On the centenary of the birth of D.S. Rozhdestvenskiĭ: Scientific legacy of D.S. Rozhdestvenskiĭ

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This paper reviews the scientific work of Academician D.S. Rozhdestvenskiĭ who was born 100 years ago. The origin and development of his work on the anomalous dispersion of light are discussed, and his researches are evaluated and compared with the results of other authors. A brief description is given of the work of Rozhdestvenskiĭ's pupils, who used his method of "hooks" in their researches. An analysis is also given of his work on the theory of spectra and the structure of atoms, and of its influence on the subsequent development of Soviet physics in these fields. The review concludes with a brief survey of his work in applied optics and, especially, on the theory of the microscope. His views on the relationship between science and technology are summarized.

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The scientific legacy of Academician Dmitriĭ Sergeevich Rozhdestvenskiĭ, the centenary of whose birth will be celebrated in 1976, is unusually great and varied. Despite the fact that over fifty years have elapsed since the publication of most of his papers, they have retained their freshness and topicality. This is a very striking fact in a time of very rapid development of science.

Rozhdestvenskiĭ's research topics were never chosen at random: they emerged after careful consideration and were intended to provide solutions to fundamental problems in the science of his time, and problems of great practical significance. The mastery with which his papers were written and the precision and, at the same time, imagery of his language can serve as a sublime example not only for beginners in science, but also for those who have some years of research behind them.

A very considerable, and the most fruitful, part of Rozhdestvenskiĭ's activity took place during the first few years of the Soviet state. These were the years not only of great political achievement, but also years of establishment and development of the national economy and technology on new social, economic, and scientific foundations. Rozhdestvenskiĭ took on the solution of scientific and technological problems that were of vital importance to the country with great enthusiasm and energy. He was one of the organizers and founders of the Soviet optics industry, especially optical glass manufacture. Since this aspect of his activity has been adequately discussed, we shall confine our attention to his more "abstract" (his word) researches. It is, however, very characteristic of the Dmitriĭ Sergeevich that, even when he was engaged in "abstract" research, he never lost sight of the close connection with practical application and frequently spoke about this. Describing the activities at the State Optics Institute, which he founded, he wrote: "The SOI is exactly right as a scientific institute in a socialist country where it is essential to support technology with abstract science, and vice versa." Again: "to cut off either component, science or technology, would mean to deaden both."

The best known part of the scientific legacy of Academician Rozhdestvenskiĭ is his research into the anomalous dispersion of light. He frequently returned to this topic throughout his scientific life. He began with it when preparing his Master's thesis as a young man, and his last paper published after his death was also devoted to this topic. His numerous pupils and successors at the State Optics Institute, at Leningrad University, and in other scientific establishments, have continued working in this field up to the present day. The original method which he developed for the experimental investigation of anomalous dispersion, known as the "method of hooks," has led to the formulation and solution of a large number of problems of major importance for the theory of the structure of atoms, plasma physics, astrophysics, and the physics of the atmosphere. Studies of anomalous dispersion by the Rozhdestvenskiĭ method became the monopoly of Soviet scientists. The relatively few researches on anomalous dispersion performed abroad were carried out mainly by the method of hooks, using apparatus copied from that developed by Rozhdestvenskiĭ.

When he started his work on anomalous dispersion of light in 1908, Rozhdestvenskiĭ faced a specific and, at the time, very topical task in physics, namely, the confirmation of the Lorentz hypothesis of the quasielastic character of the oscillations of electrons in the interior of atoms. It is well known that the quasielastic model of the electron predicts that the refractive index n of a monatomic vapor or gas with a discrete series of narrow absorption lines is given by the Sellmeier formula

$$n^2 - 1 = \sum_i \frac{a_i}{\nu_i^2 - \nu^2}, \tag{1}$$

where ν_i are the frequencies of the proper oscillations of electrons in the interior of the atom. The quantities a_i are constants related to the charge e, mass m, and
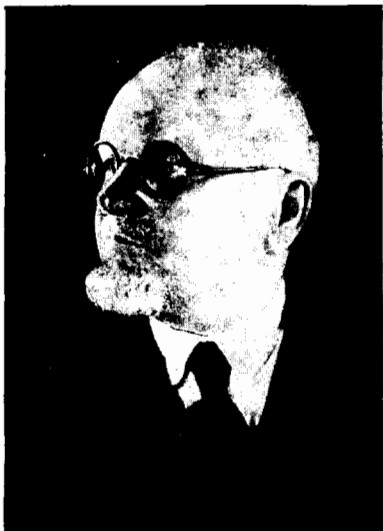
D. S. Rozhdestvenskiĭ (1876–1940).

number N_i of electrons with proper frequencies ν_i. This relation is given by

$$a_i = \frac{e^2}{\pi m} N_i. \qquad (2)$$

Rozhdestvenskiĭ set himself the task of quantitative verification of the validity of Sellmeier's formula. Any departure from it would indicate a departure from the linear character of the equations describing the interatomic oscillations of electrons. It is clear that the verification is particularly sensitive when the measurements are carried out as close as possible to an absorption line, i.e., for values of ν approaching ν_i. These considerations demanded the development of a method whereby accurate measurements could be performed of the dispersion near an absorption line. Moreover, it was desirable to choose a vapor or gas with a small number of strong absorption lines.

Prior to the work of Rozhdestvenskiĭ, studies of anomalous dispersion were largely qualitative in character. Anomalous dispersion was observed by Wood, who used the old method of crossed prisms proposed by Newton for the investigation of dispersion in glass. However, Wood's method did not provide a means for performing reliable measurements. Puccianti's method, in which an interferometer was crossed with a spectrograph, was more promising. This method was initially used by Rozhdestvenskiĭ, who, incidentally, developed it independently and only subsequently became familiar with Puccianti's paper. The essence of the Puccianti-Rozhdestvenskiĭ method is as follows. Horizontal interference fringes obtained in a white light are projected onto the vertical slit of a spectrograph. As a result, the spectrum is crossed by light and dark fringes running along its entire length. When the material under investigation is introduced into one of the arms of the interferometer in the form of a homogeneous plane-parallel column of vapor, the fringes are displaced by an amount proportional to the extra path difference. On the other hand, this difference is proportional to $n-1$ for a given length of the column of

vapor, where n is the refractive index of the vapor. Thus, the shift of the interference fringes produced by the spectrograph reproduces the variation of dispersion throughout the region under consideration. Figure 1a shows a photograph of the interference fringes near a single narrow absorption band. It is found that the lines bend near the absorption band in accordance with the Sellmeier formula.

