

LIGHT SCATTERING FROM GEL-FORMING SYSTEMS DURING AND AFTER SETTING

PART I. ALUMINIUM MOLYBDATE AND THORIUM ARSENATE GELS: INTENSITY MEASUREMENTS

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(Communicated by K. R. Dixit, F.N.I.)

(Received February 2; read May 7, 1954)

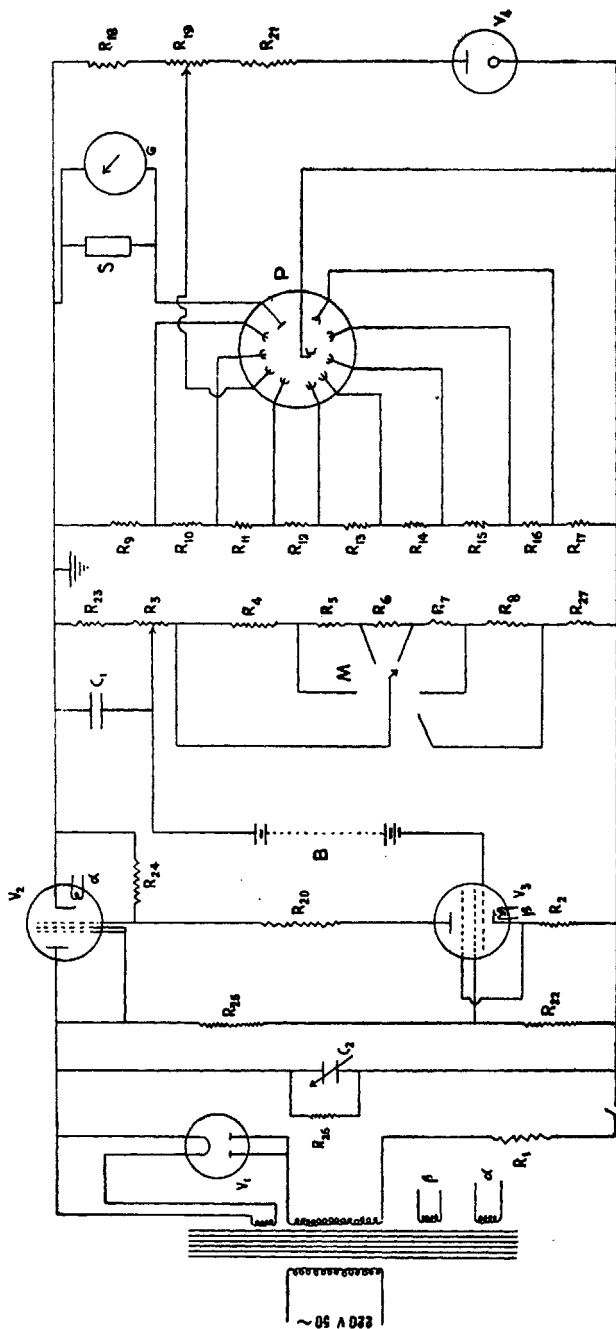
The study of the distribution of intensity of light scattered at different angles gives an idea of the size and shape of particles in solution or in suspension. The theoretical calculations of Mie (1908), Shoulejkin (1924), Blumer (1925, 1926), and Krishnan (1934) have shown that the ratio of the intensity of light scattered at an angle in the forward direction to that scattered at an angle in the backward direction situated symmetrically about the transverse direction is unity for small particles and that this ratio increases with an increase in the size of the particles. Recently, Doty and Steiner (1950) have given a Table showing the variation in the values of the ratio $I_{45^\circ}/I_{135^\circ}$ with particle size when the shape of the particles is similar to that of either rods or spheres or coils. So far the intensity of light scattered in the transverse direction only has been studied during the setting of several gel-forming systems (cf. Mardles, 1923; Krishnamurti, 1929, 1930; Ramaiah, 1937; Prasad and Guruswamy, 1944; Prasad and Doss, 1949; Desai and Sundaram, 1953; Desai, 1953). The total intensity of light scattered by 1 cm. layer of several gel-forming systems has been measured by Katti (1948, 1949, 1953). However, no work has been reported on the measurement of the angular variation of the intensity of light scattered from gel-forming systems. The present investigation deals with the measurement of the intensity of light scattered at 45° (forward), 90° (transverse) and 135° (backward) to the direction of the incident light from gel-forming systems of aluminium molybdate and thorium arsenate during their setting. The depolarization factors of the transversely scattered light have also been determined for one concentration of each of these gels in order to study the density and anisotropy scattering during their gelation.

