C. V. Raman and the Discovery of the Raman Effect

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Chandrasekhara Venkata Raman (1888–1970), discoverer of the Raman effect, was one of the founders of scientific research in India, Asia's first Nobel Prize winner in science, and a truly remarkable man. The year 1988 was a double anniversary because it was the centennial of his birth and the 60th anniversary of his great discovery. It is therefore appropriate to review his life and work (*1*). First, however, a short summary of the Raman effect will be given so that the importance of the discovery can be better appreciated.

Brief Description of the Raman Effect

A sample is illuminated by a beam of very intense monochromatic light, which today is always from a laser. If the sample is transparent, then by definition nearly—but not quite—all of the light passes through it. A tiny fraction is scattered in all directions. Most of the scattered light has the same frequency as the laser beam; it is called Rayleigh scattering and is a nuisance to a Raman spectroscopist. Raman's great discovery was finding that there are also some additional features in the scattered light that are far weaker than even the Rayleigh scattering and that are now called Raman bands. Their *displacements* from the exciting line, when measured in wavenumbers, are the vibrational frequencies of the sample. (They can also be due to pure rotational spectra of a gas or to various solid state phenomena.)

Because the displacements for a given sample are the same no matter what the frequency of the exciting line may be, the effect does not involve absorption; it is the result of scattering. It depends on a physical process that is entirely different from infrared absorption. Consequently the selection rules and intensities can be quite different for the two techniques, and infrared and Raman spectra are usually complementary. Some bands may be strong in the Raman spectrum and weak or forbidden in the infrared, or vice versa. Raman spectroscopy has been a powerful and widely used technique with many applications in chemistry and physics. More complete descriptions are available in nearly any physical chemistry textbook or monograph on experimental vibrational spectroscopy (*2*).

Raman's Early Life

Chandrasekhara Venkataraman was born on November 7, 1888, in the small village of Thiruvanaikkaval near Trichinopoly in southern India (now Tiruchirapalli, state of Tamil Nadu). He was the second of eight children.[1] Chandrasekhara was his father's name, and Venkataraman was his given name in accordance with the custom in that part of India. (It is also the name of a god.) Later he wrote it as two words, Venkata Raman, so that we now have the Raman effect rather than the Venkataraman effect. His mother was Parvati Ammal, who came from a family known for its Sanskrit scholarship, and his father was Chandrasekhara Iyer, whose family had been landholders for many generations. In India in those days it was a bold step to change one's occupation, but his father did just that and became a teacher in the local English High School and later a lecturer in physics and mathematics at the Hindu college in Vizagapatam.[2] Raman was four years old at the latter time. From his father he acquired an early interest in science and a love of music. He was educated at these two schools and then won a scholarship at Presidency College, Madras, where he was an outstanding student. His professors found him so remarkably intelligent that they exempted him from attending all science classes because they felt that they had nothing to teach him. He received his BA degree in 1904 at the age of 16, winning first place and a gold medal in physics.

His teachers suggested that he go to England for further study, which was the usual thing for the best Indian students to do. However, the Civil Surgeon of Madras disqualified him medically, saying that the English climate would kill him. "I shall ever be grateful to this man," Raman said later. He therefore stayed at Presidency College and worked on his master's degree. During this time he carried out several original investigations. While measuring the angle of a prism with a spectrometer (as many have done), he noted that diffraction bands appear when light is reflected very obliquely from the face of a prism. They formed the subject of his first paper, "Unsymmetrical Diffraction Bands due to a Rectangular Aperture", which was published in *The Philosophical Magazine* (*London*) in 1906, when he was 18 years old (*3*). This was followed by a note in the same journal on a new experimental method for measuring surface tension (*4*). These papers were a remarkable achievement for several reasons. First, to have original research published in a well-known international journal at age 18, and on two very different subjects, is certainly unusual. Second, these papers were submitted by Raman alone and contain no acknowledgment of help received from anyone. They were independent work. Third, research in modern science in India was practically unknown in those days, and Presidency College was a teaching institution with no tradition of research whatever. Doing original work independently at such an early age in this environment forecast Raman's later accomplishments. Figure 1 pictures him at this time.

Raman completed his work for an MA degree with highest honors in January 1907 at age 18. Because scientific careers were closed to Indians who did not study abroad, his teachers advised him to take the competitive examination for civil servants in the Finance Department. He topped the list and soon began 10 years of work for that department, mostly in Calcutta.

