NOVEMBER—DECEMBER 1988

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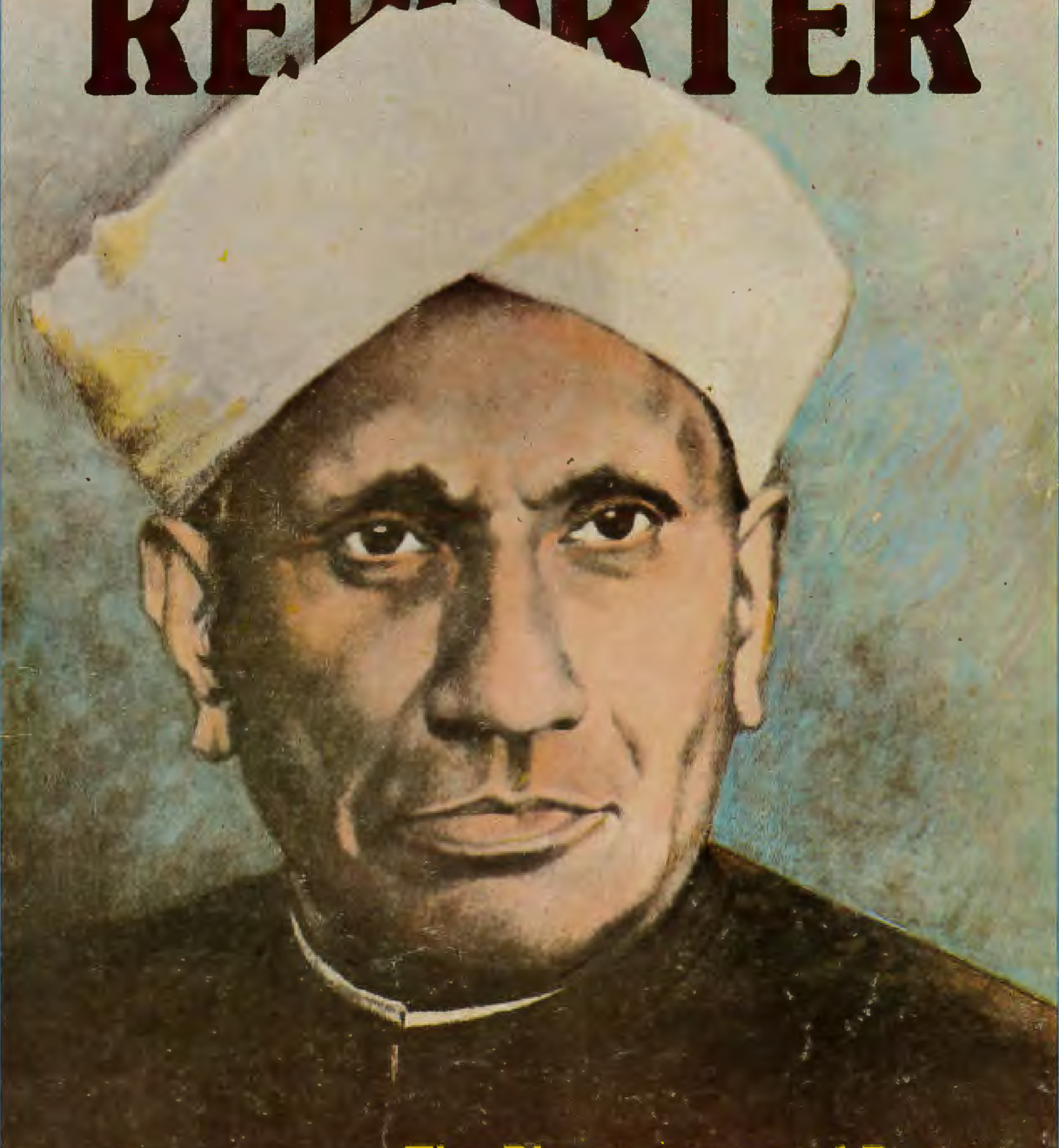

## The Phenomenon of Raman

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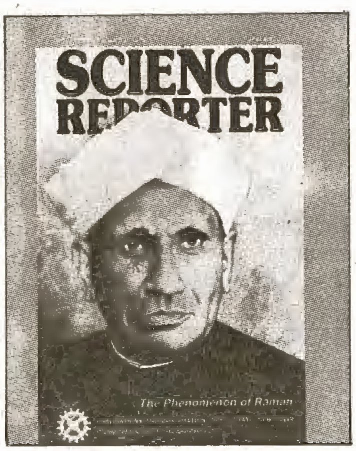


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# SCIENCE REPORTER

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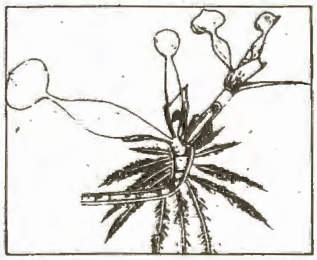

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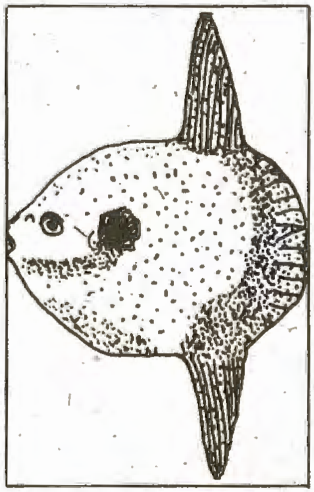

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# THE PHENOMENON OF RAMAN

G.H.KESWANI

RAMAN was one of the greatest experimental physicists of the century, a physicist of light, sound and crystals.

Let me quote Lord Rutherford. While presenting Raman the Hughes Medal of Royal Society of London in 1929, even before Raman got the Nobel prize, Rutherford said, "The Raman Effect must rank among the best three or four discoveries in experimental physics of the last decade". The winners of the Nobel prize for work in experimental physics in the preceding decade were: Millikan (charge and mass of the electron and the photoelectric effect), Siegbahn (X-ray spectroscopy), Frank and Hertz (collisions of electrons with atoms), Perrin (Brownian motion), Compton (for the effect known by his name), C.T.R. Wilson (cloud chamber for making visible the track of very small charged particles) and Richardson (thermionic emission of electrons). So, it was quite a thing for the Raman effect to be among the best three or four discoveries.

Indeed, such is the fecundity of the Raman effect that Raman (scattering) figures more often in current experimental research papers than the names mentioned above including Rutherford's, all put together!

Raman was not only an adept experimentalist with light, in the tradition of Young, Fresnel and Rayleigh, but he also fostered an active school of research in our poor country for almost half a century in the grand manner of German spectroscopists of the nineteenth century—Fraunhofer, Bunsen and Kirchoff. His own work extended to some 360 papers and four books. Among Indians, only the chemist, Prof. Seshadri, F.R.S., excelled him in the number of publications, so far as I know. Raman initiated into research nearly 150 students. He was also a charming speaker, holding his listeners spell-bound.

It is difficult to explain his enormous intellectual development. He was taught by himself alone. He dared to publish his first paper in the year 1906 in the *Philosophical Magazine* of London, then the foremost journal of physics, at the age of 18 years, on diffraction patterns due to a rectangular aperture.

Prof. R.L. Jones who had worked in the Cavendish Laboratory, was Raman's teacher in physics at the Madras University, but Raman recollected : "Professor Jones believed in letting those who were capable of looking after themselves to do so.... during the whole of my two years' work for the M.A. degree, I remember attending only one lecture, and that was on the Fabry-Perot interferometer by Prof. Jones himself." Prof. Max Born, a leading physicist of Quantum Mechanics and a Nobel prize winner, talked of the "European intensity" of Raman. Raman himself recalled at the age of 75 years, "I.... do not recollect any time during this long period when I took my mind off from my scientific interests".

Raman was, therefore, a phenomenon, almost in the same class as Ramanujan. Both were completely home-made and self-educated and produced work which will be remembered for centuries.

So, after Raman got the Nobel prize in physics in the year 1930, almost every thinking Indian felt, "We can do it". This spirit must be regenerated, particularly among our scientists.

**Raman, the aesthete**

Raman loved colour, beauty, form and rhythm in nature He collected thousands of specimens of butterflies. He purchased after personal inspection, hundreds of diamonds of different forms and fire for his studies. He was so much bewitched by the physical properties of the diamond, that at one time every researcher in his laboratories was working on the physics of this simplest of crystal structures—its properties of absorption, birefringence, Faraday effect, fluorescence, luminescence, magnetic susceptibility, photoconductivity, specific heat, ultraviolet transparency, etc. But, also, no great secrets of nature were thus revealed, although Raman believed that diamond had "characteristic properties of the solid state in a superlative degree".

He wrote extensively on the colours of foliage and flowers, and of gemstones describing the physics of it all, in words which conjure up the colours and lights of Turner's paintings. He gave a theory of the blue of the sea, correcting Lord Rayleigh's conjecture. This was the starting point and inspiration of his main work, on the scattering of light, as Raman told us in his Nobel Lecture in Stockholm on 11 December, 1930.

Incidentally, he regarded Rayleigh as his "teacher". Works of Rayleigh signed by Raman are, I suppose, still kept in the library of the Raman Institute at Bangalore. (I saw them there about ten years ago.)

He made a scientific study of the drums and the violin. His interests and papers in this field, published in *Nature* and the *Philosophical Magazine* of England went so deep that

Mr. Keswani is a Jawaharlal Nehru Fellow and biographer of C.V. Raman. He has a deep interest in physics, applications of mathematics to problems of life, and history and philosophy of science. Address : B6/17, Safdarjung Enclave, New Delhi-110029.

he was invited by the editor of the prestigious German *Handbuch der Physik* in 1927 to write an article for the *Handbuch* on musical instruments. It was a singular honour, a salutation to his experimental work in this field.

**Matter, light and their interaction**

To understand Raman's work one must know something about the structure of matter and the nature of light. The following description should suffice here.

Matter consists of atoms which can also aggregate into molecules, as the basic bricks of the structure of matter. Each atom consists of a nucleus with a positive electric charge in integral multiples of a unit of charge equal to the charge on an electron which however is negative or opposite (a smaller unit of charge has not been experimentally encountered so far, although fractional charges have been postulated in the quark theory of matter). The nucleus is surrounded by one or more electrons which have the same total electrical charge as the nucleus but opposite in sign. The electrons and nuclei of the atoms, constituting a molecule (such as hydrogen and oxygen in a water molecule), interact in a way such that the atom and the molecule hold together. This model or picture of matter, suffices to explain most of chemistry and much of physics.

The state of the electrons in each atom is determined by the energy of the atom and varies by discrete amounts, i.e., in steps, discontinuously, which are characteristic of each atom. Each of these states corresponds to an equilibrium lasting for a period which may be very short or indefinitely long.

The nature of light is still not fully understood. But an approximate verbal description may be attempted. Light is electromagnetic (em) energy in motion, that is, propagated em energy. It is a travelling electrical field, accompanied by a magnetic field. The intensity of each of these fields varies at any point it traverses, in a periodic fashion like a wave. The fields travel through vacuum with the same constant velocity, and do not require a separate carrier. However, the electromagnetic energy which constitutes light can be absorbed, partly or wholly, by matter in which the same energy is trapped within the atom by a process of change in the state of energy of the electrons. (We need not consider the nucleus for the present purpose.) An atom after absorption of electromagnetic energy, may re-emit this energy, wholly or partly, or it may even part with its own energy and emit more than what it absorbs.

The electromagnetic energy is, however, absorbed or emitted by matter in packets or quanta, not continuously like a flowing stream. Each packet is characterized by just one parameter and that is the frequency of oscillations, $\upsilon$, of the electromagnetic energy constituting it. (We shall mention later, the spin or the state of polarization of light). The energy of each packet or photon is then $h\upsilon$, where $h$ is a constant (of action, of dimensions energy x time), first postulated in the year 1900 by Max Planck of Germany.

Now consider a highly purified transparent material through which a beam of light of one frequency or colour (monochromatic) is made to pass. Most of the light will pass through but a small amount of it will be scattered in various directions by the atoms and molecules lying in the path of the beam. Lord Rayleigh had studied this phenomenon of scattering in the last century and found that for many liquid scatterers about one-thousandth part of the incident light energy is scattered, and this light has the same wave-length as the incident radiation. (However, the amount of energy scattered varies with the wave-length of the incident light.)

A German physicist, E. Lommel, had shown in 1878 from his theory of scattering, that the scattered light should contain, in addition, some light which combined the frequency of the incident light with the frequency of internal oscillations of the scattering medium but his work received little notice. Another German physicist, A. Smekal in 1923, and H.A. Kramers and W. Heisenberg in 1925 also theoretically predicted that the scattered light would contain other frequencies besides the frequency of the incident radiation and that the changes in the frequencies will be characteristic of the substance of the scatterer. Dirac had theoretically come to the same conclusion in 1927. The resultant frequency was predicted to be the sum or difference of the two frequencies, one external and the other internal. Raman was aware of the work of Kramers and Heisenberg. So were others.

**Raman was not only an adept experimentalist with light, in the tradition of Young, Fresnel and Rayleigh, but he also fostered an active school of research in our poor country for almost half a century in the grand manner of German spectroscopists of the nineteenth century**

A search was made for these "combination frequencies" by many but without success. In the year 1923, P.A. Ross of U.S.A., using an interferometer of resolving power equal to 360,000, looked for them but failed to detect any shift in the frequencies.

The theory of the Raman effect may now be stated briefly. If $h\upsilon$ is the energy of the quantum of light falling on a molecule, it may interact with an electron of the molecule in the lowest or ground energy state or a higher stage. By a well known formula of Boltzmann, the number of electrons in a lower energy state is more than the electrons in a higher energy state. So an interaction with the ground-state electrons is the most likely, when the electron will have its energy raised by level $h\upsilon$. This disturbed state lasts for a short period of time and there is a high probability that the photon will be ejected with the same frequency ($\upsilon$) and energy (h$\nu$) by the Rayleigh scattering process. However, if there exists an in-between permitted energy level of the electron h$\nu'$ ($\nu'$ less than $\nu$), the electron may release energy equal to h($\nu$-$\nu'$), not whole of h$\nu$, absorbing energy h$\nu'$ itself and remaining at level h$\nu'$ above the ground-energy state.

If the incident photon (h$\nu$) interacts with an electron in energy state h$\nu'$ above the ground state, it will raise the electron to level h($\nu$+$\nu'$) and after remaining in this disturbed state for a very short time, it may fall back into the ground state, emitting a photon of energy h($\nu$+$\nu'$). But because the number of electrons at higher energy levels is smaller, the probablity of a scattered photon of higher frequency ($\nu$+$\nu'$) is low.