EXPERIMENTAL

A. Preparation of the gel-forming systems:—

(i) *Aluminium molybdate gels.*—These gels were prepared by the method used by Desai (1952). Varying amounts of 20% solution of aluminium nitrate (A_1) and 10% solution of potassium molybdate (B_1) were mixed and the total volume (T.V.) was made to 50 c.c. in all cases by the addition of the requisite amount of distilled water. The turbid gel-forming mixture obtained immediately on mixing the two solutions was shaken till it became clear and the test-tube containing the clear liquid was transferred immediately to the observation bath for scattering measurements.

(ii) *Thorium arsenate gels.*—These were prepared by the method of Prakash and Dhar (1929). Varying amounts of 6% solution of thorium nitrate (A_2) and 10% solution of potassium arsenate (B_2) were mixed and the total volume (T.V.)



Circuit diagram of apparatus used for intensity measurements

- | | | |
|--------------------------------------|---|--|
| B — 90 V dry battery pack | R₃-R₈ — 10,000 ohms wire wound | R₂₁ — 30,000 ohms, 5 watts |
| C₁ — 0.01 μF | R₉-R₁₇ — 10,000 ohms | R₂₂ — 50,000 ohms |
| C₂ — 2.0 μF | R₁₈ — 20,000 ohms, 2 watts | R₂₃ — 140,000 ohms |
| G — 'spot' galvanometer | R₁₉ — 20,000 ohms, 2 watts, | R₂₄ — 250,000 ohms |
| P — photomultiplier RCA '931A | variable | R₂₅ — 500,000 ohms |
| M — manual control | R₂₀ — 25,000 ohms | R₂₆ — 1 megohm |
| S — shunt | | R₂₇ — 1 megohm wire wound |

was made to 48 c.c in all cases by adding the necessary amount of distilled water. The clear mixture was taken in a test-tube which was immediately placed in the observation bath for scattering measurements.

B. Measurement of the depolarization factors:—

The depolarization factors of the transversely scattered light were measured by Cornu's method taking all the necessary precautions.

C. Measurement of intensity of light scattering:—

The intensity of scattered light was measured by a photoelectric method using a photomultiplier. The apparatus consists of two parts, viz. (i) the power supply unit and (ii) the photomultiplier unit.

The power supply unit was built up using the circuit suggested by Zimm (1948). A detailed description of the circuit has been given by Zimm and only the circuit diagram is given here (cf. Plate XXII) for reference. The unit was adjusted to supply a steady current of two milliamperes at 600 volts.

The photomultiplier unit was based on the circuit given by Muller, Garmon and Droz in their book 'Experimental Electronics' (p. 76), and the circuit diagram is given in Plate XXII. The photomultiplier unit was built up on a small metal chassis which was properly earthed. The photomultiplier tube RCA 931A was placed in a metal cover mounted on the chassis. The metal cover had an extended side tube of metal through which the scattered light could enter and fall perpendicularly on the sensitive vane of the photomultiplier.

The test-tube containing the gel-forming mixture was placed in the centre of a beaker containing water at 30°C. which was used as the observation bath. The beaker was painted black on the outside and a black paper was wrapped round it. There were two slits on the paper diametrically opposite each other, which served as the entrance and the exit of the incident light. On one side of the beaker, slits were made corresponding to the angles of scattering studied. Care was taken to see that there was no black paint on the beaker at the places corresponding to these slits. All the slits were 6 mm. \times 6 mm. A slit of the same size was attached to the side tube of the metal cover of the photomultiplier tube.

A parallel beam of light, obtained by placing a lens at a suitable distance from a 400 watts mercury vapour lamp, was passed through the test-tube containing the gel-forming mixture. The photomultiplier unit was placed in front of a slit on the beaker in such a way that only the light scattered at a particular angle fell perpendicularly on the sensitive vane of the photomultiplier tube. The current generated was measured by a 'Spot galvanometer' manufactured by the Cambridge Instrument Company Ltd. The sensitivity of the galvanometer was 110 divisions per microampere, each division on the galvanometer being equivalent to 1.6 mm. Since the intensities of light scattered at different angles by different gels were not the same, suitable shunt resistances were used in each case.

Care was taken to see that the track of incident light was exactly horizontal. It was ascertained that the deflections on the galvanometer were due entirely to the scattered light falling on the photomultiplier and all stray light was eliminated by using suitable screens. The distance between the photomultiplier and the centre of the test-tube was kept the same and constant at all the angles of scattering. The solutions used for preparing the gel-forming mixtures were made dust-free by repeated filtration through sintered glass filters.