Against all Indian conventions, he arranged his own marriage with Lokasundari Ammal, who was then 13½ years old. There is a story that the first time he saw her she was playing a favorite musical piece of his on the vina, an Indian musical instrument. It was a song by a famous Indian composer addressed to the god Rama: "Rama nee samanam evaro"

[1] Raman's elder brother, C. Subrahmanya Iyer, preceded him in the Indian Civil Service and was the father of the Nobel-Prize-winning astrophysicist Subrahmanyan Chandrasekhar.

[2] Mrs. A. V. Narasinga Row College, a junior college.

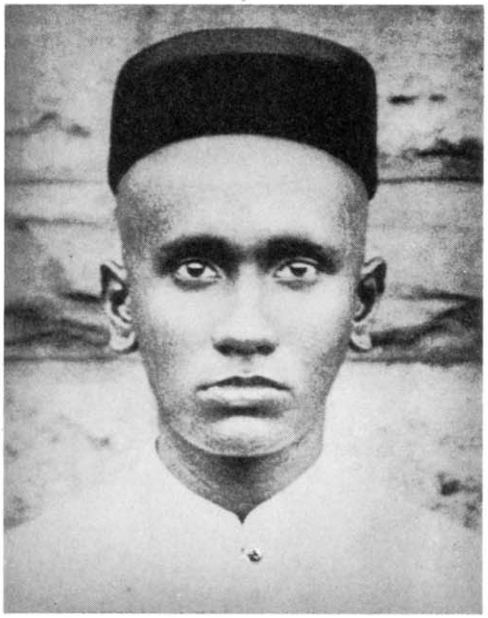

Figure 1. C. V. Raman in 1905, at age 17 while working for his master's degree.

(Rama, is there anyone who can ever be your equal?) (*5a*, *6*). It must have pleased Raman. In later years Lokasundari jokingly insisted that he married her for the extra allowance of 150 rupees per month given to married officers of the Finance Department. In June 1907 the young couple moved to Calcutta, where Raman joined the Finance Department as Assistant Accountant General—at 18½ years old, the youngest one in India.

Reseach in Calcutta

Within six or seven days of reaching Calcutta, while on his way to work by tram, Raman saw a sign saying "The Indian Association for the Cultivation of Science". On his way home that evening he stopped and knocked at the door. It was opened by Ashutosh Dey, who was to become his faithful assistant for the next 25 years. Raman saw a dusty lecture hall and a large laboratory with a lot of even dustier equipment, most of it for lecture demonstrations. The Association was a privately endowed organization that had been founded about 30 years earlier by an Indian benefactor who wanted a combination of the Royal Institution of London and the British Association for the Advancement of Science. It had started off well with many popular and scientific lectures, but there was never any research as the founder had hoped. The institution had slowly declined and become nearly inactive. When Raman appeared and asked whether he could do research there, he was welcomed and promptly given the keys. In a few years he made 210 Bowbazar Street a well-known research address. His routine was to go to the Association at 5:30 a.m., return home at 9:45 a.m. to bathe and hastily gulp his breakfast, take a taxi to the office so he would not be late, go directly from work to the Association at 5 p.m., and reach home at 9:30 or 10 p.m. On Sundays his entire day was spent at the laboratory.

Although he and Dey were the only workers at the Association, 30 papers were produced during the next 10 years from this part-time research. Characteristically, the problems originated from Raman's personal observation and experience, which was true throughout his life. In this period most of his research involved sound: vibrations of the bowed string and the struck string, the sounds of splashes and singing flames, vibrations of Indian and western drums, and the sound of the vina. Raman became a recognized world authority on sound and musical instruments.

In 1917 Raman was offered the newly created Palit Chair in Physics at Calcutta University. Although it meant a sharp reduction in salary (to one-fifth his former stipend (*1*)), he accepted the offer. This caused consternation in the Finance Department because he had become one of its best officers. There was a more serious obstacle: one of the requirements of the Palit Chair was to have been trained abroad. Raman refused to go to England to be trained, and the Vice Chancellor wisely broke the impasse by getting the terms of the endowment changed. Raman could now take research students for the first time, and he had two laboratories in which to work. He held the chair for 16 years (1917–1933).

