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The discovery of combination scattering of light in Russia and India

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Contents

Abstract. The history of the discovery of combination (Raman) scattering of light in Moscow and Calcutta is briefly described. Moscow physicists observed the lines due to the new effect on February 21, 1928 and published their results on July 13, 1928, whereas for Indian physicists the respective dates are February 28, 1928 and April 21, 1928. Raman alone was to be awarded the Nobel Prize for the discovery. Research conditions in Russia and India are discussed in brief.

1. Introduction

The blue color of the sky over our planet is accounted for by the scattering of solar light from gas molecules that make up the Earth's atmosphere. Therefore, the question of who first observed the phenomenon now called light scattering makes no sense. It is much more difficult to say who was the first to use this phenomenon. Lucretius Carus (the 1st century BC) noticed light scattered from specks of dust in a sunray and observed the motion of scattering dust particles in the air.

Eminent figures, such as Leonardo da Vinci (the 15th century), Newton (the 17th century), and Clausius (the 19th century), tried to explain the blue color of the sky. All these attempts failed, however.

Only the first laboratory experiments by Tyndall (1869) and Lord Rayleigh's theory (1899) provided the correct understanding of processes underlying light scattering and demonstrated why the sky is blue.

Critical opalescence posed an additional problem to which it was difficult to find an adequate solution. Numerous attempts to explain this phenomenon had been in vain until Smoluchowski proposed the first correct explanation for this remarkable effect in 1908. This author demonstrated marked enhancement of density fluctuations in a critical range of phase transitions leading to a noticeable rise in light scattering intensity.

Two years later (in 1910), Einstein showed how to calculate fluctuations of thermodynamic variables and found the intensity of light scattered by fluctuations rather far from the critical point.

Ornstein and Zernike made a correction to Einstein's formula for the case of scattered light intensity close to the critical point.

In other words, the theory of light scattering due to fluctuations was fairly well developed as early as the first quarter of the 20th century.

Theoretical data obtained by that time were successfully employed to explain the observed phenomena and determine Avogadro's number for light scattering in gases, as well as for other purposes.

Light scattering studies were carried out in many countries. It is well known that they were conducted in Russia, France, India, the United States of America, and Germany.

Late in the first third of the 20th century, physicists started to search for scattered light of wavelengths different from those present in incident light. To our knowledge, such studies were undertaken by C V Raman and K S Krishnan in India, G S Landsberg and L I Mandel'shtam in Russia, J Cabannes, P Daure, and Y Rocard in France.

These three groups were interested in scattered light undergoing frequency changes under the effect of different physical factors. Two of them found something they had not been aiming for. But their surveys were fruitful and the available means of research sufficient to discover combination light scattering.

February 2003 was the 75th anniversary of the discovery of combination light scattering (the Raman effect), one of the most important optical and spectral phenomena, which contributed to the understanding of diverse fields of research and greatly promoted developments in physics, chemistry, and other disciplines [1].

The number of experimental and theoretical studies on light scattering amounts to many thousands. There are many voluminous monographs on the subject (see, for instance, [2 – 5]), to say nothing about numerous publications highlighting the history of this discovery. Hence, there are inevitable recurrences, even if justified by the importance of the

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phenomenon of interest, a host of new facts, and the necessity to educate new generations of readers.

It is not infrequent that a certain phenomenon or event of importance for life or science remains 'latent' for a long time until it suddenly captures the attention of two or even more groups of researchers.

The greatest achievements in physics have been the result of casual discovery, some of them predicted theoretically.

Today, we understand that combination scattering of light is a rare example of a theoretically predicted chance discovery. In what follows, it will be shown how the discovery was made, but the case is worthy of special analysis, probably not limited to physical considerations.

The history of the discovery of combination light scattering has been described in many publications. Suffice it to mention a few recent works on the subject [6 – 11].

2. Experimental studies in Moscow

Light scattering studies in Moscow appear to have been initiated later than in India, France, and other countries. The onset of work at the Physical Faculty of Moscow State University dates to 1925.

A group of Moscow physicists invited L I Mandel'shtam [12], who then lived in Leningrad (now Saint Petersburg) and was widely known for his radiophysical and optical studies, to move to Moscow and head the Chair of Theoretical Physics at Moscow State University.

Mandel'shtam received the Chair in 1925 and formulated his first experimental task as the elucidation of the fine structure of the Rayleigh line induced by modulation of scattered light with Debye thermal waves [13].

