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PHYSICAL EXPERIMENT IN DIGITAL REALITY: CHALLENGES OF PRACTICAL ONLINE LEARNING

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The transition to distance learning in Ukraine – driven by the COVID-19 pandemic, military aggression, mass emigration, and infrastructure disruptions – has created major challenges for physics education, particularly in laboratory training. Traditional physics labs require specialized equipment, which is often inaccessible in remote settings, thus limiting students' opportunities for hands-on experimental experience. Virtual labs and simulations offer a partial solution but face limitations, such as the inability to fully replicate real conditions and the need for interdisciplinary development.

This article presents an adapted approach to remote laboratory work, using the experiment "Weiss Molecular Field" as an example. Originally performed with a pendulum magnetometer, the revised version engages students in calculating and plotting the temperature dependence of spontaneous magnetization in nickel using the Weiss molecular field theory. Students compare theoretical predictions for quantum numbers $J = 1/2$, 1, and ∞ with experimental data from the literature. Calculations are performed using MS Excel and the GRG optimization method. The results show qualitative agreement with experimental curves, particularly for $J = 1/2$, which supports the interpretation that electron spins are the primary magnetic carriers in nickel. At low temperatures, Bloch's spin-wave theory better matches experimental results than the Weiss model, while near the Curie temperature, deviations from theory are observed.

This adapted lab demonstrates that analytical and computational tasks can effectively substitute for direct experimentation in distance learning. The approach develops skills in theoretical analysis, data comparison, and scientific computing. Video tutorials, Excel templates, and interactive visualizations support transparent assessment and active engagement. Surveys revealed a 12% increase in average performance compared to in-person lab versions, along with improved motivation and deeper conceptual understanding. This method is a viable alternative for physics education in resource-limited contexts and can be extended to other lab-intensive disciplines. It also lays the groundwork for a digital lab curriculum that ensures educational continuity during crises.

Keywords: *Weiss Molecular Field, spontaneous magnetization, Curie temperature, special practical training.*

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INTRODUCTION

The series of events that have transpired in Ukraine in recent years (namely, the emergence of the Coronavirus pandemic, widespread military aggression, mass emigration of the population, and the imposition of rolling blackouts) have compelled a significant number of Ukrainian universities, especially those located in cities near the active combat zone, to transition from a full-time educational model to distance learning. Traditional physics classes are inextricably associated with the utilization of specialized, distinctive and costly laboratory equipment that requires proper operating skills. It is precisely this equipment that enables students to gain hands-on experience in conducting experiments, collecting and processing data. The transition to distance learning has deprived them of the opportunity to work directly with such equipment, which significantly narrows the range of available practical skills. The lack of physical access to laboratory facilities is one of the main obstacles to the implementation of a full-fledged special laboratory training in physics in an online format. To overcome it, it is necessary to implement alternative methodologies that will enable students to develop practical competencies in the absence of authentic technical equipment.

One potential solution to this issue is the integration of virtual laboratories and simulation platforms into the educational process. Such resources allow students to conduct conventional experiments in a virtual environment using computer models of physical phenomena or technical devices. This approach serves to partially compensate for the lack of access to real equipment, helps to master theoretical knowledge, develop skills in data collection and analysis, and understand the basic laws of physical processes. At the same time, virtual laboratories have certain functional limitations. Primarily, they are not able to fully reproduce the real conditions of the experiment, including the sensory and tactile components of interaction with the devices, which are important for developing an intuitive understanding of the material. In addition, the models used in virtual environments are often simplified and do not cover all aspects of real experiments, which can lead to a distortion of the physical phenomena. Creating high-quality educational simulations is a complex process that requires interdisciplinary collaboration between programmers, physicists, and designers, as well as significant funding. In the context of constrained resources, it is evident that not all educational institutions possess the capacity to develop their own digital laboratories. Consequently, these institutions are compelled to use third-party products, which often fail to align with the particularities of educational programs. Additional obstacles include technical factors, such as unstable Internet connections or a lack of necessary software, which make it difficult to fully implement online learning.