RESULTS

Since different shunt resistances were used in each case, from the readings obtained have been calculated the deflections which would have been observed if

no shunt resistances were used with the galvanometer. The deflections thus calculated have been plotted against the time (in minutes) elapsed from the moment the test-tube containing the gel-forming system was placed in the observation bath and the graphs obtained are shown in Figs. 1 to 6. From these graphs the values of intensity at definite intervals of time have been interpolated and the values are given in Tables I to VI, in which t represents the time interval in minutes, I_{45° , I_{90° and I_{135° represent the intensity of the light scattered at 45° , 90° and 135° , respectively, and T denotes the time of setting of the gel as determined by Fleming's method, that is, the time interval at which the gel-forming mixture just ceases to flow even when the test-tube is inverted. The other notations used, namely, A_1 , A_2 , B_1 , B_2 and T.V. have already been mentioned in the experimental section.

TABLE I

Intensity measurements

Aluminium molybdate gels $A_1 = 21.0$ c.c. $B_1 = 20.0$ c.c.T.V. = 50.0 c.c. $T = 58' 50''$

t in minutes	I_{45°	I_{90°	I_{135°	$I_{45^\circ}/I_{135^\circ}$
5	2.0	2.0	2.0	1.00
10	3.0	3.0	3.0	1.00
15	5.0	4.0	4.5	1.11
20	8.0	6.0	6.0	1.33
25	15.0	11.5	11.0	1.36
30	26.5	19.5	18.0	1.47
40	86.0	44.5	44.0	1.95
50	143.0	76.0	73.5	1.95
60	186.5	95.0	88.5	2.11
70	205.0	103.5	95.5	2.15
80	220.0	108.5	99.0	2.22

TABLE II

Intensity measurements

Aluminium molybdate gels $A_1 = 25.0$ c.c. $B_1 = 20.0$ c.c.T.V. = 50.0 c.c. $T = 66' 45''$

t in minutes	I_{45°	I_{90°	I_{135°	$I_{45^\circ}/I_{135^\circ}$
5	1.0	1.0	1.0	1.00
10	2.0	2.0	2.0	1.00
15	3.0	3.0	3.0	1.00
20	5.0	4.0	4.0	1.25
25	8.5	6.0	6.5	1.31
30	16.0	9.5	11.0	1.45
40	50.0	26.5	28.5	1.75
50	104.5	57.0	57.0	1.83
60	153.0	81.5	78.0	1.96
70	183.0	93.0	87.5	2.09
80	202.0	97.0	91.0	2.22

TABLE III

Intensity measurements

Aluminium molybdate gels $A_1 = 25.0$ c.c. $B_1 = 24.0$ c.c.T.V. = 50.0 c.c. $T_1 = 51' 40''$

t in minutes	I_{45°	I_{90°	I_{135°	$I_{45^\circ}/I_{135^\circ}$
5	4.0	4.0	4.0	1.00
10	4.5	4.5	4.5	1.00
15	8.0	7.0	6.0	1.33
20	12.5	10.5	10.0	1.25
25	25.0	19.5	19.5	1.28
30	50.0	34.0	33.5	1.49
40	135.0	69.5	68.0	1.99
50	183.5	95.0	90.0	2.04
60	204.0	109.0	98.5	2.07
70	219.0	116.0	102.0	2.15
80	230.0	120.0	104.0	2.21

TABLE IV

Intensity measurements

Thorium arsenate gels $A_2 = 36.8$ c.c. $B_2 = 4.8$ c.c.T.V. = 48.0 c.c. $T = 70' 50''$

t in minutes	I_{45°	I_{90°	I_{135°	$I_{45^\circ}/I_{135^\circ}$
5	2.0	0.8	1.0	2.00
10	4.0	1.8	2.0	2.00
15	9.0	4.5	4.0	2.25
20	18.0	8.3	7.3	2.47
25	32.0	12.3	10.8	2.96
30	50.5	16.0	13.8	3.66
40	76.5	20.8	18.0	4.25
50	90.0	23.3	21.0	4.29
60	98.5	25.0	22.0	4.48
70	104.5	26.5	22.5	4.64

TABLE V

Intensity measurements

Thorium arsenate gels

$A_2 = 40.0$ c.c. $B_2 = 4.8$ c.c.

T.V. = 48.0 c.c. $T = 55' 30''$

t in minutes	I_{45°	I_{90°	I_{135°	$I_{45^\circ}/I_{135^\circ}$
5	1.0	0.8	0.8	1.25
10	1.5	1.0	1.3	1.15
15	3.0	2.3	2.3	1.30
20	9.0	4.5	5.0	1.80
25	20.5	7.8	7.5	2.73
30	30.0	10.5	10.0	3.00
40	45.0	12.8	12.8	3.52
50	55.0	14.8	13.8	3.99
60	62.0	16.3	14.8	4.19
70	66.5	17.5	15.5	4.29

TABLE VI

Intensity measurements

Thorium arsenate gels

$A_2 = 40.0$ c.c. $B_2 = 6.4$ c.c.