Naturally, the total energy of all photons of Raman scattering at frequencies ($\nu$–$\nu'$) and ($\nu$+$\nu'$) will be less than the total energy of Rayleigh scattering at frequency $\nu$. And within the Raman scattering, the emissions at the lower frequency ($\nu$–$\nu'$) will have more total energy than those at the higher frequency ($\nu$+$\nu'$).

The spectral lines of frequency ($\nu$–$\nu'$) are called Stokes lines and those of frequency ($\nu$+$\nu'$), anti-Stokes lines. In a laser more electrons can be put in higher energy states within the molecule or the atom, by "pumping" in energy. When this stored energy is released, the laser action takes place in which the light energy emitted is coherent (the waves being in one phase), monochromatic (having almost the same frequency), highly directed (parallel propagation), and concentrated (in a small cross-sectional area with high energy per unit of area). Research with the Raman effect has gone through a renaissance with the use of laser-light.

A word about the polarization characteristic of light or electro-magnetic waves. The electric and magnetic components of these waves at any point lie in a plane at right angles to the direction of propagation or the light-ray path. The electric and magnetic fields themselves stand at right angles to each other in this plane. The direction of the magnetic field of force and the direction of the propagation, then define the plane of polarization of light. The plane of polarization of light from most sources changes irregularly; the light is then said to be unpolarized. As we shall see Raman-scattered light was found to be regular or polarized and this characteristic led Krishnan and Raman to the discovery. We need not go into the details of how the degree of polarization is determined.

**Two Indians do it**

Let me recall at the outset that the intensities of these combination frequencies are much feebler than even the Rayleigh scattered light. For example, in the case of liquid carbon tetrachloride it is 1/400 and for gaseous oxygen about 1/3300 of the Rayleigh scattering intensity.

The scattering of light by transparent media had been the subject of study in Raman's laboratory since the year 1921. In this year, he himself wrote two papers in *Nature* on the colour of the sea and the molecular scattering of light in liquids and solids. K.R. Ramanathan, then working with Raman, discovered in 1923 that the light scattered even by purified liquids show, what he called, a "weak fluorescence". Similar results were obtained by K.S. Krishnan while experimenting on 60 liquids in 1924. But this research was abandoned in 1925, to be resumed by Krishnan in January 1928, under the guidance of Raman. Soon, the discovery of what is now known as the Raman effect, was made by Krishnan, who kept a diary, related extracts from which are reproduced below :

*7th February (1928), Tuesday*

Tried to verify the polarization of 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

Dr. K.S. Krishnan

visible region, and what is much more interesting, all of them are strongly polarized...

When I told Professor (i.e., Raman) about the results, he would not believe that all liquids can show polarized fluorescence and that too in the visible region. When he came in up to the room, I had a bulb of pentane in the tank, and 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 that it was an amazing result. One after another, the whole series of liquids were examined and each 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 the house (at about 9 P.M.) and called for me. When we went down, we found he was much excited and had 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 emphasized the exciting nature of the discovery.

*9th February, Thursday*

When the Professor came from the college at about three, I announced to him the result (for gases), and there was still enough sunlight at 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...

Evening was busy and when Professor returned after his walk, he told me that I ought to tackle big problems like that and asked me to take up the problem of the experimental evidence for the spinning electron after this work (was over).

*17 February, Friday*

Professor confirmed the polarization of fluorescence in pentane vapour. I am having some trouble with my left eye. Professor has promised to make all observations himself for sometime to come.

Apparently, while Raman was checking and confirming the results obtained by Krishnan, a joint letter was drafted and sent for publication to *Nature* on 16 Feb., 1928, which was duly published in its issue of 31 March, 1928 (Vol. 121, p. 501).

On 28 February 1928, Raman announced the discovery to the press and the public.

On 16 March, 1928, Raman delivered an address to the newly formed South Indian Science Association at Bangalore with the title *A New Radiation*. Immediately on return to Calcutta, Raman had this address printed overnight at the Calcutta University Press and reprints of it were posted to thousands of scientists all over the world. I believe that this settled the question of priority of the discovery in favour of Raman. In fact, the Russians, G. Landsberg and L. Mandelstam had made the same discovery (it was later claimed that discovery was made in January 1928) and communicated their finding to the German journal *Naturwissenschaften* on 6 May 1928 (published in the 13 July, 1928 issue, vol. 16, p. 557). The Russians, working on quartz, a solid, had got quantitative results of the change in wave-lengths and a spectrum, which were published with their article. Raman's and Krishnan's work was done on liquids and they had not given any quantitative results in their first letter to *Nature*

**NEW THEORY OF RADIATION**

**PROF. RAMAN'S DISCOVERY**

(ASSOCIATED PRESS OF INDIA.)

CALCUTTA, Feb. 29.

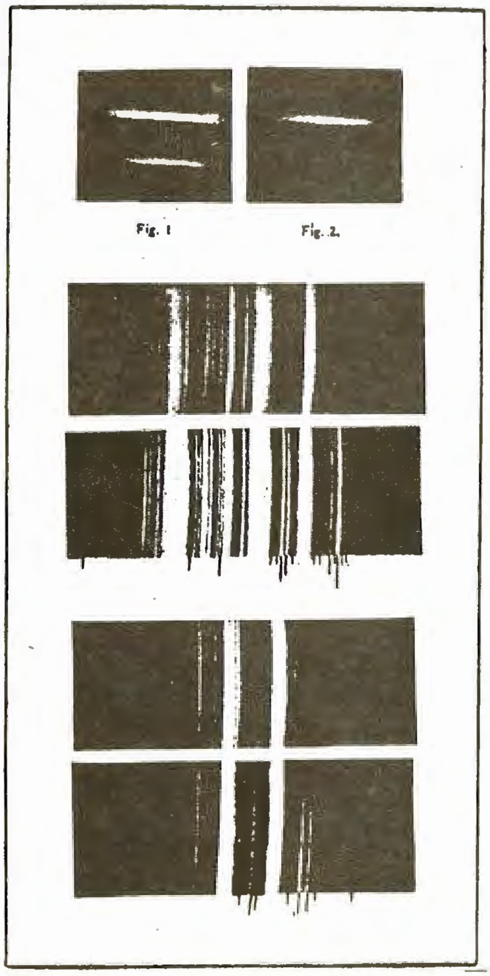
Prof. C. V. Raman, F. R. S., of the Calcutta University, has made a discovery which promises to be of fundamental significance to physics. It will be remembered that Prof. A. H. Compton of the Chicago University was recently awarded the Nobel Prize for his discovery of the remarkable transformation which X-rays undergo when they are scattered by atoms. Shortly after the publication of Prof. Compton's discovery, other experimenters sought to find out whether a similiar transformation occurs also when ordinary light is scattered by matter and reported definitely negative results. Prof. Raman with his research associates took up this question afresh, and his experiments have disclosed a new kind of radiation from atoms excited by light.

The new phenomenon exhibits features even more startling than those discovered by Prof. Compton with X-rays. The principal feature observed is that when matter is excited by light of one colour, the atoms contained in it emit light of two colours, one of which is different from the exciting colour and is lower down the spectrum. The astonishing thing is that the altered colour is ~~quite~~ independent of the nature of the substance used. It changes however with the colour of the exciting radiation, and if the latter gives a sharp line in the spectrum, the second colour also appears as a second sharp line. There is in addition a diffuse radiation spread over a considerable range of the spectrum. He will deliver a lecture demonstrating these phenomena first at Bangalore on the 16th March.

The first Raman spectra (From the paper "A New Radiation") The first newspaper report of the disovery of the Raman Effect (February 29, 1928). It is clear that the observations made with the direct vision spectroscope on 28th could not distinguish the differences in the colour (wavelength) of the new radiation emitted by different liquids. Hence the statement "the altered colour is quite independent of the nature of the substance." The changing of the word "quite" to "approximately" is almost certainly in Prof. Raman's handwriting.

published on 31 March, 1928, although they said that spectroscopic confirmation was available and that modified scattering was demonstrable in the case of high-density gases. Be that as it may, the Russians spoilt their claim, by saying at the end of their article of 6 May 1928, "At the moment it is not possible for us to judge if and to what extent, there exists a relation between the phenomenon observed by us and that for the first time briefly discussed by Raman, because of the brevity of discussion". (In those days the date of receipt of a paper by the journal concerned was not usually published.)

Raman moved on. He wrote another Letter to *Nature*, now in his own name only, on 8 March, 1928, in which he made the following statement : "The preliminary visual observations appear to indicate that the position of the principal modified lines is the same for all substances...." He seemed to believe for some time after the discovery that it was a "new radiation" with a constant shift in frequency, which had been discovered, and that the shift was therefore independent of the material of the scatterer. Indeed, in the report filed by the Associated Press of India, published on 29 February 1928, based on Raman's announcement, the following corroborative line occurs, "The astonishing thing is that the altered colour is quite independent of the nature of the substance used."




The first Raman spectra (From the paper "A New Radiation")

## Luminescence and Raman Scattering

THE discriminating characteristics of the new scattered radiation, in terms of the physical ideas current in those days (1920s) were: a decreased frequency of the scattered radiation (initially only decrease was observed) and the strongly polarized nature of the radiation as observed by Krishnan and Raman. The decrease in frequency was known to occur also in the case of fluorescence but this was ruled out because fluorescent radiation was then known to be not strongly polarized.

It can now be said that light scattering in the Raman (Rayleigh, Compton and Brillouin) interactions, might be distinguished from various luminescent processes (which are legion), including fluorescence, by the period elapsing between the excitation of, and emission by a molecule, compared to the period of one oscillation (reciprocal of frequency, $1/\nu$ in sec), of the incident light. This period is of the order of $10^{-14}$ sec for visible light. The time between excitation and emission has a magnitude of this order, viz. $10^{-14}$ second, for Raman scattering. But in the case of luminescence it is much longer, being usually in the range $10^{-14}$ sec to $10^{-10}$ sec. This is the crucial difference between the two phenomena. Also, Raman excitations are far more universal than luminescence which is markedly exhibited by only some substances.

**G.H.K.**

However, this astonishing statement of Raman's was corrected in a joint letter written by Raman and Krishnan on 22 March 1928, to *Nature* (third in the series) in which it was stated that "it may be assumed that an incident quantum of radiation may be scattered by the molecules of a fluid either as a whole or in part, etc." Incidentally, there is no mention even at this stage, of so-called anti-Stokes lines of reduced wave-length and increased frequency (or energy), as shown by the theory of Smekal (1923), Kramers and Heisenberg (1925) and Dirac (1927), although Raman was aware of the work of Kramers and Heisenberg, at least. Being a fellow of the Royal Society of London, he should have seen Dirac's 1927 article in the proceedings of the Society.

There is no doubt that the observation and measurements of the modified frequency were most difficult. Krishnan and Raman had available only sunlight and filters, and a pocket spectroscope; that is all. The total cost of the equipment was a lordly sum of Rs. 200/-. Even the mercury-vapour lamp—Alladin's lamp as Raman called it—came after the discovery was made.

Nonetheless, the theory of the effect known to Raman, predicted changes in frequency characteristic of the molecular structure of the scatterer and its internal energy levels, which varied from substance to substance. As Einstein put it in a message for the Jubilee celebrations of the Raman effect in 1953, this effect for the first time showed experimentally that a photon undergoes a partial transformation *within* matter. The atoms and molecules leave their individual fingerprints, so to speak, on the interacting photons. That is why Raman effect is, perhaps, the best technique for studying the internal structure of matter (leaving other methods behind after the development of the Laser Raman Spectroscopy).

Raman's statement that the position of the modified spectral lines, after scattering was "the same for all substances", cannot be understood. This is not even approximately true, and if it was, the Raman effect would become magic.

I shall return to the role of Krishnan presently but before I do that, I may mention a meeting I had with Prof. S. Chandrasekhar in Chicago in October, 1980. He wanted to know what I had said in my biography of Raman and I told him, among other things, what I have said above. He then went up to one of his filing cabinets and brought out a sealed envelope. He bid me to open it and read some parts which I did. I think, I can say here, that Prof. Chandrasekhar had himself come to similar views regarding the origins of the discovery.

Let us resume our narrative regarding Krishnan's role. After talking about Krishnan's work of 1924, Raman said, in his Bangalore address of 16 March, 1928, "The research was discontinued at the time but was resumed by him [that is, Krishnan] later in the current year (January, 1928). The remarkable observation was made (by whom first ?) that visible radiation which is excited in pure dry glycerine by ultraviolet radiation (sunlight filtered through Corning glass G. 586) is *strongly polarized*". (Words in square brackets are added but italics occur in the original.)

He said in the same address after mentioning award of the Nobel prize to Compton, "I immediately undertook an experimental re-examination of the subject in collaboration with Mr. K.S. Krishnan and this has proved very fruitful in results".

And later, "A more satisfactory proof was, however, forthcoming when Krishnan and myself examined the polarization of this new type of radiation and found that it was nearly as strong as that of the ordinary light scattering in many cases, and is thus quite distinct from ordinary fluorescence which is usually unpolarized."

And at the end, "I owe much to the valuable cooperation in this research to Mr. K.S. Krishnan".

The crucial point is as to who observed the strong polarization of the scattered light, first, and thus set the phenomenon apart from fluorescence which is what it had been considered earlier by everyone involved in it, in Raman's laboratory. Let me quote in this context from the Nobel Lecture of Raman delivered at Stockholm in 1930:

"Krishnan, who *very materially* assisted me in these investigations, found at the same time that the phenomenon could be observed in several organic vapours, and *even succeeded in visually determining the state of polarization of the modified radiations* from them". (Emphasis added.)

The observations on which the first letter to *Nature* announcing the discovery, were based, used ordinary sunlight. As the above passage shows, Krishnan had the extraordinary ability to determine *visually* the state of polarization using ordinary sunlight (and filters and condensers). The mercury vapour lamp giving an intense beam in a narrow band, came later.

It will be correct to say, therefore, that it was the seeing eye of Krishnan, which made the discovery in Raman's laboratory. It was Raman's experience, imagination, inspiration and status which made it possible for the discovery to be known and immediately acknowledged. And, of course, he had intimations of it and toiled for years over the phenomenon of scattering of light. Raman and Krishnan whose names rhyme, formed an excellent pair, for the observation and understanding of the phenomenon.