However, this method of studying anomalous dispersion is not very suitable for obtaining accurate quantitative data. It involves measurements at a large number of points on the sharply ascending or descending part of an interference fringe, where measurements are difficult and not sufficiently reliable. Rozhdestvenskiĭ therefore modified the Puccianti method in an important and very ingenious way. He introduced a plane-parallel glass plate of given thickness into the second arm of the interferometer. In the absence of the vapor, the insertion of the plate into the second arm of the interferometer results in highly inclined interference fringes (due to the path difference). When both vapor and glass plate are present, the shift of the interference fringes is determined by the algebraic sum of the individual shifts due to the vapor and plate separately. The dispersion in the vapor predominates near the absorption line, whereas the path difference due to the glass plate predominates at points well away from the absorption band. The net result of this is that the bands acquire the characteristic maxima and minima (Fig. 1b) which Rozhdestvenskiĭ called "hooks."

The position of the hooks for a given thickness of the glass plate is determined by the dispersion near the given vapor absorption line. The stronger the dispersion near the line, the further is the distance of the hook from it. The theory of the method was developed by Rozhdestvenskiĭ in his first major paper on anomalous dispersion[1] and was elaborated in his subsequent publications.[2,3] We shall briefly reproduce it for the special case of a single narrow absorption line.

Suppose that horizontal interference fringes are projected onto the vertical slit of a spectrograph. We shall measure the coordinate y along the length of the slit. The change in the phase φ of the oscillations may be assumed to be proportional to y. Consequently, when both the dispersive vapor and the glass plate are absent, we have
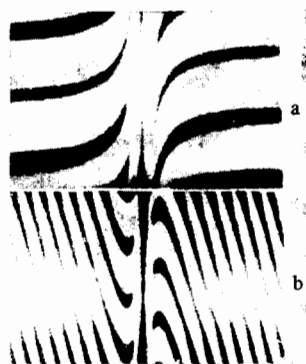

FIG. 1

$$by_k = k\lambda, \tag{3}$$

where k is the order of an interference fringe and b is a constant determined by the geometry of the system.

Rozhdestvenskiĭ introduces a cell A_1 of length l, which contained the vapor under investigation, into one of the arms of the interferometer (Fig. 2), and a compensating evacuated cell A_2 of the same length l and a plane-parallel glass plate B of thickness l' and refractive index n' into the other arm. The cell and plate introduce an additional path difference, and (3) must be replaced by

$$by_k - (n - 1)\, l + (n' - 1)\, l' = k\lambda, \tag{4}$$

where n is the refractive index of the vapor.

The condition for the maxima and minima (the "hooks") is

$$\frac{\partial y_k}{\partial \lambda} = 0.$$

In accordance with the Sellmeier formula, the refractive index n of the vapor varies rapidly near an absorption line, whereas the absorption coefficient of glass varies slowly and monotonically throughout the region, so that

$$\frac{\partial (n - 1)}{\partial \lambda} \gg \frac{\partial (n' - 1)}{\partial \lambda}.$$

This inequality enables us to neglect the term containing $\partial(n' - 1)/\partial \lambda$ when we differentiate (4). The condition for the hooks can therefore be written in the form

$$\frac{\partial (n - 1)}{\partial \lambda} = -\frac{k}{l}. \tag{5}$$

If we transform from frequencies to wavelengths, and use the Sellmeier formula for n, then in an approximation that is acceptable near an absorption line, we have

$$\frac{a_i \lambda_i^3}{4c^2 (\lambda - \lambda_i)^2} = \frac{k}{l}.$$

The position of the hooks is obtained by solving this equation for the wavelength:

$$\lambda = \lambda_i \pm \sqrt{\frac{a_i \lambda_i^3 l}{4c^2 k}}, \tag{6}$$
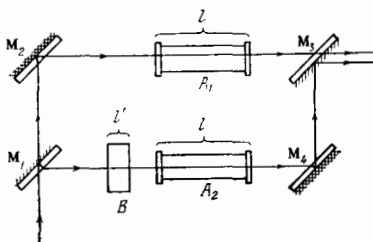
where c is the velocity of light in vacuum.

FIG. 2

It is clear that, in this approximation, the position of the hooks is determined only by the properties of the dispersive vapor (a_i, λ_i), the length l of the cell, and the interference order k. The order k can be found from the thickness l' of the glass plate and its refractive index n'. However, Rozhdestvenskiĭ showed that k could also be found from the number p of the inclined interference bands in a given wavelength interval. There is thus no need to have preliminary data about the glass plate, since the required value of k is obtained through measurements on the photograph obtained with the same apparatus that is used to observe the hooks.

As can be seen, the position of the hooks can be used to determine the constant a_i that determines the dispersion of the vapor under investigation near the given spectral line λ_i. By suitably choosing the thickness of the glass plate (through a variation of k), the hooks can always be shifted relative to the line, so that a position convenient for measurement can be achieved. This is the great advantage of the Rozhdestvenskiĭ method: measurements are simple, accurate, and can be made at short distances from the absorption line, for which other methods are unsuitable.

The method of hooks can be used to solve two problems: a) to verify the validity of the Sellmeier formula and b) to determine the number N_i of electrons having proper oscillations that correspond to the frequency of the absorption line. This can be done on the basis of (6). When the Sellmeier formula is accurately satisfied, the values of a_i for a given absorption line are all equal, independently of the interference order k (thickness of the glass plate). The second problem is solved as soon as the value of a_i is found.

Sodium vapor was the first to be investigated by Rozhdestvenskiĭ. It was known to have two closely lying absorption lines (the yellow sodium doublet) in the visible part of the spectrum. The other absorption lines of sodium lie well away from these two, and are much weaker. It follows that only two terms need be retained under the summation sign in the Sellmeier formula (1), so that it now assumes the form

$$n^2 - 1 = \frac{a_1}{\nu_1^2 - \nu^2} + \frac{a_2}{\nu_2^2 - \nu^2}, \tag{7}$$

where ν_1 and ν_2 are the frequencies of the sodium absorption lines. It was shown by Rozhdestvenskiĭ that the above theory of the method of hooks can readily be generalized to this case as well.

