of molecular oxygen, degassing is observed. In other words, the concentration of molecular oxygen can decrease with mechanical action. Usually, a decrease in the concentration of molecular oxygen dissolved in deionized water by 2–4% is registered. In general, it is necessary to be extremely careful when measuring the concentration of molecular oxygen after mechanical action on water and aqueous solutions.

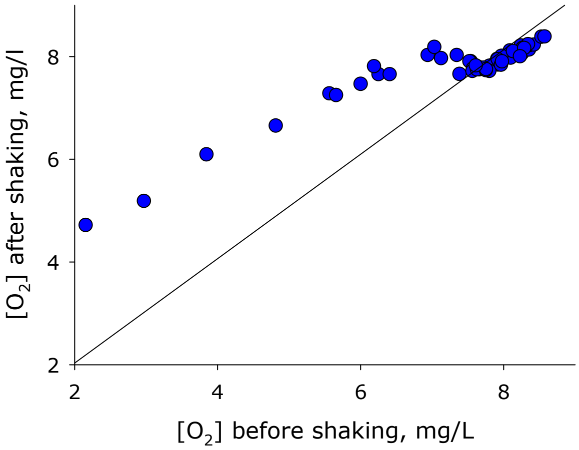


Figure 2. The influence of mechanical action on the change in the concentration of molecular oxygen dissolved in water. The abscissa is the oxygen concentration in water before shaking, the ordinate is the oxygen concentration in water after shaking. Characteristics of mechanical impact: frequency 30 Hz, amplitude 3 mm, duration 1 min. Experimental data are indicated by dots. The line indicates the theoretical dependence in the absence of external influences.

Thus, we showed that NaCl solutions have properties significantly different from deionized water at NaCl concentrations of between 0.01 and 1 M. At lower salt concentrations, the studied characteristics were quite close to those of deionized water.

Next, we investigated the dependence of physicochemical parameters of 0.01, 0.1, and 1 M NaCl solutions on the magnetic field strength. We used deionized water as a control. Figure 3 shows the change in the pH value under the influence of a magnetic field in water and NaCl solutions. There was a tendency in all cases towards a decrease in the pH value with an increase in magnetic field induction. However, no significant changes in pH were recorded.

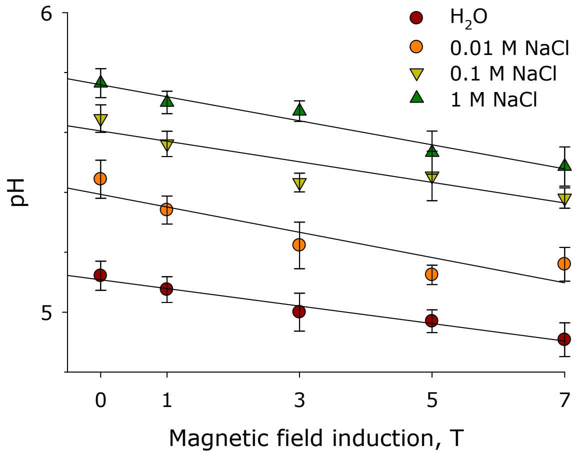


Figure 3. Change in pH value depending on magnetic field strength in water and NaCl solutions. Data are presented as means and standard errors of the mean (n = 3–6).

Changes in the redox potential of water and NaCl solutions under the influence of a magnetic field are shown in Figure 4. The redox potential of deionized water and NaCl solutions increased with increased magnetic field strength. With an increase in the concentration of ions in the solution, the relative increase in the redox potential was also slightly higher. Thus, if the relative increase in the redox potential of water was ~4 mV/T, then for a 1 M NaCl solution it was 7 mV/T. An increase in the number of charge carriers in the solution can lead to a more pronounced change in the redox potential of the solution when exposed to a magnetic field.

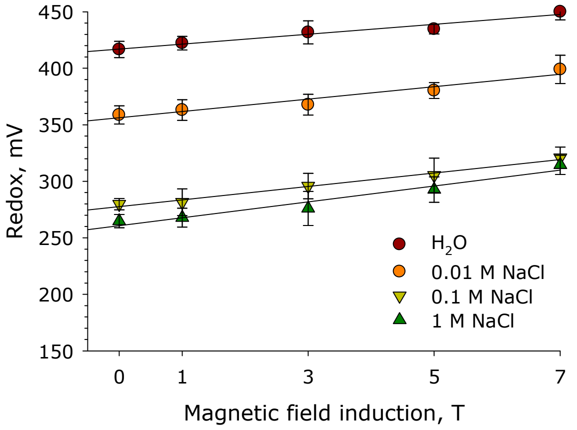


Figure 4. Change in the redox potential of water and NaCl solutions depending on magnetic field induction. Data are presented as means and standard errors of the mean (n = 3–6).

The redox potential of deionized water and aqueous solutions is usually associated with the concentration of dissolved molecular oxygen [32]. In this regard, we investigated the effect of the magnetic field on the concentration of molecular oxygen dissolved in deionized water and NaCl solutions (Figure 5). No changes were observed in the concentration of molecular oxygen in deionized water under the action of magnetic fields of different strengths. However, there was a tendency towards a decrease in the concentration of dissolved molecular oxygen in NaCl solutions with an increase in the magnetic field induction. Moreover, the higher the concentration of ions in the solution, the more pronounced the degassing of the solution became. Thus, an increase in the redox potential cannot be explained by an increase in the concentration of molecular oxygen.