So, the transition to distance learning necessitates a thorough revision of the content of the special practical training in physics and its methodological support in view of the new conditions. It is imperative to acknowledge the constraints stemming from the students' limited access to laboratory equipment, which requires the introduction of alternative educational approaches. Such measures may include the optimizing of practical classes, the reduction of traditional laboratory works, the adaptation of teaching methods to the online environment, as well as the active use of interactive simulations and digital learning resources that can partially compensate for the lack of experimental experience.

In cases where the virtual setup proves inadequate for the real experiment, or where it is not feasible to substitute the real experiment with a virtual analogue, it is possible to expand the range of tasks during the analysis of experimental data obtained earlier in the real experiment.

The present paper discusses such an approach on the example of the laboratory work "Weiss Molecular Field", which is included in the list of works of the special practical training "Physical Properties of Magnetically Ordered Substances" intended for 4th year students of the School of Physics of Karazin University.

This laboratory work was created on the basis of the laboratory work “Investigation of the temperature dependence of the specific saturation magnetization of ferromagnetics” for full-time students [1]. In the real laboratory work, the pendulum magnetometer method was used as a method of magnetization research. The method is quite simple, convenient and has good accuracy. The students conducted studies on this setup in two stages. In the initial phase, it was imperative to ascertain the field dependences of magnetization at varying temperatures within the low-temperature region (80–300) K. Subsequent to this, the focus shifted to the high-temperature region (300–700) K. Following the processing of the results, the obtained data were analyzed.

In the context of distant work, the goals and objectives of the lab work are changed. In accordance with the molecular theory of Weiss, students are required to calculate and construct curves depicting the temperature dependence of the spontaneous magnetization of nickel at In the context of remote work, the goals and objectives of the work are subject to modification. In accordance with the molecular theory of Weiss, students are required to calculate and construct curves depicting the temperature dependence of the spontaneous magnetization of nickel at $H = 0$ for the cases $J = 1/2$, $J = 1$, $J = \infty$. These curves are then to be compared with experimental data taken from literature sources.for the cases $J = 1/2$, $J = 1$, $J = \infty$. These curves are then to be compared with experimental data taken from literature sources

THE WEISS THEORY

In 1907, Weiss hypothesized the existence of an internal effective field in ferromagnets, which, like the external magnetic field in paramagnets, produces an orienting effect of the magnetic moments of atoms. This internal effective field was later designated the molecular Weiss field. In fact, the introduction of the molecular field meant replacing the pairwise interaction of the magnetic moments of atoms by the interaction of the magnetic moment of an atom and the average magnetic field produced by the other magnetic moments.

Using the concept of molecular field, Weiss constructed a phenomenological theory of ferromagnetism, which successfully explained the primary experimental data. The molecular field was introduced as a quantity proportional to the magnetization of the substance, given by $H_\omega = \omega I$, where ω is the molecular field constant and I is the saturation magnetization of the substance. Next, Weiss applied the molecular field hypothesis to Langevin's theory of paramagnetism by replacing the external field H with the effective field $H + H_\omega$. Consequently, the expression for spontaneous magnetization assumed the following form:

Consequently, the expression for spontaneous magnetization assumed the following form:

$$I = I_0 L\left(\mu \frac{H + \omega I}{kT}\right). \tag{1}$$

where L is the Langevin function [2], I_0 is the saturation magnetization at 0 K.

The formal assumption of the dependence of the internal energy of a ferromagnet on spontaneous magnetization allowed Weiss to correctly explain the main features of the properties of ferromagnets, namely the occurrence of spontaneous magnetization, the anomalously high magnetic susceptibility, the temperature-dependent magnetization, and the temperature at which magnetic order is destroyed, known as the Curie temperature.