Experiments were started by Mandel'shtam and G S Landsberg. It was decided to use a perfect solid crystal. The best one available at that time was quartz monocrystal which was, however, difficult to obtain. I have already written how Landsberg managed to find it [6, 14]. Briefly, he looked for a suitable specimen in antique shops. But the search for the needed material was not the sole obstacle to be overcome. A much more serious problem was posed by the lack of publications on molecular scattering in solids.

There was a single work by R J Strutt (Lord Rayleigh's son) [15], who studied light scattering in quartz and came to the conclusion that what he had actually observed was not the light scattered by quartz molecules but the light reflected from foreign inclusions and crystal defects, or the so-called false light. Nevertheless, Raman stated in his brief note in *Nature* [16] that Strutt had observed molecular light scattering rather than false light.

There was no doubt as regards molecular light scattering in quartz. The question was how to study it in a real crystal. Researchers were apprehensive that it might be masked by false light. Landsberg was to find a quartz monocrystal suitable for the purpose and a source of molecular light scattering in this material detectable by experimental techniques.

This difficult work done by Landsberg was a great success. He found the necessary crystal specimens, observed molecular light scattering in them, and proposed a criterion for the differentiation between scattered light and false light.

The results of these studies were published by Landsberg in the then most reputed physical journal [17]. In other words, Landsberg and Mandel'shtam set to work on the problem formulated by the senior researcher as early as 1927. Certainly, they had been fully aware of the forthcoming difficulties much before that time. The most serious problem was now to record a very small alteration in the light frequency. It was known from calculations made by Mandel'shtam [18] and Brillouin [19] that a change in the scattered light frequency could be found from the expression

$$\Delta\Omega = \pm 2n\omega \, \frac{V}{c} \sin \frac{\theta}{2} \,. \qquad (1)$$

Here, n, ω, V, c, and θ are the refractive index, light frequency, velocity of sound, velocity of light, and light scattering angle, respectively.

Because at $\theta = 90°$ $2n \sin(\theta/2) \cong 2$ and the ratio $V/c \sim 10^{-5}$, the frequency shift $\Delta\Omega \sim 10^{-5}\omega$. As regards a possible change in the light wavelength, that of green light may be expected to be $\Delta\lambda \cong 0.3$ Å.

All this was perfectly well known to Mandel'shtam and Landsberg. They knew as well that a high-resolution interferometer or diffractometer was needed to observe doublet lines produced upon modulation of scattered light by elastic thermal waves. At that time, however, the Optical Laboratory of the Physical Faculty at Moscow State University, where Landsberg and Mandel'shtam carried out their studies, was not properly equipped for this purpose.

At the beginning, light scattered from crystal molecules was analyzed using a 'Fuss B' spectrograph. The results surprised the researchers. They identified additional spectral lines (called 'lightspots'), in addition to lines of unshifted frequency, and had to look for a method to eliminate them.

Light scattering in quartz was excited by mercury spectrum lines with $\lambda = 4358.3$ Å and $\lambda = 2536.5$ Å.

Landsberg and Mandel'shtam were exceedingly thorough researchers, whether it came to the measurement, observation, or interpretation of the phenomenon of interest. Never in their life-long research work did they have to reconsider or even correct their primary data. Whenever they happened to make an unexpected observation, they recognized the fact and did their best to find its adequate explanation. This approach is exemplified by the discovery of combination light scattering.

Combination scattering of light observed in the experiments of Landsberg and Mandel'shtam as described in the present paper was a chance discovery. The very first lines of their publication in *Naturwissenschaften* [20] were the following: "In the investigation of molecular scattering of light in solids which we undertook to find out whether a change in wavelength occurs that might be expected in the framework of the Debye theory of heat capacity, **we ran into a new phenomenon** which seems to us to be of certain interest. The phenomenon consists in a change of wavelength whose value however has an order of magnitude and origin other than we expected."

Thus, in the very first report written on the 6th of May and published on 13 July 1928, the authors stated that they had observed an absolutely new phenomenon of interest ("**we ran into a new phenomenon**"). They therefore focused on the improvement of the experimental device in order to obtain even more convincing data in support of their discovery.

In their first report, the authors avoided making a comprehensive theoretical analysis but pointed out that the appearance of new lines (satellites) was due to the interaction between the light and infrared molecular vibrations. It was a general but fully correct definition of the nature of the new phenomenon. The same report contained a spectrogram and a table illustrating the displacement of combination scattering lines and compared the obtained values with the predicted infrared vibrations of quartz molecules. The experimental and theoretical data were in excellent agreement. There is little doubt that Landsberg and Mandel'shtam had more data in stock than they published in their first report and also had a very definite plan of further studies.