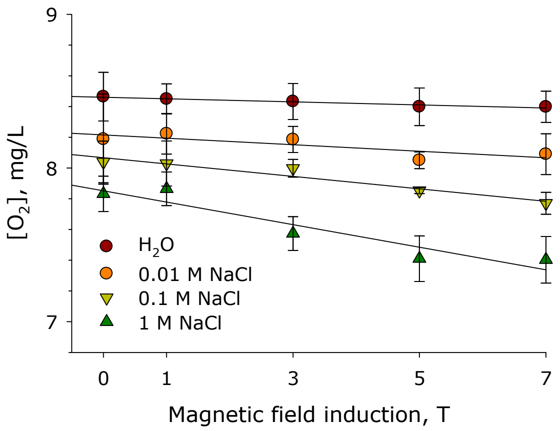


Figure 5. Changes in the concentration of molecular oxygen dissolved in water or NaCl solutions depending on magnetic field strength. Data are presented as means and standard errors of the mean (n = 3–6).

In addition to the role of molecular oxygen, the generation of reactive oxygen species can also lead to an increase in redox potential. The most stable type of reactive oxygen species is hydrogen peroxide. The influence of magnetic fields on the generation of hydrogen peroxide in water and aqueous solutions of NaCl was investigated (Figure 6). It was found that under the influence of a magnetic field, the generation of hydrogen peroxide occurs both in deionized water and in aqueous salt solutions, depending on the magnetic field strength. The relative increase in the concentration of generated hydrogen peroxide in water was 1 nM/T. With an increase in the salt concentration, the relative increase in the concentration of generated hydrogen peroxide was higher, so in a 1 M NaCl solution it reached almost 2.5 nM/T. At the same time, with an increase in the concentration of salt in water, the base level of hydrogen peroxide slightly increased. Thus, under the influence of a magnetic field, an increase in the number of charge carriers in the solution leads to a relative increase in the concentration of generated hydrogen peroxide.

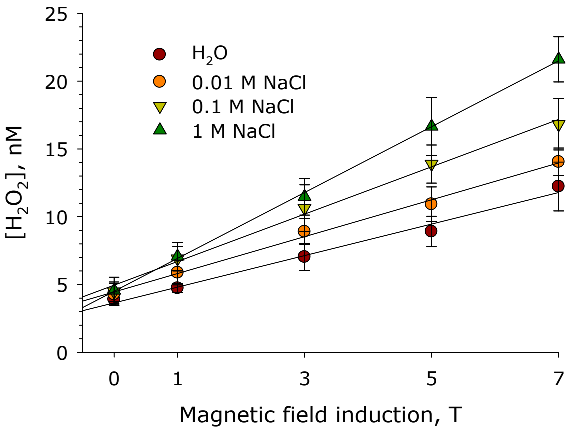


Figure 6. Change in the concentration of hydrogen peroxide in water and aqueous NaCl solutions depending on the magnetic field strength. Data are presented as means and standard errors of the mean (n = 3–6).

We found that it is often necessary to stir solutions during measurements in order to obtain stable results, including using a magnetic stirrer. Therefore, the various methods of stirring or mixing aqueous solutions during the dilution process may affect their basic physicochemical properties. To clarify this technicality, a series of experiments was carried out in which the effect of flow-mixing solutions using a microfluidic system was investigated.

In order to take into account the impact of ionic strength, both NaCl solutions and deionized water were mixed. To minimize the additional introduction of ions during measurement, the following mixing and dissolution scheme was used. A 1 M aqueous solution of NaCl was mixed with water in a microfluidic system at a ratio of 1/99. As shown earlier, microfluidic systems mix the samples most thoroughly. The mixing procedure was repeated five more times and as a result the calculated concentration of NaCl decreased to 10^{-12} M. Using this approach, such a solution cannot be distinguished from water. Therefore, the direct effect of the ions of the resulting solution can be neglected. We performed similar operations with deionized water. Such highly diluted solutions were mixed with water and a 2 M aqueous solution of NaCl. In the resulting mixtures, the pH, redox potential, and concentration of molecular oxygen were measured (Table 1).

Table 1. Changes in pH value, redox potential, and molecular oxygen concentration after mixing a solution of sodium chloride (2 M) or water with solutions diluted 10^{12} times at a v/v ratio of 1:1.

Samples	Content	pH	Redox, mV	[O_2], mg/L
Sample 1	2 M NaCl solution mixed with highly diluted NaCl	5.65 ± 0.01	290.2 ± 2.9 *	7.88 ± 0.01
Sample 2	2 M NaCl solution mixed with highly diluted H_2O	5.65 ± 0.02	291.6 ± 4.3 *	7.86 ± 0.02
Sample 3	NaCl without mixing	5.63 ± 0.01	275.1 ± 2.0	7.84 ± 0.02
Sample 4	H_2O mixed with highly diluted NaCl (10^{-12} M)	5.13 ± 0.04	424.9 ± 8.1 *	8.43 ± 0.03 *
Sample 5	H_2O mixed with highly diluted H_2O	5.04 ± 0.07	428.2 ± 8.8 *	8.45 ± 0.03 *
Sample 6	H_2O without mixing	5.15 ± 0.05	416.5 ± 5.1 *	8.42 ± 0.04 *

Note: highly diluted NaCl solutions (10^{-12} M) were obtained using a continuous flow microfluidic device. Data are presented as mean ± SEM of six independent experiments. * Mean is significantly different from "NaCl without mixing" group at $p < 0.05$.