T.V. = 48.0 c.c. $T = 45' 15''$

t in minutes	I_{45°	I_{90°	I_{135°	$I_{45^\circ}/I_{135^\circ}$
5	14.5	11.3	11.0	1.32
10	30.5	18.8	17.5	1.74
15	54.0	25.0	23.0	2.35
20	83.0	30.5	28.0	2.96
25	112.0	35.3	32.3	3.47
30	141.5	39.5	36.0	3.93
40	189.0	45.5	41.8	4.52
50	217.5	49.3	45.8	4.75
60	237.0	51.8	48.5	4.89
70	250.5	53.5	50.3	4.98

The results obtained on the measurement of the depolarization factors of the light transversely scattered are given in Tables VII and VIII, in which ρ_u , ρ_v and ρ_h represent the depolarization factors of the transversely scattered light when the incident light is unpolarized, vertically polarized and horizontally polarized, respectively.

TABLE VII

Depolarization measurements

Aluminium molybdate gels

$A_1 = 21.0$ c.c. $B_1 = 20.0$ c.c.

T.V. = 50.0 c.c. $T = 58' 50''$

t in minutes	ρ_u (%)	ρ_v (%)	ρ_h (%)
1	0.4	..	88.5
3	..	0.2	86.9
5	0.6	0.2	..
7	..	0.3	85.3
10	1.3	0.5	81.1
15	2.0
20	2.6	1.0	63.3
25	3.1	1.1	..
30	3.8	1.2	..
40	..	1.3	61.0
50	5.8	1.8	59.9
60	6.5	2.5	..
70	7.2	2.5	..
80	7.2	2.5	59.9

TABLE VIII

Depolarization measurements

Thorium arsenate gels

$A_2 = 40.0$ c.c. $B_2 = 6.4$ c.c.