An earlier paper by Landsberg and Mandel'shtam dated 9 June 1928 was published in *Zeitschrift für Physik* under the title "On Light Scattering in Crystals" [22]. It was a fundamental and detailed work containing a comprehensive explanation of experimental findings and references to theoretical predictions of their observations. Unfortunately, they appear to have been unaware of the works of A Smekal [23] and H Kramers and W Heisenberg [24] at the onset of their studies.

The validity of observations made by Landsberg and Mandel'shtam is best confirmed by their own arguments.

This is how they described the experimental setup used to carry out this remarkable study [22, 25]:

"The very first spectrograms of light scattered from a quartz crystal during a relatively short period of exposure (up to 15 h) revealed a phenomenon that consisted of the appearance of new lines in the vicinity of mercury-related ones, with each main intense line having satellites.

Exactly the same picture obtained with another quartz crystal, as well as the obvious regularity in the distribution of new lines makes it highly improbable that these are false lines due to unforeseen reflections. For all that, we deemed it necessary to verify the results in control tests. The following experiment was designed to obtain a decisive proof. It is known that a resonance line of 2536.5 Å is readily absorbed by nonluminous mercury vapour. We placed an evacuated quartz cuvette filled with mercury vapour on an electrical hotplate between the scattering crystal and the slit of the spectrograph. It was possible to have the 2536.5 Å line completely absorbed by the adequate choice of the current in the lamp and the proper adjustment of temperature. As a result, this line was lacking from the spectrogram which still exhibited its satellites. This means that they had a different wavelength.

In the first spectrograms, each mercury line (if sufficiently intense) was accompanied by two satellites shifted toward the red end of the spectrum. The intensity of the stronger satellite line farthermost from the main one was roughly 30% that of the latter."

The authors went on as follows: "The last spectrograms for quartz were obtained after an almost 100 h exposure with a narrow (about 1/20 mm) slit. They exhibited 72 new (i.e., absent in the mercury spectrum) lines that could be easily categorized into five systems such that the difference between the frequencies of the main line and its satellite was constant if expressed in absolute values."

Figure 1 shows a scattered light spectrum in Iceland spar and the reference spectrum. Spectra of combination light scattering in quartz compared with the reference spectrum are presented in Fig. 2.

The experimental findings of Landsberg and Mandel'shtam cited in the present communication and their theoretical interpretation by the authors lead to the conclusion that they were the first to observe the new phenomenon of combination light scattering in quartz and Iceland spar crystals on 21 February 1928; they correctly explained the nature of this phenomenon [20–22] and did a lot of work with reference to theoretical surveys [22] of this problem of primary importance. The discovery proved very fruitful for advances in physical science.

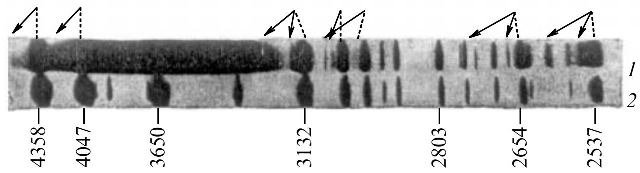

Figure 1. Scattered light spectrum in Iceland spar (double magnification): *1* — at 20 °C and 40 h exposure, *2* — reference spectrum.

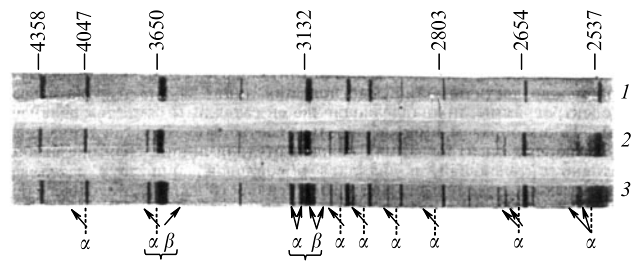

Figure 2. Spectra of scattered light in quartz (double magnification): *1* — reference spectrum, *2, 3* — scattered light spectra obtained at 20 °C and 220 °C (105 h exposure); α — red satellites; β — violet satellites.

It has been mentioned above that Landsberg and Mandel'shtam first observed the new phenomenon on 21 February and again on 23–24 February 1928 but reported it in *Naturwissenschaften* only on 13 July 1928. In other words, there was rather a long delay between the discovery and the publication. Hence, a natural question: why were the results of the study submitted for publication (May 6, 1928) more than two months after the authors had observed the new phenomenon? Unfortunately, the reason for the delay had nothing to do with science although it had effect on its further development.