A large number of experimental difficulties had to be overcome in the development of the necessary apparatus. The most important requirement was that the interference pattern had to be highly stable. This stability was easily disturbed because an electric heater for the cell containing the sodium vapor had to be introduced into one of the arms of the interferometer. In addition, the spectrum was recorded photographically, which meant that a bright source of light had to be employed, and this gave rise to an additional and nonuniform heating of the interferometer mirrors.

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Having considered all the components of the system, Rozhdestvenskii concluded that none of the interferometers available at the time (Jamin and Michelson) could satisfy these conditions. He therefore decided to use an interferometer in which the light beams were divided by reflection at four mirrors (Fig. 2), two of which (M_2, M_4) were total reflectors and the other two (M_1, M_3) were semitransparent. A system of this kind had already been used under the name of the Mach–Zender interferometer (this was apparently not known to Rozhdestvenskii), but the four mirrors in the Mach–Zender system were mounted on individual supports, which complicated the adjustment of the instrument and made it sensitive to mechanical disturbances and temperature non-uniformities. Rozhdestvenskii developed his own variant of this interferometer (he called it the Jamin-type interferometer) in which the mirrors were held in pairs $(M_1, M_2$ and M_3, M_4; Fig. 2) on a common metal block. The two blocks were then mounted on a vibration-proof concrete plate. This interferometer can justifiably be referred to as the Rozhdestvenskii interferometer. Rozhdestvenskii subsequently gave a complete theory of this system.[4] The Rozhdestvenskii interferometer is relatively simple to make, is convenient in practice, and produces a very stable interference pattern.

Rozhdestvenskii first used his experimental arrangement to verify the validity of the Sellmeier formula. He showed that, in the case of the sodium vapor, the ratio a_1/a_2 [formula (7)] turns out to be the same, independently of the thickness of the glass plate, i.e., independently of the position of the hooks relative to the absorption line. The thickness of the glass plate was varied between 6 and 24 mm, and the measurements were performed up to points located at 0.5 Å from the absorption line. A large number of careful measurements showed that the Sellmeier formula was accurately satisfied in a broad range of wavelengths. The experimental uncertainty did not exceed 2.5%. Some departures were observed at very small distances from the absorption line (distances of 1 Å or less). However, it was found that these departures depended on the resolution of the spectrograph. The magnitude of the discrepancy was found to be different for spectra in different orders of the diffraction grating. Rozhdestvenskii therefore concluded that the discrepancies were instrumental in character, and this interpretation was subsequently confirmed.

Rozhdestvenskii was thus in a position to provide a specific answer to his question: the Sellmeier formula was satisfied accurately up to frequencies very close to the frequency corresponding to the absorption line. The Lorentz hypothesis about the quasielastic character of the oscillations of electrons in the atom was thus confirmed.

It is well known that the quasielastic electron theory did not survive in physics for very long. It was replaced at first by Bohr's theory and then by quantum mechanics. However, the importance of Rozhdestvenskii's measurements has remained: any theory, whatever its character, must take into account the fact that the Sellmeier formula is accurately satisfied. In this connection, it is interesting to recall Rozhdestvenskii's statement at a meeting of the USSR Academy of Sciences in 1936 in connection with the observed anomalous dispersion curves. He said: "Scarcely anyone has investigated these curves more extensively than I and my answer was: yes, these curves are hyperbolas and, consequently, the electron is coupled quasielastically. Fortunately, my intrinsic scepticism made me add: however, it is sufficient for the equations for the oscillations of the electron to be linear in order to ensure that a hyperbola will be produced, without going into the question of the nature of the coupling."

The second problem considered by Rozhdestvenskii was, as we have already noted, the determination of the number N_i of electrons corresponding to proper oscillation frequency ν_i. By determining the constant a_i from the position of the hooks, one can directly determine N_i from (2). This is the number of electrons per unit volume of the dispersive vapor. From the theoretical standpoint, it is, of course, important to know the number n_i of electrons with given proper oscillation frequency ν_i per atom. It is clear that n_i is equal to N_i/N_0, where N_0 is the total number of atoms of the given element per unit volume. However, at the time when Rozhdestvenskii was carrying out his research, the saturated vapor pressure of sodium was not well known, and this meant that a reliable value corresponding to the experimental conditions could not be obtained for N_0. Rozhdestvenskii therefore measured the ratio N_1/N_2 of the number of electrons corresponding to the two components of the sodium doublet (subscript 1 refers to the stronger, short-wave component). The results of this determination turned out to be very interesting. He found that, for the yellow sodium doublet ($\lambda_1 = 5889.96$ Å and $\lambda_2 = 5895.93$ Å), the ratio N_1/N_2 was very close to the integer 2. The average value for a large number of measurements was found to be $N_1/N_2 = 1.98$ with an uncertainty not exceeding 2.5%.

It is important to note that, at that time, there was a considerable discrepancy between the various published values of N_1/N_2 for the yellow doublet of sodium, and these values appeared to depend on vapor density and temperature. Rozhdestvenskii first set himself the task of showing that this ratio did not depend on the conditions of observation, and was therefore an atomic constant. As a matter of fact, even his early measurements showed that N_1/N_2 was independent of the temperature of the heater on the sodium-vapor tube. However, since the tube was made of glass, the temperature could be varied only in a relatively small interval. Some time later, therefore, Rozhdestvenskii and his research student V. I. Turoverov[5] performed measurements on sodium vapor introduced into the flame of a voltaic arc burning at low pressure. The value of N_1/N_2 was again found to be close to 2. Similar measurements were subsequently carried out for the main doublet of potassium in an arrangement in which the vapor pressure could be varied within very broad limits. The ratio N_1/N_2 was again found to be independent of the conditions of observation. On the basis of all these experi-

ments, Rozhdestvenskiǐ was able to maintain that the ratio of the number of dispersive electrons for the doublet components was an atomic constant independent of vapor pressure and temperature.

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The determination of the relative number of dispersive electrons was considered in Rozhdestvenskiǐ's next paper, "Simple Relationships in the Spectra of Alkali Metals."[2] This was the topic for his doctoral thesis which he successfully defended in 1915.