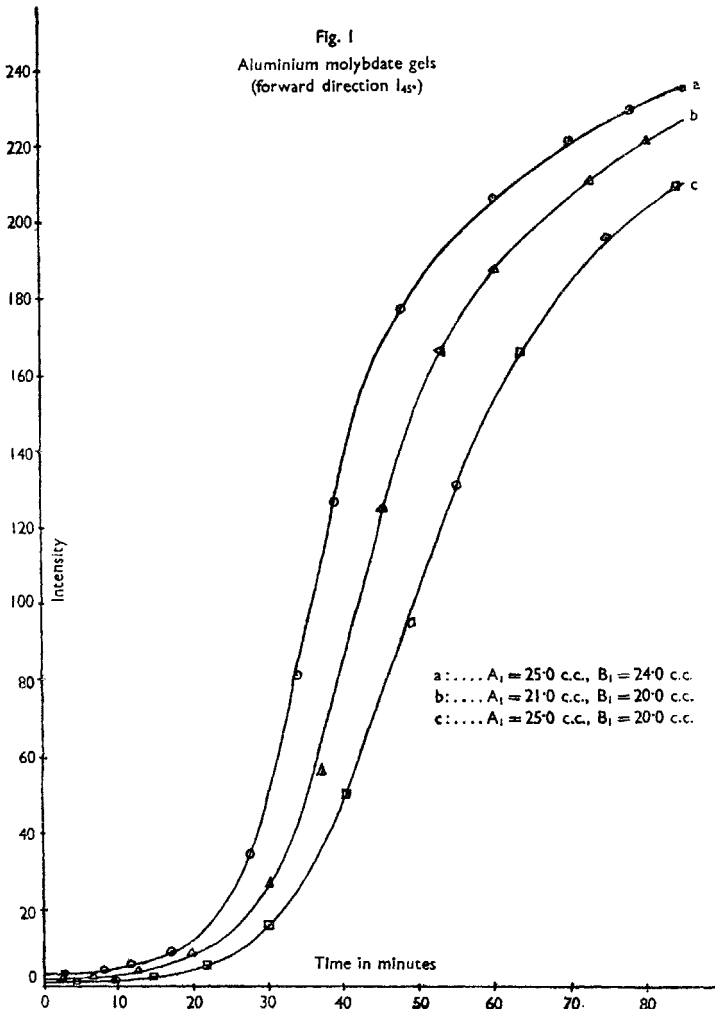
T.V. = 48.0 c.c. $T = 45' 15''$

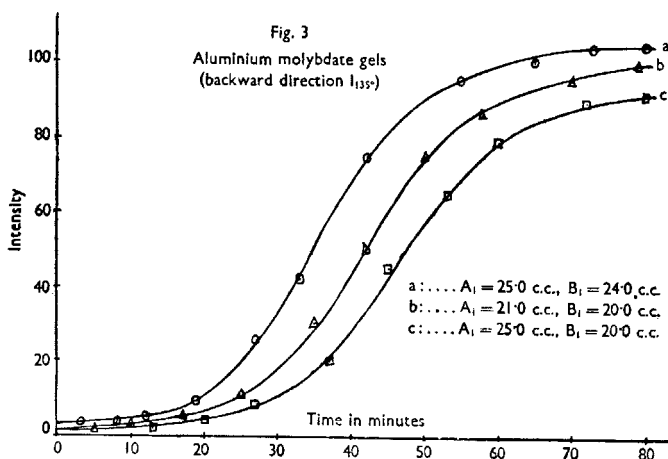
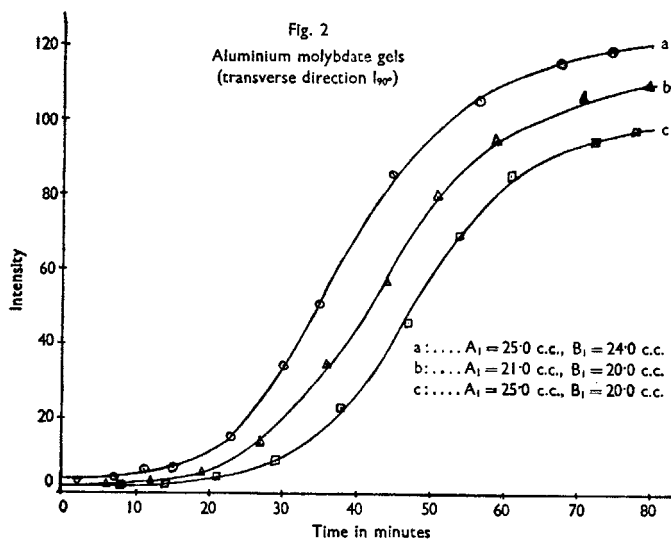
t in minutes	ρ_u (%)	ρ_v (%)	ρ_h (%)
1	4.1	..	91.6
3	4.3	2.1	..
5	4.9	2.2	..
10	5.1	2.2	89.0
15	..	2.5	82.5
20	6.7	2.7	78.3
25	7.2	..	70.4
30	7.7	3.0	..
40	..	3.1	65.6
50	8.2	3.3	62.1
60	8.8	3.4	..
70	8.8	3.4	59.8

DISCUSSION OF RESULTS

It is seen from Tables I to VI and Figs. 1 to 6 that, in both aluminium molybdate and thorium arsenate gels, the intensity of light scattered at any angle is initially small and that the intensity increases at first slowly and then rapidly and finally attains an almost constant value. From this it can be inferred that the particles increase in size and/or number during gelation. The results also show that the increase in intensity, that is, the increase in the size and/or number of the particles, continues even after the systems have ceased to flow (i.e. the time of setting of the gel).

The intensity of the transversely scattered light, I_{90° , can be split up into I_D , the density scattering resulting from the local inhomogeneities produced due to the thermal agitation of the particles in the medium, and I_A , the anisotropy scattering

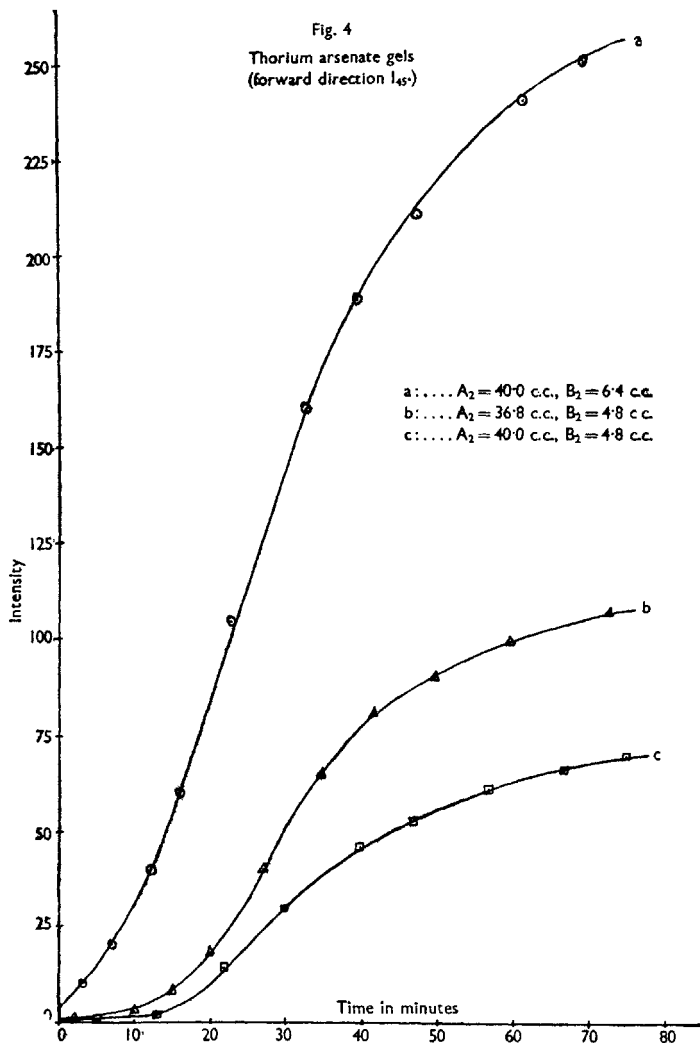




arising from the fact that the moment induced by an electric vector is not, in general, parallel to the direction of the incident electric vector, using the relations (cf. Ramanathan, 1923; Zimm, Stein and Doty, 1945),