What happened is that just at that time, L I Gurevich, a relative of Mandel'shtam, was arrested and sentenced to death. Mandel'shtam had to suspend the work and completely devote himself to mitigate the punishment. At the end, he succeeded in having the capital penalty commuted to exile to the city of Vyatka. Gurevich's life was saved, but the publication of the discovery was postponed. More details related to this episode can be found in the previously cited work of E L Feĭnberg [12].

Landsberg and Mandel'shtam continued their studies, the value of which did not suffer in the least from the delay in publication.

Independent scientific research should not be evaluated the same way as a running competition.

3. Studies of scattered light in Calcutta

In Moscow, Landsberg and Mandel'shtam studied light scattering in quartz and Iceland spar crystals in search of lines with frequency shifted due to the scattered light modulation by elastic thermal waves.

Just at the same period, C V Raman and K S Krishnan of Calcutta, India, thousands of kilometers from Moscow, undertook an independent study designed to search for frequency shifts in scattered light due to the optical analogue of the Compton effect.

Both studies were initiated in early 1928. Raman wrote [26]: "Pondering on the phenomenon described by Ramanathan and Krishnan as 'faint fluorescence', I concluded that here we have to do with a totally different type of secondary radiation taken for fluorescence." He then formulated his hypothesis of frequency changes for the light scattered in a liquid in the following words [26]: "In the beginning of this year, a powerful impetus to further research was provided when I conceived the idea that the effect was some kind of optical analogue of the X-ray scattering discovered by professor Compton for which he was recently awarded the Nobel prize for physics. I immediately undertook an experimental reexamination of the phenomenon in collaboration with Mr Krishnan." It means that Raman and Krishnan searched for scattered light with the frequency modulated by the optical analogue of the Compton effect [1].

The first attempt to observe a change in the scattered light wavelength was undertaken with an instrument in which an intense ray of sunlight fell on a liquid- or gas-filled vessel. The scattered light was visible to the naked eye, while changes in its wavelength were recorded using the method of complementary light filters.

Raman and Krishnan [27] stated that they observed light passing through the complementary filters. Certainly, they could not see additional lines of combination scattering because it was induced by a continuous-spectrum beam of sunlight.

For all that, the authors did not hesitate to ascribe what they viewed through a pair of complementary filters to "a new type of secondary radiation". They did not regard it as fluorescent light because of its low intensity and polarization. Their note in *Nature* was entitled "A New Type of Secondary Radiation".

The next paper by Raman and Krishnan [28] reported the use of a mercury vapor lamp (mercury spectral line $\lambda = 4358$ Å) to induce light scattering. The spectra thus obtained showed satellites of combination light scattering. The paper had the title "The Optical Analogue of the Compton Effect". The authors hypothesized that they had observed the optical analogue of the Compton effect. Having investigated 60 different liquids, they expressed the conviction (not very firm, however) that the position of the modified lines was the same for all substances. Also, the paper contained comparisons with infrared frequencies of molecules.

The third letter of Raman and Krishnan to *Nature* [29] was entitled "The Negative Absorption of Radiation". The opening paragraphs of the letter can be understood as stating that anti-Stokes satellites, i.e., combination scattering lines, appeared as a result of interaction between the light and excited molecules due to the negative absorption of radiation predicted by Einstein in the derivation of the Planck formula and underlying the principle of the laser.

[1] It should be noted that the optical analogue of the Compton effect is hardly observable in visible light. X-ray quantum energy is much higher than the energy of electron binding in light atoms. For this reason, X-rays are actually scattered from free electrons. According to quantum theory, a change in the wavelength $\Delta\lambda = 2d \sin(\theta/2)$, $d = h/(m_0 c)$, where h is the Planck constant, m_0 is the electron mass, and d is the universal length, is the same for all substances, while $\Delta\lambda$ depends only on the scattering angle θ and particle mass m. For an electron, $\Delta\lambda = 2.4 \times 10^{-10}$ cm, for a proton, $\Delta\lambda = 1.3 \times 10^{-13}$ cm.

Raman and Krishnan interpreted their observations of combination scattering lines in a very peculiar way. First they believed they had observed the optical analogue of the Compton effect, then they attributed the appearance of anti-Stokes satellites to the negative absorption of radiation predicted by Einstein.

In the meantime, the two effects have nothing to do with the combination scattering of light that the authors first observed in the study reported in [28]. In their previous work [27], they excited scattering by the continuous spectrum of the Sun and made observations with the naked eye. Therefore, it is difficult to judge what kind of light they actually saw.

