RAMAN EFFECT— DISCOVERY AND AFTER

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WHEN any transparent medium is irradiated by monochromatic light, the radiations scattered by the molecules contain spectral lines of modified frequencies, the difference between the incident and scattered frequencies corresponding to a characteristic infrared absorption frequency of the molecule. Most of the modified lines are of a smaller frequency than the exciting line. There are some relatively feeble lines the frequencies of which exceed the frequency of the exciting line by an infrared frequency of the molecule. In these lines we have for the first time direct experimental proof of *induced emission* (or negative absorption) or radiation by molecules.

The scattered lines are sometimes accompanied by a nebulosity or continuous spectrum extending unsymmetrically on the two sides. The modified radiations scattered at 90^0 exhibit striking polarisation, the degree of depolarisation being different for lines corresponding to different frequency shifts. This scattering phenomenon, which is of a fundamental character, was discovered by Professor C.V. Raman nearly sixty years ago on 28 February 1928 and is since known as "Raman Effect". Due publicity was given to it in the newspapers the next day. Raman submitted a note entitled "Change of wavelength in light scattering" on March 8, 1928 to *Nature* of London. The story goes that this important communication to *Nature* by Raman announcing the discovery of a new effect was referred for comments to a referee who rejected it outright as he thought that such a change of frequency in the scattering process was not possible. Sir Richard Gregory who was the editor of *Nature* took the responsibility on himself and published the same in *Nature* dated 21st April 1928. The effect was observed by C.V. Raman and his student and close associate, K.S. Krishnan simultaneously in gases, liquids, crystals and glasses, thereby establishing its universal character.

Let us trace briefly the sequence of experimental work starting from the summer of 1921 which finally led to the discovery of Raman effect in February 1928.

History of the discovery

In the history of science one often finds that the study of some natural phenomenon has been the starting point in the development of a new branch of knowledge. We have a very good example of this principle in the discovery of the Raman effect which had its origin in the wonderful blue colour of the Mediterranean Sea. Lord Rayleigh had attributed the colour of the sea to the blue of the sky reflected by water. In 1921 Prof. Raman was chosen as one of the delegates to the Universities' Conference held at Oxford. While passing through the Mediterranean Prof. Raman was struck by the deep blue opalescence of its water and conducted some experiments with the aid of nicol prism while on board the ship *S.S. Narkunda* and came to the conclusion that Lord Rayleigh's explanation was not correct. To him it appeared not unlikely that phenomenon owed its origin to the scattering of light by the molecules of sea water.

Immediately after his return to Calcutta in September 1921 he carried out a number of experiments in his laboratory in the Indian Association for the Cultivation of Science with waters collected from different seas. As a result of these experiments he came to the definite conclusion that light molecularly scattered by the oceanic waters played a prominent part in making them look blue. The blue colour of ice in glaciers is also an example of this phenomenon. This was a turning point in his scientific career as the foundation for the discovery of the Raman effect was unconsciously laid during his voyage to Europe. It became evident to Prof. Raman that the subject of molecular light scattering offered unlimited scope for research.

To clarify his own ideas on the subject Raman critically reviewed the results till then obtained in a monograph entitled the *Molecular Diffraction of Light* published by the Calcutta University in 1922. He had clearly indicated in his monograph that there might be experimental observations in light scattering which might require the use of Einstein's photon concept in place of the classical wave theory. As he was convinced that the study of light scattering might carry one into the deepest problems of physics and chemistry, this subject became the main theme of experimental and theoretical activities at the Indian Association by Prof. Raman and his brilliant students.

During the next six years, they established the various laws of molecular scattering of light in diverse media with particular reference to the structure of molecules, the state of matter, pressure and temperature and the phase transition at the critical temperature. Fifty six original

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research papers were published from Raman's laboratory. During the course of these investigations a certain puzzling new phenomenon came to light as early as in 1923 which was pursued systematically to its logical conclusion by Prof. Raman. I shall give below a short history of these developments.