It would, therefore, be just to call it Raman-Krishnan effect. I might say here that many knowing authors now attribute the discovery to Raman and Krishnan jointly. I may mention the latest edition of the *McGraw Hill Encyclopedia of Science & Technology* (1986) and *Encyclopedia of Physical Science and Technology*, Academic Press (1987).

So while we remember Raman today, with all our heart, we should equally remember his most able and inspired collaborator K.S. Krishnan. No doubt, as the French historian of science, Taton, has said, both chance and reason play a part in discovery. One is tempted to add that chance meets the prepared mind.

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# RESEARCH WITH STYLE : The Story of Raman's Study of Light Scattering

S. RAMASESHAN

TO those of us who knew C.V. Raman well, what struck us most was his intense love of and preoccupation with Nature. In one of his lectures he said:

> "The face of Nature as presented to us is infinitely varied; but to those who love her, it is ever beautiful and interesting. The blue of the sky, the glories of sunrise and sunset, the ever shifting panorama of the clouds, the varied colours of the forest and field and the star sprinkled sky at night—these and many other scenes pass before our eyes on the never ending drama of light and colour which Nature presents for our benefit".

In another lecture:

> "The man of science observes what Nature offers with the eye of understanding but her beauties are not lost on him for that reason. More truly it can be said that understanding refines our vision and heightens our appreciation of what is striking and beautiful".

Clearly a different view from Goethe's who wrote that Newton's analysis of the rainbow colours "would cripple Nature's art". Among the natural phenomena that most fascinated Raman were the beautiful coronae and haloes one can see around the sun and the moon when thin clouds come in front of them. This fascination never ceased. In 1910, when he was an Assistant Accountant General in Nagpur. his clerks noticed him at lunch-time studying the solar coronae reflected in a pool of water in front of his office. Later in Calcutta, he was seen often making observations on the lunar coronae, when taking his evening stroll in the *maidan*. I myself have seen him measuring the polarization of the coronae in 1967 in Bangalore when he was 79! Wordsworth's lines on *The Rainbow* come to mind

So was it when my life began
So is it now that I am a man
So will it be when I shall grow old...

Raman stated that purely from the size of the rings, the vividness of the colours, and the polarization characteristics, one can not only estimate the size and distribution of the particles but also deduce whether these are droplets of liquid water, amorphous solidified water or ice crystals. Raman produced these coronae in the laboratory over a wide range of droplet sizes and states that these artificial coronae are more striking in colour than those seen in Nature, as the colours of the latter were diluted by the finite angular dimensions of the sun or moon. He was often up very early in the morning at Bangalore observing the coronae formed around the planet Venus!

It is also remarkable how much science Raman could extract from his study and contemplation of this one phenomenon. I shall give three examples.

**Raman's observation of "Speckles" in 1919**

Who has not seen the *radiant spectra* — the rays that seem to emanate — when a small intense source of light is viewed against a dark background — the long coloured streamers of light which are seen to diverge from the source in all directions. Raman commenced his detailed studies of this phenomenon around 1918. He noted that when the source is monochromatic, the streamers become spots and faint haloes encircle the source near the outer limit. He connected this phenomenon with the coronae.

Coronae round the sun and the moon are the result of Fraunhofer diffraction by spherical droplets. Raman argued that when radiations diffracted by the individual particles are superposed at any given point of observation, there must be interference. If the particles are distributed at random and execute rapid uncorrelated movements as in a real cloud, these interference effects will be unobservable. The observed intensity would be $n$ times the Fraunhofer diffraction of an individual droplet (assuming $n$ particles of equal size). If on the other hand, the particles occupy stationary positions within the cloud, the interferences between the individual particles must be observable, even if the particles are numerous. For a random distribution of particles, while the most probable resultant intensity would be zero, the average intensity would be $nA^2$ (where $A$ is the amplitude of the wave scattered by one particle). Hence a point source of monochromatic light, when viewed through a stationary cloud, will exhibit a diffraction corona on which will be "superposed" this interference effect. The net result

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is that instead of a continuous distribution of intensity, one would observe violent fluctuations. The corona, to use Raman's expression must have a "mottled" appearance, each point or "mottle" being like an optical image of the original source produced by the cloud of particles! If the source is one of white light, each point is spread radially into a spectrum (the red being the farthest from the centre) giving the effect of long coloured streamers. The intensity distribution of the spots will be that obtained from the random walk problem, i.e., the Rayleigh law.

Much later, Raman and his (now renowned) student G.N. Ramachandran verified all these deductions in coronae produced by a cloud of lycopodium particles on a glass plate. Incidentally the *mottles* of Raman are the 'speckles' which became prominent when the laser was discovered a few decades later. Raman used to project the halo produced by the colloidal particles of dilute milk and showed that the bright spots (speckles) in the central disk of the corona continually changed, appearing and disappearing in the field of view — an effect due to the Brownian motion of the colloidal particle. In 1919 Raman proposed that the diffracting structures which produced the *radiant spectra* were in the eye. They were in the refractive media of the eye—opaque or transparent particles or small regions with small differences in refractive index in the cornea, the vitreous or aqueous humour or even the lens. These ideas which he put forth, anticipated, in a sense, the modern concepts of twinkling of stars and the speckle formation in telescopes — a connection which was even hinted at by him.

**X-ray diffraction by liquids**

It is almost certain that Raman's interest in crystal structure determination and in X-ray diffraction arose due to his meeting Sir William Bragg (Senior) in London. Bragg showed him the structure of naphthalene that he had determined. Raman's preliminary calculations showed that the structure shown to him was not consistent with the birefringence of the crystal, and in fact the structure was later modified. This led him on to the idea of using optical and magnetic effects as accessories to X-ray methods for crystal structure determination — concepts which were so elegantly extended and perfected later by his famous student and collaborator K.S. Krishnan.

On his return to India he got his assistants to build an X-ray tube at the Indian Association for the Cultivation of Science. Since the theories of X-ray diffraction by a liquid were quite inadequate at that time, he (with K.R. Ramanathan) developed a satisfactory theory (which A. H. Compton mentions in his book *X-rays and Electrons).*

When a pencil of homogenous X-rays passes through a thin layer of liquid and is received on a photographic plate, there appears in addition to the central spot (given by the undeviated beam) diffraction haloes surrounding the centre. The surprise is that the central disk, i.e., the first peak of the classical diffraction is absent. It was Raman's interest and insight into the halo phenomenon which provided the explanation. He noted that the X-ray case had to be treated differently from the optical one, since the wavelength of the radiation is of the order of the interatomic distance. The discrete structure of the medium would have to be considered when applying the Einstein-Smoluchowski fluctuations theory. These fluctuations occur over distances varying from that between molecules up to that of the containing vessel. If the density were uniform (i.e., if there are no fluctuations), no scattering would occur, as the interference would be complete. Raman showed that this theory could easily explain why liquids scattered X-rays so little at low angles. At larger angles the variations in the intermolecular distances also have to be computed to explain the spread of the halo. This was done from statistical and thermodynamical considerations again using the Einstein-Smoluchowski ideas as the basis.

**The classical derivation of the Compton Effect**

In 1924 at the British Association meeting at Toronto, Canada, there was a debate on the recently discovered Compton Effect in which Compton and Raman took part. The discussion is of some interest as it underscores the problems that Physics and Physicists faced in 1924, just before quantum mechanics was formulated. In addition to the X-ray scattering of degraded frequency (the Compton Effect), there is an unmodified secondary radiation. Compton had explained this as due to the whole group of electrons in the atom, scattering conjointly. To this view Raman raised the question:

> "If one electron acting alone can scatter a quantum and also all the *Z* electrons in the atom acting together, then why do we not observe scattering by two, three or more electrons acting together at a time, with their corresponding fractional Compton shifts in wavelengths? To the alternative explanation of the unmodified scattering given by Professors Compton and Jauncey that it represents the scattering by an electron, which the impinging quantum is unable to detach from the atom, the equally pertinent question may be asked, then why is the intensity of this type of radiation proportional to $Z^2$ and not $Z$?"

In 1927 Raman's study of the halo again came to the rescue. Using a simplified atomic model in which electrons are regarded as a gas distributed in a spherical enclosure surrounding the nucleus, he showed that the classical wave principles lead directly to a quantitative theory of the Compton Effect

"The problem is very similar to those which continually

**Among the natural phenomena that most fascinated Raman were the beautiful coronae and haloes one can see around the sun and the moon when thin clouds come in front of them**

## Raman's researches on the musical instruments of India

IT was Raman's veiw that although music played an important role in the cultural life of ancient india, the material now available for writing its history is all too meagre. A better method of probing into the development of musical knowledge in ancient India would therefore be a scientific study of the musical instruments which have been handed down as heirlooms for untold generations.

The work of Raman on the musical drums of India is epoch-making and reveals the acoustical knowledge of the ancient Hindus—which is the title of a paper published by Raman. It was Pythagoras who first formulated what makes a sound seem musical to the human ear. If the string of an instrument is plucked (struck or bowed) it not only emits a note having a fundamental frequency, but also produces higher notes. If these overtones are in the ratio of the natural numbers (2,3,4, etc. to the fundamental), the effect is musical, otherwise it is discordant or unpleasant. Scientifically it is well known that percussion instruments as a class can only produce inharmonic overtones and are therefore in a sense only noise makers. Raman's ear however detected that the Indian percussion instruments stand in an entirely different category in that they produce truly musical sounds. He showed that this was achieved by the partial loading of the drum membrane with a firmly adherent but flexible paste. As a consequence the Indian *mridangam* or *tabla* produces a succession of musically harmonic overtones in the same way as any stringed instrument.

The famed stringed instruments of India, the *vina* and the *tanpura*, are of undoubted antiquity and revered as a gift of the gods because their sound is considered closest to the human voice. Their tone exhibits a quality much superior to most "plucked" instruments. Raman made the surprising discovery that certain overtones, which according to acoustical principles should be entirely absent, sing out with great intensity in these instruments. He showed that the violation of what is called the Young-Helmholtz law is due to the curved bridge which the ancient Hindus had cunningly fashioned so that the *vina* (and the *tanpura*) could produce sounds richer in quality, worthy of Saraswati, the goddess of music whose favourite instrument it was.

Raman's acoustical studies were not confined to Indian musical instruments and they extended also to other western ones. While his wife was an accomplished *vina* player, it is hardly known that Raman himself was once a reasonably competent violin player. His mathematical theory of the bowed string and its experimental verification, his theory of how the impact of the hammer produces the exquisite vibration in the pianaforte and his demonstration of the peculiar Wolf Note produced by the violin and cello were all accepted and recognized by the experts of the musico-acoustical world. As a consequence he was invited to contribute to the *Handbuch der Physik* (published by Springer Verlag). This article entitled "Musik-instrumente und ihre Klange" (Musical Instruments and Their Tones) published in this prestigious German encyclopaedia of physics is considered an authoritative one of this subject. Raman wrote the article in English and it was translated into German. S.R.

(Excerpted from "C.V. Raman and the German connectioin" published in *Science Age*, February 1987)

arise in such optical problems as the theory of coronae..... The answer to it can be given forth by analogy with the known results in optical cases. The resultant of the *Z* vibrations can be divided into two parts, *the first part* is entirely determinate, its amplitude being a function of the angle between the primary and secondary rays which is invariable with time. *The second part* is entirely indeterminate so that neither the amplitude nor the phase can be specified at any given time in any given direction and consequently the frequency is also variable. Nevertheless it is possible to specify the statistical expectation of the intensity of this second the highly *fluctuating* type of secondary radiation."

Compton and Allison in their well known book *X-rays in Theory and Practice* say:

"Raman showed from purely classical considerations that two components must exist....."

and go on to give the theory of the scattering of X-rays by an electron cloud.

"The derivation given closely follows Raman.

It must be mentioned that Compton too derived the same results independently by a different method two years later."

This paper (which was again inspired by his interest in coronae and haloes) is an important one.

He says in it:

"......our expression represents merely a statistical average of a quantity that *fluctuates with time*...... the fluctuations with time of the secondary radiation from the atom involve the corresponding fluctuations in the state of the electrical state of the atom.....

To avoid misapprehension it should be made clear that the fluctuations of the atom we are considering are quite different in nature from the fluctuations contemplated in thermodynamics and kinetic theory. We are here concerned with the fluctuations of the atom from its normal condition under the influences of external radiation."

It was this work which convinced him that light radiation can excite molecules and hence there must exist an optical analogue of the Compton Effect—i.e., interaction between light quanta and molecular vibrations.

### The blue of the sea

It is an open question as to how much the books one reads in one's youth influences one's activities in later years. In Raman's case. I think there appears to be a connection. I was able to trace two books which were available in Mr R. Chandrasekhara Iyer's (Raman's father's) house which were *certainly* read by Raman when he was between 11 and 13.

*"New Fragments"* by John Tyndall published in 1893 contain an article "about common water" which says

> "water of the Lake (of Geneva) is known to be beautifully blue.....Blue is the natural colour of both water and ice. On the glaciers of Switzerland are found deep shafts and lakes of beautifully blue water. The most striking example of the colour of water is probably that furnished by the Blue Grotto of Capri in the bay of Naples......the walls and water of which shimmer forth a magical blue light.....The bluest of the blue waters are clear and have no detectable suspended impurities."

*Popular-Lectures on Scientific Subjects* by Hermann von Helmholtz contains some magnificent essays—On Goethe's Scientific Researches. On the Physical Causes of Harmony in Music. On the Relation of Optics to Paintings—essays that must have fascinated young Raman. "On Ice and Glaciers" Helmholtz says:

> "In the depths of the crevasses ice is seen of a purity and clearness with which nothing we are acquainted with in the plains can be compared. From its purity it shows a splendid blue colour like that of the sky, only with a greenish hue......Their vertical dark blue walls of crystal ice glistening with moisture from the trickling water form one of the most splendid spectacles which Nature can present to us..... The beautiful blue colour they exhibit is the colour of natural water: liquid water as well as ice is blue, though to an extremely small extent so that the colour is visible in layers from ten to twelve feet thickness".