The papers by Raman and Krishnan produce a strange impression. In one case, the authors compared the lines of combination light scattering with infrared molecular vibrations which leads the reader to believe that they were on the right path. But the titles of the other papers ("The Optical Analogue of the Compton Effect" and "The Negative Absorption of Radiation") suggest that they did not understand the nature of the observed phenomenon.

4. After the discovery

The new phenomenon observed by the Moscow and Calcutta groups greatly impressed physicists especially those interested in spectroscopy.

Indeed, there was good reason for surprise. Light of a certain frequency ν entered a transparent medium (crystal or liquid), and the scattered light spectrum contained lines of a changed frequency $\nu \pm \Delta\nu$. The value of $\Delta\nu$ was so high that even a primitive spectrograph permitted to see the additional lines fairly well (the Stokes frequency $\nu - \Delta\nu$, the anti-Stokes frequency $\nu + \Delta\nu$).

In 1928, the description of this phenomenon in the scientific literature greatly influenced physicists engaged in spectroscopic research and made all those interested in scattered light and fluorescence turn to the study of the remarkable new effect, combination light scattering.

Landsberg and Mandel'shtam believed that the fine structure of the Rayleigh line [30] originated from the modulation of scattered light at frequencies corresponding to the acoustic, or Debye, branch of the spectrum whereas combination light scattering resulted from the modulation of scattered light at frequencies corresponding to the optical, or Born, branch.

The attitude of Landsberg and Mandel'shtam toward scientific work was quite different from that of Raman and Krishnan. The difference was partly explained in my earlier papers [6, 7]. Here, suffice it to note that Landsberg and Mandel'shtam treated the object of their research as a source of new data about the nature of the phenomenon they observed, awaiting cautious analysis and fit for publication no sooner than the validity of the new knowledge was unambiguously established.

The style of work and the approach to publication of the results were equally different between the two groups of scientists.

Raman himself said [6, 7, 14] and Bhagavantam, his pupil and co-worker, confirmed [26, 31] that as soon as he observed combination scattering lines for the first time on 28 February 1928, he pushed the announcement of the discovery in a Calcutta daily newspaper issued the next day (February 29, 1928).

Raman was as quick to give publicity to his discovery as a sensation-mongering pressman. Then, he immediately submitted a series of reports with the results of the experiment to *Nature*.

When I wrote about the studies of Landsberg and Mandel'shtam and Raman and Krishnan in my earlier papers, I was fairly well aware of the conditions in which the two former authors had worked but knew very little about those of the latter and still less about their personalities.

After the publication of the interesting paper [10] by R Singh and F Riess, we know more about these researchers. For example, the paper cites a collaborator of Raman who worked with him in Calcutta: "Raman preferred to quickly publish his results, but he made very exacting demands as regards writing and editing his papers... He frequently had no time left to deliver a paper to the publisher in the usual way. In such cases, he took a taxi, rushed at full speed to the General Post-Office, paid a fine, and in the end succeeded in having the paper duly dispatched." One more episode described in Ref. [10] is the following: "He showed special concern for papers that reported his discovery. For example, he submitted the text of his lecture to the South Indian Science Association, Bangalore, on 16 March 1928. The lecture entitled "A New Radiation" ... was written immediately after his return to Calcutta and printed in the evening of the same day through the courtesy of the Calcutta University Publishing House. Thousands of preprints of this unique paper were sent on the same day to as many scientists around the world. The *Indian Journal of Physics* was started in 1927 and did not have much of a circulation in 1928."

"In order to give maximal publicity to his discovery, Raman obtained 2000 preprints of his historic paper after publication in the *Indian Journal of Physics* and posted it to all physicists of importance including those working on the scattering of light in France, Germany, Russia, Canada, and the USA and to scientific institutions all over the world, thus ensuring Raman's priority to the discovery". According to Raman's co-workers, Raman behaved like that before he came to know that Landsberg and Mandel'shtam had made exactly the same discovery simultaneously with him. (In fact, it became clear after a time that they observed combination light scattering one week earlier than Raman.)

Singh and Riess [10] write further that "After the Russian physicists published their results, Raman became more concerned with matters of priority." The support came from Germany where P Pringsheim, an expert in fluorescence, luminescence, and light scattering, repeated Raman's experiment, confirmed its results, and introduced the term 'Raman effect'. After Pringsheim had published his work, Raman felt fully confident that the question of priority was resolved in his favor. According to one of his co-workers, "He (Raman) told us that the matter of priority was settled since the discovery was given his name alone."