Later, and with consideration for the spatial quantization of magnetic moments, the fundamental equation of Weiss molecular field theory began to assume the following form [3]:

$$I = N g \mu_B J B_J\left(\frac{g\mu_B J}{kT}(H + \omega I)\right), \tag{2}$$

Curie temperature is defined as a value equal to:

$$T_C = (J+1) g \mu_B \omega \frac{I_0}{3k}, \tag{3}$$

where N is the number of magnetic ions in the unit volume, g is the Lande factor, $\mu_B$is the Bohr magneton, J is the total momentum of the magnetic ion, B_J is the Brillouin function, k is the Boltzmann constant.

CALCULATION OF THE TEMPERATURE DEPENDENCE OF SPONTANEOUS MAGNETIZATION

In the first part of the calculation-graphic assignment in the distance lab work, students are tasked with calculating and plotting the temperature dependences of the spontaneous magnetization of a ferromagnet at $H = 0$ for the cases $J = 1/2$, $J = 1$, $J = \infty$, and subsequently comparing these with experimental data for nickel. The experimental values of the temperature dependence of the spontaneous magnetisation of nickel were previously obtained from the monograph by R. M. Bozorth [4], by digitizing the corresponding curves. The students are provided with a predetermined table of experimental data.

In order to calculate the theoretical dependencies $I = f(T)$ at different values of the quantum number J, students must first convert the basic molecular field equation into a form that is convenient for calculations:

$$y = \frac{I}{I_0} = \frac{2J+1}{2J} cth\left(\frac{2J+1}{2J} x\right) - \frac{1}{2J} cth\left(\frac{x}{2J}\right), \tag{4}$$

where $x = (J g \mu_B \omega I)/kT$, here it is taken into account that $H = 0$.

Then for the case $J = 1/2$, $g = 2$ (one magnetically active electron in an atom) after simple calculations students should get the expressions:

$$T_C = (J+1) g \mu_B \omega \frac{I_0}{3k} = \frac{\mu_B \omega I_0}{k},$$
$$x = \frac{J g \mu_B}{kT}\omega I = \frac{T_C}{T}\frac{I}{I_0} = \frac{y}{T/T_C},$$
$$y = \frac{2J+1}{2J} cth\left(\frac{2J+1}{2J} x\right) - \frac{1}{2J} cth\left(\frac{x}{2J}\right) =$$
$$= 2\, cth\,(2x) - cth\, x = th\, x = th\left(\frac{y}{T/T_C}\right). \tag{5}$$

For the case $J = 1$, $g = 2$ (two magnetically active electrons in the atom) we have:

$$T_C = (J+1) g \mu_B \omega \frac{I_0}{3k} = \frac{4\mu_B \omega I_0}{3k},$$
$$x = \frac{J g \mu_B}{kT}\omega I = \frac{3 I T_C}{2T\, I_0} = \frac{3y}{2\, T/T_C},$$
$$y = \frac{2J+1}{2J} cth\left(\frac{2J+1}{2J} x\right) - \frac{1}{2J} cth\left(\frac{x}{2J}\right) =$$
$$= \frac{3}{2}\, cth\, \frac{9y}{4\, T/T_C} - \frac{1}{2}\, cth\, \frac{3y}{4\, T/T_C}. \tag{6}$$

The case $J = \infty$, $g = 2$ (absence of spatial quantization of magnetic moments):

$$T_C = (J+1) g\mu_B \omega \frac{I_0}{3k} = J g\mu_B \omega \frac{I_0}{3k},$$
$$x = \frac{J g\mu_B}{kT}\omega I = \frac{3T_C I}{T\, I_0} = \frac{3y}{T/T_C},$$
$$y = \frac{2J+1}{2J} cth\left(\frac{2J+1}{2J}x\right) - \frac{1}{2J} cth\left(\frac{x}{2J}\right) =$$
$$= cth(x) - \frac{1}{x}. \qquad (7)$$

All calculations of Weiss curves are performed by students using the mathematical software package MS Office Excel [5]. Since all the obtained Weiss equations are nonlinear equations, the GRG method (reduced gradient method) was used as a solution method, using the “Solution Finder” tool in MS Excel.