Anomalous dispersion was then measured near the components of a number of doublets in the principal series of K, Rb, and Cs. For the first doublets of all these elements, the ratio of the number of electrons was again found to be close to the integer 2. In the case of the second doublet of rubidium, on the other hand (4202–4216 Å), the ratio N_1/N_2 was found to be 2.57, which differed from the integer by an amount much greater than the experimental uncertainty. For the subsequent doublets in the principal series of cesium, measurements yielded the values 2.053, 4.07, 7.4, and 9.1, respectively. It is clear from these results that, firstly, the ratio N_1/N_2 does not remain constant for a succession of doublets in the principal series of alkali metals, but rapidly increases as the higher members of the series are approached. Secondly, N_1/N_2 is not necessarily an integer (which was assumed previously).

Rozhdestvenskiǐ was then able to estimate the ratio of the number of dispersive electrons for the next two doublets in the principal series. For potassium, this was found to be approximately 100, and for rubidium and cesium 60.

This exceedingly interesting and important experimental material had to be theoretically interpreted. Initially, and in accordance with the Lorentz hypothesis, Rozhdestvenskiǐ suggested that, for example, the fact that, in the case of sodium, $N_1/N_2 = 2$ indicated that the sodium atom contained twice as many electrons with proper oscillation frequency corresponding to the brighter component of the first doublet than in the weaker component. Comparison of the numerical value of $N_1 + N_2$ with the total number of sodium atoms per unit volume, estimated from the vapor pressure, showed that these two numbers were of the same order. This indicated that the total number of electrons governing the dispersive properties near the yellow doublet of sodium was small (three, or some other relatively small number). A similar result was obtained for the first doublet of potassium. However, it was then quite unclear how to explain the fact that the ratio of the number of dispersive electrons for the first and second doublets of potassium was 100. This and a number of other considerations meant that the assumption that the number of electrons in the atom was equal to the number of its proper oscillation frequencies (or half that if the vibrators were anisotropic) had to be abandoned. This led to the proposal that the same electron could vibrate with different proper frequencies, depending on the conditions of excitation. This does not contradict the fact established by Rozhdestvenskiǐ that the ratio N_1/N_2 is an atomic constant independent of external con-

ditions. We now know that the answer to this dilemma emerged after the advent of the Bohr theory, and in a more comprehensive form after the development of quantum mechanics.

First and foremost, the expression for the constant a_i in the Sellmeier formula can be transformed in a formal fashion by replacing the number N_i of dispersive electrons by the product $N_i = f_i N_0$, where N_0 is the number of atoms per unit volume. The quantity f_i, which was given the somewhat inappropriate name "oscillator strength," can be interpreted as the mean number n_i of electrons with given proper oscillation frequency ν_i per atom. Instead of (2), we then have

$$a_i = \frac{e^2}{\pi m} f_i N_0. \tag{8}$$

The experimental value of a_i obtained from measurements of anomalous dispersion can be used to determine the product $f_i N_0$. In the case of doublet components, the ratio $a_1/a_2 = N_1/N_2 = f_1/f_2$, i.e., the ratio N_1/N_2 of the number of electrons is replaced by the ratio f_1/f_2 of the oscillator strengths.

After Einstein introduced the probability description of the processes of emission and absorption of light by atoms, it was established that the oscillator strengths and the probabilities A_{ki} of spontaneous transitions are related by the formula

$$f_{ki} = \frac{g_k}{g_i} \frac{mc^3}{8\pi^2 e^2 \nu_{ki}^2} A_{ki}; \tag{9}$$

where g_k and g_i are the statistical weights of the stationary states, the transitions between which result in a spectral line of frequency ν_{ki}. It was thus found that Rozhdestvenskiǐ's experimental studies of anomalous dispersion led to a method for an accurate determination of the transition probabilities A_{ki} which are among the fundamental atomic constants.

It is well known that the transition probabilities can be determined not only from anomalous dispersion but also from other phenomena, for example, the emission and absorption of spectral lines. The latter two methods are, incidentally, more sensitive than the Rozhdestvenskiǐ method. Why then does this method remain important? There are two reasons. Firstly, the measurement results are independent of the shape of the emission or absorption line. The only condition is that the hooks must lie at a sufficient distance from the line center, and this is valid even when the line has a hyperfine structure. On the other hand, methods based on the emission and absorption of light must take into account both the structure and the broadened profile of the line, which is frequently a very difficult problem. Secondly, the method of hooks is not sensitive to inhomogeneities in the dispersing medium in the direction of propagation of light. When inhomogeneities are present, the quantity N_0 need only be replaced by the average

$$\bar{N}_0 = \frac{1}{l} \int_0^l N_0(l)\, dl.$$

Emission and absorption methods, on the other hand,

involve very complicated calculations in the case of a spatially inhomogeneous object, so that the final results are frequently not very reliable.

For the doublets in the principal series of alkali metals, $n^2S_{1/2}-n'^2P_J$, the lower energy levels are simple and the upper are doublets for which the quantum number J can assume the values $J_1 = \frac{3}{2}$ and $J_2 = \frac{1}{2}$. In the Bohr–Sommerfeld theory, the probabilities of the two transitions, i.e., $A_{ki}(^2P_{3/2} \to {}^2S_{1/2})$ and $A_i(^2P_{1/2} \to {}^2S_{1/2})$ are equal, so that it follows from (9) that the oscillator strengths corresponding to the two components of the doublet are in the same ratio as the statistical weights of the upper level. The statistical weights, on the other hand, are equal to $2J+1$, so that it turns out that the ratio of the oscillator strengths for two close components of doublets in the principal series is

$$\frac{f_{ki}}{f_{li}} = \frac{g_h}{g_l} = \frac{2J_h - 1}{2J_l + 1} = 2.$$

This result agrees with Rozhdestvenskiĭ's measurements on the first doublets in the principal series of sodium, potassium, rubidium, and cesium, but differs from his results for the subsequent doublets in these series. The necessary improvement of the theory was achieved only on the basis of the Schrödinger quantum mechanics. However, before we say any more about the comparison between quantum-mechanical calculations and experimental data, let us consider one misunderstanding which is sometimes encountered when Rozhdestvenskiĭ's papers are discussed. These explanations are not new but we return to them, nevertheless, because an impression may otherwise be given that some incorrect statements are due to Rozhdestvenskiĭ.