In 1921 Raman was induced to make his first trip abroad as a delegate to the British Empire Universities' Congress in Oxford. It was a turning point in his career. There he met many of England's greatest scientists, including J. J. Thomson, Ernest Rutherford, and W. H. Bragg. He was impressed by the whispering gallery of St. Paul's Cathedral in London, and he later published three papers on such galleries. Above all he was led to initiate research on the scattering of light, which culminated seven years later with his discovery of the Raman effect. It came about because he was struck with wonder at the beautiful deep blue opalescence of the Mediterranean Sea. His experiments on light scattering began on shipboard during the return voyage. Lord Rayleigh had explained the color of the sky as due to the scattering of sunlight by air molecules. Because blue light is scattered more than red, the sky appears blue. When Rayleigh extended this argument to liquid water, he concluded that because the water molecules are packed closely there would be phase cancellation and no scattering. He therefore wrote "The much admired dark blue of the deep sea has nothing to do with the color of water, but is simply the blue of the sky seen by reflection" (*7*). Raman demolished this explanation by doing a simple experiment during his return voyage. He removed the light reflected from the surface of the ocean by observing the water at Brewster's angle through a polarizing Nicol prism. (Brewster's angle is the angle at which light reflected from a dielectric material is completely plane polarized. For water and blue light, it is about 53° from the normal.) Even with the sky reflection thus extinguished, he saw the sea glowing with a vivid blue that appeared to emerge from beneath the surface. This suggested to him that the blueness of the sea is due to the scattering of light by water. In his note to *Nature* describing these observations, his return address is given as "S. S. Narkunda, Bombay Harbour" (*8*). When he returned to Calcutta he initiated a vigorous program of research on the scattering of light. He wrote 94 papers on the subject between 1919 and 1945, and more than half of them preceded his great discovery.

In 1924 Raman was elected a Fellow of the Royal Society of London, an especially great honor for a foreigner. An episode occurred then that illustrates his supreme self-confidence. At a meeting arranged in his honor, the Vice-Chancellor of Calcutta University congratulated him on this mark of esteem. Raman replied that, while he of course appreciated it, this was not the ultimate; he expected to have a Nobel Prize for India within five years! (*5b*). (It was actually six before he received it.)

Discovery of the Raman Effect

The discovery of the Raman effect occurred early in 1928. Far from being a fortuitous stumbling onto an unexpected observation, it was the culmination of many years of well-thought-out experiments. Numerous papers on the scattering of light had appeared from Raman's laboratory before the discovery was made.

Because Raman scattering is an exceedingly feeble effect, strenuous steps are taken to observe it. Today one uses a powerful light source (a laser), spectrometers with high light-gathering optics, and very sensitive detectors. It may therefore surprise the reader to learn that the discovery was made with ridiculously simple equipment. The source of light was the sun, the spectroscope was a small pocket model, and the detector was a human eye! It was characteristic of Raman to use simple means to obtain profound results.

The experiment was as follows. Sunlight was brought into the laboratory by a heliostat on the roof and was focused into a spherical bulb containing a carefully purified colorless liquid. Before reaching the sample the sunlight was passed through a filter that transmitted only blue light. When the beam was observed from the side, its path through the liquid could be seen as a blue track because of the scattered light. If the observation was then made through a complementary filter, that is, one that absorbed blue but would pass longer wavelengths, the blue track disappeared, but the path of the light in the liquid could still be seen in a hue of longer wavelength, although it was much fainter.

For several years it was thought that this feeble track was due to fluorescence by a small trace of some impurity. Two things finally convinced Raman that this was not the case. (1) The effect was found for 80 different carefully purified liquids. It was unlikely that all of them contained the same impurity. (2) In glycerol the scattered light was more intense, was strongly polarized, and was green, which was an exceptionally large change in wavelength. (Apparently they were observing light shifted by the O–H stretching modes of glycerol, which give an unusually large displacement of about 3400 cm^{-1} to longer wavelengths. However, O–H stretches are notoriously weak in the Raman effect, and it is surprising that they were observable, even though glycerol has a large concentration of such groups.)

Raman concluded that a small fraction of the scattered light had undergone a change of wavelength during the scattering process. It was a case of inelastic scattering—an optical analogue of the Compton effect. A tiny fraction of the scattered light had left some energy behind in the molecule and therefore had less energy and a longer wavelength. This allowed it to pass through the second filter and be seen. On February 16, 1928, Raman and K. S. Krishnan sent a cablegram to *Nature* describing the experiment and giving their explanation. This was published 44 days later, on March 31 (*9*). (It is now known that Raman's first three notes on this subject were sent to *Nature* as cablegrams that he paid for personally (*6*). He was fully aware of the significance of the findings.)