In 1923, K.R. Ramanathan, the oldest and most distinguished of Raman's students discovered that associated with Rayleigh-Einstein type of molecular scattering, there was another and still feebler type of secondary radiation which he designated as "Weak fluorescence" in chemically purified water, ether, methyl and ethyl alcohols, which could not be attributed to any fluorescent impurity. He employed a system of complementary filters and sunlight as a source of radiation. In 1925, K.S. Krishnan, another of Raman's distinguished students, observed the same phenomenon in 65 carefully purified liquids. He also made a crucial observation that the new radiation was partially polarised thus distinguished it from ordinary fluorescence. Towards the end of 1927 Raman himself observed the new phenomenon in optical glasses and in ice.

In January 1928, S. Venkateswaran, a chemist and a Government of India employee working in Raman's laboratory as a part time student outside office hours, made a highly interesting observation that the colour of sunlight (filtered through Corning Glass G 586) scattered by pure dry glycerine was a brilliant green instead of the usual blue and was strongly polarised. The phenomenon appeared to be similar to that observed by K.R. Ramanathan but of much greater intensity, and therefore, more easily studied. The discovery of Compton Effect in 1923 had made familiar the idea that the wavelength of radiation could be degraded in the process of scattering. Raman finally decided to clinch the issue and asked K.S. Krishnan who had been doing excellent theoretical work on mechanical, electrical and magnetic birefringence, to take up the experimental work on the anomalous scattering in liquids and vapours in collaboration with him on a war footing. What followed afterwards is contained in the diary which K.S. Krishnan kept at that time. It gives us an idea of the intense excitement and tireless energy with which the research was pursued and brought to fusion on 28th February 1928. I give below extracts from Krishnan's diary from 5th to 28th February 1928.

5th February, 1928

For the last 3 or 4 days, I have been devoting all my time to "fluorescence". The subject promises to open out a wide field for research, since at present, there is no theory of fluorescence which could explain even the outstanding facts.

Studied anthracene vapour. It exhibits strong fluorescence which does not show any polarisation, when viewed through a double image prism. Prof. has been working with me all the time.

Recently, Professor has also been working with Mr. Venkateswaran on the fluorescence exhibited by many aromatic liquids in the near ultra-violet region present in sunlight and the fluorescence of some of the liquids was found to be strongly polarised. However, in view of the fact that the fluorescence of anthracene vapour does not show any polarisation, Professor has asked me to verify again the observations on the polarisation of liquids.

7th February, Tuesday

Tried to verify the polarisation of the fluorescence exhibited by some of the aromatic liquids in the near ultraviolet region. Incidentally, discovered that all pure liquids show a fairly intense fluorescence also in the visible region, and what is much more interesting, all of them are strongly polarised: the aromatics. In fact, the polarisation being the greater for the aliphatics than for the aromatics. In fact, the polarisation of the fluorescent light seems in general to run parallel with the polarisation of the scattered light, i.e., the polarisation of the fluorescent light is greater the smaller the optical anisotropy of the molecule.

When I told Professor about these results, he would not believe that all liquids can show polarised fluorescence and that in the visible region. When he came in up to the room, I had a bulb of pentane in the tank, a blue-violet filter in the path of incident light, and when he observed the track with a combination of green and yellow filters he remarked "you do not mean to suggest, Krishnan, that all that is fluorescence". However, when he transferred the green yellow combination also to the path of the incident light he could not detect a trace of the track. He was very much excited and repeated several times 'it was an amazing result'. One after another, the whole series of liquids were examined and every one of them showed the phenomenon without exception. He wondered how we missed discovering all that five years ago.

In the afternoon took some measurements on the polarisation of fluorescence.

After meals at night, Venkateswaran and myself were chatting together in our room when Professor suddenly came to house (at about 9.00 P.M.) and called for me. When we went down we found he was much excited and has come to tell me that what we had observed that morning must be the Kramers-Heisenberg effect we had been looking for all these days. We therefore agreed to call the effect modified scattering. We were talking in front of our house for more than a quarter of an hour when he repeatedly emphasised the exciting nature of the discovery.

8th February, Wednesday.

Took some preliminary measurements of the polarisation of the modified scattering by some typical liquids.

9th February, Thursday.

Set up this morning the long telescope and made preliminary arrangements for observing the effect with vapours. Before the arrangements were completed, Professor left for the college for his lecture.