**Even from the beginning, Raman's intuition seems to have told him to look for a change in colour in scattering. He and his collaborators used sunlight and the method of complementary filters to detect this change**

Put these along with very different views he read later like the following statement by Lord Rayleigh whose every paper Raman is believed to have read:

> "We must bear in mind that absorption or the proper colour of water cannot manifest itself unless the light traverses a sufficient depth before reaching the eye. In the ocean the depth is of course adequate to develop the colour, but if the water is clear, there is often nothing to send the light back to the observer. Under these circumstances the proper colour cannot be seen. ***The much admired dark blue of the deep sea has nothing to do with the colour of water, but simply the blue of sky seen by reflection."***

Sir Asutosh Mukherjee (the Vice-Chancellor of Calcutta University) insisted that Raman should definitely go to Oxford for the Universities Congress and this was indeed fortunate. It was on this voyage that he saw the incredible blue of the Mediterranean Sea. He could not believe that the sea could be so blue and so beautiful, nor could he believe that this deep azure was "simply the blue of the sky seen by reflection". Even on board-ship he disproved this conjecture of Rayleigh's noting that when the reflection of the sky by the sea is quenched with an analysing nicol prism

> "the colour far from being impoverished by suppression of the sky reflection was wonderfully improved.... it was abundantly clear from the observations that the blue colour of the deep sea is a distinct phenomenon by itself....."

The rest is history; how, by applying the Einstein-Smoluchowski theory of fluctuations, he established quantitatively that the blue of the sea is due to scattering by molecules—molecular diffraction as he called it; how by laboratory experiments on ice he proved that the blue of the glaciers too arose from molecular scattering. He also showed that molecular scattering was a universal phenomenon in gases, liquids and solids, i.e., irrespective of the physical state of the scatterer.

### The scattering of light and the light quanta

In 1921, even before he voyaged to England, Raman had discussed how molecular movements and molecular vibrations could affect the light scattered by a group of molecules (or a cloud of particles). He had concluded that the movements of the molecules would exhibit themselves as a Doppler shift in the frequency of the incident light, that the shift would be dependent on the angle between the primary and scattered radiation and that it should vanish in the exact forward direction. From his vast experience in acoustical studies, he deduced that if the molecular vibrations are anharmonic, combination tones—sum and difference frequencies—may possibly result. (E. Lommel as early as 1878 considered such a possibility!). However, after his visit to England he seemed to be more concerned with understanding the mechanism of scattering. By imagining molecular scattering to take place in a black body enclosure, Raman convinced himself that Rayleigh Scattering must also take place in a discontinuous manner.

> "We must therefore draw the inference either that the Rayleigh law of scattering is not valid or that molecules do not scatter the radiations incident on them continuously. Since the Rayleigh law of scattering is

supported by experiment, at least over a considerable range of wavelengths, it seems more reasonable to accept the latter conclusion, and to infer that the *molecular scattering of light* cannot take place in a continuous manner as contemplated by the classical electrodynamics..... We are apparently forced to consider the idea that light itself may consist of highly concentrated bundles or quanta of energy travelling through space".

This was strong support of the Einstein idea of the light quantum, a point of view not too popular at that time. As Raman said then:

"though Planck's hypothesis of quantum emission, reinforced as it has been by the success of Bohr's theory of line spectra, has passed into general acceptance, Einstein's idea of light-quanta has apparently been regarded as unnecessarily revolutionary in character".

In 1922, Einstein was awarded the Nobel Prize for his services to theoretical physics and for his work on the photoelectric effect. Pais in Einstein's biography says:

Even when the Einstein photoelectric law was accepted, almost no one but Einstein himself would have anything to do with light quanta!

About two years before his death' Nagendra Nath, another of Raman's reputed students told me that in the thirties, [When Raman and Born were great friends (!)] Max Born had told him that he was impressed with Raman's strong advocacy of Einstein's concept of the light quantum in 1921, that he was very pleasantly surprised at Raman's grasping the basic theoretical implications of the Kramers-Heisenberg process, but was truly astounded by Raman's insight in 1921 that Maxwell's field equations would have to be modified to suit the quantum theory!

In the last chapter of his monograph *Molecular Diffraction of Light* Raman writes:

"The belief in the validity of Newtonian dynamics as applied to the ultimate particles of matter has, however, received a rude shock from the success of the quantum theory as applied to the theory of specific heats, and there seems no particular reason why we should necessarily cling to Newtonian dynamics, in constructing the mathematical framework of field-equations which form the kernel of Maxwell's theory. Rather, to be consistent, it is necessary that the field-equations should be modified so as to introduce the concept of the quantum of action. In other words, the electrical and magnetic circuits should be conceived not as continuously distributed in the field but as discrete units each representing a quantum of action, and possessing an independent existence".

The words were written in 1921. It is interesting that this programme suggested here of quantizing the electromagnetic field was commenced by Dirac in 1928 and by Heisenberg in 1930!

**The discovery of the Raman effect**

After the publication of this monograph in February 1922, the search started.

"Bohr's theory has made the idea familiar that the emission or absorption of light from the atom or the expulsion of an electron involves something in the nature of a catastrophic change. If therefore we wish to look for experimental support for Einstein's conception that light itself consists of quantum units, we must consider those optical phenomena in which obviously no such catastrophic change in the atoms or molecules are involved. The molecular diffraction or scattering of light is obviously such a phenomenon".

Even from the beginning, Raman's intuition seems to have told him to look for a change in colour in scattering. He and his collaborators used sunlight and the method of complementary filters to detect this change. Strangely enough, even in the earliest of these experiments he did with K.R. Ramanathan this colour change was noticed but it was attributed to "a weak fluorescence" caused by impurities. At the insistence of Raman, the liquid was purified again and again but the effect persisted.

Said Ramanathan to me later

"Even in 1923 Prof. Raman refused to believe that this "weak fluorescence" was due to impurities. He said time and again that he felt it was a genuine effect".

The "weak fluorescence" also showed polarization effects but Raman did not, for some strange reason, follow up this important clue as he did later in 1928. In 1924 the "weak fluorescence" was again observed by K.S. Krishnan and in 1925 Raman asked S. Venkateswaran to try to obtain a spectrum of this "weak fluorescence" but no spectrum could be recorded. I have not been able to determine whether this attempt has anything to do with the appearance of the Kramers-Heisenberg paper earlier the same year.

Things came to head in the fall of 1927. Raman, on a holiday in Waltair, worked on and wrote the paper on the classical derivation of the Compton Effect and came back to Calcutta convinced that an "Optical Analogue of the Compton Effect" must exist; and S. Venkateswaran, one of the most diligent of Raman's collaborators made the remarkable observation that the so-called "fluorescence" in glycerine was strongly polarized. This clearly indicated to Raman that the phenomenon could not be the conventional fluorescence—a point of view he had always taken and for which he was seeking proof.

Venkateswaran was a part-time student who could only work after working hours and on holidays. Raman wanted some one to use the sunlight available all through the day, particularly as he himself had lecturing commitments at the University. And so he pursuaded K.S. Krishnan, the best student he had at that time, to get on to these experiments. Krishnan's diary says:

"5th February 1928: For the past three or four days I have been doing some experimental work..... the last experimental work I did was in the summer of 1926....." "As Professor says it is not quite healthy for a scientific man to be out of touch with actual experimental facts for any length of time".

Krishnan takes up the problem assigned to him as a dutiful Indian student would, but he is obviously not convinced of the reasons for pursuing these experiments. But within a few days this line of attack led to momentous discoveries.

"...I took up (at the suggestion of Prof.) the general problem of the 'fluorescence'* of organic vapours, rather than the pressing nature of any specific problem in the subject, awaiting experimental solution which usually draws a man to a new field.....studied anthracene vapour. It exhibits strong 'fluorescence'; which does not show any polarization.....".

Raman tactfully suggests changing over first to the study of organic liquids, particularly to that of the polarization of the scattered light and verifying his earlier observations.

"Professor has been working with me all the time. Recently Professor has been studying with Mr Venkateswaran the fluorescence exhibited by many aromatic liquids..... However in view of the fact that anthracene vapour does not show any polarization. Professor has asked me to verify again his observations on the polarization in some of the liquids....."

It is remarkable that within two days of Raman's suggestion. Krishnan confirms the observations of Raman and Venkateswaran in many liquids.

"Tuesday, 7th February.....all pure liquids show fairly intense 'fluorescence' ..... and what is much more interesting all of them are strongly polarized".

Raman verified these observations and wondered why he missed discovering this phenomenon as early as 1923 when Ramanathan had made similar observations.

"He was very much excited and repeated several times that it was an amazing result ..... One after the other, 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".

Raman then realises that this was the effect he had been looking for, since 1922 (or 1925), a scattering with a modified frequency due to the Kramers-Heisenberg process.

".....Professor suddenly came to the house (at about 9 p.m.) and called for me. When we went down, we found he was very much excited and had come to tell me that what we had observed this morning must be the Kramers-Heisenberg effect we had been looking for all these days. We therefore agreed to call the effect modified scattering ...... He repeatedly emphasized the exciting nature of the discovery."

Raman then asks Krishnan to go back to the study of vapours to the study of the "modified scattering" in them.

"Thursday, 9th February ......Tried ether vapour and it was surprising that the modified radiation was conspicuous...... Professor came from the college at about three......and there was enough sunlight to see for himself".

and Raman was in a state of euphoria—a man who has at last come to end of a trail.

"He ran about the place shouting all the time that it was a first rate discovery, that he was feeling miserable during the lecture because he had to leave the experiment..... 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".

All that remains is to observe it and record it in a spectrograph.

'Tuesday; 28th February. 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.... This encouraged us to use monochromatic incident light".

* The quotation marks are mine. The 'fluorescence' referred to (and the 'weak fluorescence' mentioned earlier) is the light seen from the track of the incident beam through a filter complementary to that in the path of the sunlight incident on the liquid or vapour, and is, therefore, of a colour different from that of the Rayleigh Scattered light.

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# RAMAN EFFECT—DISCOVERY AND AFTER

R.S. KRISHNAN

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° 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

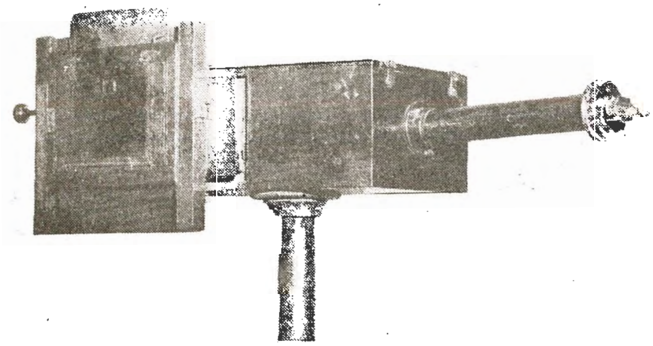
THIS encouraged me to take up observations with a monochromatic source of light. A quartz mercury lamp with a filter which completely cuts out all the visible lines of longer wavelengths than the indigo line 4358 A.U. was found to be very effective. When the light from such a lamp was passed through 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. .s 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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# Professor Sir C.V. Raman—Reminiscences

R.S. KRISHNAN

IN 1933, five years after the discovery of the Raman effect and nearly two and half years after he was awarded the Nobel Prize, Prof. Raman moved from Calcutta to Bangalore to join as the first Indian Director of the Indian Institute of Science. Immediately a new Department of Physics was created for him where he pursued his scientific activities for a period of fifteen years. I was one amongst the first batch of 8 students, fresh from the University who joined to work under him in July 1933. I was associated with him for the next fifteen years, first as a research scholar and later as a senior member of his academic staff.

Anybody who wished to work under Professor as a regular student had to undergo a searching oral examination in which the candidate's knowledge of fundamentals and capacity for original thinking would be seriously tested. Although he attached some importance to the academic records of the applicant, he always made his own assessment of a student. He never believed in admitting students to work under him on the basis of recommendations from friends and V.I.P's.

Once having selected, the student felt at ease with Prof. Raman. He was kind, generous and large hearted provided the student was sincere and hard working. He had his own ways of developing self confidence and self reliance in his students whom he treated as equals while discussing scientific matters. It was his habit to go round the laboratory every morning, meeting each student, discussing the progress of his work and often suggesting new ideas. He would give free expression to his thought when a new result was brought to his notice. In his public lectures in those days he gave the maximum publicity to the work of his students and would mention their names. All these were a thrilling experience to us as his students who under his influence imbibed intense zeal and enthusiasm for more and more creative research and sustained hard work. Professor Raman encouraged the students to develop capacity for clear talk and exposition. He often used to remark that one should be able to 'think on one's feet'. Whenever an old student called on him, the topic of discussion would always be scientific.

Only his students know Prof. Raman's humanism. He would lend full support to the work carried out by his students. He was always anxious that all the credit for the work should go to the students. As far as he was concerned he guided the students so completely, and looked through every word of the final published paper that any distinction between his work and the student's work ceased to exist.

**Raman always encouraged senior students and research assistants who had taken their Doctorates to leave his laboratory and take up responsible positions outside**

He would follow the career of the student even after they had taken up job elsewhere. He seldom issued open certificate to any of his students. Whenever any student wanted a certificate to be sent to the authorities where he was seeking fresh employment, Prof. Raman was always very prompt in sending his recommendations directly to the authorities concerned. The students could always count on his support. In this context one is reminded of the famous Malayalam poet Vallathol's poem "Student and Son". As with Lord Siva, the student took precedence over the son in the case of Prof. Raman also. He often gave the following advice to his students whenever they left him for taking up job elsewhere. "Since you are going to earn your livelihood through scientific work, never grudge buying books. You will find an investment in books and journals very rewarding".

The range of Professor's scientific interests was amazing. He had working under him at the same time students of physics, mathematics, physical chemistry, organic and inorganic chemistry and even geology all of whom received his directions and guidance on the problems on which they were working.

At least once a week there would be seminars where one of the students would report on the work he had been doing, experimental or theoretical, the difficulties encountered by him, the results obtained, etc. During these seminars Prof. Raman would think aloud and one would see and hear his intellectual brilliance and get illuminated and inspired. An interesting incident took place in 1935 to which the author was an eye witness. Parthasarathy, a student of Prof. Raman, was working on the diffraction of light by ultrasonic waves in 1935. While giving a seminar talk on the subject, he described the experimental set-up in detail and also the peculiar results reported by Debye and Sears in USA, by Biquard and Lucas in France in 1932, and Bar in Switzerland in 1933 which could not be accounted for satisfactorily with the well-known theory of Brillouin given in 1922 which was able to explain only the first order diffraction pattern. As soon as Parthasarathy finished talking, Prof. Raman got up and said that the entire phenomenon could be satisfactorily accounted for on the basis that the wave front of the incident light beam which was plane before entering the cell containing the liquid became corrugated due to compressions and rarefactions produced in the medium by the ultrasonic waves traversing it in the transverse direction. He immediately asked one of his students, N.S. Nagendra Nath who had a basic degree in mathematics and who was present in the audience, to work out the mathematical analysis and derive the formula for the intensities of the different orders of the diffraction pattern. Nagendra Nath brought the results of his calculations the next day. Then followed a series of papers of fundamental importance by Raman and Nagendra Nath wherein what is now called the Raman-Nath theory of the diffraction of light by ultrasonic waves was developed. Their treatment not only explained fully the observed facts already reported, but also led to several interesting new ideas and anticipations that were later verified by experiment. This is a typical instance of Raman's flash of intuition which led to the clue for solving a difficult problem using ordinary mathematical logic. In this context, it is worthwhile to quote what Prof. Max Born once said:— "Raman's quick mind leaps over mathematics". While discussing scientific matters with his students he often used to remark "something tells me that this is so and so". He combined in the highest measure the intuitive perception of a genius and the ability of an understanding experimental physicist.