Fig. 1 shows the curves of temperature dependences of the spontaneous magnetization of a ferromagnet at different quantum numbers J ($J = 1/2$, $J = 1$, $J = \infty$). calculated by the Weiss model. The figure also illustrates the experimental points for nickel derived from [4]. A comparison of the theoretical curves of temperature dependences of magnetization with experimental data demonstrates a satisfactory qualitative agreement between theory and experiment. The optimal coincidence at moderate temperatures is observed when considering the spatial quantization of magnetic moments (curve $J = 1/2$). This finding suggests that electron spins are the primary carriers of magnetism in nickel. The most significant difference in the behavior of the temperature dependences of magnetization is observed when the experimental dependence is approximated by the Langevin function ($J = \infty$, the classical case).

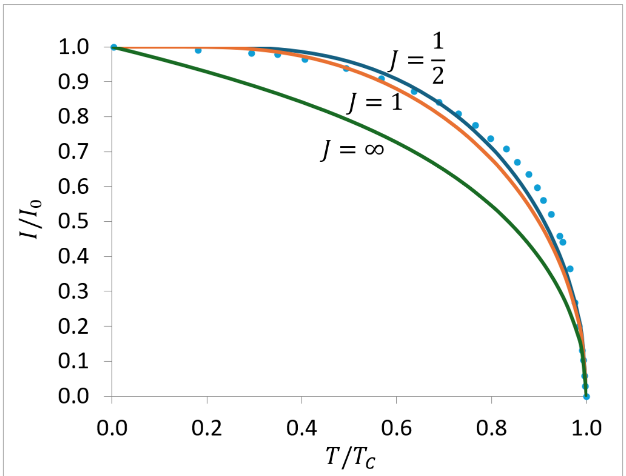

Fig. 1. Comparison of the temperature dependences of spontaneous magnetization, calculated using the Weiss theory for different quantum numbers *J*, with the experimental dependence for nickel, taken from [4].

The circles indicate the experimental points.

In the second part of the calculation-graphic assignment in the distance lab work, students are asked to investigate in more detail the behavior of the temperature dependence of the spontaneous magnetization of a ferromagnet in the vicinity of the points 0 K and T_C.

As illustrated in Figure 2, the calculated curves of the temperature dependence of the magnetization near 0 K are presented according to the Weiss theory for the cases of quantum numbers $J = 1$ and $J = 1/2$. Furthermore, Figure 2 presents the experimental data for nickel, in addition to the temperature dependence of the magnetization of a ferromagnet, as predicted by the Bloch spin wave theory, for comparative analysis. It is evident that within this temperature range, the Weiss curves are positioned above the experimental curve. However, the temperature dependence of the spontaneous magnetization, as derived from the theory of spin waves (i.e. Bloch's law $T^{3/2}$ [6]), aligns closely with the experimental observations. In this case, the Bloch law for a face-centered cubic lattice was used: $I/I_0 = 1 - 0.25(T/T_C)^{3/2}$ (Ni). The validity of Bloch's law extends to the low-temperature region; however, the definition of "low" is quite broad. So, at T/T_C ~0.3 (~*190* K) the error margin is 1.5%. It should be taken into account that the fundamental theory of magnetization is only applicable at low temperatures due to a number of approximations. The main ones are the assumptions that spin waves with low wave numbers are excited at low temperatures and that the interaction of spin waves can be neglected.