On February 27, 1928, Raman decided to view the path of the light in the liquid with a small, hand-held, direct-vision pocket spectroscope. By the time the equipment was ready the sun had set. The next morning, February 28, the first observation of the Raman effect was made. The path of the light in the sample was viewed from the side through the spectroscope but without the second filter. The scattered light contained the blue color of the incident light, followed by a dark band in the spectrum and then by another region of different color at longer wavelengths.

So far the work had been done with a broad band of exciting radiation selected from the sun's continuum by the blue filter. Clearly it would be helpful to have a monochromatic source. That same day, February 28, the assistant was asked to set up a mercury arc to be used in place of the sun. The mercury arc is a relatively intense source with only a few spectral lines. (Later someone called it "God's gift to Raman spectroscopists".) A filter was placed in the incident beam to remove all wavelengths longer than the intense blue line at 435.8 nm. The small spectroscope showed that light scattered from the sample of benzene contained two lines at longer wavelengths that are not in the incident beam. This observation was made in the evening hours. The following day, February 29, 1928, the discovery was communicated to the Associated Press of India. The first public announcement appeared in a daily newspaper in Calcutta that same day! There is nothing new in the race for priority and the use of the public press for scientific claims.

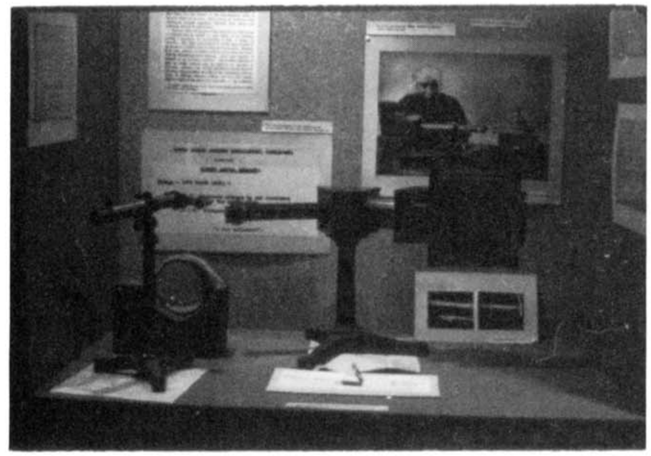

Figure 2. Raman's original apparatus, photographed at the Raman Research Institute in Bangalore. On the left is a small direct-vision spectroscope and on the right a small prism spectrograph.

Figure 3. C. V. Raman and apparatus for Raman spectroscopy.

Raman sent a second note describing these results to *Nature* by cablegram on March 8, 1928, and it was published April 21 (*10*). It is said that a referee rejected the note but that the Editor, Sir Richard Gregory, overruled him and published it anyway (*5c*, *11a*).

Today the minimum cost of equipment for Raman spectroscopy is tens of thousands of dollars. Raman's apparatus for this early experiment consisted of five items: a mercury lamp, an appropriate filter, a large glass condensing lens, a flask of benzene, and a direct-vision pocket spectroscope. It could all have been bought for less than 200 rupees, or about $50 at the prevailing rate of exchange (*12a*, *13a*, *14a*). Seen in hindsight, it was an exceedingly simple experiment, like many other great discoveries. Figures 2 and 3 picture some of his early apparatus.

Soon thereafter spectra were photographed with a Hilger Baby Quartz spectrograph and later with a larger instrument. It was then possible to measure the displacements of the new and very feeble lines from the exciting line. The displacements were found to correspond to vibrational frequencies as measured in the infrared. Raman realized that occasionally in the scattering process a portion of the energy of an incident photon was used to excite a vibration and that the resulting scattered photon had its energy diminished by just that amount.