$$I_D = I_{90^\circ} \times \frac{6 - 7\rho_u}{6 + 6\rho_u}; \quad I_A = I_{90^\circ} - I_D.$$

Recently, Zimm, Stein and Doty (1945) have pointed out that the above relations are valid only when the particle size is small and the value of ρ_u is due to the anisotropy of the particles only, and that, whenever the value of ρ_u is partly due to the appreciable size of the particles, the value of ρ_u in the above relations should be substituted by that of the factor $\frac{2\rho_v}{1 + \rho_v}$ which represents, to a first approximation,



the part of ρ_u value due to the anisotropy of the particles. In the present case, the low values of ρ_h (cf. Tables VII and VIII) indicate that in both gels the particle size becomes appreciable in the later stages of gelation and hence the values of I_D and I_A have been calculated using the factor $\frac{2\rho_v}{1+\rho_v}$ instead of the value of ρ_u in the

above relations. The values of I_D and I_A thus separated are given in columns 6 and 7, respectively, of Tables IX and X. It can be seen from these tables that the values of both I_D and I_A increase during gelation indicating that the particles increase in size and anisotropy as gelation proceeds. It is also seen that the density scattering predominates over anisotropy scattering throughout the process of gelation.

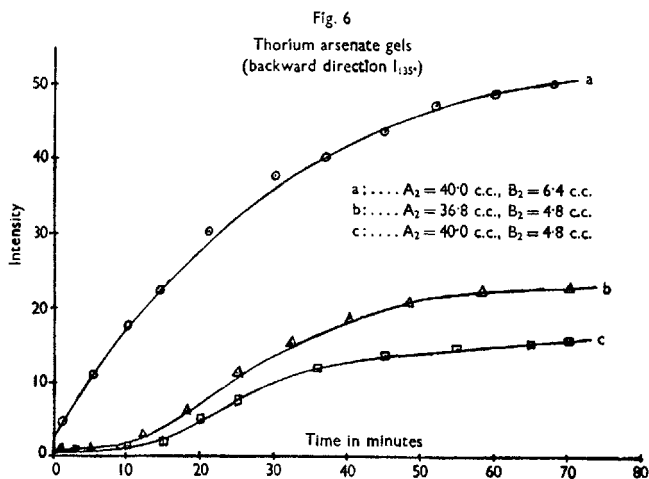
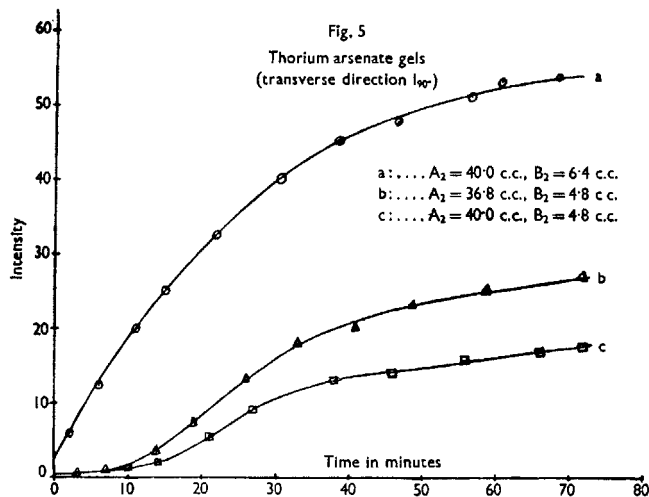


TABLE IX

Values of I_D and I_A of the light transversely scattered during the setting of aluminium molybdate gels

$A_1 = 21.0$ c.c.; $B_1 = 20.0$ c.c. (cf. Tables I and VII)

t in minutes	ρ_v (%)	$\rho = \frac{2\rho_v}{1+\rho_v}$	$\frac{6-7\rho}{6+6\rho}$	I_{90°	$I_D = I_{90^\circ} \times \frac{6-7\rho}{6+6\rho}$	I_A
5	0.2	0.004	0.99	2.0	1.98	0.02
10	0.5	0.010	0.98	3.0	2.94	0.06
20	1.0	0.020	0.96	6.0	5.76	0.24
30	1.2	0.024	0.95	19.5	18.52	0.98
40	1.3	0.026	0.94	44.5	41.83	2.67
50	1.8	0.035	0.93	76.0	70.68	5.32
60	2.5	0.049	0.90	95.0	85.50	9.50
70	2.5	0.049	0.90	103.5	93.15	10.35
80	2.5	0.049	0.90	108.5	97.65	10.85