These facts leave no doubt that Raman believed in the effect of quick publication, whereas the Russian physicists lost too much time. The 'first come first served' principle has always been applicable to scientific priority issues. Raman was well aware of this fact. Moreover, he knew how to assert himself.

I have already mentioned some actions taken by Raman to give publicity to his works, and much more can be added. In what follows, I shall cite other examples of Raman's behavior which seem somewhat unusual to a detached observer.

In a previous section, I told about a family misfortune that Mandel'shtam suffered in the midst of his and Landsberg's experiments on light scattering in quartz and Iceland spar. After the legal affair ended, the two scientists completed their study and published its results [20–22].

For Landsberg and Mandel'shtam, who were people of culture and education, any noisy attention-getting demonstration or sensational propaganda of their discovery was out of the question.

Mandel'shtam recalled: "G S Landsberg presented our joint study "On a New Light Diffusion Phenomenon" at a colloquium in the Institute of Physics, People's Commissariat of Health, on 27 April 1928." To the best of my knowledge, it was the first public presentation of combination light scattering discovered by Landsberg and Mandel'shtam. The authors simply reported their results to their colleagues.

In a few months, the work of Landsberg and Mandel'shtam was presented to a wider physical audience at the 6th Congress of the Association of Russian Physicists attended by almost 400 participants, including 21 foreigners. The Congress opened in Moscow on the 5th of August 1928. Thereafter, the participants moved to Nizhniĭ Novgorod where they boarded a ship on the Volga and went as far as the city of Saratov. The foreigners present at the Congress included Born, Brillouin, Darwin, Debye, Dirac, Paul, Pringsheim, F Frank, Shell, and other prominent scientists. The Congress was closed on 15 August 1928.

Foreign participants of the 6th Congress published a few enthusiastic reviews of their journey.

Here are short extracts from the notes of M Born and C Darwin containing their impression of the report made by Landsberg and Mandel'shtam. Born [34] wrote as follows: "The phenomenon discovered by Landsberg and Mandel'shtam in crystals is essentially identical to the effect observed by Raman and his colleague Krishnan in liquids. Russian physics can justly take pride in the fact that this important discovery was made by Moscow researchers independently of the Indians and nearly simultaneously (20 February 1928). This coincidence is one more demonstration of the international nature of our science which now spans the entire world."

Darwin published a note about the 6th Congress of the Association of Russian Physicists with special reference to combination light scattering in *Nature* [35]: "Perhaps the most interesting works are that of Prof. Ioffe on the reflection of electrons — including an unsuccessful attempt to detect polarization — and that of Profs. Mandel'shtam and Landsberg. The latter described how they had independently discovered Raman's phenomenon, the scattering of light with changed frequencies."

Both Born [34] and Darwin [35] gave a correct and objective assessment of the discovery made by Landsberg and Mandel'shtam and identified it with the phenomenon described by Raman and Krishnan.

Judging by what is known about the subsequent course of events, Raman did not like the statements of Born [34] and Darwin [35] and responded with the publication of one more article in *Nature* [36]. The principal objective of this publication was to reaffirm his priority by ascribing the success of light scattering and luminescence studies exclusively to himself and his co-workers and to convince Darwin and other readers that the Russian physics had made no original contribution to the discovery.

Raman's letter stated that the existence of radiation of modified wavelength in scattered light had been established as early as 1923 by investigations made in Calcutta, although it is clear from the aforesaid that what he actually observed was Stokes luminescence.

This is really an extraordinary assertion because luminescence is known to have been an object of scientific research much earlier than 1923 and far from Calcutta. According to S I Vavilov [37], luminescence studies have a 400-year history. In fact, Galileo was among those interested in this phenomenon.

Raman's note [36] appears to have been written for the sake of its last paragraph, where he states: "The Russian physicists, to whose observation about the effect in quartz Prof. Darwin refers, made their first communication on the subject after the publication of the articles in *Nature* of March 31 and April 21. Their paper appeared in print after sixteen other printed papers on the effect, by various authors, had appeared in recognized scientific periodicals."

The work of Raman and Krishnan [29], in which they reported the observation of combination scattering lines, was published in *Nature* on 21 April 1928.

Landsberg and Mandel'shtam [20] observed combination light scattering independently of Raman and Krishnan and published their results in *Naturwissenschaften* of July 13, 1928. The two publications are separated by 83 days (less than three months).