On March 16, 1928, Raman gave the first detailed announcement before a scientific audience. It was a talk in Bangalore inaugurating the South Indian Science Association and was titled "A New Radiation". In this talk, less than three weeks after the initial discovery, he described all the main features of the effect and its interpretation. The full text, including photographs of the Raman spectrum of benzene, was published on March 31, 1928, as a special issue of the *Indian Journal of Physics* (*15*). Because this journal was then only a year old and had a small circulation, Raman ordered 2000 reprints of the paper and sent copies to leading physicists and research institutions all over the world.[3]

On March 22, 1928, Raman and Krishnan sent a third cablegram to *Nature* entitled "The Optical Analogue of the Compton Effect", which was published on May 5 (*16*). There were only 36 days between sending the first and third cablegrams. This shows how quickly Raman had developed his experimental technique and his understanding of the results. It is also interesting to find that for each of the three notes in *Nature* there was an interval of only 44 days between submission in Calcutta and publication in London.

Competing Work

Obviously Raman was anxious to establish his priority, and it is a good thing that he did so because related work was being done in both Paris and Moscow. In Paris, Rocard had done theoretical work that predicted Raman scattering, but he had delayed publication pending experimental verification. His colleague Cabannes was trying to observe the effect but was unsuccessful because he had chosen to work with gases. Scattering is very feeble in gases because of the low molecular concentration. When Rocard and Cabannes saw Raman's first two notes, they quickly presented their results (*17, 18*).

In Moscow, Landsberg and Mandelstam discovered the effect independently and reported a new line in the scattering of mercury radiation from a quartz crystal. They referred to Raman's first two notes as follows (*19*):

> Whether and how far the phenomenon observed by us is related to that observed by Raman we are not able to decide at the moment because his description is too terse.

Naming the Effect

Raman had termed the effect simply "A New Radiation". In 1928, the year of the discovery, Pringsheim wrote a detailed report on it. He concluded that the effect discovered by Raman was an entirely new phenomenon and suggested that it should be called the "Raman effect" and the spectrum of new lines the "Raman spectrum" (*20*). This terminology was quickly adopted by all except the Russians, who refused to use the term "Raman effect" until the 1960's or 1970's and instead called it "combination scattering".

Spread of Raman Studies

The significance of the Raman effect was recognized immediately. At that time measurement of vibrational and rotational spectra by absorption in the infrared was so difficult that it was being done in only six to eight laboratories around the world. Spectroscopists needed a more convenient method. The Raman effect suddenly provided one by giving the desired data as difference frequencies measured in the visible region. All that was required was a mercury arc, a suitable filter, and a spectrograph, and since these were available in nearly every laboratory, many scientists entered the field. It seemed that every common colorless liquid was examined, its Raman shifts were tabulated, and a paper was written. Initially it was puzzling why some frequencies agreed with known infrared values but others did not. In 1934 Placzek published a semiclassical theory of Raman scattering that explained this observation on the basis of symmetry and selection rules (*21*).

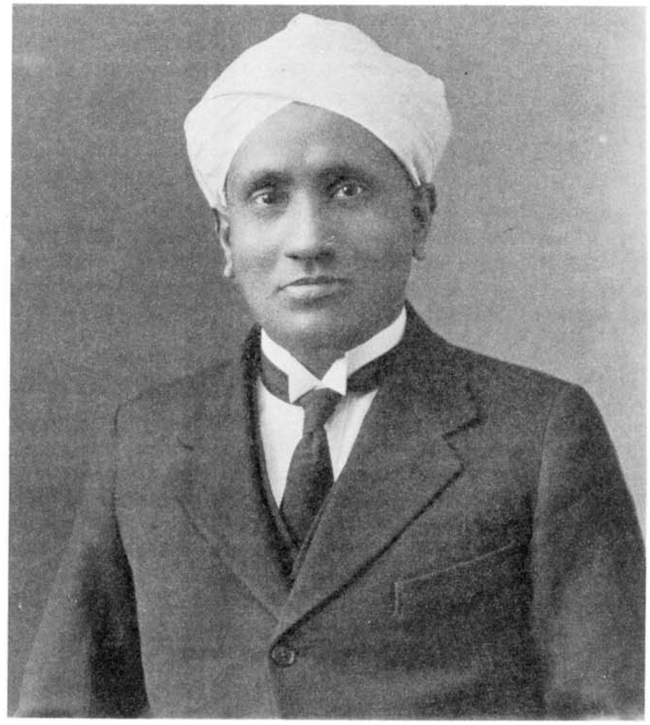

Figure 4. Sir C. V. Raman. Taken in 1930, the year he received the Nobel Prize. Reproduced by permission of the AIP Niels Bohr Library.