TABLE X

Values of I_D and I_A of the light transversely scattered during the setting of thorium arsenate gels

$A_2 = 40.0$ c.c.; $B_2 = 6.4$ c.c. (cf. Tables VI and VIII)

t in minutes	ρ_v (%)	$\rho = \frac{2\rho_v}{1+\rho_v}$	$\frac{6-7\rho}{6+6\rho}$	I_{90°	$I_D = I_{90^\circ} \times \frac{6-7\rho}{6+6\rho}$	I_A
5	2.2	0.043	0.91	11.3	10.3	1.0
10	2.2	0.043	0.91	18.8	17.1	1.7
15	2.5	0.049	0.90	25.0	22.5	2.5
20	2.7	0.053	0.89	30.5	27.1	3.4
30	3.0	0.058	0.88	39.5	34.8	4.7
40	3.1	0.060	0.88	45.5	40.0	5.5
50	3.3	0.064	0.87	49.3	42.9	6.4
60	3.4	0.066	0.86	51.8	44.5	7.3
70	3.4	0.066	0.86	53.5	46.0	7.5

The results given in Tables I to VI also show that initially the intensity of the light scattered in the forward direction (45°) is the same as that in the backward direction (135°); however, during gelation, the increase in intensity of light scattered in the forward direction is far greater than that in the backward direction. This statement is clearly brought out by the values of the ratio $I_{45^\circ}/I_{135^\circ}$ given in the last columns of Tables I to VI. The continuous increase in the values of this ratio definitely indicates that the particles increase in size during gelation.

It has been pointed out by Oster (1950) that, in a system containing large independent particles, with increase in particle size the values of the ratio $I_{45^\circ}/I_{135^\circ}$ approach the limiting values of 2.44 in the case of rod-shaped particles and 5.98 in the case of disc-shaped particles, whereas in the case of spherical particles the value of the ratio increases very rapidly with increase in particle size and the limiting value is very high. In both aluminium molybdate and thorium arsenate gels the particle size is fairly large as can be inferred from the low values of ρ_h (cf. Tables VII and VIII). Although in gel systems the particles cannot be considered to be strictly independent of each other, the fact that the final value of the ratio $I_{45^\circ}/I_{135^\circ}$ is about 2.2 in aluminium molybdate and about 4.6 in thorium arsenate gels indicates that the particles in aluminium molybdate gels are probably rod-shaped while those in thorium arsenate gels are probably disc-shaped.

A comparison of Tables II and V with III and VI, respectively, shows that, in both aluminium molybdate and thorium arsenate gels, an increase in the amount of potassium molybdate or potassium arsenate in the corresponding gel-forming mixture increases the intensity of the light scattered and in the case of thorium arsenate gels the final value of the ratio $I_{45^\circ}/I_{135^\circ}$ is also increased with the increase in the amount of potassium arsenate. On the other hand, a comparison of Tables I and IV with II and V, respectively, shows that an increase in the amount of thorium nitrate or aluminium nitrate in the corresponding gel-forming mixture causes a decrease in the intensity of the light scattered in both thorium arsenate and aluminium molybdate gels and a decrease in the final value of the ratio $I_{45^\circ}/I_{135^\circ}$ in the case of thorium arsenate gels. Since the amount of aluminium nitrate or thorium nitrate, as the case may be, in the gel-forming mixture is always in excess of that required to combine with potassium molybdate or potassium arsenate, it is possible that with an increase in the amount of potassium molybdate or potassium arsenate a larger amount of the gel-forming substance (aluminium molybdate or thorium arsenate) is formed; this increase in the amount of the gel-forming

substance may be resulting in the increase in the number and in the size of the gel-forming particles, as revealed by the increase in the values of the intensity of the light scattered and of the ratio $I_{45^\circ}/I_{135^\circ}$. The reverse effect observed on increasing the amount of aluminium nitrate or thorium nitrate is evidently due to the peptizing action of aluminium or thorium ions.

SUMMARY

The measurement of the intensity of light scattered in different directions during the setting of gel-forming systems of aluminium molybdate and thorium arsenate shows that the size and anisotropy of the particles increase continuously during gelation. The ratio $I_{45^\circ}/I_{135^\circ}$ is found to increase continuously during the process of gelation and it has been inferred from the final values of these ratios that the particles in aluminium molybdate gels are probably rod-shaped while those in thorium arsenate are probably disc-shaped. The ultimate size and number of the particles is found to increase with an increase in the amount of potassium molybdate or potassium arsenate in the corresponding gel-forming mixture while the reverse is observed when the amount of aluminium nitrate or thorium nitrate, as the case may be, is increased.