We found that samples 1–3 did not differ in pH value or molecular oxygen concentration. However, both sample 1 and sample 2 had a statistically significant difference in redox potential compared to sample 3. Thus, the possibility of the sample preparation technology affecting the physicochemical properties of aqueous solutions of NaCl was demonstrated. We did not find any differences between sample 1 and sample 2: i.e., the ionic composition of the substance successively diluted by flow-mixing to a factor of 10^{12} did not affect the studied properties of the solutions.

We also found no differences between samples 4–6 in any of the measured parameters. Consequently, the characteristics of the mixtures containing no significant amounts of NaCl did not depend on the presence of a component produced by 10^{12}-fold serial dilution using continuous flow mixing.

3. Discussion

In the current study we investigated the changes in pH value, redox potential, and molecular oxygen concentration in NaCl solutions under the influence of magnetic fields of various inductances and in the absence of a magnetic field (Figure 1). Our results are generally consistent with the literature data both under the influence of a magnetic field [19,33,34], and in its absence [35–37].

When diluting NaCl solutions, we used a mechanical method (mechanical pipettes and shaking to stir one solution into another). It is known that mechanical action can affect the concentration of molecular oxygen in an aqueous solution [38]. We investigated the effect of shaking on the concentration of molecular oxygen in water (Figure 2). When shaking water saturated with gases, deaeration occurs. Conversely, when shaking degassed water, a rapid saturation of water with gases is observed. These processes are probably due to the fact that the water–gas area of contact increases many times during shaking. Comparing the results of this work with the results of [39] allows us to conclude that there is a certain critical concentration of molecular oxygen below which mechanical action causes an increase in concentration, and above which a decrease. In addition, we investigated the effect of magnetic fields of various strengths on the pH of water and NaCl solutions (Figure 3). We showed that with an increase in magnetic field strength, the pH decreased, the effect being similar both in deionized water and in aqueous solutions of NaCl at different concentrations. We assumed that under the influence of a magnetic field in the presence of NaCl, the concentration ratio of H^+ and OH^- ions would differ from that of water. This is indirectly confirmed by an increase in the redox potential observed under the same conditions.

We also investigated the effect of magnetic field strength on the redox potential in water and NaCl solutions (Figure 4). We demonstrated that with an increased magnetic field induction, the redox potential also increased; the relative increase depended on the NaCl concentration. Usually, the change in redox potential in deionized water is directly related to the concentration of dissolved molecular oxygen [32], and less often to atmospheric carbon dioxide, which dissolves in water to form carbonic acid [40].

However, the change in the pH values is probably not associated with the presence of sodium cations or chlorine anions in water. The change in pH values is not always associated with the presence of sodium cations or chlorine anions in the water. There are studies that show that new hydrogen bonds are formed in water placed in strong magnetic fields. The authors interpreted the shift of the absorption maximum of water in the near-IR spectrum for water in a magnetic field with an induction of 14 T as an increase in hydrogen bonds [41]. In another study, the authors attributed the decrease in surface tension and increase in water viscosity when exposed to a 500 mT magnetic field to the increasing the number of hydrogen bonds [42].

On the other hand, there are works that show, on the contrary, a decrease in hydrogen bonds in strong magnetic fields. A large number of hydrogen bond breaks under the influence of a magnetic field with an induction of 200 mT or more was recorded in [43]. Effects of a decrease in the friction coefficient were found in [44] and a decrease in heat capacity and boiling point in [45] can also be interpreted as a decrease in the quantity of hydrogen bonds.

Changes in the number of hydrogen bonds in water can explain the increase in the yield of peroxide with an increase in the magnetic field induction in our experiments. However, the effect of increasing peroxide is associated with a decrease in molecular oxygen in the water. It is characteristic that both of these effects depended on the concentration of NaCl, while the changes in pH and redox potential did not. It is interesting that previous authors had also recorded the dependence of magnetic effects on the concentration of solutes. For example, from NH_4Cl in [46] or d-glucose [41].

When studying the effect of a magnetic field on the concentration of molecular oxygen dissolved in deionized water and in aqueous NaCl solutions, a decrease in the concentration of dissolved molecular oxygen with an increase in the magnetic field induction was shown (Figure 5). The magnitude of this effect depends on the concentration of NaCl. It transpired that an increase in the redox potential cannot be explained by a decrease in the molecular oxygen concentration. We assume that this change is associated with the generation of reactive oxygen species. Indeed, when a magnetic field acts on aqueous solutions, hydrogen peroxide is produced, which depends on field induction (Figure 6). The relative increase in hydrogen peroxide generated is higher as NaCl concentration increases. A possible mechanism for the generation of peroxide in an aqueous solution is the reduction of singlet oxygen to a superoxide anion radical, the protonated form of which dismutes to form hydrogen peroxide and a singlet oxygen molecule [47–49].

However, another mechanism of relatively rapid changes of concentration of molecular oxygen under magnetic field exposure is possible. It is known that nano-bubbles can exist in water for a long time [50]. A decrease in the concentration of molecular oxygen may also indicate the transfer of oxygen dissolved in the water into these bubbles.