Studies of the Raman effect proliferated rapidly. As early as 1928, the year of the discovery, 58 papers appeared on it! In 1929, an additional 175 papers were published (*14b, 22*). (Incidentally, one of the latter was by C. P. Snow, the scientist and author who later wrote about the two cultures (*23*)). In the first 10 years after the discovery (1928–1937) 1785 papers were published on the subject (*14b*), and more than 2500 compounds were studied (*11b*). Then about 1946 commercial infrared spectrometers became available, and infrared dominated the scene for the next 20 years. It replaced Raman spectroscopy almost completely except for some fundamental studies that continued to be carried out in a few laboratories.

In 1962 S. P. S. Porto and Darwin Wood used a laser in Raman spectroscopy for the first time (*24*). The advent of the laser revived the technique dramatically because lasers are ideal sources for Raman studies. Their availability led to a great resurgence of work in the field. In the first 50 years of Raman spectroscopy (through 1978) nearly 23,600 original papers were published on the subject (*11c*). The pace continued, for in the five-year period 1977–1982 a total of 10,384 papers appeared in *Chemical Abstracts* having the word "Raman" in their titles (*25*). The importance of Raman spectroscopy has been further augmented by the use of the resonance Raman effect, of ultraviolet excitation, and of Fourier transform techniques. Raman spectroscopy has been a powerful and useful technique for 60 years, and its discoverer deserves our honor.

Raman's Nobel Prize

Raman was knighted in 1929, and in 1930 was awarded the Nobel Prize in Physics (*26*). (Figure 4 is a formal portrait taken that year.) This was remarkably soon after his discov-

[3] The paper was written immediately upon his return to Calcutta, was printed overnight, and copies were mailed the next day (*1*)! It has been reprinted in ref *31b*.

ery and made him Asia's first Nobelist in science. There are two revealing stories concerning it.

Word of the Nobel award came to Raman in his laboratory via a telephone call from one of the news agencies in Calcutta. The call was taken by a student, S. Bhagavantam, who rushed excitedly to his mentor to tell him the great news. After hearing it, Raman said "Am I the sole Awardee, or must I share the bed with strangers?" (*13b*). He was the only one.

The Nobel Prizes were announced in early November 1930 and presented on December 11. In this short interval it would have been difficult for Raman to arrange steamship passage that would get him from India to Stockholm in time for the ceremony. In July of that year he had had the audacity to book passage for his wife and himself in anticipation of the award so that they would be able to leave promptly. Not only did he book passage but also he stated publicly that he had done so (*5b*, *13c*)! He was a man of supreme confidence and towering ego.

Work on Diamonds

Shortly after the discovery of the Raman effect in 1928, Raman casually noticed that his younger brother, C. Ramaswamy, was wearing a diamond wedding ring. The brother, then a research student in physics, made a brief spectroscopic examination of the stone and was the first to report the strong, sharp Raman line at 1332 cm^{-1} (*13d*, *27*). Raman's student Bhagavantam repeated the experiment in Raman's laboratory in Calcutta (*28*). This aroused Raman's interest in diamonds, an interest that lasted until the end of his life. He and his students needed many diamonds for their studies, in all sizes, shapes, and qualities. How does a university professor obtain them? By borrowing from shops and wealthy owners and by purchases. Raman made an extensive study of the value of diamonds and became an expert who could compete successfully with professional dealers. He bought many diamonds after a personal examination of each one, and he ultimately acquired an impressive collection of about 500 of them.[4]

Quite early Raman borrowed two very large diamonds from the Maharajah of Darbhanga. One was a 20-carat colorless and flawless stone. The other was an extraordinary gem of 143 carats (~28 g or 1 oz), clear, pale yellow, and about 3 cm in linear dimensions. The loan was for a limited time, and Raman had to sign a security bond for a considerable sum of money. He then gave the two diamonds to his student Bhagavantam to study intensively for the next 48 hours. He cautioned Bhagavantam to guard them carefully and told him how history is replete with stories of professional thieves who followed great Indian diamonds to watch for opportunities to steal them. For two nights Bhagavantam slept under the spectrograph while exposures were being made (*13d*), and then the gems were returned safely to their owner. The publication that resulted (*29*) was summarized in an abstract journal. According to Bhagavantam the abstractor included a statement that the diamond studied had weighed 140 carats and followed this with three or four exclamation marks (*13b*).[5]

[4] Several sources state that Raman used most of his $40,000 Nobel Prize money to buy diamonds (e.g., (a) Wallechinsky, D.; Wallace, I., Eds. *The People's Almanac #2*; Bantam: New York, 1978; p 1021. (b) Asimov, I. *Asimov's Biographical Encyclopedia of Science and Technology*, 2nd ed.; Doubleday: New York, 1982; p 718). S. Ramaseshan, who was a student of Raman's and knew him well, says that this is not correct, that Raman spent only a small fraction of his prize money on diamonds. He lost most of it in the speculative investment mentioned later (*6*).