Extracts from Prof. Raman's address to the South Indian Association in Bangalore on 16th March, 1928

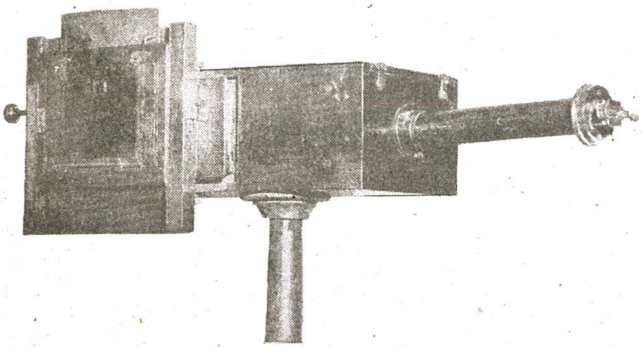
THIS encouraged me to take up observations with a monochromatic source of light. A quartz mercury lamp with a filter which completely cuts out all the visible lines of longer wavelengths than the indigo line 4358 A.U. was found to be very effective. When the light from such a lamp was passed through the bulb containing a dust free liquid, and the spectrum of the scattered light was observed through a direct vision spectroscope, it was found to exhibit two or more sharp bright lines in the blue and green regions of the spectrum. These lines are not present in the spectrum of the incident light or in the unfiltered light of the mercury arc, and are manufactured by the molecules of the liquid.

There has, as yet, not been sufficient time for photographing the spectra from a large number of liquids, or even for measuring the photographs already obtained, visual observations have however been made with a large number of liquids. There is an astonishing similarity between the spectra obtained with different liquids. When only the 4358 line was used, most liquids showed in the spectrum of the scattered light a bright line in the blue-green region of the spectrum (about 5000 A.U.) whose position was practically the same for chemically similar liquids such as pentane, hexane and octane for instance.* There was however recognizable difference in the position of the modified line when other liquids such as benzene or water were used. When the 4047 line of the mercury arc was let in by removing the quinine sulphate solution, a second modified line in the blue region of the spectrum was seen with most liquids....

We are obviously only on the fringe of a fascinating new region of experimental research which promises to throw light on diverse problems relating to radiation and wave-theory, X-ray optics, atomic and molecular spectra, fluorescence and scattering, thermodynamics and chemistry. It all remains to be worked out.

I have to add in conclusion that I owe much to the valuable co-operation in this research of Mr. K.S. Krishnan and the assistance of Mr. S.Venkateswaran and other workers in my laboratory.

The line spectrum of the new radiation was first seen on 28th February, 1928. The observation was given publicity the following day.



First model of Raman spectrometer designed by C.V. Raman

* This statement we now know to be erroneous. Prof. Raman and K.S. Krishnan photographed the scattered spectrum using a Hilger Baby Quartz Spectrograph which had only very poor dispersion in the visible region and hence small differences in frequency shifts of Raman lines due to the same chemical bond in different organic substances could not be detected and hence the statement referred to above.

In the afternoon, tried ether vapour and it was surprising that the modified radiation was very conspicuous. Tried a number of others in quick succession without however the same success.

When Professor came from the College at about three, I announced to him the result, and there was still enough sunlight all the time. He said that it was a first rate discovery, that he was feeling miserable during the lecture because he had to leave the experiment and that, however, he was fully confident that I would not let the grass grow under my feet till I discovered the Phenomenon in gases. He asked me to "call everybody in the place to see the 'Effect' and immediately arranged in a most dramatic manner, with the mechanics to make arrangements for examining the vapours at high temperatures.

Evening was busy, and when Professor returned after his walk he asked me to take up the problem of the experimental evidence for the spinning electron after this work was over.

10th February to 15th February

Studied a number of vapours, though a number of them showed the effect, nothing definite could be said regarding the polarisation of the modified scattering.

16th February, Thursday.

Studied today pentane vapour at high temperature and it showed a conspicuous polarisation in the modified scattering. We sent a note today to *Nature* on the subject under the title "A new Type of Secondary Radiation".

17th February, Friday.

Professor confirmed the polarisation of fluorescence in pentane vapour. I am having some trouble with my left eye. Professor has promised to make all observat. is himself for some time to come.

18th February to 26th February.

Studied a number of other vapours.

27th February, Monday

Religious Ceremony in the house. Did not go to the Association.