The particular point is the connection between Rozhdestvenskiĭ's work on anomalous dispersion and the intensities of spectral lines. Let us first carefully note that we are dealing with emission lines and, secondly, let us replace the somewhat vague term "intensity" by the precise photometric term "brightness." For an extended source of low optical density, the brightness of a spectral line is determined by the power radiated per unit volume. According to Einstein, on the other hand, the power emitted per unit volume as a result of spontaneous emission of a line of frequency ν_{kl} is given by

$$W_{kl} = N_k A_{ki} h\nu_{kl}.$$

Hence, using (9), we find that the brightness ratio for the components of the doublets in the principal series (Fig. 3b) is given by

$$\frac{I_{ki}}{I_{li}} = \frac{N_k}{N_l} \frac{g_l}{g_h} \frac{f_{ki}}{f_{li}} \left(\frac{\nu_{kl}}{\nu_{li}}\right)^3.$$

All the ratios on the right-hand side of this formula, except for the ratio N_k/N_l, are constants for a given doublet. The quantities N_k and N_l are, respectively, equal to the number of atoms per unit volume in the k-th and l-th excited states. These numbers depend on the experimental conditions and their ratio may vary without any particular restriction. For example, in
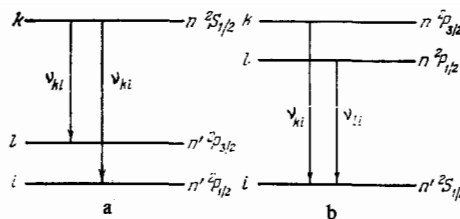

FIG. 3

his well-known experiments on the fluorescence of sodium vapor, Wood succeeded in populating one of the two levels $3^2P_{1/2}$, $3^2P_{3/2}$, whereas the second level remained unpopulated.

Only for the doublets in the sharp series ($n^2P_J - n'^2S_{1/2}$; Fig. 3a), both components of which have the same bottom level $n'^2S_{1/2}$, is the brightness ratio given by

$$\frac{I_{ki}}{I_{li}} = \frac{g_l}{g_l} \frac{f_{ki}}{f_{li}} \left(\frac{\nu_{kl}}{\nu_{li}}\right)^3,$$

i.e., it is independent of the conditions of excitation of the atoms (in the absence of the absorption of light or some other secondary processes in the source).

It is clear from the foregoing that the allegation frequently made without explanation that Rozhdestvenskiĭ showed that the intensity ratio for the components of the doublets was constant and equal to an integer is incorrect. Each special case requires special examination. Rozhdestvenskiĭ himself referred in his papers either to the ratio of the numbers of dispersive electrons or the ratio of oscillator strengths. A more detailed analysis of all the problems related to this topic has been given by A. N. Filippov, a pupil of Rozhdestvenskiĭ.[6]

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A fundamental change took place in our views on the structure of atoms during the period between the beginning of Rozhdestvenskiĭ's work on anomalous dispersion and the middle thirties. Nevertheless, as we have said, his work has not only retained its importance, but has assumed a new topicality. Measurements of transition probabilities by the method of hooks are among the more important problems in experimental atomic physics. It was therefore natural for him to return to the study of anomalous dispersion at the end of the 1930's. During the last two years of his life, 1939–1940, he carried out a new major investigation at the university to which he returned after a break of eight years.[3]

The experimental arrangement used previously was suitable for relatively volatile elements. Eventually, a natural need arose for apparatus that could be used with high-melting elements as well. Rozhdestvenskiĭ decided to use a King-type vacuum furnace for this purpose, with a graphite tube as the heating element. New experimental difficulties, still greater than those encountered earlier, had to be overcome. A large furnace had to be introduced into one of the arms of the interferometer (a very sensitive optical device), which easily disturbed the necessary strict temperature conditions. After a year of intensive work, in which he was assisted by a young collaborator, N. P. Penkin, the apparatus
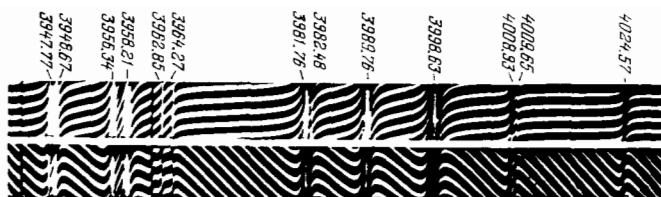
FIG. 4

was completed. A furnace supplied by a 30-kW reducing transformer was introduced into one of the arms of a large interferometer incorporating 30-cm supports. The furnace produced temperatures up to 3000 °C for a current of 1800 A.

The experimental possibilities were greatly extended as a result of the development of this apparatus. An extensive program of research was mapped out, including, first and foremost, the investigation of elements in the region of the closed d-shell (Sc, Ti, V, Cr, Mn, Fe, Co, Ni). The apparatus justified all the effort put into it: it could be used to observe anomalous dispersion in the vapors of iron and chromium, and later a number of other elements. For the narrow $^5S_2-^5P_{1,2,3}$ chromium multiplet, the measured oscillator-strength ratio was found to be 3.004 : 4.997 : 7.00, which is in agreement with the theoretical ratio of 3 : 5 : 7. Figure 4 shows a photograph of the interference bands and hooks near the titanium lines in the range 4025–3957 Å.

This last research of Rozhdestvenskiĭ was a kind of testament to his pupils and collaborators, a call to continue and extend the work on the application of the method of hooks to problems in atomic physics. The value of a particular piece of scientific research is determined not only by its direct results, but also as the beginning of new researches. In this respect, Rozhdestvenskii's work on anomalous dispersion is exceptionally important. It was followed by a long series of studies that began during his lifetime, and was extensively developed in subsequent years.

It is important to note one characteristic feature of Rozhdestvenskiĭ: he never included his name among the authors of a particular paper unless he directly took part in the measurements or calculations. The total number of his published papers on anomalous dispersion (including the papers on the theory of the interferometer) is only seven. However, even during his lifetime, his pupils published, without mentioning his name among the authors, many researches in which he closely participated. Vladimir Konstantinovich Prokof'ev recalls that, when he brought to Rozhdestvenskiĭ the text of his first paper for review, the latter deleted his name from the head of the paper and explained: "it was my duty as your supervisor to help you in carrying out this research, but I cannot include may name next to yours because you carried out the work and your name must stand at the head of the paper."

At the same time, unless we take into account the work of his pupils and collaborators, we cannot evaluate the depth of Rozhdestvenskiĭ's ideas and the value of

the research methods developed by him.