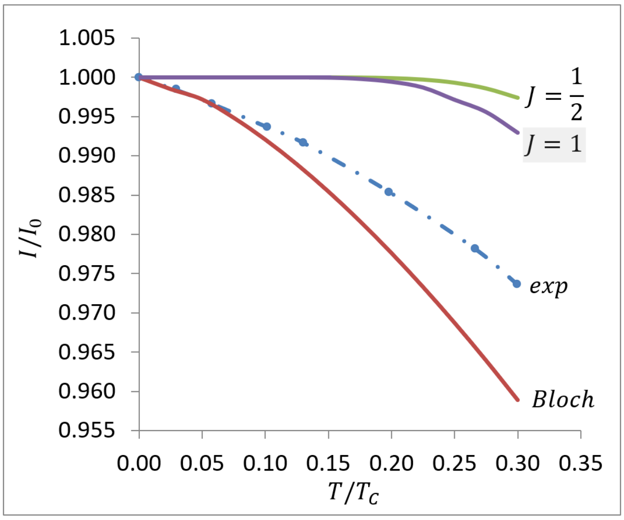

Fig. 2. Temperature dependence of spontaneous magnetization of nickel in the vicinity of 0 K. Theoretical curves according to the Weiss theory (for *J = 1/2* and *J = 1*) and the Bloch spin wave theory, as well as experimental data are shown.

Fig. 3. shows the curves of spontaneous magnetization calculated in accordance with the quantum Weiss model in the vicinity of the Curie temperature for the cases of

quantum numbers $J = 1$ and $J = 1/2$. The experimental data of the temperature dependence of the spontaneous magnetization of nickel for this temperature region are also given there. It can be seen that in this case the experimental curves lie much higher than the theoretical curves.

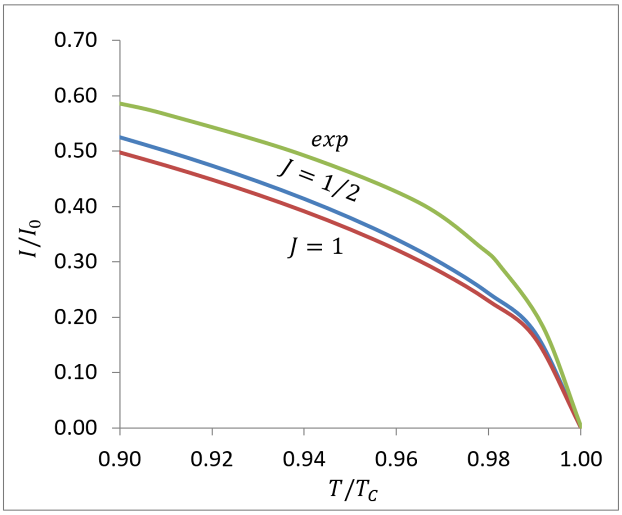

Fig. 3. Temperature dependence of the spontaneous magnetization of nickel in the vicinity of T_C. The theoretical curves according to the Weiss theory (for $J = 1/2$ and $J = 1$) and experimental data are shown.

CONCLUSION

The transition to distance learning necessitates the adaptation of traditional forms of laboratory practicals in the study of natural sciences. The article presents an example of the laboratory work “Weiss Molecular Field”, in which the experimental component is partially replaced with calculation and graphical assignments.

The tasks proposed for students include deriving the temperature dependence of spontaneous magnetization for different values of the quantum number, numerically solving the Weiss model equations using the reduced gradient method in MS Excel, and comparing theoretical curves with experimental data for nickel taken from literature sources.

The chosen format is aimed at developing key competencies such as analytical thinking, numerical modeling, data visualization, and the ability to correlate theory with experiment.

The proposed distance-learning approach can be adapted to other topics and serve as a basis for creating digital practicals under conditions of limited access to laboratory equipment.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interests.

