CHAPTER II

Scattering of light by gases

11. In view of the very satisfactory explanation by Lord Rayleigh and Schuster of the blue of the sky and the observed degree of transparency of the atmosphere on the basis of molecular diffraction, it became obviously a question of great importance to detect, and if possible, to measure, the scattering of light by dust-free air in the laboratory. The first successful attempt in this direction was made by Cabannes.* Later work on the experimental side of the subject, including scattering by other gases and vapours, has been done by Prof. R J Strutt† (the present Lord Rayleigh), Cabannes‡ himself, Smoluchowski§ and Gans‖.

12. The methods adopted by these investigators are essentially similar. The gas is contained in a cross-tube dead-blacked inside. An intense beam of light is sent along one of the tubes, and the scattered light is observed in a perpendicular direction. Owing to the extreme faintness of the scattered light, the background has to be perfectly black in order that the track of the beam may be visible. The best arrangement to secure this is that adopted by Strutt in his later work. He used as a prolongation of the observation tube a curved horn blown out of green glass and covered outside with black paint. The object of the glass horn is to reflect any stray light that falls on its mouth repeatedly towards the narrow end and thus to absorb it. With such a background the track of a beam of sunlight concentrated by a lens in dust-free air is easily visible. Of course, the gas under observation has to be carefully freed from dust before introduction to the chamber by *slow* filtering through a tube tightly packed with cotton wool, and in the case of gases attacked by light, care has to be taken to exclude rays having any chemical action.

Intensity and polarisation of the scattered light

13. According to Lord Rayleigh's calculation, the intensity of the light scattered by one cubic centimetre of a gas having symmetrical molecules in a direction

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*Cabannes, *Comptes Rendus*, **160**, p. 62, 1915.
†R J Strutt, *Proc. R. Soc. London*, **94**, p. 453, 1918.
‡Cabannes, *Ann. de Physique* Tome **15**, pp. 1–150.
§Smoluchowski, *Bulletin Academic Cracovie*, p. 218, 1918.

perpendicular to the incident beam should be proportional to $(\mu - 1)^2$.* The experiments of Strutt led him to the conclusion that this was so, within the limits of experimental error. The following table gives his results:

Gas	Scattered light	Refractivity
Air (assumed)	1·00	1·00
Hydrogen	0·230	0·229
Nitrous oxide	3·40	3·12
Ether vapour	26·0	27·1

The careful experiments of Cabannes,† showed however, that although the law was true in its main features, there were differences in the value of the observed scattering from the calculated values too large to be explained as being due to experimental error.

14. On the assumption of symmetrical molecules, the light scattered in a direction perpendicular to the incident beam should be completely polarized with the electric vector perpendicular to the plane containing the incident and scattered beams. Strutt examined the polarisation of the scattered beam and obtained for the first time the remarkable result that, in many gases, the scattered light is only partially polarised.

The experimental method adopted by Strutt for the examination of polarisation was to place a double image prism with its principal section perpendicular to the incident beam in the path of the scattered light and obtain an image of the luminous track on a photographic plate. Two images were in general obtained, a strong one with the electric vector in the direction indicated by the ordinary theory and a weak one with the electric vector in the perpendicular direction. The two images could be made of equal intensity by inserting a nicol between the double image prism and the camera and properly orienting the nicol, and from the known angle between the principal planes of the nicol and double image prism, the ratio of the weak component to the strong could be calculated.‡

15. The imperfect polarisation of the light scattered by gases has also been observed *visually* and measured in experiments undertaken at the author's

*Cabannes (*loc. cit.*) has calculated the scattering coefficient on the basis of the electromagnetic theory and obtains a value $[(\pi^2/2n\lambda^4)](\mu^2 - 1)^2$. When $(\mu - 1)$ is small, this reduces to $[(2\pi^2)/(n\lambda^4)](\mu - 1)^2$. (See also Schuster *Proc. R. Soc. London*, **98**, p. 248.)

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‡In his earlier work, Strutt used a series of graded blackened photographic plates in the path of the

suggestion by Mr K R Ramanathan at Calcutta. For this purpose, an apparatus was used similar to that of Lord Rayleigh and the gas was illuminated by means of a concentrated beam of sunlight, great care being taken to shield the observer's eye from extraneous light. With air at ordinary pressure, the intensity is not sufficient to make more than a rough photometric estimate feasible, but when we use carbon dioxide which scatters nearly three times as much light as air, fairly accurate measurements are possible by visual observation. Such a comparison leads to a value 10% for the ratio of the weak to the strong components as against 9·9% obtained by Cabannes and 11·7% obtained by Strutt. More accurate measurements can be made visually with the gases at higher pressure and an apparatus is nearly ready for the purpose.

16. I give below for comparison the values of the ratios of the weak component to the strong for different gases obtained by Strutt and Cabannes.

The figures give the weak component as a percentage of the strong component.