Raman [36] informed Darwin [35] that the paper by Landsberg and Mandel'shtam [20] "appeared in print after sixteen other printed papers on the effect, by various authors, had appeared in recognized scientific periodicals." What he meant was to demonstrate that the work published in Ref. [20] was not an independent study. In effect, it was akin to a charge of plagiarism.

The large bibliographic article by M A Ganesan [38] containing references to 160 publications and abstracts of some of them was written in the same tone. All the works included in the bibliography concerned combination light scattering and were done before August 1929. The first 16 were those mentioned by Raman in Ref. [36].

In this bibliography, each work where the authors made use of what is now called the Raman effect had a note "Refer to the Raman effect", as if no other original studies had been conducted except Raman's.

Items 16 and 17 (Landsberg and Mandelshtam's papers) in Ganesan's list [38] had the same note "Refer to the Raman effect". It means that the truly original study by Landsberg and Mandel'shtam was regarded by the author of the bibliography as ensuing from the works of Raman and Krishnan. In the meantime, the two groups are known to have worked independently and, as became clear afterwards, discovered the same physical effect.

The checklist [38] cited one more paper by Landsberg and Mandel'shtam [22] under No. 30. The annotation to No. 30 contained no reference to the Raman effect but failed to indicate that the authors had observed satellite lines before Raman and Krishnan. More importantly, it did not even mention that the work was done independently of the Indian researchers.

It is interesting to clarify what Raman meant when he spoke about 'various authors', his paper [36] containing no list of references. It turns out that six of the first 16 papers listed in [38] were published by Indian authors (Raman and Krishnan), nine by French physicists [2], and one by Landsberg and Mandel'shtam.

The French physicists suspected the existence of combination scattering of light and sought to observe it. However, they apprehended that strong intermolecular interactions might interfere with the observation of discrete shifted lines and therefore studied light scattering in a gas.

Ironically, the French physicists purposely looked for combination light scattering and failed to find it. They were certainly aware that the intensity of light scattered in gases should have been small but it did not occur to them that it was as low as it proved to be. The intensity of scattered light they managed to obtain was simply insufficient to record the effect.

Conversely, their colleagues in India and Russia discovered combination light scattering quite unexpectedly.

As soon as Raman and Krishnan published the paper entitled "The Optical Analogue of the Compton Effect" [28], the French scientists understood what these authors had actually observed and immediately set to work for which they were psychologically motivated and technically equipped. As a result, nine studies were performed within a narrow time span. True, some of them were theoretical works shedding light on the physical nature of the phenomenon of interest.

It should be emphasized once again that Landsberg and Mandel'shtam observed combination scattering of light in Moscow earlier (even if only a few days earlier) than Raman and Krishnan in Calcutta. This allows us to conclude that Landsberg and Mandel'shtam were the first to discover combination light scattering.

Raman and Krishnan observed the same phenomenon later than Landsberg and Mandel'shtam but published their data less than three months earlier than the latter authors. The time of the first publication is not as important as the value of a discovery. Indeed, the publication is secondary to the discovery (in our case, observation of combination light scattering). The Nobel Prize Committee had enough time to consider the achievements of Landsberg, Mandel'shtam, Raman, and Krishnan when it discussed the nominees in December 1930. I am of the opinion that the prize should have been awarded to Landsberg, Mandel'shtam, and Raman (I am not aware of the contribution of Krishnan to this work). The fact that the 1930 prize was given to Raman alone is obviously a mistake by the Nobel Committee. But its members share the responsibility for this mistake with others, first and foremost with Landsberg and Mandel'shtam's countrymen, who had the right to nominate candidates

[2] The number to the left of the author's name indicates the number under which the paper is listed in [38]:

4. Rocard Y *Comtes Rendus* (*CR*) **186** 1107 (1928)
5. Cabannes J *CR* **186** 1201 (1928)
7. Cabannes J, Daure P *CR* **186** 1533 (1928)
8. Cotton A *CR* **186** 1475 (1928)
10. Bogros A, Rocard Y *CR* **186** 1712 (1928)
11. Cabannes J *CR* **186** 1714 (1928)
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Paper Nos 4, 5, 7, 8, 10, and 11 discuss the physical nature of the new phenomenon, No. 12 presents spectra of organic fluids and solutions, and Nos 13 and 14 are oral reports (with no reference to their contents).

The list of 'various authors' also includes Landsberg and Mandel'shtam (No. 16) whose work was actually the sole original study conducted independently of Indian and French physicists.

for the prize but did not use it. Foreign scientists are also to blame. Many of them were well aware that the contribution of Landsberg and Mandel'shtam to the discovery of combination light scattering was at least as large as that made by Raman but did not nominate them.