To obtain stable results during experiments, it was often necessary to stir the solutions. On the one hand, it has already been shown that mixing can affect the basic physicochemical properties of water and, consequently, aqueous solutions [38]. In the present study, it was found that flow-mixing of solutions using a microfluidic system does not affect the measurement of pH and the concentration of molecular oxygen. However, it can change the redox potential of NaCl solutions under certain conditions. This may mean that redox reactions in salt solutions prepared using solutions (NaCl or water) diluted by flow-mixing will proceed differently than in similar salt solutions prepared with unmixed water.

One noteworthy point is that measurements were carried out immediately after exposure to the magnetic field. It would certainly be better to carry out measurements directly during exposure and we plan to perform such experiments. However, the experiment plan in its present form makes sense as there is evidence that the effects of strong magnetic fields on aqueous solutions persist for minutes or even tens of minutes. The memory time for demagnetization of water and aqueous solutions of NH_4Cl was 30–80 min for different mass fractions (from 1% to 28%) [46]. In another paper, the value change of infrared absorption for magnetized water after removing the magnetic field also occurred in the tens of minutes [17] and the increased rate of evaporation after the end of exposure persisted for tens of minutes [34].

4. Conclusions

In this work we investigated the physicochemical properties of aqueous solutions of NaCl in a wide range of concentrations. We found that constant magnetic fields with induction up to 7 T have a significant effect on the physicochemical properties of NaCl solutions of different concentrations. We observed a decrease in pH under the influence of a magnetic field. At the same time, the change in the pH values was not associated with the presence of sodium cations or chlorine anions in water. We showed that with an increase in magnetic field induction, the redox potential of aqueous solutions also increased. In water there were no changes in the concentration of dissolved molecular oxygen under the influence of a magnetic field, while in aqueous NaCl a concentration-dependent tendency towards a decrease in the concentration of dissolved molecular oxygen was observed. We also showed that in water, hydrogen peroxide is produced under the influence of a magnetic field. The relative increase in hydrogen peroxide was higher with an increase in the concentration of sodium chloride.

Thus, the physicochemical properties of an aqueous solution, which is a non-equilibrium dynamic system, are determined not only by its chemical composition, but also by external influences, such as a magnetic field and vibration. Moreover, the degree of effect of these influences can be different depending on the presence of impurities in the solution.

5. Materials and Methods

5.1. Materials

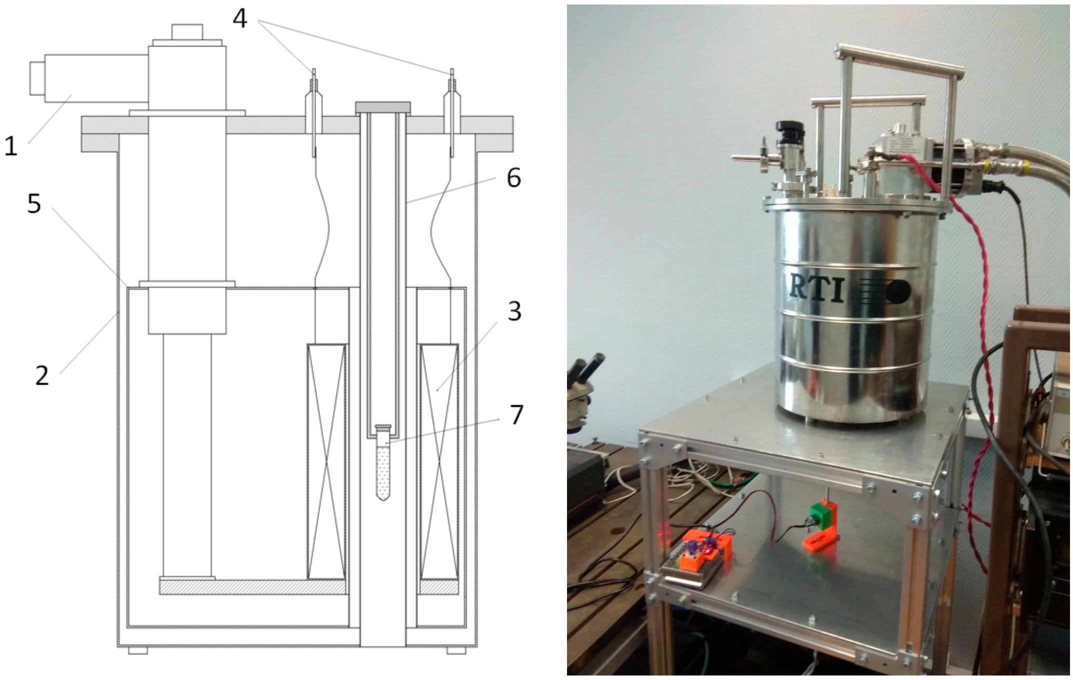
In all experiments, deionized water with a resistivity of 18 $M\Omega \times cm$ was used. A 1 M NaCl (ACS reagent, Panreac, Spain) stock solution was prepared, from which a series of solutions with concentrations ranging between 1 and 10^{-7} M was obtained by successive 10-fold dilutions with deionized water. In addition, the following solutions were prepared: (1) a mixture of a NaCl solution (2 M) and a NaCl solution with a concentration of 10^{-12} M in a v/v ratio of 1:1 (sample 1). A solution of NaCl at a concentration of 10^{-12} M was prepared using a microfluidic system as described below. (2) A mixture of NaCl solution (2 M) and a dilution of water prepared by the same technology as the NaCl solution at a concentration of 10^{-12} M in a v/v ratio of 1:1 (sample 2) was used as a control. (3) A mixture of NaCl solution (2 M) and water in a v/v ratio of 1:1, not manipulated in a microfluidic system (sample 3), was also used as a control. Additionally we investigated the properties of mixtures of water, namely: (1) a mixture of deionized water and NaCl solution in a concentration of 10^{-12} M in a v/v ratio of 1:1 (sample 4); (2) a mixture of deionized water and dilution of water prepared using the same technology as the NaCl solution at a concentration of 10^{-12} M in a v/v ratio of 1:1 (sample 5); (3) a mixture of deionized water and untreated water in a v/v ratio of 1:1 (sample 6).