28th February, Tuesday.

Went to the Association only in the afternoon. Professor was there and we proceeded to examine the influence of the wavelength of the incident light on the phenomenon. Used the usual blue-violet filter coupled with a uranium glass, the range of wavelengths transmitted by the combination being much narrower than that transmitted by the blue-violet filter alone. On examining the track with a direct vision spectroscope we found to our great surprise the modified scattering was separated from the scattering corresponding to the incident light by a dark region.

(S. Venkateswaran was also with them at that time.)

Further work carried out on that day was described by Raman himself in his address under the title "A New Radiation" on 16 March 1928, while inaugurating the South Indian Science Association in Bangalore. The full text of the lecture was subsequently published as a special number of the *Indian Journal of Physics* on 31 March 1928.

The apparatus used by Raman for the discovery consisted of a mirror for deflecting sunlight, a condensing lens, a pair of complementary glass filters, a flask containing benzene, and a pocket spectroscope

The article gave detailed description of all the principal features of the new effect with a photograph of the scattered spectrum of benzene. In this paper Raman had stressed the universality of the phenomenon and its usefulness for obtaining information about molecular structure. 2000 reprints of the same paper were posted to physicists and scientific institutions all over the world. This ultra-quick printing and immediate distribution of reprints so quickly fully ensured Prof. Raman's priority of discovery, for, once announced, many other scientists began to work on it. It was immediately hailed by leading scientists of the world as a very important discovery of a useful method for elucidation of molecular structure.

Thus we see that the discovery of the new type of radiation called universally the Raman effect was the culmination of a line of research initiated by him in 1919 and intensively pursued by him and his collaborators at the Indian Association for the Cultivation of Science during the years 1921 to 1928, that he could not reconcile himself to the explanations of "feeble fluorescence" for the anomalous results; an intuitive perception of a genius that it was something new and his persistence in trying to solve the anomaly resulted in this great discovery of fundamental importance to Modern Physics.

Immediately following the announcement of the discovery, Raman and Krishnan carried out systematic investigations on the new effect and established all the important characteristics of the new effect and its full significance. Their results were published jointly in the *Indian Journal of Physics* and the *Proceedings of the Royal Society*.

Reactions of the scientific community

The importance of Raman's discovery was immediately recognised by Pringsheim in Germany and by R.W. Wood of USA and their subsequent work confirmed Raman's findings. Pringsheim compared Raman scattering with Tyndall scattering, Rayleigh scattering, fluorescence and Compton effect and concluded that Raman scattering was an entirely new phenomenon which enabled one to record the characteristic molecular frequencies more conveniently in the visible region. He called the effect "Der Raman Effect" and the spectrum of new lines as Raman spectrum. He concluded his paper with the following words:—

"With the increasing number of new researchers coming into this field, new problems will show up in increasing proportions. One can state without doubt that through his discovery Raman has opened up a big and completely new field of spectroscopy".

This prophesy has been amply justified by the discovery of new Raman types of excitations using lasers as the source of radiation.

Prof. R.W. Wood sent the following cable to *Nature*. "Prof. Raman's brilliant and surprising discovery that transparent substances illuminated by very intense monochromatic light scatter radiations of modified wavelength and that the frequencey difference between the emitted radiation and one exciting the medium is identical with the frequency of the infrared absorption bands, opens up a wholly new field of study of molecular structure. I have verified this discovery in every particular with improved apparatus which makes it possible to photograph strongest lines in a few minutes.... "It appears to me that this very beautiful discovery which resulted from Prof. Raman's long and patient study of the phenomenon of light scattering is one of the most convincing proofs of the quantum theory of light which we have at the present time".

Dr. L.A. Ramdas who was an old student of Prof. Raman and had taken his Ph.D., degree on the scattering of light on liquid surfaces was working in the Meteorological Department at Karachi at the time of the discovery. He took leave and returned to Calcutta to work on the Raman effect in gases. He was the first to photograph The Raman spectrum successfully with ether vapour. The Raman lines appeared in the same position as in the liquid. He was the first to christen the new phenomenon as "Raman Effect". Based on his work with gases, Ramdas came to the conclusion that Raman effect was probably responsible for the special spectral character and polarisation of the zodiacal light.