[5] The authors have not been able to find this abstract. Ref *29* is summarized in *Sci. Absts.* **1931,** *34A*, abstract 1238, and in *Chem. Abstrs.* **1931,** *25*, 1159, but there is no mention of the 143-carat diamond and no exclamation mark.

Raman knew that some of the world's greatest diamonds have come from India, including the Great Mogul, Koh-i-noor, Orloff, Hope, Shah, and Regent. In fact all the great diamonds of antiquity must have been Indian. The diamonds of Golconda, a cutting center, are legendary. Only a few years before his death Raman spent a great deal of time studying the geology and geography of the Krishna Valley and nearby rivers because he knew that at one time 60,000 people were engaged in diamond mining there, and he thought that it still might have a future (*12b*, *13b*).

Work in Bangalore

In April 1933 Raman left Calcutta to assume a new post in Bangalore as Director of the Indian Institute of Science. The Institute had been founded in 1909 by J. N. Tata, a wealthy industrialist and visionary. There Raman studied the colors of bird plumage, seashells, soap bubbles, and old iridescent glass. He also worked on a wide range of problems on ultrasonic waves, scattering of light, magneto-optical properties, and X-ray topography. Unfortunately, there was friction with the governing board, and in 1937 he was forced to resign the Directorship but continued as Professor of Physics until 1948. That year the newly independent Government of India made him its first National Professor, and he left the Indian Institute of Science.

Raman had planned to use his life's savings to start a small institute for himself where he could work independently. However, at age 60 he lost most of his savings in a speculative investment. Most people would have been totally discouraged, but he went around the country to raise money to carry out his project. "Our greatest men were beggars," he said, "The Buddha, Shankara, and Gandhi." He collected enough to build his institute but not enough to maintain it. With the advice of a former student he then used the remainder of his savings to start a factory to manufacture Welsbach mantles for kerosene lamps. The income from it was sufficient to support the operation of his Raman Research Institute and keep it independent of government grants (*30*). Raman again took students and did work on a great variety of topics, including optical studies of his beloved minerals, the physiology of vision (43 papers), and the colors of flowers. (He was one of the first to study flowers spectroscopically.) The institute building is shown in Figure 5. It is now in part a research laboratory and in part a museum. The latter displays his minerals and crystals, including the diamonds. There are also collections of other objects that he studied such as musical instruments, iridescent bird feathers, and iridescent beetles.

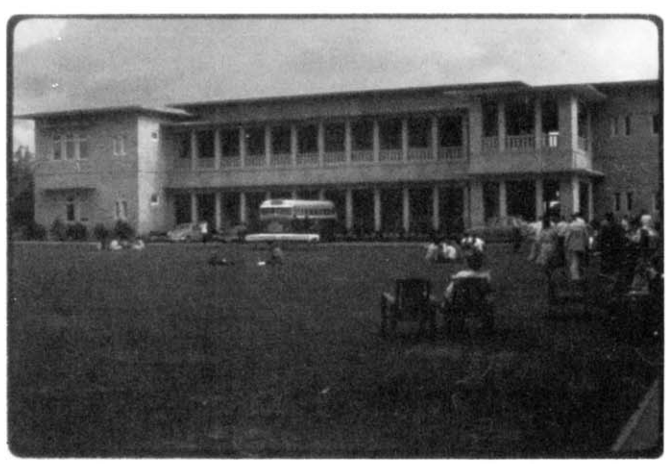

Figure 5. The Raman Research Institute, Bangalore, photographed during a meeting in 1978.

Figure 6. Raman in the 1960's.