Prof. Raman's first research paper on the "unsymmetrical diffraction bands due to a rectangular aperture" was published in the *Philosophical Magazine* of London in November, 1906, when he was still a student of the M.A. class in his 18th year. The paper was communicated by Prof. Jones of the Physics Department of the Presidency College, Madras, even though there was no acknowledgement or thanks to him. He, being an Englishman, knew that he had not suggested the problem and had nothing to do with the work reported in the paper and that it was his duty to forward the research paper of his student. This kind of rare magnanimity Raman also developed to the highest degree and in his later years he never allowed his name to be added to the papers published by his students based on the work carried out by them even though in many cases the problems would have been suggested by him and many useful tips would have been given by him during the course of the work.

I shall quote what Dr. P.R. Pisharoti, a retired Director of the Institute of Tropical Meteorology and a former student of Prof. C.V. Raman wrote about Raman:

> "On one occasion I was feeling depressed while carrying out an experiment with an X-ray apparatus at the Indian Institute of Science. Professor came in at about 7.00 A.M. and noticed my mood. He asked me the cause of my depression. I replied that a distinguised scientist in the United Kingdom was working on the same problem as myself and that he had a 5 KW X-ray tube at his disposal. He asked me about the power of my X-ray tube. "1 KW, Sir". He said: "That is all; there is a very simple solution. Put a 10 KW brain on the problem", smiled and moved off. He meant what he said. He had supreme self confidence; and more than that he generated it in his students. Time in and time out he would show by precept and example, that ambition, endeavour and courage are the three qualities essential for good scientific work".

Raman believed that it was essential for the Research Assistants and students to live close to the place of work so that they could devote maximum time for work. When he was given permission to work outside office hours in the Indian Association for the Cultivation of Science at Calcutta in 1907 while working as a Finance Officer of the Government of India, he himself took up a house adjoining the Institution, though it was not a desirable locality and had a door opened between his house and the Association so that he could reach the Laboratory informally for work at any time, by day or by night. After assuming the duties of the Director of the Indian Institute of Science in Bangalore he was the first Director to insist upon providing accommodation in the premises for the Research Assistants in preference to the supporting subordinate staff. Each research student was given a key of his room which enabled him to come and work in the Laboratory outside office hours and at night. Prof. Raman was the Central Sun around which the whole institution revolved and from which each part received its energy.

Prof. Raman used to admit students of different disciplines, physics, mathematics, chemistry, geology, etc., to work under him as research scholars. This has paid rich dividends. The development of the Raman-Nath theory was a typical example how a pure mathematics student like N.S. Nagendra Nath, who was working under Raman in 1935, was able to solve the problem of the diffraction of light by ultrasonic waves once the basic physical principle of the formation of the corrugated wave front flashed to Raman's quick mind and he wanted the resulting mathematical analysis to be worked out.

S. Venkateswaran and P. Krishnamurthi who were basically post-graduates in Chemistry were working as part time students outside office hours in Raman's laboratory at Calcutta at the time of the discovery. S. Venkateswaran along with A.S. Ganesan and S. Bhagavantam studied the Raman Spectra of a series of homologous related organic compounds of similar structure. Their work led to the important conclusion that each chemical bond could be identified by a characteristic Raman frequency. They along with the group under K.W.F. Kohlrausch at Graz were the pioneers in establishing the Raman finger-print for each and every chemical bond. P. Krishnamurthi was the first to investigate systematically a series of inorganic compounds, such as carbonates, nitrates, sulfates, etc., and established the characteristic internal vibration frequencies of various chemical radicals and the way in which they were influenced by the metal ion.

Prof. Raman was very fastidious regarding the upkeep of equipment in good condition and he could not tolerate any student found handling the apparatus rashly. He had a member of his academic staff always to be in charge of apparatus and facilities of the laboratory. In Calcutta it was Ashutosh De, while at the Bangalore Institute, it was C.S. Venkateswaran in the beginning and later myself. At the Raman Research Institute it was one Padmanabhan. One of the research students working on the Raman Spectra of uranyl nitrate had obtained some new results. While measuring the spectrogram he got the screw of the measuring microscope jammed and the matter had to be reported to Professor Raman who got terribly annoyed and enquired from C.S. Venkateswaran whether the student was given proper instructions for using the micrometer. The latter's answer was in the affirmative. Prof. Raman asked the student to explain how he got the instrument jammed. On being told by the student that he wanted to find out how far the screw would go and in the process it got jammed. The student concerned was immediately asked to leave the Department even though he had done some good work.

**Prof. Raman could be placed on a par with two other world renowned physicists : Lord Rutherford of Cambridge and Prof. Niels Bohr of Copenhagen**

Since 1928, it was Raman's policy to publish all the contributions from his Laboratory in Indian Journals, instead of in well-known journals published from abroad. Of course, he continued to contribute the first announcement of important discoveries in the correspondence columns of *Nature*. While at Calcutta, papers from Raman School appeared almost exclusively in the *Indian Journal of Physics*. From 1934, the papers from his Laboratory at the Indian Institute of Science and later at the Raman Research Institute appeared in the *Proceedings* of the Indian Academy of sciences, Bangalore which he started and of which he was President till his death in 1970. He thereby raised the prestige of these journals. He used to encourage the students to get reprints of their papers and send them freely to scientists working in the respective fields abroad. This ensured maximum publicity to the work of his laboratory. The notable feature of the Academy was the unfailing regularity with which the *Proceedings* were issued on the last day of every month during the 35 years of Raman's association with the Academy. This is entirely due to Professor Raman's initiative and hard work.

Well over one hundred and fifty young men— mathematicians, physicists, chemists and geologists, etc., had their first training in research under Prof. Raman. Many of his past students occupied important positions all over the country as Professors, Readers or Lecturers in Universities and colleges or members of the scientific services of the Central and State Governments in India. Quite a large number of his students continued to make valuable scientific contributions after they left his laboratory. However, it was also not uncommon that some students who had done extremely well when they were with him, were never heard of again in the scientific field once deprived of his guiding spirit.

Raman always encouraged senior students and research assistants who had taken their doctorates to leave his laboratory and take up responsible positions outside. In this respect he followed the principle adopted by prestigious American universities of encouraging post graduate students to take up faculty positions in other Universities after they had obtained their doctorate degrees. Very few students of Raman had continued to work in his laboratory for more than five years. Even K.S. Krishnan, who joined as a research student in 1924 and was one of Raman's distinguised students and a close collaborator in the experiments leading to the discovery of Raman Effect, had to take up the post of Reader in Physics in the Dacca University in early 1929. I was an exception to this rule. I was associated with him for a period of fifteen years first as a research student, later as a seniormost member of his Academic Staff, and finally succeeded him as Professor and Head of the Department of Physics when Prof. Raman retired from the Indian Institute of Science, Bangalore. Prof. Raman often suggested to me to take up more lucrative positions outside the Institute.

Prof. Raman discouraged the practice of post doctorate students going abroad for further training. One of his students who was with him for just over ten years expressed a desire to take leave for a couple of years to take up a fellowship under a professor in one of the American universities. Prof. Raman was very much against it and when the candidate persisted he was asked to resign and leave the Institute permanently. Of course, he is much better off for that now. But after this incident Professor got disgusted with the behaviour of his students not heeding to his advice. He immediately asked the remaining five research assistants and students who had all taken their doctorate degrees to leave. He got them all good positions in different Institutions in India.

Unlike the practice adopted by many Indian Professors and senior scientists, whenever Raman shifted from one laboratory to another he seldom took any of his old associates with him. When he shifted his activities from Calcutta to the Indian Institute of Science he started his researches with a fresh band of students. The same was the case when he moved from the Indian Institute of Science to the Raman Research Institute in Bangalore in 1948.

There was scarcely any university or cultural organisation in India during Raman's hay-days which had not in the past invited him to give lectures on scientific and other topics. Raman's exposition of any subject was masterly and most impressive. He had a good command of the English language. He started from the fundamentals and built up as he went along in a masterly way. His popular lectures on scientific subjects, always delivered extempore, attracted large audience and were listened to with rapt attention. He could talk on even the most obtruse subject in a simple and lucid way so that even a lay man could easily follow the same and go back satisfied.

According to Prof. Raman, the principal requisite for success in scientific research is not the maturity of knowledge associated with age and experience but the freshness of outlook which is the natural attribute of youth. The principal function of the older generation of scientific men is to discover talent and genius in the younger generations and to provide ample opportunities for free expression and expansion. Intellectual beauty is indeed the highest kind of beauty. Science is the fusion of man's aesthetic and intellectual functions devoted to the representation of nature. It is therefore the highest form of creative art.

Prof. Raman could be placed on a par with two other world renowned physicists: Lord Rutherford of Cambridge and Prof. Niels Bohr of Copenhagen. All the three had trained a large number of students who in turn have become world famous in the scientific field. Both Raman and Rutherford were outspoken, outgoing and direct. They liked physics, their experiments were simple, and they described their work in simple and concise language. Both had a loud and booming voice. Both were in the habit of making decisions easily and firmly. They could be rude and unreasonable at occasions. Both were fond of making disparaging remarks about theoreticians who were very much attached to formal mathematics.

Both Raman and Niels Bohr believed that truth and clarity are complementary. They were capable of enormous enthusiasm for a promising new idea in physics. They regarded mathematics as an important tool but never as an end itself. They were not deflected by unimportant details but gave painstaking attention to detail when it mattered.

The similarities in the behaviour of Lord Rutherford, Prof. Niels Bohr and Prof. C.V. Raman were responsible for the mutual respect they had for one another. In the inaugural address to the South Indian Science Association at Bangalore on March 16, 1928 announcing the discovery of a "New Radiation", Raman had used the first person singular only once in the whole lecture. He was taught this modesty by the late Lord Rutherford who had said that a true man of science simply would say that he found something and if somebody helped him, he would say that so-and-so helped him. The lecture delivered at Bangalore, being of a historical nature, was meant to convey what Prof. Raman really felt.

**Subjects like colours of flowers, origin of minerals and gem stones, plumage of birds, butterflies, the blue of the sky and the ocean and other natural phenomena were his primary concern**

All the three Nobel Laureates were very fond of meeting their old students at least once a year to exchange scientific ideas. Prof. Raman, on his part, used the Annual Meeting of the Indian Academy of Sciences to meet all his past students who were still active in research for mutual discussion of scientific problems. Prof. Raman used to enjoy this annual treat, while his students got inspiration from his brilliant Presidential Addresses and scintillating after dinner speeches. During the year 1936-37 when Prof. Raman was passing through troublesome days in the Indian Institute of Science, it was said that Lord Rutherford had written to the Viceroy of India to ensure that under no circumstances should Raman's scientific activities be jeopardized by any action which the Governing Council of the Institute might take. Sir Mirza Ismail, the then Diwan of Mysore, was also responsible for insisting on Professor Raman's retention in the Institute at least as Professor and Head of the Department of Physics. This noble gesture had enabled Prof. Raman and his associates to continue to make notable scientific contributions in the field of crystal physics, X-ray diffraction, lattice dynamics, Raman and Brillouin spectroscopy, the physics of diamond, etc., thus bringing further recognition to the Indian Institute of Science in the world of science.

Prof. Raman was an egotist to the core and he took real pride in being a self-made man. He owed no man—European or Indian—any debt of gratitude for his achievements as one of the leading scientists of the world. His only inspiration was the *Collected Papers* of the Rayleighs (father and son) and his own ever enquiring mind and his intuitive perception of the deepest concealed secrets of Nature. Nature was his object of worship and inspiration. Subjects like colours of flowers, origin of minerals and gem stones, plumage of birds and butterflies, the blue of the sky and the ocean and other natural phenomena were his primary concern.

Prof. Raman was very frank in expressing his views. He was one of those rare courageous men who would call 'a spade a spade'. He was not tactful enough in administrative matters and in this process he created enemies for himself. Most of his students were "Yes men", an epithet given by an American professor (Visiting Professor in the E.C.E. Department of the Institute) who was staying in the Raman Research Institute campus. Very few of Raman's students had the courage to warn him about the consequencies of some of his administrative decisions.

He was a man of emotion and he could violently get angry. In this connection I would like to narrate a personal experience. One of my students, N. Krishnamurthy had published a paper in the *Indian Journal of Pure and Applied Physics* in 1966, on the lattice dynamics of caesium bromide crystal using Born's theory of lattice dynamics. Prof. Raman could not see eye to eye on this subject with Prof. Max Born and they became bitter enemies. A request for a reprint of this paper went inadvertantly to the Raman Research Institute. This brought to his notice the existence of such a publication from any laboratory at the Indian Institute of Science, and the fact that *my* students were working on lattice dynamics of alkali halides using Born's theory and explaining the observed spectroscopic data of such crystals satisfactorily. This he disliked very much. A few days later I went to meet Professor in some other connection. He was so angry and annoyed with me that he abused me profusely. I coolly pocketed what all he said and quietly walked out of his room in the Raman Research Institute.

We have a right to be proud of Chandrasekhara Venkata Raman. He was a graduate of the Madras Presidency College. He got no training in foreign laboratories or universities. He was the son of a poor school-master. He did not have a posh laboratory and modern ready made equipments to work with. He did everything from what he got in India and what his assistants fabricated and yet earned many laurels including the Hughes Medal of the Royal Society of London and the Nobel Prize in Physics for a fundamental and far-reaching discovery recognized as great by the whole world of science. This is not just foolish insular pride but an argument for greater confidence in ourselves (Indian) than that generally prevails now.

Sir C.V. Raman himself was grateful to Calcutta and the big men of Bengal. He always remembered and said that his scientific work was made possible only through the greatness of Dr. Mahendra Lal Sarkar who founded the Indian Association for the Cultivation of Science in Calcutta. No less was Raman's gratitude to Sir Asutosh Mukherjee who it was that pursuaded Raman to give up his post in the Finance Department of the Government of India and devote himself entirely to the pursuit of science under the aegis of the Calcutta University. But for this C.V. Raman would have respectfully retired as a faultless Accountant-General.