Immediately after the discovery of Compton effect in 1923, A. Smekal, an Austrian physicist was working out theoretically the interaction of radiation with matter quantum mechanically and came to the conclusion that the energy of the incident radiation might be lowered by an amount equal to the energy difference between the normal and excited energy states of the system. He published his results as a note in *Naturwissenschaften* in 1923. The developments that followed the above publication have been summarized by Placzek in his book *Rayleigh-Streuung und Raman Effekt.*

"Encouraged by Smekal's note, Kramers and Heisenberg showed how the origin of this modified scattered radiation can be understood classically, and after this they were able to derive their quantum mechanical scattering formula by combining the correspondence principle with the classical theory of the electromagnetic radiation. The importance of this investigation by far exceeds this field of problems: It was the origin of modern quantum mechanics".

In 1927, Dirac developed a quantum mechanical scattering theory from which he derived the formula for the intensity of scattered radiation. Thus the theory of Raman effect was firmly established one full year ahead of its experimental discovery. These publications were highly mathematical and no experimental physicist working on light scattering took any notice of them. It was only after Raman's independent discovery that the full implications of the dispersion theory came to be recognized. Max Born in a note entitled "Theory of Raman effect" stated that Raman's discovery had been predicted by quantum mechanics in all its entirety and could be thought of as a proof for the same.

The appratus used by Raman for the discovery consisted of a mirror for deflecing sunlight, a condensing lens, a pair of complementary glass filters, a flask containing benzene and a pocket spectroscope, the total cost not exceeding Rs. 200/-. It could also be inferred from the above account that the discovery was not the result of an accident, but was the culmination of seven years of systematic and sustained work carried out with devotion by Raman and his band of students. The achievement is all the more creditable when one considers the fact that scienfitic research in India was not liberally supported by the Government of the day as it is today.

The history of the discovery of the Raman effect teaches us many lessons. Firstly, hardly any discovery appears immediately in its clear and final form. The truth is approached step by step. Secondly, it is the calibre of the scientist that matters for scientific progress and not the provision of very costly equipment. Thirdly, sustained effort in a single field only will ultimately lead to success and fame. Fourthly, great discoveries always appear incredibly simple, but only after some devoted person has made the discovery.

Professor Raman was awarded the Hughes Medal of the Royal Society of England in 1930 and the Nobel Prize for Physics in the same year for his discovery. While presenting the Hughes Medal, Lord Rutherford of Nelson, then President of the Royal Society, made the following observation:

"Sir Venkata Raman is one of the leading authorities on optics, in particular on the phenomenon of the scattering of light. In this connection, about three years ago he discovered that the light's colour could be changed by scattering. This had been predicted theoretically some time before, but inspite of search the change has not been found. The "Raman Effect" must rank among the best three or four discoveries in experimental physics of the last decade. It has proved, and will prove, an instrument of great power in the study of the theory of solids. In addition to important contributions in many fields of knowledge, he has developed an active School of research in physical science in the University of Calcutta".

The Chairman of the Nobel Committee for Physics while presenting the medal to Prof. Raman concluded his presentation speech with the following words:

"Thus the Raman effect has already yielded important results concerning the chemical constitution of substances; and it is to foresee that the extremely valuable tool that the Raman effect has placed in our hands will in the immediate future bring with it a deepening of our knowledge of the structure of matter.

"Sir Venkata Raman, the Royal Academy of Sciences has awarded you the Nobel Prize in Physics for your eminent researches on the diffusion of light and for your discovery of the effect that bears your name. The Raman effect has opened new routes to our knowledge of the structure of matter and has already given most important results.

"I now ask you to receive the prize from the hands of His Majesty".