Let us briefly review these papers. They were published up to approximately the end of the 1940's. Subsequent research was so extensive that it would require a separate article to do it justice. V. K. Prokof'ev and A. N. Filippov measured the transition probabilities for a series of successive lines belonging to the principal series of the alkali metal atoms. This required the development of new apparatus because most of these series lay in the ultraviolet. A. N. Filippov, a talented and skillful experimenter who died prematurely, built an interferometer with fluorite optics. This unique instrument could be used throughout the spectral range, right up to extreme ultraviolet. Filippov and Prokof'ev used this fluorite interferometer[7] to observe the anomalous dispersion for 25 successive terms in the principal series of sodium, and measured the transition probabilities for 16 of them. They showed that, beginning with the 11th term, the predicted inverse proportionality of the transition probability to the cube of the principal quantum number held with good accuracy. However, for the first terms of the principal series of sodium, the transition probabilities decreased more rapidly. In lithium, Filippov discovered a still greater departure from the inverse cube law: the transition probabilities did not vary monotonically, and the transition probability for the third term in the principal series was greater than for the second.

The measurements of Filippov and Prokof'ev resulted in a comparison between theory and experiment in one further respect.[8] According to the so-called Thomas–Kuhn rule, the algebraic sum of all the oscillator strengths of a given level should be equal to 1/3 of the number of degrees of freedom of the radiating atom:

$$\sum_i f_i = \frac{1}{3} k.$$

Filippov and Prokof'ev found that the Thomas–Kuhn rule was not valid for sodium, and especially for thallium.

The emergence of discrepancies between theory and experiment had to be explained. At that time, theoretical calculations were usually partially based on models, and could not pretend to be accurate. Such calculations had to be based on the development of an accurate quantum-mechanical method of determining the eigenfunctions for atoms with one or more valence electrons. The first step in this direction was taken by V. K. Prokof'ev,[9] who calculated the transition probability for the next series of doublets in the principal series of sodium, using the work of the Japanese physicist Sugiura, which had only recently been published. The results of these calculations were in good agreement with the experimental data. Having taken an interest in this success, Rozhdestvenskiĭ decided to set up a special group of computational theoreticians. V. A. Fock was invited to head it. It included M. G. Veselov, M. I. Petrashen', and A. R. Krichagina. The work of this group turned out to be exceptionally successful. In a very short time, Fock developed an approximate method for calculating the eigenfunctions, which became would famous under the name of the Fock–Hartree method.

It was used to calculate the transition probability for the atoms of a series of elements, and the results turned out to be in good agreement with experiment. Fock also showed[10] that the discrepancy between the experimental data and the Thomas–Kuhn rule could be fully explained.

The importance of the Fock–Hartree method goes well beyond the limits of problems associated with the calculation of transition probabilities. For the sake of historical accuracy, however, it must be recalled that Fock's work on approximate methods of calculating atomic eigenfunctions began as a result of searches for the solution of problems put forward by Rozhdestvenskiĭ.

The next important group of papers was based on the possibility of using Rozhdestvenskiĭ's method to determine the density of atoms in a vapor or gas under investigation. In (8), the constant a_i is related to the product $N_0 f_{0k}$. When the lower level is the normal state, N_0 represents the density of normal atoms. On the other hand, when the lower state is an excited level of energy W_i, then a_i can be used to determine the product $N_i f_{ik}$, where N_i is the density of excited atoms. Thus, when the oscillator strengths f_{ik} are known, the Rozhdestvenskiĭ anomalous–dispersion method can be used to determine the density of normal or excited atoms with high precision. Their relative values can be determined even when the oscillator strengths f_{ik} are not known.

The work of G. S. Kvater[11] is particularly interesting in this connection. He investigated anomalous dispersion in thallium vapor in which the atoms have a metastable $^2P_{3/2}$ level above the normal $^2P_{1/2}$ level. At sufficiently high temperature, an appreciable fraction of the thallium atom is found in the metastable $^2P_{3/2}$ state and two series are present in the absorption spectrum. By measuring anomalous dispersion, it is then possible to determine the ratio of the numbers of atoms in these two states, $N_1(^2P_{1/2})/N_2(^2P_{3/2})$. On the other hand, according to Boltzmann's law, this ratio is

$$\frac{N_1}{N_2} = \frac{g_1}{g_2} e^{-(W_1 - W_2)/kT}.$$

By comparing experimental and theoretical data, it was possible to show that the two agreed to within 1.5%, i.e., well within experimental error. Prior to the appearance of this work, there were only more or less indirect methods for the experimental verification of Boltzmann's law. Kvater's work showed that Rozhdestvenskiĭ's method of hooks provided the most direct and accurate way of verifying this fundamental law of statistical physics.

Observations of anomalous dispersion resulted in a verification of another conclusion of statistical physics, namely, the so-called Saha formula, which gives the density of ions during thermal ionization. N. P. Penkin,[12] who continued to use the above apparatus with the King furnace after Rozhdestvenskiĭ's death, measured the density of barium ions in high-temperature vapor. His empirical results were found to be in good agreement with Saha's formula. In other words, the results of these observations can be interpreted by saying that the barium vapor was in thermodynamic equilibrium with the walls of the furnace, characterized by a definite temperature T.

In a similar way, the method of hooks can be used to determine the density of particles in gas-discharge plasmas, and to determine whether thermodynamic equilibrium has or has not been reached in plasmas. Observations of this kind have become particularly interesting since the advent of lasers, and the mechanism responsible for the appearance of population inversion has become a topical problem. It is interesting to note that the first suggestion that the method of hooks could be used in an experimental study of stimulated transitions was made as far back as 1924. This occurred during a congress of physicists held in Leningrad when P. S. Ehrenfest discussed with Rozhdestvenskiĭ the possibility of direct experimental confirmation of the existence of stimulated transitions that had been introduced by Einstein. However, experimental techniques available at the time turned out to be inadequate for this purpose. It was hoped that this could be overcome by measuring the absorption-line intensities and then comparing the reduction in absorption relative to the predictions of the classical model (the possibility of stimulated emission of light had not occurred to anyone at the time). It was therefore decided to try to observe the effect of stimulated transitions on anomalous dispersion. It was already known that the inclusion of stimulated transitions resulted in the appearance of an additional term in the Sellmeier formula:

$$n^2 - 1 = \frac{e^2}{\pi m} \sum_k \frac{f_{ik} N_i}{v_{ik}^2 - v^2} \left(1 - \frac{g_i}{g_k} \frac{N_k}{N_i} \right). \tag{10}$$

The additional term in (10) reduces the dispersion, and this may be regarded as a manifestation of "negative dispersion." However, the density of atoms in the upper excited states is usually much smaller than in the lower, so that $N_k N_i \ll 1$. Negative dispersion is, therefore, not very appreciable. Consequently, it was necessary to choose the experimental conditions so that the ratio N_k/N_i would be large enough to ensure that the departure from the usual form of the Sellmeier formula should be large enough. A few years later, as a result of correspondence with Rozhdestvenskiĭ, the study of negative dispersion was taken up by the well-known German physicist, Ladenburg. Rozhdestvenskiĭ gave direct help in this research, which was also carried out by the method of hooks. He sent drawings of his interferometer to Ladenburg and subsequently gave him extensive advice during a personal meeting in Berlin.