Gas	Strutt	Cabannes
H_5	3·83	Between 1 and 2
N_2	4·06	” 2·5 and 2·8
Air	5·0	” 3·7 and 4·0
O_2	9·4	” 5·1 and 5·4
CO_2	11·7	” 9·5 and 9·9
Argon	$<0·5$	$<0·8$
He	$<6·5$	

Strutt estimates the error of his results to be not more than 5%. In view of the great care that Cabannes also seems to have bestowed on his work, it is remarkable that Strutt's results should be systematically higher than those of Cabannes.* One reason that suggests itself for this systematic difference is the difference in the quality of the light employed by the two experimenters. Strutt used a carbon arc, while Cabannes used a mercury arc, the active radiations being 4358, 4046 and 3650 A.U., the rest of the radiations being filtered out. Since both the experimenters used the photographic method, it is the violet and ultraviolet that would have been most effective. Considering the very great intensity of the carbon arc in the region of 3000–4000 A.U., it is possible that the effective wavelength in the case of Strutt's experiments was smaller than in those of Cabannes. The question of the influence of wavelength on the ratio of the components in the imperfect polarisation of the scattered light is one of great importance, and is being examined experimentally by Mr Ramanathan at the author's laboratory.

Explanation of imperfect polarisation

17. The imperfect polarisation of the scattered light has been explained on the basis of a suggestion made tentatively in a much earlier paper by the late Lord Rayleigh* that the molecules have three principal axes of symmetry and that they are oriented at random. His method consists in resolving the primary vibrations along three mutually perpendicular directions in the molecule and introducing separate coefficients of radiation for the different axes and integrating the effect due to a large number of molecules in all possible orientations. He obtains for the ratio of the weak component to the strong in the scattered radiation the value

$$\frac{i}{I}=\rho=\frac{A^2+B^2+C^2-AB-BC-CA}{3(A^2+B^2+C^2)+2(AB+BC+CA)}$$

where A, B, C are three parameters characteristic of the molecule and to some extent, dependent on the frequency of the incident light. Taking the imperfection of polarisation into account, Cabannes has shown that the intensity of the scattered light is not given by the formula

$$\frac{\pi^2}{2}(\mu-1)^2\frac{1}{N\lambda^4},\quad \text{but by}\quad 3\pi^2\frac{(\mu-1)^2}{N\lambda^4}\frac{1+\rho}{6-7\rho}.$$

Since ρ differs for different gases, the intensity of the scattered light would not be proportional to the square of the refractivity, but to

$$(\mu-1)^2\frac{1+\rho}{6-7\rho}$$

18. The following table shows the nature of the agreement between the observed† and calculated values according to Cabannes:

19. Sir J J Thomson* has calculated the ratio of the weak to the strong component in the light scattered at different angles with simple molecular models for the hydrogen molecule and comes to the conclusion that, with two positive charges at A and B and two electrons rotating in a circle at the opposite ends of a diameter in a plane bisecting AB at right angles, the ratio of the minimum to the maximum intensity of the components of the scattered light would only be 0·4% while the actual experimental value is nearly 4%. But with two electrons kept in equilibrium by a modified inverse square law, a value for the ratio nearly the same as the experimental ratio is obtained. His calculations indicate that although the

Ratio of intensities of scattered light

	Observed	$\frac{(\mu_1-1)^2}{(\mu_2-1)^2}$	$\frac{(\mu_1-1)^2\frac{1+\rho_1}{6-7\rho_1}}{(\mu_2-1)^2\frac{1+\rho_2}{6-7\rho_2}}$
$\frac{\text{Argon}}{N_2}$	0·829	0·90	0·823
$\frac{CO_2}{\text{Argon}}$	3·31	2·53	3·12
$\frac{CO_2}{\text{Air}}$	2·62	2·35	2·65
$\frac{CO_2}{O_2}$	2·93	2·80	3·07
$\frac{H_2}{O_2}$	0·255	0·276	0·255

polarisation is imperfect in a direction perpendicular to the incident beam, it may be perfect in a different direction. Experimental work on the intensity of scattering and polarisation in other than transverse directions might therefore prove of interest. Born[†] and later, Born and Gerlach,[‡] have tried to calculate the scattering on the basis of the Bohr-Sommerfeld models of the molecules. Their results also indicate a dependence of the imperfection of polarisation on the frequency of the incident light, the imperfection increasing as the natural frequency of the molecule is approached. The values which Born obtains for the imperfection of polarisation do not however agree with the experimental results. The position appears to be, therefore, that models based on the quantum theory have not yet succeeded in solving the problem of molecular scattering.

20. It is also pretty certain that Rayleigh's law must break down when the frequency of the incident light is sufficiently increased. The phenomenon of resonance radiation is sufficient proof of the fact. The transition from ordinary scattering to resonance would be very interesting to study, although the subject is beset with considerable experimental difficulties. It would also be of interest to study by the scattering absorbing gases like chlorine on either side of the region of absorption.