May the example and memory of Professor Chandrasekhara Venkata Raman's life and work, his courage, his faith in young men and women and his ceaseless quest for truth be an inspiration to the young people of our country

## Raman's thoughts

"WHAT is Research? It is only seeking after knowledge and must therefore be of the utmost fundamental significance in all schemes of education. You must remember that knowledge at the present day is not a dead knowledge enshrined in books but a living and growing knowledge with which we are all concerned. Can you imagine for a moment that living knowledge can be procured, can be obtained merely by the study of books, by turning your teachers and students into mere book-worms? No! your teachers and students will have to take part in that stream of human activity, which I have referred to. A university is not a university if this is not understood, if this is not daily practised. It is in the attempt to discover new facts and new relations between known facts, which we call research, that a true insight into the new and growing body of knowledge is obtained. You must be one of the seekers, or else you will be left behind."

* * *

"I would warn my young friends very specially against regarding research as a pathway to self-advertisement and self-glorification. Self-advertisement for whatever reason it may be pursued, soon becomes an end in itself and its results are most evil when seemingly it is most successful. The man of science who habitually indulges in it soon comes to believe in his own perfection and infallibility and loses that clearness of vision and rigid self-criticism, essential to an investigator. Self-praise is scientific suicide".

* * *

"SCIENCE is nothing but a research for truth—truth not only in the physical world, but in the world of logic, psychology, behaviour and so on. The virtue of a truly scientific frame of mind is the readiness to reject what is false and untrue. It proclaims from the house-tops that there is no virtue in sticking to untruth. I think the latest biological discovery is that there is no fundamental cleavage between the life of man and the life of the lower creation and that salvation lies in the perfection of the biological instinct for the perpetuation of the race—the instinct to sacrifice the individual for the sake of the species". (Excerpted from *Indian Scientists—Biographical Sketches*, G.A. Natesan & Co., Publishers, Madras)

# The Colours Of Roses

SIR C.V. RAMAN

THE popularity of the rose has led to great efforts being made towards the development of varieties exhibiting diverse habits of growth and flowering and especially those producing large blooms with numerous petals and attractive colours. Hundreds of named varieties have thus been created and widely distributed. They are to be found listed and illustrated in several publications. The colours which are forthcoming are so striking and so varied that considerable interest attaches to the problem of their origin.

The first step towards the elucidation of these colours is to classify them into distinct groups. We may begin with some familiar groups. We may begin with some familiar colours, viz., yellow, orange, scarlet, red and crimson—limiting ourselves to those cases in which these colours exhibit the maximum degree of saturation or fullness. But not all roses can thus be described. Many present similarity in colour to spectral yellow, orange or red, but are of less saturated hues. Other colours, again, bear no resemblance to any of the pure spectral colours. Various special names have been given to rose colours, viz., cream, pink, salmon, vermilion, mauve and lilac. To this list must be added the multicoloured roses which display different colours on the front and reverse faces of the petals, e.g., scarlet and yellow, or red and white, while others present areas different in colour on the same side of the petals.

**The genesis of the colours**

We are chiefly interested here in the chemical problem, in other words, with ascertaining the nature of the pigments present in the petals which absorb the light rays incident on them, the rays which escape such absorption and emerge as diffused light determining the observed colours. Observation of the flowers held in sunlight through a pocket spectroscope reveals that roses exhibiting vivid colours such as scarlet, red or crimson completely absorb most of the visible spectrum, allowing only limited regions of it to escape as diffused light. Similar observations with the less vividly coloured roses indicate only the parts of the spectrum which suffer the greatest measure of absorption. Thus, in either case, the information which is forthcoming does not enable any definite conclusions to be arrived at regarding the absorptive properties of the pigment over the entire range of the visible spectrum.

In these circumstances, it becomes necessary to rely on the study *in vitro* of the pigments extracted from the rose petals by solvents which do not fundamentally alter their optical behaviour. The two solvents which have been employed in the author's studies are ethyl alcohol and acetone respectively. Rose petals immersed in ethyl alcohol are bleached and given sufficient time become practically colourless. With yellow roses, or with multicoloured roses exhibiting yellow faces or sectors, the alcoholic solution exhibits a golden yellow colour. On the other hand, the alcoholic extract of other roses is quite colourless, from which we infer that the pigment responsible for the colour of such roses has gone into solution, but has simultaneously been transformed into a colourless product.

Rose petals immersed in acetone behave differently. Yellow roses, and the yellow areas in multi-coloured roses are not immediately affected. But roses of all other colours and the areas on multi-coloured roses exhibiting colours other than yellow are quickly decolourised, and as the pigment is extracted from the petals, it dissolves in the acetone which then acquires its colour. The acetone extract may then be transferred into an observation tube with flat ends. Viewed against a bright source of white light through a pocket spectroscope, the absorption spectrum of the solution is seen by the observer. The concentration of the acetone extract can be varied by using fewer or more petals as the case may be and adjusting the quantity of acetone used for the extraction. It is also useful to have observation tubes of greater or shorter length, as may be found desirable, depending on the strength of the coloured extract.

Observations made in this manner with the acetone extracts reveal that the extracted material is much of the same nature in all the cases which have been studied by the author. Crimson roses, red roses, scarlet roses, orange roses and roses which are a light pink or a deep pink, all present spectra which are very similar in appearance. The long wavelength region in the spectrum extending from 600 m$\mu$ upto the red end comes through in full strength. But the yellow and green sectors of the spectrum between 600m$\mu$ and 500m$\mu$ are strongly absorbed. Darker bands in which such absorption is a maximum are clearly visible respectively in the green and yellow parts of the spectrum. There is also an observable transmission of light in the blue region of the spectrum.

The alcoholic extract from yellow roses examined spectroscopically exhibits an absorption which covers the short-wave end of the spectrum and extends a little beyond the blue upto about 515 m$\mu$.

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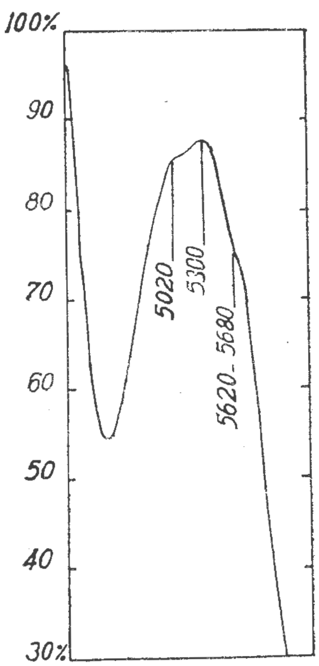
**Spectrophotometric study**

Fig. 1 is the spectrophotometric record obtained with the acetone extract from a rose of a deep red colour held in a cell of one centimetre thickness. The figures entered are wavelengths in angstroms. The extract had to be diluted with acetone to enable the nature of the absorption to be clearly recorded. It will be seen that the record exhibits three distinct humps appearing respectively in the yellow, in the green and in the blue-green regions of the spectrum. These features exhibited by the record indicate that the pigment responsible for the colour of the red roses may be identified with the material designated by the author as Florachrome B.

Fig. 2 is the spectrophotometric record of the alcoholic extract from a yellow rose. The figures entered are wavelengths in angstroms. The absorption is manifested only in the blue region of the spectrum and the three peaks which appear in the record are an indication that the pigment which gives the characteristic golden-yellow colour to the extract belongs to the well-known class of organic compounds known as the carotenoids.



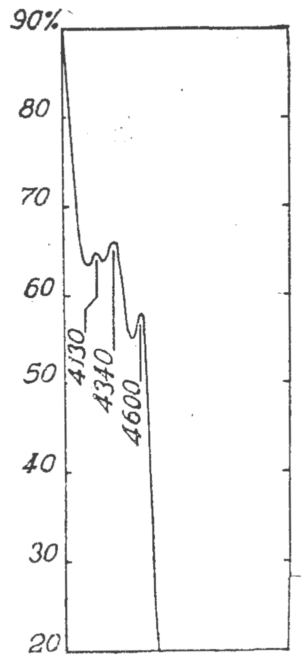




**Fig. 1. Absorption spectrum of red rose  Fig. 2. Of yellow rose**

**Explanation of the colour variations**

The features noticed in the recorded curve of absorption appearing as Fig. 1 enable us to give a reasonable explanation of the great range of colours actually exhibited by roses. The factor which is different for the roses of different colour is the quantity of pigmentary material present in the petals. On the basis of such variation, it is possible to deduce the results to be expected and compare them with the actual facts of observation.

We may begin with the cases in which the pigment is present in minimal quantities. It is evident from Fig. 1 that in such cases, the absorption of light by the petals would be principally observed in the range of wavelength from 500 m$\mu$ to 550m$\mu$ and that it would be much less both at greater and smaller wavelengths, becoming altogether insensible as we approach the red end of the spectrum. Examination of pink roses held in bright light through a pocket spectroscope discloses just such a situation. Further, it is found that the deeper the pink colour of the rose, the greater is the absorption noticeable in the green sector of the spectrum between 500 m$\mu$ and 550 m$\mu$. But both the red and the blue regions of the spectrum persist.

We may next consider the cases in which the pigment is present in substantial quantities, sufficient to make the absorption by the petals completely effective except in the regions of the spectrum where the absorptive power is quite small. Referring again to Fig. 1, it will be seen that in such cases the light which escapes such absorption could appear only at the extreme red end of the spectrum, and the rose would appear of a deep crimson colour. With less pigment available, wavelengths upto about 600 m$\mu$ could escape complete absorption and the colour of the rose would then be a bright red instead of a deep crimson. When the quantity of pigment available is still smaller, wavelengths between 570 m$\mu$ and 600 m$\mu$ would commence to appear in the light diffused by the petals and the colour of the rose would alter from red to scarlet. With further diminution of the quantity of pigment available, the light diffused by the petals would extend further towards still shorter wavelengths and the colour of the rose would alter from scarlet to orange. Actually, when orange roses are viewed through a pocket spectroscope, we find that the spectrum from the extreme red upto 550 m$\mu$ comes through. while shorter wavelengths are absorbed. In all these cases, the blue region of the spectrum is scarcely to be seen.

The author has not had an opportunity of examining roses which have been described as exhibiting purplish hues. If blue roses were ever forthcoming, they would assuredly exhibit the spectrum of Florachrome A, with its characteristic bands of absorption in the red, yellow and green regions.

The spectrophotometer records reproduced above were made in the Instruments Laboratory of the Indian Institute of Science, to the authorities of which the author's thanks are due.

**Ambition, Courage and Endeavour have been my watchwords —C.V. Raman**

# THE COLOURS OF GEMSTONES

SIR C.V. RAMAN

COLOUR is the sensation experienced by an observer when he views the material under study. It is, therefore, essentially a subjective phenomenon. While the optical properties of the material alter the spectral character of the light falling thereon and emerging therefrom which reaches the eye of the observer, the visual impression which such light produces is determined by the physiological characteristics of the sensory apparatus. These characteristics accordingly play the leading role in the perception of colour and must necessarily take precedence in all considerations regarding the subject.

The products of the plant world, including especially the leaves and flowers of living plants, constitute a very large class of materials exhibiting colour which invite study. Being products of biological activity, they conform to set patterns and are therefore exceptionally well suited for precise scientific investigations. The number of species of flowering plants is enormous, and the colours displayed by their flowers are of the most varied nature.

Another class of objects which exhibit colour and are worthy of study form the subject of the present communication, namely gemstones. In several respects, they are an antithesis to the products of the plant world when considered from the present point of view. For a material to be classed as a gemstone, it must be a rarity or at least so scarce as to be an expensive commodity, usually available only in small pieces and generally only after it has been converted by lapidaries into a form calculated to exhibit its lustre and beauty to the maximum extent and for that same reason wholly usuitable for any precise scientific investigation of its spectroscopic behaviour. It is the rarity and costliness of the gems which are natural products which motivated the efforts made to produce them synthetically, thereby creating for buyers and sellers alike, the acute problem of distinguishing between the natural and synthetic gemstones. Nevertheless, such questions, as for example, why is emerald green, why is ruby red and why is sapphire blue, possess both a human and a scientific interest. One can, of course, escape the difficulty of obtaining material suitable for the studies by employing the synthetic instead of the natural gems. But, then, the interest of the investigation and of its results would be materially diminished.

To the reader interested in gemstones and the practical problems arising in the identification of gemstones and of distinguishing between natural and the synthetic gems, Mr. B.W. Anderson's book on gem-testing (6th Edition, Heywood and Co., London) may be heartily recommended. The following remarks made by him which are pertinent to the subject may usefully be quoted here: "Minerals can be classified into the idiochromatic ('self-coloured') type which owes its colour to an element which is an essential part of its composition—*e.g.,* the iron in almandine garnet or peridot, the copper in malachite—and the allochromatic type, in which the colouring element is present in quite small quantity as an 'accidental' impurity. The majority of gem minerals are allochromatic: that is, the mineral itself has no distinctive colour, and is in fact colourless when pure, but exhibits a range of coloured varieties according to the presence of traces of different colouring elements. Quartz, beryl, corundum, tourmaline, topaz, spinel, zircon, and many others are in this category.

Anderson's book also contains a chapter on the use of the spectroscope in gem-testing which contains material relevant to the present topic, viz., the colours of gemstones. In that chapter are reproduced four charts which contain drawings made from visual observations of the spectra of 35 different gemstones, grouped together under the four headings of red, yellow, green and blue stones. The spectra exhibit very varied features, and this fact is of considerable assistance in the identification of the gemstones. The usefulness of the charts from this point of view should not however be allowed to obscure the fact that they cannot serve as a basis for the explanation of the colours of the gemstones. It is not merely the positions of the absorptions noticeable in the spectrum of the gemstones, but also the strength of such absorptions that has to be considered in relation to the intensity of the unabsorbed parts. In other words, we need a complete picture of the energy distribution or at least of the visual luminosities in the spectrum of the light emerging through the gemstone before we can proceed to consider the explanation of its visually observed colour.

It is naturally to be expected that the results which have emerged from the studies on floral colours would be found to be equally well applicable to the case of gemstones and enable us to give a satisfactory interpretation or explanation of their colours. The interest of the subject and the fact that a considerable collection of gem minerals was available in the museum of the Raman Research Institute induced the author to undertake some preliminary studies

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in this field with a view to find whether this is actually the case. The present communication is a brief report on the results.