It is usually stated in modern literature that Ladenburg demonstrated the existence of negative dispersion in excited neon.[13] In reality, however, the interpretation of the results of his observations is not entirely satisfactory, and the confirmation of (10) by the Rozhdestvenskiĭ method of hooks is still to come.

* * *

Rozhdestvenskiĭ's work on anomalous dispersion does not by far exhaust his scientific activity. Many other problems in theoretical and applied optics attracted his attention. He devoted a considerable amount of time to

the theory of the structure of atoms and atomic spectra.

In December, 1919, during the celebrations of the first anniversary of the founding of the Optics Institute, Rozhdestvenskiĭ delivered a paper entitled "Spectral analysis and the structure of atoms."[14] With great scientific courage and insight, he generalized Bohr's theory, which was concerned only with the hydrogen atom, to the case of other and more complicated atoms. It subsequently became known that many of his assumptions were, at the same time, discovered by Western scientists, but this did not lessen his achievement. On the contrary, it emphasized it. Working on his own, he put forward in a more complete and general form the predictions that were also made abroad by several of the most eminent scientists.

For a correct evaluation of Rozhdestvenskiĭ's work, we must recall that Soviet Russia was at that time cut off from world science by a blockade, and information about the structure of atoms was confined to publications issued prior to 1917. Sommerfeld's work on elliptical orbits in the hydrogen atom was the latest news. With striking scientific foresight, Rozhdestvenskiĭ formulated the basic assumptions for an extension of the theory to the spectra of all atoms. These assumptions were as follows:

1) spectral series determine the orbits of valence electrons in atoms;

2) distant orbits in alkali metal atoms are similar to distant orbits in the hydrogen atom;

3) the number of orbits involving valence electrons in the alkali metal atom is equal to the number of orbits in the hydrogen atom;

4) doublets and triplets are due to the internal magnetic field of the atom;

5) the reason for the anomalous Zeeman effect lies in the existence of a magnetic field in atoms;

6) the spectrum of a singly ionized atom of a particular element should be similar to the spectrum of the neutral atom of the element preceding it in the Mendeleev periodic table.

Many of the ideas put forward by Rozhdestvenskiĭ are, in fact, fundamental discoveries lying at the basis of spectral systematics, and justice demands that they should be associated with his name.

Rozhdestvenskiĭ had the acute facility to recognize relationships, some of which were of secondary importance at first sight but which, in reality, could be used to formulate far-reaching conclusions. Thus, having noted the similarity between the infrared spectra of hydrogen and of the alkali-metal atoms, he was able to compare correctly their higher energy states, and show that the spectra of alkali metals were merely strongly disturbed hydrogen spectra. In a characteristically picturesque way, he said: "if we had infrared eyes, i.e., an instrument that would be as sensitive in the infrared as the eye and the photographic plate are in the visible, then we would see a whole series of lines

so close to the hydrogen lines that the correspondence between the spectra of all the atoms and the spectrum of hydrogen would have been established long ago, immediately after the discovery of spectral analysis."

Rozhdestvenskiĭ put forward the idea that the spectral doublets and triplets were of magnetic origin, which meant that he came close to the modern mathematical theory and its connection with the theory of the Zeeman effect.[15] Although this idea was disputed by many distinguished physicists, it was clear to Rozhdestvenskiĭ, who had the facility for generalizing experimental data, that only magnetic forces could have been responsible for the appearance of doublets and triplets. In the course of vindication of his theory, he was acutely aware of the difficulties which it had to face at the time. Of course, we now know that a complete theory of spectral multiplets can be constructed only by the inclusion of electron spin, the existence of which was not known at the time.

Rozhdestvenskiĭ was the first to give a complete analysis of the spectrum of the magnesium ion.[16] This work was a model for the subsequent numerous analyses of the spectra of ions. His paper on the analysis of the neon spectrum is of particular interest.[17] He made more complete use than anyone else of the hypothesis that a single monochromatic line can be emitted during the simultaneous rearrangement of the states of two electrons. This hypothesis is not only of fundamental importance, but is also the key to the structure of complicated spectra of atoms and ions with many valence electrons. Finally, we must recall his paper to the Mendeleev Congress in September of 1934, entitled "The periodic law based on the analysis of spectra."[18] By comparing Moseley plots for successive elements, Rozhdestvenskiĭ was able to provide a very clear picture of the order in which the electronic shells of atoms were filled. He made extensive use of the latest theoretical data but, at the same time, warned against the attractions of formalism and the danger of isolation from experiment. He emphasized the enormous importance of quantum mechanics for the understanding of the structure of spectra and, at the same time, maintained that "it is not only dangerous but simply futile to plunge into its secret depths without direct experimental indications."

Reviewing existing experimental data, he immediately recognized a striking gap: there was practically no information about the spectra of the rare earths. With characteristic purposefulness, he immediately made the practical decision to organize systematic research into these spectra. He noted that nothing was known about 14 out of the 92 elements in the Mendeleev periodic table. They had to have some properties that were not only of scientific but of major practical importance. However, words were not sufficient, and he proceeded to energetic action. On his suggestion, the USSR Academy of Sciences organized a Commission on research into the rare earths, and put him in charge of it. This Commission, which subsequently (1939) became the Spectroscopic Laboratory of the USSR Academy of Sciences, existed for a relatively short time but, never-

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theless, it initiated and in part completed a series of interesting and original researches into the spectra of rare earths.

After a few years, it became clear that knowledge of the physical properties of the elements in the rare-earth group was unusually important for nuclear power engineering. His unusual intuition was thus found to be right once again, and his idea of the intimate connection between "abstract" science and technology was confirmed.