5.2. Mixing with Microfluidics

Dilutions were prepared by flow mixing using a continuous-flow microfluidic system with a microreactor chip (USA, Dolomite microfluidics, Part No. 3200122), an Atlas syringe pump (Syrris Ltd., Royston, UK), and a personal computer with a solution preparation algorithm [38]. The two streams were mixed within the microfluidic flow chip by means of Dean vortices forming at the turns of the channel. The chip's microchannels were 1 mm^2 in cross-sectional area and 1080 mm long, and the flow rate was 400 L/min. The water flow ratio of the second channel to the first channel was 1/100. The Reynolds number and the Peclet number were 6.6 and 46.3 in the straight portion of the channel and 35.5 and 250.6 in the curved part, respectively. One part of a 1 M NaCl solution was flow-mixed with 99 parts of deionized water. This process was repeated 5 more times. The calculated concentration of NaCl in the final dilution was 10^{-12} M. The corresponding dilution of water was prepared by using deionized water instead of 1 M NaCl solution

5.3. Exposure of Samples to a Magnetic Field

To generate a magnetic field, we used an installation (Figure 7), which consisted of a cryostat with a superconducting NbTi solenoid with a warm field (FIAN, Moscow, Russia), cooled using a Gifford–McMahon cycle cryogenic refrigerator (Sumitomo, Tokyo, Japan). An experimental chamber is located on the solenoid axis, in which the samples are placed at room temperature. The magnet generates a magnetic field with an induction of up to 8 T. The size of the axial region of the uniform field in the solenoid is approximately 25 mm vertically. The object of study at a volume of 15 mL was placed in a specially designed 50 mL plastic bottle. The samples were exposed to a magnetic field of induction of 1, 3, 5, or 7 T for 5 min.



(**A**) (**B**)

Figure 7. Schematic diagram (**A**) and photograph (**B**) of the magnetic field generating device. 1—cryogenic refrigerator; 2—cryostat; 3—solenoid; 4—input wires; 5—radiation shield; 6—pipe; 7—sample holder.

5.4. Measurement of the Concentration of Hydrogen Peroxide in Aqueous Solutions

The concentration of hydrogen peroxide (H_2O_2) in aqueous solutions was measured by a highly sensitive method of enhanced chemiluminescence in the luminol-p-iodophenol-horseradish peroxidase system using a highly sensitive luminometer Biotox-7AM USE

(Autonomous Noncommercial Agency ANO Inzhenernyi Tsentr-Ekologiya, Russia). The concentration of hydrogen peroxide generated was calculated using calibration curves which were constructed by measuring the intensity of chemiluminescence of samples containing hydrogen peroxide of a known concentration [51]. The initial hydrogen peroxide concentration used for calibration was determined spectrophotometrically at a wavelength of 240 nm using a molar extinction coefficient of 43.6 ($M^{-1} \times cm^{-1}$). To determine the nanomolar hydrogen peroxide concentrations, the samples were placed in polypropylene vials (Beckman, Brea, CA, USA), and 1 mL of counting solution containing 10 mM Tris-HCl buffer pH 8.5, 50 µM p-iodophenol, 50 µM luminol, and 10 nM horseradish peroxidase. The counting solution was prepared immediately before the measurements. The sensitivity of the method allows hydrogen peroxide to be detected at concentrations below 1 nM. A more detailed description of the method is in [52].

5.5. Measurement of the Concentration of Dissolved Molecular Oxygen in Aqueous Solutions

To measure the concentration of molecular oxygen, an AKPM-1-02 (REM, Moscow, Russia) gas analyzer was used. Calibration was carried out before each series of experiments in air, in an atmosphere of nitrogen gas or in water incubated at different temperatures for 2 h. Atmospheric pressure was determined using a built-in pressure sensor PRX-7001T (Casio, Tokyo, Japan). The main measurement steps have been described earlier [53]. In a number of experiments, some of the samples were vigorously shaken using a Multi Reax vibrating shaker (Heidolph, Schwabach, Germany) with an amplitude of 3 mm and a frequency of 30 Hz.

An I-500 ionometer with an external reference electrode and a temperature sensor (Laborkomplekt, Moscow, Russia) was used to measure the pH. The measurements were carried out using a magnetic stirrer (mixing close to laminar, frequency 2 Hz); a modified protocol was used for measurements [54].