Russian works

During the same period, Landsberg, who was working in the Institute for Theoretical Physics in Moscow under the guidance of Mandelstam, was carrying out investigations on the scattering of light in solid bodies using a 'Point-O-lite' lamp as a continuous source of illumination. He f nd that the intensity of scattering in crystalline quartz is directly proportional to absolute temperature. He communicated two papers on the subject to *Zeitschrift fur Physik* on 10 May and 1 August 1927. They were published on 12 July and 18 October 1927 respectively. While looking for a change of wavelength in scattering on the basis of Debye's theory of specific heat. Landsberg and Mandelstam reported on 6 May 1928 the independent observation of a modified line in the scattered spectrum of a crystal of quartz when excited by the radiations from a quartz mercury arc. Their letter, 'Zhuchrift' was published in *Naturwissenschaften* on 13 July. A similar communication was also sent to the *Russian Journal of Physical Chemistry* on 10 May. The frequency shifts arising from Debye's elastic waves should be much less than a wave number and could not therefore be resolved by an ordinary spectrograph. The observed frequency shift was of an entirely different order of magnitude and they explained its appearance in the following words:

'When light is scattered by quartz, some of the infra-red frequencies of the crystal can be excited at the expense of the energy of the scattered light and the scattered quanta; hence their frequencies decrease by the amount of the respective infra-red quanta'.

Although their letter was communicated well over two months after the publication of Raman's detailed paper a reprint of which should have been sent to them also, there is no reference to this (Raman's) paper. They did, however, refer to Raman's two notes in *Nature*, with the following remark; "Whether and how far the phenomenon observed by us is related to that described by Raman in brief, we are not able to decide at the moment as his description is too terse."

No other discovery in science has shown such a dramatic rejuvenation and renaissance as Raman effect. Nearly 47,000 original papers had been published up to the end of 1987 starting from 1928

After attending the Sixth Congress of Russian Physicists on August 5th, 1928, Prof. C.G. Darwin gave an interesting account in *Nature* of the work of Prof. Mandelstam and Landsberg who claimed that "They had independently discovered Raman's Phenomenon, the scattering of light with changed frequency". In reply to the above Prof. C.V. Raman made the following observations in a note to *Nature*.

"It appears desirable in this connection to point out that the existence in the light scattered by liquids and solids of radiations of modified wavelength was established so early as 1923 by investigations made at Calcutta. Dr. K.R. Ramanathan showed (*Proc. Ind. Assn. Sc.*, Vol. 8, P. 190; 1923) that when violet rays pass through carefully purified water or alcohol there is an appreciable quantity of radiations in the green region of the spectrum present in the scattered light. Further studies of the effect in other substances are described by Mr. K.S. Krishnan in the *Phil. Mag.* for October 1925 and by me in *Jour. Opt. Soc. Am.* for October 1927. These investigations were of course well known to workers in this field.

"In a lecture delivered at Bangalore on Mar. 16, 1928 and published on Mar. 31, investigations were described showing firstly, the universality of the effect, namely, that it is observed in the widest variety of physical conditions (gas, vapour, liquid, crystal, or amorphous solid) and in the largest possible variety of chemical individuals (more than eighty different substances); secondly, that the modified radiation is strongly polarised and is thus a true scattering effect; thirdly, that each incident radiation produces a different set of modified scattered radiations; fourthly, that the scattered radiations consist in many cases of fairly sharp lines in displaced positions; and fifthly, that the frequency differences between the incident and scattered radiations represent the absorption frequencies of the medium. These observations established and emphasised the fundamental character of the phenomenon in a manner which any isolated observation with a single substance would have quite failed to achieve. The Russian physicists to whose observation on the effect in quartz Prof. Darwin refers, made their first communication on the subject after the publication of the notes in *Nature* of Mar. 31 and April 21, 1928. Their paper appeared in print after sixteen other printed papers on the effect by various authors, had appeared in recognised scientific periodicals."

It is interesting to note that of the twelve papers published by Professor Raman on the new effect, eight were in collaboration with K.S. Krishnan who himself published four more papers only dealing with some important aspects of the Raman spectra of crystals and on temperature effect and on Raman effect in X-ray scattering. The most crucial communication entitled "A change of wavelength in light scattering" was published by Raman himself. It is also significant to note that after leaving the Indian Association for the Cultivation of Science to take up the post of Reader in Physics in Dacca University in 1929 and later joining the Association as Mahendra Lal Professor of Physics in 1933 when Professor Raman left for Bangalore, Professor K.S. Krishnan completely abstained from carrying on any work in the field of Raman spectroscopy by himself or by any of his students. From the point of view of the progress of Indian Raman spectroscopy this should be considered as a loss.