By way of example, this is what E Rutherford [40], the then President of the Royal Society of England, wrote about the discovery of Landsberg and Mandel'shtam: "An excellent account of these beautiful experiments was given this year by Raman and Krishnan in our 'Proceedings'. Similar effect was observed by Landsberg and Mandel'shtam in examining the light scattered by common crystals. Such experiments are not easy, for the intensity of scattered light is very small, and long exposures with intense sources of light are necessary to bring out the relatively faint new lines. An examination of the results showed that the changes in the frequency of spectral lines depend on characteristic frequencies of the molecule connected with its vibrational state."

This quotation shows that Rutherford not only fairly well understood the physical nature of the new phenomenon and the experimental conditions needed for its observation, but also realized that Raman, on the one hand, and Landsberg and Mandel'shtam, on the other hand, independently discovered one and the same effect.

At the same time, Rutherford nominated Raman alone as the candidate for the 1930 Nobel prize. Why?

Khvol'son, for example, did otherwise and nominated Landsberg, Mandel'shtam, and Raman together.

Singh and Riess [10] are right in saying that personal contacts with foreign colleagues are of great help in many aspects, especially when it comes to the support of a known person worthy of an award.

Landsberg and Mandel'shtam had much less opportunity of maintaining contacts with foreign scientists than Raman had. Moreover, I am sure that these contacts were organized on a quite different basis.

Raman did not hesitate to extensively exploit his connections for personal benefit. Specifically, Ref. [10] mentions that Raman several times received official and unofficial invitations to visit such reputed scientists as Rutherford (England), Bohr (Denmark), and Millikan (USA) even before he made his discovery. He knew perfectly well that he could obtain support from a Nobel prize winner having the right to nominate his own candidate. Indeed, Rutherford and Wilson enthusiastically recommended him to the Nobel Committee as the candidate for the 1930 prize.

Another impressive example cited in Ref. [10] is the letter of congratulation addressed to Raman by the great N Bohr that read as follows: "I am pleased to have an opportunity to bring my sincere congratulations on your remarkable discovery of new radiation that will considerably extend our knowledge in the field of optics and atomic physics." This flattering remark equally well refers to Landsberg and Mandel'shtam, who made the same discovery independently of their Indian colleagues and even before them.

As mentioned above, the Nobel prize for physics in 1930 was awarded to Raman alone. He was nominated by ten distinguished physicists including E Bloch, N Bohr, L de Broglie, M de Broglie, O Khvol'son, J Perrin, R Pfeiffer, E Rutherford, J Stark, and C T P Wilson.

Mandel'shtam was nominated by O D Khvol'son and N D Papaleksi, and Landsberg by O D Khvol'son alone.

It is appropriate to cite here the story told by Bhagavantam [31] about Raman's reaction to the news that he had been awarded the Nobel prize. Bhagavantam says: "I had the privilege of being one of his active collaborators when he was awarded the Nobel prize for physics, and I vividly recall his reaction when I communicated to him the first news of the award after hearing it on telephone from one of the Indian news agencies in Calcutta. He asked if he was the sole awardee or was he to share the bed with foreigners." His emotional exuberance and other such traits often won him the description of a person lacking tact in dealing with people[3].

Two months before he knew he was awarded the Nobel prize, he had the supreme audacity of booking his steamer passage to be in time for the ceremony at Stockholm."

The Nobel Prize Committee had at its disposal all necessary materials demonstrating that the Indian and Russian physicists made one and the same great discovery. Individuals to be considered as nominees were few [11].

It should be hoped that the Nobel Prize Committee takes into consideration the value of the discovery rather than the merits of nominators.

It is certainly a mistake to award a prestigious prize to one and turn down the others who made the same discovery. But even the most prestigious prize can not be regarded as a model against which to measure scientific achievements.

There is no doubt that the discovery by G S Landsberg and L I Mandel'shtam adds a glorious page to the history of science and contributes to its further progress.

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[3] In 1957, Raman visited Moscow to receive the Lenin Peace Prize. He was invited to read a lecture about his theory of solids at a seminar run by P L Kapitza at the Institute of Physical Problems. I attended the seminar. Some 15 – 20 minutes into the lecture, L D Landau, sitting in the front row, made a remark. Raman appeared to have nothing to say in response. Instead, he began shouting, stamping his feet, swinging his arms, insulting Landau, and talking rot. Landau stood up and left the conference hall. The chairman did not utter a word. I have never seen the like of that.

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