5.6. Measurement of Redox Potential of Aqueous Solutions

To measure the redox potential, we used an Expert-001 pH meter/ionometer (Econiks-Expert, Moscow, Russia) with an internal reference electrode. During measurements, mixing of solutions was performed using a magnetic stirrer; a modified protocol was used for measurements [55].

5.7. Statistical Data Analysis

Statistical analysis was performed using RStudio software (Version 1.2.1335, RStudio PBC, Boston, MA, USA) with R version 3.6.1. The data assumptions were checked using the Shapiro–Wilk test for normality and Bartlett's test for the homogeneity of variances. The groups were compared using analysis of variance with Tukey test as a post-hoc. Differences were considered significant at $p < 0.05$.

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References

1. Cerrato-Carretero, P.; Roncero-Martin, R.; Pedrera-Zamorano, J.D.; Lopez-Espuela, F.; Puerto-Parejo, L.M.; Sanchez-Fernandez, A.; Canal-Macias, M.L.; Moran, J.M.; Lavado-Garcia, J.M. Long-Term Dietary and Physical Activity Interventions in the School Setting and Their Effects on BMI in Children Aged 6–12 Years: Meta-Analysis of Randomized Controlled Clinical Trials. *Healthcare* **2021**, *9*, 396. [CrossRef]
2. Noda, Y.; Suzuki, H.; Kanai, T.; Samejima, Y.; Nasu, S.; Tanaka, A.; Morishita, N.; Okamoto, N.; Hirashima, T. The Association Between Extracellular Water-to-Total Body Water Ratio and Therapeutic Durability for Advanced Lung Cancer. *Anticancer. Res.* **2020**, *40*, 3931–3937. [CrossRef]
3. Piglowska, M.; Guligowska, A.; Kostka, T. Nutritional Status Plays More Important Role in Determining Functional State in Older People Living in the Community than in Nursing Home Residents. *Nutrients* **2020**, *12*, 2042. [CrossRef] [PubMed]
4. Hevesy, G.; Hofer, E. Elimination of water from the human body. *Nature* **1934**, *134*, 879. [CrossRef]
5. Stoot, L.J.; Cairns, N.A.; Cull, F.; Taylor, J.J.; Jeffrey, J.D.; Morin, F.; Mandelman, J.W.; Clark, T.D.; Cooke, S.J. Use of portable blood physiology point-of-care devices for basic and applied research on vertebrates: A review. *Conserv. Physiol.* **2014**, *2*. [CrossRef]
6. Banani, S.F.; Lee, H.O.; Hyman, A.A.; Rosen, M.K. Biomolecular condensates: Organizers of cellular biochemistry. *Nat. Rev. Mol. Cell Biol.* **2017**, *18*, 285–298. [CrossRef] [PubMed]
7. Koshland, J.; Daniel, E. Effect of Catalysts on the Hydrolysis of Acetyl Phosphate. Nucleophilic Displacement Mechanisms in Enzymatic Reactions1. *J. Am. Chem. Soc.* **1952**, *74*, 2286–2292. [CrossRef]
8. Gulyaev, Y.V.; Markov, I.A.; Ten, Y.A. Reagentless Modified Water and Its Biological Activity. *Phys. Wave Phenom.* **2020**, *28*, 98–102. [CrossRef]
9. Kononov, M.A.; Pustovoy, V.I.; Svetikov, V.V. Specific Features of the Excitation of Surface Plasmons at the Interface between Metal and Aqueous Solution of Extremely Low Concentration. *Phys. Wave Phenom.* **2020**, *28*, 94–97. [CrossRef]
10. Korenbaum, V.; Chernysheva, T.; Galay, V.; Galay, R.; Ustinov, A.; Zakharkov, S.; Bunkin, N. Possible Effect of Human-Experimenter on Homeopathic-Like Aqueous Preparations. *Water* **2021**, *13*, 1475. [CrossRef]
11. Penkov, N.V. Temporal Dynamics of the Scattering Properties of Deionized Water. *Phys. Wave Phenom.* **2020**, *28*, 135–139. [CrossRef]
12. Stunzhas, P.A. Mechanochemical Instability of Water and Its Applications. *Phys. Wave Phenom.* **2020**, *28*, 111–115. [CrossRef]
13. Joshi, K.M.; Kamat, P.V. Effect of magnetic field on the physical properties of water. *J. Ind. Chem. Soc* **1966**, *43*, 620–622.
14. Quickenden, T.I.; Betts, D.M.; Cole, B.; Noble, M. Effect of magnetic fields on the pH of water. *J. Phys. Chem.* **1971**, *75*, 2830–2831. [CrossRef]
15. Gonet, B. Influence of Constant Magnetic Fields on Certain Physiochemical Properties of Water. *Bioelectromagnetics* **1985**, *6*, 169–175. [CrossRef]
16. Ueno, S.; Iwasaka, M.; Kitajima, T. Redistribution of dissolved oxygen concentration under magnetic fields up to 8 T. *J. Appl. Phys.* **1994**, *75*, 7174–7176. [CrossRef]
17. Pang, X.F.; Deng, B.; Tang, B. Influences of magnetic field on macroscopic properties of water. *Mod. Phys. Lett. B* **2012**, *26*, 13. [CrossRef]
18. Seyfi, A.; Afzalzadeh, R.; Hajnorouzi, A. Increase in water evaporation rate with increase in static magnetic field perpendicular to water-air interface. *Chem. Eng. Process.-Process. Intensif.* **2017**, *120*, 195–200. [CrossRef]
19. Parsons, S.A.; Wang, B.L.; Judd, S.J.; Stephenson, T. Magnetic treatment of calcium carbonate—Effect of pH control. *Water Res.* **1997**, *31*, 339–342. [CrossRef]
20. Ayrapetyan, S.N.; Grigorian, K.V.; Avanesian, A.S.; Stamboltsian, K.V. Magnetic fields alter electrical properties of solutions and their physiological effects. *Bioelectromagnetics* **1994**, *15*, 133–142. [CrossRef] [PubMed]
21. Al Helal, A.; Soames, A.; Gubner, R.; Iglauer, S.; Barifcani, A. Influence of magnetic fields on calcium carbonate scaling in aqueous solutions at 150 degrees C and 1 bar. *J. Colloid Interface Sci.* **2018**, *509*, 472–484. [CrossRef] [PubMed]
22. Silva, I.B.; Neto, J.C.Q.; Petri, D.F.S. The effect of magnetic field on ion hydration and sulfate scale formation. *Colloids Surf. Physicochem. Eng. Asp.* **2015**, *465*, 175–183. [CrossRef]
23. Wang, X.L.; Zhao, J.D.; Liu, Z.A.; Zhao, E.J.; Yang, X.; Shao, X.J. Effect on the calcium carbonate scale in circulating cooling water: Constant magnetic and pulsed magnetic fields. *Desalination Water Treat.* **2018**, *124*, 125–133. [CrossRef]
24. Dempsey, M.F.; Condon, B.; Hadley, D.M. MRI safety review. *Semin. Ultrasound CT MRI* **2002**, *23*, 392–401. [CrossRef]
25. Glaser, R. *Biophysics: An Introduction*, 2nd ed.; Springer Science & Business Media: Heidelberg, Germany, 2012; p. 407.
26. Lai, H.C.; Singh, N.P.; IOP. Medical Applications of Electromagnetic Fields. In Proceedings of the Conference on Electromagnetic Phenomena and Health—A Continuing Controversy, London, UK, 10 September 2008.
27. Wang, J.; Xiang, B.; Deng, J.X.; Freed, D.H.; Arora, R.C.; Tian, G.H. Inhibition of Viability, Proliferation, Cytokines Secretion, Surface Antigen Expression, and Adipogenic and Osteogenic Differentiation of Adipose-Derived Stem Cells by Seven-Day Exposure to 0.5 T Static Magnetic Fields. *Stem Cells Int.* **2016**, *2016*, 7168175. [CrossRef]