The account of the early history of the effect would not be complete without a reference to an important theoretical contribution made by G. Placzek in 1934. In this article Placzek had developed the bond-polarizability theory of Raman scattering. Although the quantum mechanical theory of scattering was proposed a year before Raman's discovery, it remained a curiosity for a long time as the numerical calculation of the intensity of scattering required the knowledge of all eigenstates of the scattering systems, viz., a molecule or a crystal, in order to calculate the first and second derivatives of the molecular polarizability. Quantum chemical methods are not so far developed as to make the calculation of such derivatives easily possible. It is in this context that Plackzek's semi-classical bond-polarizability theory became handy for physicists and chemists as a practical proposition.

In order to calculate Raman intensity, Placzek considered the nuclei of the molecules as being fixed. He concluded that the polarizability was a function only of the position of the nuclei, and not of their velocity when the following conditions were satisfied. Firstly, the frequency of the exciting light must be far away from all the electronic transition frequencies. This conclusion excludes the so-called resonance Raman effect which has come into prominence recently. Secondly, the exciting frequency should be large compared to the nuclear frequency of the electronic ground state. Thirdly, the electronic ground state should not be essentially degenerate.

With these assumptions Placzek derived an expression for the intensity of Raman scattering in terms of the parameters related to the electronic ground state only. The influence of all other states is contained in a term called the polarizability tensor and its derivatives with respect to nuclear coordinates. This tensor is of rank two and is symmetric except for special cases. The main advantage of the polarizability theory was that group theoretical methods could be applied for deriving the selection rules for Raman effect from the symmetry behaviour of the polarizability. On the basis of Placzek's theory all the details of molecular Raman effect could be quantitatively accounted for. His theory is even now finding applications in the derivation of formulae for the hyper, stimulated, inverse, and electronic Raman effect and other nonlinear phenomena which have come to prominence with the development of high power lasers and tunable dye lasers.

Epilogue

Immediately following the discovery, the Raman effect began to be used by physicists and chemists alike for solving a wide range of problems, and many important contributions to our knowledge in physics and chemistry were reported in a short span of five years. This upsurge can be attributed to the fact that the data obtained from Raman spectra depend essentially on the structure of the molecules of the scattering substance. It is thus possible to obtain information of great value to physicists and more so to chemists by a single observation of the Raman spectrum instead of a whole series of difficult experiments in the IR region. More than 2500 chemical compounds were studied by the Raman effect during the first decade following the discovery.

The development of gas lasers in the early sixties and the first successful use of laser radiation as exciter for Raman spectroscopy by S.P.S. Porto and D.L. Wood in 1962 completely revolutionised the practice of Raman spectroscopy. The modern laser radiation is completely monochromatic, completely polarised, perfectly coherent, easily tunable and controllable, of exceptionally high intensity and on negligible divergence. Due to the very small cross-sectional area of a laser beam and the high power densities of light that can be made available at the focal point of the laser radiation as a consequence of its coherence, a new vista of micro-Raman spectroscopic analysis has opened up enabling one to extend Raman effect studies to biological specimens, either by themselves or in solution.

The most startling developments during the laser era were the discoveries of new type of Raman excitations envisaged in the quantum theory of dispersion of Smekal, but not realised in the pre-laser era because of the limitations of the experimental techniques used. They are Raman scattering by polaritons, magnons, plasmons, plasmaritons, Landau levels, excitons soft modes connected with phase transition, and nonlinear processes such as stimulated Raman scattering (SRS), inverse Raman scattering (IRS), hyper Raman scattering (HRS), coherent Raman gain scattering (CRGS), coherent anti-stokes Raman scattering (CARS), coherent Stokes Raman scattering (CSRS), Raman induced Kerr effect scattering (RIKES), surface enhanced Raman scattering (SERS), resonance Raman scattering (RRS), and time resolved Raman scattering (TRRS). No other discovery in science has shown such a dramatic rejuvenation and renaissance as Raman effect. Nearly 47,000 original papers have been published up to the end of 1987 starting from 1928. More than 2,750 papers are published on Raman spectroscopy every year now. A complete Bibliography has been prepared by the author and is expected to be published in due course. Nobody including the discoverer would have ever dreamt about this wide vista of activity of Raman spectroscopy as we witness today.

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