We may first consider the case of emerald. The rich green colour characteristic of this gem is exhibited by numerous pieces of beryl purchased by the author some years ago at Jaipur in Rajputana and included in the collection of beryl specimens of various sorts deposited in his museum. Unfortunately, however, none of these specimens is transparent enough to permit of light transmitted in the regular fashion through it being observed or examined. However, the author was presented by Sri Chand Golecha, a leading jeweller of Jaipur, when he recently visited Bangalore, with a hexagonal crystal of beryl from the Colombian mines about one centimetre thick. The two faces of the plate facing each other were ground down and polished, and the material was then found to be fairly transparent and the transmitted light also exhibited the characteristic green colour of emerald. Visual spectroscopic examination, confirmed by photographically recorded spectra, showed that in the passage of light through the plate, the violet and blue sectors of the spectrum were noticeably weakened, especially the former. But there was a readily observable transmission in the wavelength range between 450 $m\mu$ and 500 $m\mu$. The green and the red sectors of the spectrum were also visibly diminished in their intensities in the light emerging through the plate. But such diminution was not more than could reasonably be ascribed to the loss by reflection at the two surfaces of the plate as well as the imperfect transparency of the material. On the basis of these facts, we should have expected the colour of the light emerging through the emerald to be a bright yellow, while actually it was a clear green.

We have now to consider the explanation of this striking discrepancy. There is indeed a weakening of intensity (including a narrow band of absorption) noticeable at and near the red end of the spectrum. But the visual luminosity of this part of the spectrum is so small that such absorption is incapable of explaining the fact that the observed colour of the gem is green and not yellow. A careful examination of the spectrum shows, however, that the part of the spectrum between 570 $m\mu$ and 600 $m\mu$, in other words, the yellow sector of the spectrum is greatly weakened. It is clear that it is this extinction of the yellow that is responsible for the observed colour of emerald.

The results obtained with the hexagonal beryl crystal were confirmed with a fine piece of emerald of gem quality which was purchased from a jeweller at Bangalore. It is of much smaller thickness (about two millimetres) but exhibits a deep green colour. The yellow of the spectrum is found to be greatly weakened in the passage of the light through the gem. The aggregate intensity of the red sector relatively to the green sector is distinctly less than it is before entry into the gem, but it is far from being negligible. The observed vivid green hue of the emerald indicates that in the circumstances of the case, the visual sensation excited by the red sector is more or less completely masked by that of the more luminous green sector, in other words, prevented from influencing the perceived colour of the gem.

We shall next consider the case of the ruby. The author's collection of corundum from Ceylon includes numerous individual specimens exhibiting varied colours. Placing them under the ultra-violet lamp and picking out those which exhibit the characteristic red glow enables us to separate the rubies from other species of corundum. Such separation resulted in the interesting discovery that some rubies exhibit a purple colour. They show a strong absorption in the region of wavelengths between 560 $m\mu$ and 590 $m\mu$, in other words, of the yellow sector in the spectrum. Their spectral behaviour thus closely resembles that of the purple flowers mentioned earlier.

Rubies which appear red owe their colour to the existence of an absorption covering both the yellow and green sector of the spectrum. It is a remarkable fact that the blue of the spectrum is transmitted more or less freely by such rubies. But it does not appear to influence the observed colour. We are led to infer that in the particular circumstances of the case, the weaker sensation due to the blue part of the spectrum is masked or prevented from being perceived by the more luminous red sector.

Flowers which appear of a blue colour invariably exhibit a strong absorption of the yellow of the spectrum. A very similar behaviour is found to be exhibited by blue sapphire.

We may sum up all that has been said above in a few words, viz., that the colours of gemstones exhibit features which are in complete accord with those met with in the realm of flowers.

**The true role of scientists is the discovery of truth, they have no concern either with the application or misapplication of the results of scientific discoveries. All the same, scientists owed an obligation to society, to improve it —C.V. Raman**

# RAMAN— THE TEACHER EXTRAORDINARY

A. JAYARAMAN

I had the greatest good fortune to be closely associated with Professor C.V. Raman for eleven years (from Nov. 1949 to Oct. 1960), from the very beginnings of the Raman Research Institute, an Institution Raman created for pursuing his scientific interests, after retirement from the Indian Institute of Science. I began my scientific career with him as a research assistant and won his confidence and affection. He was extraordinarily kind to me and shared his scientific and other interests without any reserve.

Raman was a true scientist and lived all his life as an active researcher. In his scientific career he pursued his research interests with great vigour and set for himself highest-standards and goals. His immense curiosity for understanding natural phenomena, power of observation and persistence led him to make one of the greatest discoveries in physics namely "The Raman effect". It is of particular significance that the equipment which Raman employed for the discovery were very simple and amounted to a total cost of Rs. 500 at the time. Raman's discovery and his getting the Nobel prize was not only a personal triumph for him but was very significant for India and India's scientific development. For almost six decades Raman's personality made its deep impression on the Indian scientific scene. He inspired generations of students and was the most loved spokesman for Science. The story of his success has few parallels at least in the Indian context. His achievement can only be attributed to the singular nature of his personality, and the energy and vigour with which he pursued his goals. Raman showed an uncommon ability for independent thinking right from the beginning and gave up a lucrative government job in favour of a scientific career. When he took to scientific research he was supremely confident of outstanding achievement. Apparently he used to remark that he would bring the Nobel prize for physics east of Suez. Rabindranath Tagore had won a Nobel prize for literature in 1913, but Raman was the first Asian to win the Nobel prize in a scientific field. Viewed from the times in which he was born and raised, it was a statement no one lesser than Raman in determination could have made.

Raman was a towering scientific leader and trained a large number of scientists in India to assume leadership in the field. During his lifetime scores of students passed through his laboratory where they learned scientific methods of thinking, and methodology of scientific research. Raman was a source of tremendous inspiration for the young minds and he kindled their creativity and true interest in science. He gave them interesting problems, worked with them in understanding their results, and developed their analytical thinking and skills. He taught them how to write scientific papers and how to give an effective presentation to an audience. Raman's scientific papers were written in such a delectable style, they were like literary expositions. He often used Latin phrases to emphasize a point. His enthusiasm and curiosity about Nature were infectious. One imbibed a great deal of knowledge just observing him. Raman was indeed a teacher extraordinary the like of whom would be very hard to find.

The life and achievements of Raman are told in other articles in this issue and hence I will not dwell on these topics. My purpose will be to show what a great and gifted teacher Raman was and how he inspired his students and coworkers. He did not teach in the conventional way, although during his tenure as Pallt Professor in Calcutta University he taught the M. Sc. classes to which I shall refer to later. One learned an incredible amount of physics by just being associated with him, listening to his lectures, in discussions with him and by observing him when he was working in the laboratory on a scientific problem. From him one learned how to appreciate Nature, for he had an intense curiosity about Nature and natural phenomena. Colours and symmetry in nature fascinated him and he tried to understand them deeply from the point of view of a physicist. It was the colour of the sky and the blue of the ocean that set him on the trail of discovery of the light scattering effect named after him.

Dr. Jayaraman was a close associate of Professor C.V. Raman with whom he worked from 1949 to 1960, at the Raman Research Institute in Bangalore. He is currently a Distinguished Scientist in the Physics Research Division of AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, NJ 07974-2070, USA.

**Raman the scientist**

Raman went through four distinct phases in his life. Following a brilliant academic career he entered the Financial Civil Service in 1907, at the tender age of 18 ½, as an Assistant Accountant General in Calcutta. Driven by an irresistible urge to do scientific research Raman discovered the Indian Association for Cultivation of Science, soon after he arrived in Calcutta. From 1907 to 1917 he conducted experiments at the Laboratories of the Association during his leisure hours, which meant most mornings, evenings and weekends, and he published a stream of papers in the *Bulletins* of the Association and in foreign journals. His outstanding work on the acoustics of musical instruments and optics earned him name and international fame. Soon, students and disciples started gathering around him for participating in scientific research, and the Raman School of Physics came into being. This may be called the first phase and Raman's entry into physics seriously.

In 1917 Raman was offered the Palit Professorship at the Calcutta University by its distinguished Vice Chancellor Sir Asutosh Mukherjee. Raman gave up the lucrative government job and took up the Palit Professorship for a fraction of the salary that he was getting as an Officer of the Finance Department. Thus from 1917 Raman's career entered the second phase and he now became a full time researcher and a teacher at the Calcutta University. He took full control of the laboratories of the Indian Association for the Cultivation of Science as well as the laboratories at the Calcutta University. From 1917 to 1933 Raman held the Palit Professorship of the Calcutta University and it was during this period he took to light scattering studies which culminated in the discovery of the Raman effect.

**Raman showed an uncommon ability for independent thinking right from the beginning and gave up a lucrative government job in favour of a scientific career**

In 1933 he left Calcutta to become the Director and Professor of Physics at the Indian Institute of Science, Bangalore. He remained at the Institute of Science until his retirement in 1948. During this period Raman took a large number of students, trained them in research and launched them as physicists. He started the physics department and initiated research in several branches of physics; optics, spectroscopy, light-scattering, ultrasonics, x-ray diffraction. The period from 1933 to 1948 may be called the third phase in Raman's scientific life.

In 1949, after retirement from the Indian Institute of Science, Raman founded the Raman Research Institute for the purpose of pursuing his scientific interests, without the shackles of bureaucratic constraints. He took a few students in the beginning but that was only a trickle compared to the previous phases. He carried out research on the colours of gems and minerals, floral colours, diamonds, physiology of vision and a host of other topics in which he was interested. Whatever interested him became a topic of his study. He gave lectures on such diverse subjects as clouds, weather, atmosphere, vision, earthquakes, sound and hearing, apart from lectures on his scientific research studies. His customary Gandhi Memorial lecture every year in October became an event in Bangalore, when scientists and laymen heard Raman speak with great enthusiasm and fervour. Groups of college students and high school students visited the Raman Research Institute to have a darshan of the great scientist. His museum collection enthralled them. The Raman Research Institute itself with Raman as its central figure became a Mecca of science. A visit to this Institute and seeing Raman and talking to him became the most inspiring experience for anyone, particularly young students of science. Raman was an active scientist until the very end. Only for a month or so towards the end he had to be kept away from his beloved Institute. This may be called the fourth and final phase.

Raman was a staunch nationalist and was proud of his Indian heritage and its past achievements. He admired Mahatma Gandhi and Jawaharlal Nehru although he did not agree with all their policies. In the matter of scientific research he insisted that Indian scientists should not be camp followers and imitate what is being done in the west. He has proclaimed too often that what one does should not only be original but also be relevant to India's needs when it comes to application of research. He was opposed to Indian scientists going abroad for advanced research and believed that it impeded originality of thinking. It is difficult to say whether he was right or wrong but it is a fact that independent India is yet to produce scientists of Raman's caliber, although the money spent on scientific research is enormous compared to the Raman's days. Raman was a man of emotion and could get violently angry. But he had an incredible sense of humour and could keep an audience roaring with laughter just describing what could have been commonplace incidents. Anyone who met him could not but be struck by his zest for life. His exuberance was infectious. Chatting with him for some time was like taking tonic. To him scientific activity was the fulfillment of an inner need. His approach to science was one of passion, curiosity and simplicity. Science was to him a personal endeavor, and aesthetic pursuit, and above all joyous experience.

**Raman as a classroom teacher**

I quote from L.A. Ramdas' article on Raman as a classroom teacher "Prof. Raman, as a Palit Professor had no teaching responsibilities, but he enthusiastically took part in M.Sc. teaching. He held the view that when a leading research worker takes on some special teaching course, he brings to his teaching the freshness of research and the questioning attitude which makes all the difference between dull pedagogy and inspired teaching. To some of us who had joined the M.Sc. course at Calcutta (both myself and the late Dr. K.S. Krishnan had joined the M.Sc. course in physics at Calcutta by 1920) Prof. Raman once made the side remark that the best way for him to master or revise any subject in physics was indeed to lecture on it to the M.Sc. classes.

"The M.Sc. teaching used to be naturally shared by the various Professors and Lecturers. Prof. Raman took 'Electricity and Magnetism' in the year 1920-21 and 'Physical Optics' in 1921-22. Both sets of M.Sc. students felt that they were indeed listening to a type of inspired teaching to which was brought all the original flavour and excitement of the great giants of the past who had built up the subject under treatment. In listening spell-bound to Prof. Raman's lectures in 'Electricity and Magnetism', covering a series of nearly 30 lectures, we had shared with him much of the excitement and superb thrill that Benjamin Franklin, Oersted, Arago, Gauss, Faraday, Maxwell, Hertz, Lord Kelvin and many others must have felt while they were making their actual discoveries. This was indeed no routine text-book learning, but reliving the actual past history of the subject. Almost regularly, Prof. Raman with his genius for the subject, his extraordinary eloquence, imagery and fullness of precise expression used to forget himself as well as the time and used to lecture for far more than the prescribed one hour, while the next lecturer had to politely (and perhaps with a sense of relief) retire from the scene after seeing Prof. Raman still at his lecture! Often he used to take the entire forenoon, more than 2 and sometimes even 3 hours—such was his tremendous love of teaching. The mathematics was worked through often with his own improvised simplifications and fully illustrated with physical analogies. Any question or point raised by a student would start off towards uncharted grounds, not touched upon in any text-book. His ready wit and sparkling intellect were a treat to the classes. And after each lecture we used spontaneously to look up original papers and classical treatises like Maxwell's *Electricity and Magnetism*, J.J. Thomson's *Conduction of Electricity*, Faraday's *Experimental Researches*, Lord Rayleigh's and Kelvin's *Collected Papers* and so forth. The lecture in which he worked out Maxwell's field equations and showed that light waves are only electromagnetic waves and the thrill he communicated to the class are still fresh memories.

"In physical optics, a topic on which he himself was conducting several investigations at the time, the students were introduced to all the topics coming, as it were, hot from the 'Lab' and the lecturer's flair for dipping straight into the works of great masters like Huygens, Fresnel, Mascart, Schuster, Wood, Rayleigh, and others of the late 19th and the early twentieth centuries imbued the students with a real love and enthusiasm for what they learned at Prof. Raman's feet, as it were. Whether the subject was Thermodynamics, or the Kinetic theory of gases, or Modern physics, Prof. Raman's treatment of the topic at hand was original and inspiring and left a permanent impression in the student's mind.

"Now let me record a few reminiscences. As an M.Sc. student having direct and free access to Prof. Raman's own personal library, I was astounded to discover that in each and every text book from which he had learned in his own student days, there were marginal criticisms or appreciations of the author. There was no book in which every example and question had not been worked out by Raman. Some questions had the side remark "excellent", while not a few were apostrophized as "elementary" or "silly"! I had no doubt that Prof. Raman had been a most painstaking student and that the definition of 'genius' as the 'capacity to take infinite pains' is indeed true."