ACKNOWLEDGEMENTS

The authors desire to express their sincere thanks to Dr. Mata Prasad, D.Sc., F.R.I.C., F.N.I., for valuable suggestions and advice and to Dr. K. R. Dixit, Ph.D., F.N.I., for his keen interest in the work. One of the authors (V. S.) is indebted to the Council of the National Institute of Sciences of India for the award of a Junior Research Fellowship and the other (R. L. D.) to the authorities of the University of Bombay for the award of a Research Studentship.

REFERENCES

- Blumer, H. (1925). Radiation diagrams of small dielectric spheres. *Z. Physik*, **32**, 119-134.
 ——— (1926). Radiation diagram of smaller dielectric globes. *Z. Physik*, **38**, 304-328.
 Desai, R. L. (1952). A note on the preparation of aluminium molybdate gels. *J. Univ. Bombay*, **20**, Pt. 5, 24.
 ——— (1953). Studies on the optical properties of gels. Part IV. Aluminium molybdate gels. *J. Univ. Bombay*, **22**, Pt. 3, 8-14.
 Desai, R. L. and Sundaram, V. (1953). Studies on the optical properties of gels. Part I. Ceric arsenate gels. *J. Univ. Bombay*, **22**, Pt. 3, 24-28.
 Doty, P. and Steiner, R. F. (1950). Light scattering and spectrophotometry of colloidal solutions. *J. Chem. Phys.*, **18**, 1211-1220.
 Katti, P. K. (1948). Studies in colloid optics. Part I. The sol-gel transformation in agar-agar gels. *Proc. Indian Acad. Sci.*, **28A**, 216-235.
 ——— (1949). Studies in colloid optics. Part II. The sol-gel transformation of gelatin gels. *Proc. Indian Acad. Sci.*, **30A**, 35-48.
 ——— (1953). Studies in colloid optics. Part III. Sol-gel transition of some lyophobic gels. *Proc. Indian Acad. Sci.*, **38A**, 148-160.
 Krishnamurti, K. (1929). The scattering of light in colloidal solutions and gels. I. Agar sol and gel. *Proc. Roy. Soc.*, **A122**, 76-103.
 ——— (1930). Scattering of light in protein solutions. I. Gelatin solutions and gels. *Proc. Roy. Soc.*, **A129**, 490-508.
 Krishnan, R. S. (1934). Scattering of light by particles suspended in a medium of higher refractive index. *Proc. Indian Acad. Sci.*, **1A**, 147-155.
 Mardles, E. W. J. (1923). The scattering of light by organosols and gels of cellulose acetate. *Trans. Faraday Soc.*, **18**, 318-326.
 Mie, G. (1908). Optics of turbid media. *Ann. Physik*, **25**, 377-445.
 Oster, G. (1950). Chapter on 'Scattering of visible light and X-rays by solutions of proteins' (pp. 73-84) in Vol. I of 'Progress in Biophysics and Biophysical Chemistry' (Butterworth-Springer Ltd., London), p. 80.
 Prakash, S. and Dhar, N. R. (1929). Preparation of jellies of some inorganic substances. *J. Indian Chem. Soc.*, **6**, 587-598.
 Prasad, M. and Doss, K. D. V. (1949). Scattering of light during the process of gel-formation. *J. Colloid Sci.*, **4**, 349-365.

- Prasad, M. and Guruswamy, S. (1944). Study of the optical properties of gels. Part I. Thorium molybdate gels. Part II. Thorium arsenate gels. Part III. Silicic acid gels. *Proc. Indian Acad. Sci.*, **19A**, 47-65, 66-76, 77-87.
- Ramaiah, K. S. (1937). Colloid optics. II. Scattering of light by silicic acid sols and gels. *Proc. Indian Acad. Sci.*, **5A**, 138-147.
- Ramanathan, K. R. (1923). Electromagnetic theory of the scattering of light in fluids. *Proc. Indian Assoc. Cultivation Sci.*, **8**, 1-22, 181-198.
- Shoulejkin, W. (1924). Scattering of light by very big colloidal particles. *Phil. Mag.*, **48**, 307-320.
- Zimm, B. H. (1948). Apparatus and methods for measurement of the angular variation of light scattering; preliminary results on polystyrene solutions. *J. Chem. Phys.*, **16**, 1099-1116.
- Zimm, B. H., Stein, R. S. and Doty, P. M. (1945). Classical theory of light scattering from solutions. *Polymer Bull.*, **1**, 90-119.

Issued November 20, 1954.