Raman's Last Years

Figure 6, taken in the 1960's, shows Raman during the final decade of his life. Sad to say, it was an unhappy period. He was estranged from his two sons. He became involved in an unfortunate polemic with Max Born over the lattice vibrations of diamond that lasted many years. The affair was ironic because they had been good friends earlier, and in the late 1930's, when many scientists were trying to leave Hitler's Germany, Raman had tried to arrange an appointment for Born at the Indian Institute of Science in Bangalore.

Raman became a recluse. He built a high wall around his institute and put up a sign stating that visitors were not welcome. It was a period of agony and torment for him. Fortunately, he came out of this despondency toward the end of his life. He died in Bangalore on November 21, 1970, at the age of 82 and was cremated in his beloved rose garden on the grounds of his institute.

Shortly after his death Prime Minister Indira Gandhi telephoned a close acquaintance of Raman's to ask whether his widow would have sufficient financial resources. If not, perhaps the government could help. Assistance was not needed, but the event indicates Raman's stature in India as well as Mrs. Gandhi's thoughtfulness (*6*).

One of the authors (FAM) met Lady Raman by chance while in India for the 50th anniversary of the Raman effect. Did she remember the period of the discovery? Yes, very well, for it was an exciting time. She had not been trained in science, but she had tried to aid her husband as best she could. For example, on some occasions she helped adjust the heliostat by going to the roof and turning the mirror as he called instructions from the laboratory below.

Figure 7 pictures the commemorative stamp that India issued in Raman's honor the year following his death. It shows his portrait and signature, the Raman spectrum of carbon tetrachloride, and a diamond, the substance to which he devoted so much study.

Evaluation of Raman's Work

Raman was a great scientist. Although self-trained and working in an environment where research was very difficult, he made notable contributions in many areas and became a giant of international, as well as Indian, science (Fig. 8). His career extended over 66 years, and in that time he published more than 450 papers, while his students published about three times that many under his direction (*31*). The research involved an amazing variety of topics, many of which have not even been mentioned here. Most of it resulted from his perceptive observation of everyday things. He relied greatly on intuition, and he was able to design simple experiments that gave profound results. In the course of his life he received many honorary degrees, memberships, prizes, and other honors (*12c*).

Raman had a great zest for life. He enjoyed nature immensely and got great pleasure from such things as the beauty of crystals and the color of birds, flowers, or the sky. He had a gift for seeing questions in such phenomena that were worth investigating, and he demonstrated repeatedly that a deeper understanding of everyday observations can lead to fundamental discoveries. He often said "Make full use of what you have before you ask for what you do not have" and "The essence of science is independent thinking and hard work, and not equipment" (*13a*).

Raman was also a proud and sometimes arrogant man and a supreme egotist. He could become very angry and be very difficult, but he could also be charming and delightful company. He was a great teacher and a superb lecturer who drew large audiences. His sense of humor was excellent, and he could make his listeners—one or hundreds—roar with laughter.

Figure 7. Commemorative stamp issued by India in 1971 after Raman's death.

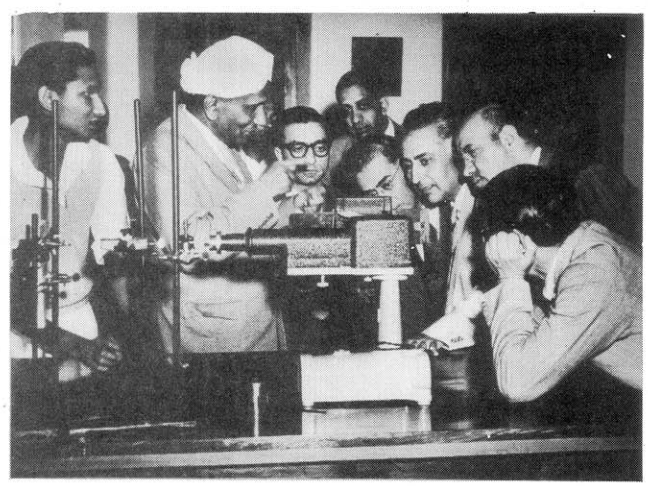

Figure 8. Raman with interested visitors to his laboratory.

His discovery of the Raman effect was very important, but so also was his influence on Indian science. He stimulated interest in it and obtained support for it. He contributed to the building up of nearly every research organization in India. He trained hundreds of students, encouraged and inspired them, generously gave them credit, and sent them to important posts throughout the country. He left a great legacy.

Acknowledgment

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