Professor Raman thus fully participated in teaching and inspired his students with his enthusiastic lectures. M.N. Saha who later became famous for the "Ionization equation" named after him and S.N. Bose, discoverer of "Bose statistics" were some of the other lecturers at the university college in 1917.

**He was opposed to Indian scientists going abroad for advanced research and believed that it impeded originality of thinking**

**Professor extraordinary**

The period between 1920 to 1928 may be said to be the golden period in the scientific life of Raman. With the combined control of the Association and the University Laboratories he had a hectic schedule. L. A. Ramdas has summarized this activity as follows:

"The daily activities at the laboratories of the 'Association' usually started by 7 a.m. Having started an experiment, one would go on working until 1 p.m. After a quick lunch the scholars would be back by 2 p.m. and work on far into the evening and often until 9 or 10 p.m., until the job on hand had reached a satisfactory stage. Working at this furious rate it is no wonder that many of the pupils could work through 5 or 6 major investigations each year. Those who could not cope with such a fast tempo of work would automatically drop off.

"By 1920, Prof. Raman had gathered round himself an increasing number of extremely bright and capable pupils so that, more and more, he could get his research programme executed rapidly by them. He inspired his scholars to use their own initiative and ingenuity to the fullest extent. He would see what was going on and discuss results at intervals. At any given time, however, he would concentrate his attention on the particular scholar who was then entering the most critical phase of his research. Interpretation of results, fruitful suggestions to carry the investigation several stages further and quick discussion of results already obtained resulted in an immediate publication from this effective type of collaboration between the Professor and the pupil. Each of his pupils had his opportunity for such exhilarating collaboration at the developing phase of his investigation. All the time, the pupils enjoyed the fullest freedom to think, work and improvise for themselves. Spoon-feeding of any kind was absolutely taboo. A spirit of perfect understanding and goodwill pervaded the entire 'Association', with Ashu Babu, the Assistant Secretary, ever ready to help us with any material or facility that we needed, the scholars themselves helping each other spontaneously."

Raman very much maintained the above mode of working and dealing with students throughout his career. Anyone who wished to work under Professor Raman as a regular student had to undergo a searching oral examination in which the candidate's knowledge of fundamentals and capacity for original thinking would be severely tested. Although Raman attached importance to academic records, he always made his own assessment. Once selected, the students felt at ease and he was kind and large-hearted. He had his own way of developing self-confidence and self-reliance in them. He would treat them as his equals, while discussing scientific matters. It was his habit to go round the laboratory every morning, meeting each student, discussing the progress of his work and often suggesting new ideas. He would give free expression to his joy when a new result was brought to his notice. Nagendra Nath, an illustrious pupil of Raman says "One day when I told him that I had found the explanation of the Raman line in diamond which had been mentioned by him as an outstanding problem in his Nobel address, he asked me what it was. I said that the Raman line was to be attributed to the mutual vibration of the two face-centered lattices composing the diamond lattice; he simply yelled out, "You are right, you are right," and insisted that the research paper should be immediately written up. He was in ecstasy over this work. I found myself elected to the Fellowship of the Indian Academy of Sciences, at the age of 23, of which Professor had given no inkling to me."

Raman's students came from all over India. He chose them on the basis of merit and shaped them into scientists who went out to carry on the tradition of research wherever they went and worked in their subsequent career. Throughout his life he had a very warm corner in his heart for his many pupils and they knew they could always look up to him for any help that they may need.

In his public lectures, he would refer to his students by name and talk about their work. All this was thrilling experience to young students and powerful incentive for hard work. A unique rapport was established between him and his students.

**Raman as a lecturer**

Raman excelled in public speaking and could give a lecture, for instance, on Egyptian History off his cuff. His scientific lectures were a treat and he was a superb entertainer. His lectures were replete with spontaneous jokes and were delivered in his high-pitched resonant voice which reached the entire audience (no loud-speakers necessary). Rich in imagery and eloquence, the lectures were rendered in so popular a style that every listener felt that he understood all the science that the learned lecturer was discussing. Once he told me that "the hallmark of a good speaker is that the audience must be under the delusion that they have understood everything that was said by the speaker." In the minds of thousands of his listeners, whenever he gave a public lecture, he used to create the illusion that they understood everything of what he spoke about.

Raman's typical way of giving a lecture is beautifully summarized by Kashyap. "A tall, turbaned figure, casting those searching and curious eyes almost with child-like fitfulness, would walk directly to the dais, with an occasional turn to the right or left, acknowledging a remark or answering a query by the sponsors of the lecture who were leading him to the dais. Confidence incarnate was the figure and even before he started speaking, one got the impression that here was a lecturer who would deliver the goods.

**Anyone who wished to work under Professor Raman as a regular student had to undergo a searching oral examination... Although he attached importance to academic records, he always made his own assessment.**

"His very presence perhaps cut short the longwinded preambles and welcomes that often mar the beautiful effect of a nice lecture. Prof. Raman meant business and a disapproving look would stop a vagrant introduction. His first words uttered in a characteristically punching manner would set the pace for the lecture.

"He spoke of soap bubbles. And, mind you, for some half an hour the evanescent soap bubble that hardly lasts for a couple of seconds blissfully lived!

Raman asked 'Have you ever thought of keeping the soap bubble alive for a long time?' An intriguing question — a question that had never occurred to many. The problem you know, Raman went on to say, is to see that the droplet of water does not collect at the bottom. Then he went on to say how he and other scientists, some in France, managed to keep a soap bubble alive for a few days by subjecting the bubble to an oppositely directed force.

"One would never have a dull moment and would not even realize that the lecture is over. To listen to Raman was something more than learning physics. He had the knack of using the most appropriate expressions, which no textbooks could give. He had the habit of tugging the lapels of his coat which was a Raman characteristic. He would invite questions and answer them all with astounding clarity."

He was forthright when he criticized. During the annual meeting of the Indian Academy of Science in Baroda in 1958, he interrupted the talk of a high-energy physicist who was filling the blackboard with mathematical equations and said "my dear fellow please try to explain what you have done in a few sentences. If you cannot do this, it is not worth knowing."

**Concluding remarks**

No single person has done so much for Indian science as Raman. Through personal example of his highest dedication to science, through his success as a teacher-cum-leader in training generations of physicists who in turn have created independent schools of research, through creating scientific Institutions and facilities for research and founding scientific Academies and Journals for dissemination and propagation of science and through his gift of eloquence which served to inspire and stimulate a widespread interest in science, Raman as a single individual has tremendously influenced the progress of science in India.

He was one of the rare breed of men who are no more, who ranged freely in all fields of science from physics to chemistry to biology. Raman stands alone as the greatest scientist that India gave to the world. Just as our poet Valmiki in describing the battle between Rama and Ravana has said in the great epic *Ramayana* "The sky is comparable only to the sky, the ocean only to the ocean and the battle between Rama and Ravana only to the Rama-Ravana yuddham (battle)," in modern India, Raman is comparable only to Raman.

## C.V. Raman—Honours and Awards

1. Gold Medal for standing first in M.A. Exam. of Presidency College, Madras—1901
2. Elected Fellow of the Royal Society of London—1924
3. Mateuchi Medal (Rome)—1928
4. Knighted by the British Government—1929
5. Hughes Medal of the Royal Society—1929
6. Nobel Prize in Physics—1929
7. Appointed First Indian Director of the Indian Institute of Science—1933
8. Appointed First National Research Professor of Physics—1949
9. Franklin Medal of the Philadelphia Institute—1951
10. Bharat Ratna—1954
11. International Lenin Prize—1957
12. Appointed Member of the Pontifical Academy of Sciences by Pope John XXIII—1961

# Raman's Humour

Raman was rarely seen minus his familiar turban. He was once questioned as to the regularity of its presence on his head. "Why, to prevent the head from swelling", he promptly quipped.

* * *

Raman was equally famous for his ego. In early 1907 after passing the M.A. examination with flying colours, he appeared for the Final Civil Service, which is the forerunner of today's IAS. After returning from the interview Raman said to his brother, "I took one look at the faces of all the fellows who had come for the interview, and I knew I was going to stand first!" Raman duly stood first in the FCS examination.

* * *

On one occasion when he was provoked by a newspaper reporter, he said pointing towards the Raman Research Institute set up by him, "This Institute is a monument to my egotism. I am an egotist and just as the Egyptian Kings used to build pyramids before their death, so is this Institute my pyramid".

* * *

He was one of those courageous men who did not hestitate to call 'a spade, a spade'. If he felt that the approach to a problem was wrong, he bluntly said so. In a function organised on the occassion of his 80th birthday speaker after speaker extolled his science. When it came to Raman's turn to reply to the felicitations, he remarked, "I wish someone had said that I had the heart of a lion".

* * *

Once while returning to India from abroad Raman was deeply attracted by the intense blue of the Mediterranean Sea. It was there he began his studies on the scattering of light by liquids. In fact, Raman started his investigations right on the ship using polarizers, a small prism and a pocket spectroscope which he always carried with him. And he wrote two papers for *Nature* on board the ship S.S. Narkuda, one of which he mailed from Aden and the other from Bombay harbour. Perhaps the first instance of papers being written on a ship.

* * *

Raman once introduced one Dr Rahm to Mahatma Gandhi. Dr Rahm was a Swis Scientist who was studying the tiny organisms known as Tardigrada which survived even when held at very low temperatures. Dr Rahm after paying his respects to Gandhiji asked him if there was no way of ending the conflicts so rampant in the world. "If we cannot unite, can't we fight atheism which seems to be so much on the increase?" he asked.

Sir C.V. Raman put in : "I shall answer your question. If there is a God we must look for him in the universe. If he is not there, He is not worth looking for. I am being looked upon in various quarters as an atheist but I am not. The growing discoveries in the science of astronomy and physics seem to me to be further revelations of God. Mahatmaji, religions cannot unite. Science offers the best opportunity for a complete fellowship. ~~All men of Science are brothers~~".

"What about the converse? All who are not men of science are not brothers?" Gandhiji asked.

The distinguished physicist saw the joke and said "But all can become men of Science".

* * *

On an occasion when introduced to a gathering as having been born in 1888, Sir C.V. Raman remarked wryly: "And now I have been introduced to you as a hang-over from the 19th century".

* * *

Raman was known for his brisk habits and almost irrepressible energy. Once as Deputy Accountant General he was transferred to Rangoon. One day an Accountant General who went round on a tour of inspection, was so much struck by Raman's aggressive individuality that he asked his superior. "How do you manage Raman?"

* * *

On another occassion Dr. King of the Benares Hindu University being struck by the marvellous energy of Raman's movements was forced to remark, "It is indeed a matter of surprise that flasks and test-tubes survive Mr. Raman's handling in the laboratory".

* * *

He was very fond of gardening and trees in particular. Once just before his last birthday he was taken ill. He spent a short while in St. Martha's nursing home, but wished to be taken back to his residence. Lying on the bed in his house he complained, "If I knew I was going to die here like this, I would have had the windows put in differently".

When asked what he meant, he said. "I can't see my trees!" And so the bed was raised so that he could feast his eyes.

* * *

Raman always took pride in the fact that his researches never involved costly equipment. Raman discovered the Raman Effect with the crudest of instruments, namely a mercury lamp, a flask of benzene and a direct vision pocket spectroscope! On one occassion, Raman is said to have remarked : "The essence of Science is independent thinking, hard work and not equipment. When I got my Nobel Prize I had spent hardly Rs 200/- on my equipment."

* * *

Excerpted from *Professor Chandrasekhara Venkata Raman* by S. Bhagavantam, Andhra Pradesh Akademi of Sciences, Hyderabad. and lecture delivered by Dr. G.Venkataraman, J N Fellow, Indira Gandhi Reactor Research Centre *by* Hasan Jawaid Khan

Engrossed in deep study

Explaining his experiment to Jawaharlal Nehru

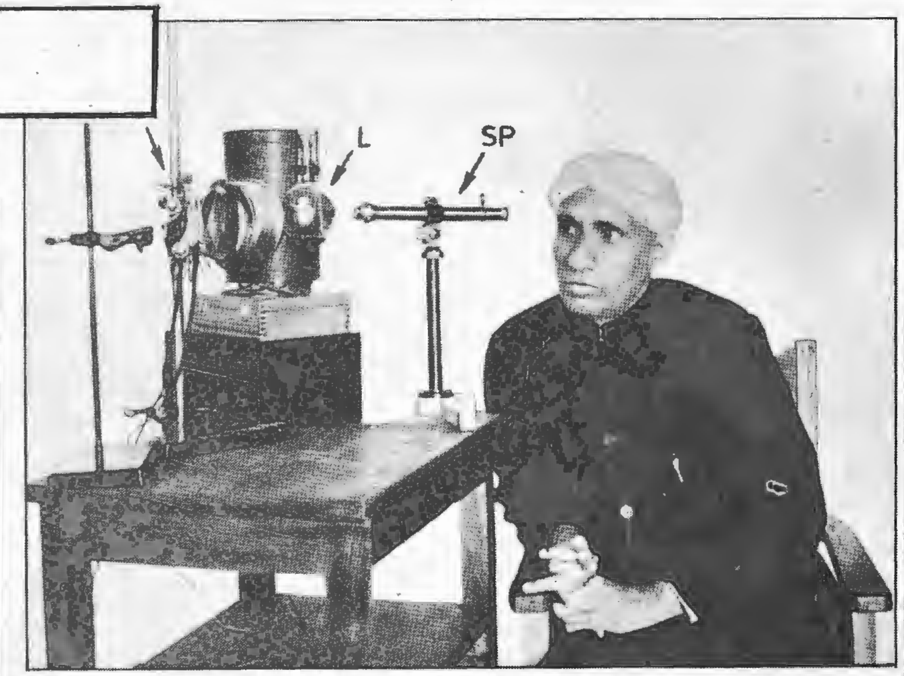
In his lab

Contemplating a model of a crystal

# A RAMAN ALBUM

At the Indian Science Congress 1950 at Indian Institute of Science, Bangalore. Sitting left to right: C.V. Raman, M.S. Thacker, H.C. Dasappa (Minister, Mysore Govt.), Homi J. Bhabha (General President), Maharaja of Mysore. Prime Minister Nehru is seen addressing the gathering.


Discussing the law of quantum reflection in his lecture room at the physics department of the Indian Institute of Science




Prof Raman observing Raman scattering phenomenon