СПИСОК ВИКОРИСТАНИХ ДЖЕРЕЛ

1. Ю. А. Попков, Ю. А. Мамалуй, В. Н. Горбач, Е. Ф. Ковтун, Л. П. Ольховик, З. И. Сизова. Методические указания к выполнению лабораторных работ по спецкурсу «Физические свойства магнитоупорядоченных веществ», Ч. 2, Харьковский государственный университет, Харьков (1983), 60 с.
2. C. Kittel. Introduction to Solid State Physics, John Wiley & Sons, New York (1976), 600 p.
3. A. Aharoni. Introduction to the Theory of Ferromagnetism, Oxford University Press, Oxford (2001), 332 p.
4. R. M. Bozorth. Ferromagnetism, Van Nostrand, New York (1951), 968 p.
5. W. J. Orvis. Excel for scientists and engineers, Sybex, San Francisco (1998), 547 p.
6. S. Chikazumi. Physics of Ferromagnetism, Oxford University Press, Oxford (2009), 668 p.

REFERENCES

1. Y. A. Popkov, Y. A. Mamaluy, V. N. Gorbach E. F. Kovtun, L. P. Olkhovik, Z. I. Sizova. Methodological instructions for laboratory works on the special course «Physical properties of magnetically ordered substances». P. 2, Kharkiv State University, Kharkiv, (1983), 60 p. (In Russian).
2. C. Kittel. Introduction to Solid State Physics, John Wiley & Sons, New York (1976), 600 p.
3. A. Aharoni. Introduction to the Theory of Ferromagnetism, Oxford University Press, Oxford (2001), 332 p.
4. R. M. Bozorth. Ferromagnetism, Van Nostrand, New York (1951), 968 p.
5. W. J. Orvis. Excel for scientists and engineers, Sybex, San Francisco (1998), 547 p.
6. S. Chikazumi. Physics of Ferromagnetism, Oxford University Press, Oxford (2009), 668 p.

ФІЗИЧНИЙ ЕКСПЕРИМЕНТ У ЦИФРОВІЙ РЕАЛЬНОСТІ: ВИКЛИКИ ПРАКТИЧНОГО ОНЛАЙН-НАВЧАННЯ

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Перехід до дистанційного навчання в Україні, спричинений пандемією COVID-19, воєнною агресією, масовою еміграцією та пошкодженням інфраструктури, поставив фізичну освіту перед новими викликами. Найвразливішою виявилася лабораторна складова: класичні експерименти потребують спеціалізованого обладнання й роботи з ним, що у віддаленому режимі неможливо. Віртуальні лабораторії та симуляції дають частковий вихід, проте не передають усю складність реального досліду і потребують значних ресурсів.

Стаття пропонує дистанційний варіант лабораторної роботи «Молекулярне поле Вейсса». Замість маятникового магнітометра студенти користуються MS Excel і оптимізатором GRG для розв'язання рівнянь теорії Вейсса та побудови температурних кривих спонтанного намагнічування нікелю. Теоретичні залежності для $J = 1/2, 1$ та ∞ порівнюються з літературними експериментальними даними. Найкращий збіг дає $J = 1/2$, що підтверджує спінову природу магнетизму нікелю. Біля абсолютного нуля точніша спін-хвильова теорія Блоха, а поблизу точки Кюрі спостерігаються відхилення від моделі Вейсса.

Методика поєднує аналітичні та обчислювальні прийоми, розвиває уміння працювати з теорією, даними й цифровими інструментами і майже не потребує матеріальних ресурсів. Відеоінструкції, шаблони Excel та інтерактивна візуалізація забезпечують прозорий контроль знань. Опитування засвідчили високий рівень залучення студентів і зростання середнього балу на 12 % проти очної версії. Підхід легко переноситься на інші теми (теплопровідність, фазові переходи) і може сформувати банк цифрових практикумів, що гарантуватиме безперервність підготовки фахівців навіть у кризових умовах. Курс також покращив навички аналізу даних і критичного зіставлення теорії з експериментом, а негайна візуалізація результатів підвищила мотивацію.

Ключові слова: *молекулярне поле Вейсса, спонтанне намагнічення, температура Кюрі, спеціальний практикум.*