Rozhdestvenskiĭ's work in atomic spectroscopy was also the beginning of further researches. Even during his lifetime, A. N. Terenin performed numerous and very interesting experiments on the fluorescence of a series of elements, which provided more accurate information on their energy levels.[19] S. É. Frish performed an analysis of the spectrum of ionized sodium[20] and showed its similarity with the spectrum of neon. Rozhdestvenskiĭ's suggestion that the spectrum of an ion was similar to the spectrum of the neutral atom preceding it in the Mendeleev table was thus confirmed at the contact between two different rows of the periodic table.

There is no doubt that subsequent Soviet work in atomic spectroscopy was influenced by the pioneering studies of Rozhdestvenskiĭ in this field. There is one other very important fact: when the blockade was broken, Russian science was not lagging behind the spectroscopy of Western Europe and America and, in fact, was totally up to date.

The scientific work of Rozhdestvenskiĭ was also concerned with the theory of optical instruments and, especially, the theory of the microscope. He devoted considerable effort and attention to the study of the properties of optical glass and the technology of its manufacture. This work was of major importance, but we shall not consider it here. Instead, to complete our sketch of Rozhdestvenskiĭ's scientific work, let us conclude by noting his interest in chemistry. He spoke frequently and with great conviction of the importance of a deep penetration of physical ideas into chemistry. He maintained that "a clear understanding, a detailed picture of chemical phenomena, is the end point of chemical empiricism; calculation and prediction replace the sample in the flask or retort. The mathematical chemist becomes the final arbiter." Again: "knowledge of the properties of molecules necessarily includes the recognition of the structure of atoms and the ability to construct and to break molecules. This is a chemistry but not the pre-Bohr chemistry, purely empirical and controlled by the phenomenological laws of thermodynamics; it is a specific chemistry capable of understanding the process in its fine details and of controlling the atom just as a driver controls an automobile."

Rozhdestvenskiĭ saw the importance of chemistry not only in the "building" of new molecules, but also in the solution of problems in solar-energy utilization through the use of photochemical processes. He maintained that "we blandly and foolishly watch the flood of this precious energy descending on the earth around us,

quite uselessly and without providing us with power." He was optimistic that the problem of solar-energy utilization would soon be solved and a new era would begin for mankind: "in its scope, this new era will greatly exceed that of the old. It will provide us not merely with a new form of energy, but energy that will be free like the air we breathe."

Dmitriĭ Sergeevich Rozhdestvenskiĭ was not only an outstanding physicist and thinker, but a great patriot and an enthusiastic supporter of the new Socialist society. His scientific and fundamental general ideas retain their significance to this day. One hundred years after his birth, we would do well to emulate his shining example.

[1]D. S. Rozhdestvenskiĭ, Anomal'naya dispersiya v parakh natriya. Magisterskaya dissertatsiya (Anomalous Dispersion in Sodium Vapor. Master Thesis), St. Petersburg, 1912; see also: Raboty po anomal'noĭ dispersii v parakh metallov (Papers on Anomalous Dispersion in Metal Vapors), Izd. AN SSSR, M.-L., 1951, p. 7 (this will subsequently be referred to as RAD).

[2]D. S. Rozhdestvenskiĭ, Prostye sootnosheniya v spektrakh shchelochnykh metallov. (Simple Relationships in the Spectra of Alkali Metals), Doctoral Thesis, Petrograd, 1915; see also RAD, p. 145.

[3]D. S. Rozhdestvenskiĭ, "Determination of oscillator strengths in the spectra of atoms" (jointly with N. P. Penkin). Izv. Akad. Nauk SSSR Ser. Fiz. 5, 635 (1941); see also RAD, p. 307.

[4]D. S. Rozhdestvenskiĭ, "An interferometer for the investigation of anomalous dispersion," Izv. Akad. Nauk SSSR Ser. Fiz. No. 8, 1119 (1934); Tr. Gos. Opt. Inst. No. 101 (1935).

[5]D. S. Rozhdestvenskiĭ, "A ratio for the D_1 and D_2 lines of the sodium doublet" (jointly with V. I. Turoverov), Zh. Russk. Fiz. Khim. Obshch. Ch. Fiz. 49, 128 (1918).

[6]A. N. Filippov, Tr. Gos. Opt. Inst. 8, No. 85 (1932).

[7]W. K. Prokofiew and A. N. Filippov, Z. Phys. 56, 458 (1929).

[8]W. K. Prokofiew and A. N. Filippov, Z. Phys. 85, 647 (1933).

[9]W. K. Prokofiew, Z. Phys. 58, 255 (1929).

[10]W. A. Fock, Z. Phys. 89, 744 (1934).

[11]G. S. Kvater, Zh. Eksp. Teor. Fiz. 11, 421 (1941).

[12]N. P. Penkin, Izv. Akad. Nauk SSSR Ser. Fiz. 11, 217 (1947).

[13]R. Ladenburg, Rev. Mod. Phys. 5, 243 (1933).

[14]D. S. Rozhdestvenskiĭ, "Spectral analysis and the structure of the atom," Tr. Gos. Opt. Inst. 1, No. 6 (1920); "The significance of spectral series," Tr. Gos. Opt. Inst. 2, No. 7 (1921); see also Izbrannye trudy (Collected Works), Nauka, M., 1964, pp. 5, 66 (abbreviated as CW).

[15]D. S. Rozhdestvenskiĭ, "Doublets in spectral series," Nature 107, 203 (1921).

[16]D. S. Rozhdestvenskiĭ, "The series in the spectrum of ionized sodium deduced from a comparison with the spectrum of ionized helium," Tr. Gos. Opt. Inst. 2, No. 9 (1921); see also CW, p. 108.

[17]D. S. Rozhdestvenskiĭ, "Two independent sets of series in the spectrum of neon," Tr. Gos. Opt. Inst. 3, No. 18 (1924); see also CW, p. 111.

[18]D. S. Rozhdestvenskiĭ, Periodicheskii zakon na osnove analiza spektrov (doklad na Mendeleevskom s'ezde, 1934) [The Periodic Law on the Basis of Spectrum Analysis (Paper read to the Mendeleev Congress in 1934)], Proceedings of the Congress, 1936, p. 65; see also CW, p. 120.

[19]A. N. Terenin, Tr. Gos. Opt. Inst. 4, No. 32 (1928).

[20]S. É. Frisch, Naturwiss. 15, 507 (1927); Tr. Gos. Opt. Inst. 8, No. 81 (1932).

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