28. Blyakhman, F.A.; Melnikov, G.Y.; Makarova, E.B.; Fadeyev, F.A.; Sedneva-Lugovets, D.V.; Shabadrov, P.A.; Volchkov, S.O.; Mekhdieva, K.R.; Safronov, A.P.; Armas, S.F.; et al. Effects of Constant Magnetic Field to the Proliferation Rate of Human Fibroblasts Grown onto Different Substrates: Tissue Culture Polystyrene, Polyacrylamide Hydrogel and Ferrogels gamma-Fe(2)O(3)Magnetic Nanoparticles. *Nanomaterials* **2020**, *10*, 1697. [CrossRef] [PubMed]
29. Raylman, R.R.; Clavo, A.C.; Wahl, R.L. Exposure to strong static magnetic field slows the growth of human cancer cells in vitro. *Bioelectromagnetics* **1996**, *17*, 358–363. [CrossRef]
30. Zefirov, N.S. Chemical encyclopedia. *Soviet Encycl.* **1998**, *5*, 3355.
31. Chernikov, A.V.; Gudkov, S.V.; Shtarkman, I.N.; Bruskov, V.I. Oxygen effect in heat-mediated damage to DNA. *Biofizika* **2007**, *52*, 244–251.
32. Zobell, C.E. Studies on redox potential of marine sediments. *AAPG Bull.* **1946**, *30*, 477–513.
33. Chibowski, E.; Hotysz, L.; Szczes, A. Time dependent changes in zeta potential of freshly precipitated calcium carbonate. *Colloids Surf. Physicochem. Eng. Asp.* **2003**, *222*, 41–54. [CrossRef]
34. Holysz, L.; Szczes, A.; Chibowski, E. Effects of a static magnetic field on water and electrolyte solutions. *J. Colloid Interface Sci.* **2007**, *316*, 996–1002. [CrossRef] [PubMed]
35. Arps, J.J. The effect of temperature on the density and electrical resistivity of sodium chloride solutions. *J. Pet. Technol.* **1953**, *5*, 17–20. [CrossRef]
36. Scatchard, G.; Hamer, W.J.; Wood, S.E. Isotonic solutions. I. The chemical potential of water in aqueous solutions of sodium chloride, potassium chloride, sulfuric acid, sucrose, urea and glycerol at 25. *J. Am. Chem. Soc.* **1938**, *60*, 3061–3070. [CrossRef]
37. Shatkay, A.; Lerman, A. Individual activities of sodium and chloride ions in aqueous solutions of sodium chloride. *Anal. Chem.* **1969**, *41*, 514–517. [CrossRef]
38. Gudkov, S.V.; Penkov, N.V.; Baimler, I.V.; Lyakhov, G.A.; Pustovoy, V.I.; Simakin, A.V.; Sarimov, R.M.; Scherbakov, I.A. Effect of Mechanical Shaking on the Physicochemical Properties of Aqueous Solutions. *Int. J. Mol. Sci.* **2020**, *21*, 8033. [CrossRef] [PubMed]
39. Shcherbakov, I.A. Specific Features of the Concentration Dependences of Impurities in Condensed Media. *Phys. Wave Phenom.* **2020**, *28*, 83–87. [CrossRef]
40. Yablonskaya, O.; Voeikov, V.; Buravleva, E.; Trofimov, A.; Novikov, K. Physicochemical Effects of Humid Air Treated with Infrared Radiation on Aqueous Solutions. *Water* **2021**, *13*, 1370. [CrossRef]
41. Iwasaka, M.; Ueno, S. Structure of water molecules under 14 T magnetic field. *J. Appl. Phys.* **1998**, *83*, 6459–6461. [CrossRef]
42. Cai, R.; Yang, H.W.; He, J.S.; Zhu, W.P. The effects of magnetic fields on water molecular hydrogen bonds. *J. Mol. Struct.* **2009**, *938*, 15–19. [CrossRef]
43. Ding, Z.R.; Zhao, Y.J.; Chen, F.L.; Chen, J.Z.; Duan, S.X. Magnetization mechanism of magnetized water. *Acta Phys. Sin.* **2011**, *60*, 432–439.
44. Wang, Y.F.; Zhang, B.; Gong, Z.B.; Gao, K.X.; Ou, Y.J.; Zhang, J.Y. The effect of a static magnetic field on the hydrogen bonding in water using frictional experiments. *J. Mol. Struct.* **2013**, *1052*, 102–104. [CrossRef]
45. Wang, Y.K.; Wei, H.N.; Li, Z.W. Effect of magnetic field on the physical properties of water. *Results Phys.* **2018**, *8*, 262–267. [CrossRef]
46. Chen, S.; Wang, X.Y.; Li, F.; Yuan, J.S. Study of Raman Spectroscopy on the Structure of NH4Cl Aqueous Solution Under Strong Magnetic Field. *Spectrosc. Spectr. Anal.* **2021**, *41*, 116–121. [CrossRef]
47. Bruskov, V.I.; Chernikov, A.V.; Gudkov, S.V.; Masalimov, Z.K. Thermal activation of the reducing properties of seawater anions. *Biophysics* **2003**, *48*, 942–949.
48. Bruskov, V.I.; Chernikov, A.V.; Ivanov, V.E.; Karmanova, E.E.; Gudkov, S.V. Formation of the Reactive Species of Oxygen, Nitrogen, and Carbon Dioxide in Aqueous Solutions under Physical Impacts. *Phys. Wave Phenom.* **2020**, *28*, 103–106. [CrossRef]
49. Lyakhov, G.A.; Shcherbakov, I.A.; Shermeneva, M.A. Layering Phase Transition in a Liquid Solution with Cross Hydrogen Bonds: Bond Number Density as the Second Order Parameter. *Phys. Wave Phenom.* **2020**, *28*, 236–240. [CrossRef]
50. Ushikubo, F.Y.; Furukawa, T.; Nakagawa, R.; Enari, M.; Makino, Y.; Kawagoe, Y.; Shiina, T.; Oshita, S. Evidence of the existence and the stability of nano-bubbles in water. *Colloids Surf. Physicochem. Eng. Asp.* **2010**, *361*, 31–37. [CrossRef]
51. Ivanov, V.E.; Karp, O.E.; Bruskov, V.I.; Andreev, S.N.; Bunkin, N.F.; Gudkov, S.V. Formation of long-lived reactive products in blood serum under heat treatment and low-intensity laser irradiation, their role in hydrogen peroxide generation and DNA damage. *Indian J. Biochem. Biophys.* **2019**, *56*, 214–223.
52. Baimler, I.V.; Lisitsyn, A.B.; Gudkov, S.V. Water Decomposition Occurring During Laser Breakdown of Aqueous Solutions Containing Individual Gold, Zirconium, Molybdenum, Iron or Nickel Nanoparticles. *Front. Phys.* **2020**, *8*, 600. [CrossRef]
53. Baymler, I.V.; Gudkov, S.V.; Sarimov, R.M.; Simakin, A.V.; Shcherbakov, I.A. Concentration Dependences of Molecular Oxygen and Hydrogen in Aqueous Solutions. *Dokl. Phys.* **2020**, *65*, 5–7. [CrossRef]
54. Sarimov, R.M.; Binhi, V.N.; Matveeva, T.A.; Penkov, N.V.; Gudkov, S.V. Unfolding and Aggregation of Lysozyme under the Combined Action of Dithiothreitol and Guanidine Hydrochloride: Optical Studies. *Int. J. Mol. Sci.* **2021**, *22*, 2710. [CrossRef] [PubMed]
55. Shcherbakov, I.A.; Baimler, I.V.; Gudkov, S.V.; Lyakhov, G.A.; Mikhailova, G.N.; Pustovoy, V.I.; Sarimov, R.M.; Simakin, A.V.; Troitsky, A.V. Influence of a Constant Magnetic Field on Some Properties of Water Solutions. *Dokl. Phys.* **2020**, *65*, 273–275. [CrossRef]