PHOTOPHORESIS AND ITS INTERPRETATION BY ELECTRIC AND MAGNETIC IONS. *

BY

FELIX EHRENHAFT.

I. EXPERIMENTAL FACTS ABOUT PHOTOPHORESIS, ELECTRO- AND MAGNETOPHOTOPHORESIS.

The experiments were carried out in an Ehrenhaft condenser (1) with a plate diameter of 8 mm. A vertical electric and magnetic homogeneous field absolutely free from residual electricity or magnetism was applied when needed. The strength and direction of this field could be chosen. The last description of the apparatus and the method is also given in "Photophorese, Electrophotophorese, Magnetophotophorese," *Annales de Physique*, 13, 151, 1940.†

The arrangement allowed the directing of a beam of light from the right, from the left or from both sides simultaneously through the space between the condenser plates. Each of these beams could be screened off instantly and could be weakened at will. Since each of the illuminating lenses could be shifted in the three dimensions of space, the intensified beams could be placed at any positions relative to each other, or diffused light could be applied from one side and a coaxial beam could be concentrated and applied from the other side. The visual field of the microscope was arranged at right angles (horizontally) to the light beam.

Particles of different substances were led to the space between the condenser plates. If only diffused light was applied for illumination one could see the particles fall with constant velocity only superposed by Brownian movement. The velocities depend on their sizes (mobilities). A guard ring condenser was provided which allowed the rising and the holding of charged particles for a practically unlimited time

* A short summary of this paper has been given in Science wkly vol. 94 (1941), 232.

† The apparatus in which the phenomena were observed was rebuilt by Carl Zeiss, Inc., New York.

and their movement to any desired place in the condenser. Thus the possibility was given to repeat one experiment on a single particle many times and to determine the mean values of velocities. All experiments were carried out in carefully cleaned inert gases.

1. Longitudinal Photophoresis.

A beam of concentrated light is applied from one side. Particles of the same kind and size then move under the influence of the light. Some move away from the light (light positive) [(1) p. 835] some toward the light (light negative longitudinal photophoresis) [(2) p. 952] (Ref. 1 to 11) [(56) see fig. 5, p. 386]. This was also observed by R. Whytlaw-Gray and Patterson (Leeds) (42), who performed these experiments quite independently of the authors, and also by many of his own pupils (15, 27, 28, 29, 37, 38, 39, 40, 41, 43, 44). The movement depends upon the material and the intensity and the frequency of the light beam. The phenomena were also observed in liquids by the author's pupil Satiendra Nath Ray (34) (Lucknow, India) and independently of the author by W. W. Barkas (35) (London). The latter also found photophoresis with X-rays.

Since the velocity v of a particle in the beam is found uniform it can be considered a measure of the force P acting on the said particle thus giving the relationship $v = P \times B$, where B is the mobility of the particle.

The weights of the particles were of an order of magnitude down to 10^{-10} dynes. All photophoretic forces were compared with this weight. Therefore the measurement of forces are more sensitive by the factor of 10^4 than any direct measurement of forces made thus far.

It should be mentioned that all particles do not show photophoresis. A certain number of particles stand still at first and only start to move after some time elapses. Others do not move at all. Changes in the velocity of the movement occur sometimes during short periods and at other times after hours (11) (41). Some particles even change their direction of movement spontaneously. The mechanical properties of these particles however were not changed.

If the direction of the beam is reversed the direction of movement of the particles is in almost all cases also reversed. By means of an electric field in the direction of the light beam the movement of a particle can be accelerated or retarded at will (37). It is also possible to make a particle stop and thus to compensate the photophoretic force. Furthermore it is also possible to compensate the movement by means of two symmetrical beams.

2. Electro-Photophoresis.

If two symmetrical light beams are applied from two sides the longitudinal photophoresis disappears. If in that arrangement an electric field perpendicular to the light beam is applied a movement in the direction of this field takes place, which phenomenon the author calls electro-photophoresis (8, 37, 38, 40, 43). The speed of this movement depends on the intensity of the light, on its frequency and on the intensity of the field, and is different for the various materials. Some particles do not show such a movement, some start suddenly and others change their direction of motion spontaneously or move with a decreasing speed (41). The electro-photophoretic velocity is proportional to the intensity of the light and to the strength of the electric field but for high fields saturation values are observed (41). It is remarkable that the dependency of the velocity upon the material is sometimes very great i.e., Te, Sb and As require about 1000 times smaller field-strength than Se. In other materials such as oil and sulphur as well as phosphorus no electrophotophoresis has been observed.

3. Magneto-Photophoresis.

When a homogeneous magnetic field is applied at right angles to an intense beam of light as described above some of the small particles start moving with uniform velocity, the value of which depends upon the particles mobility. Some of the particles move toward the North some toward the South magnetic pole [Ehrenhaft (8, 39, 56)]. The rising particles are lifted against gravity and the falling particles fall faster. Others do not show any change in their motion. The motion due to the photophoretic force ceases instantly if the light is shut off. The speed of the magneto-photophoresis depends upon the intensity and the frequency of the light, and upon the intensity of the magnetic field as well as on the material itself. For nickel and iron particles, for instance, the intensity of the geomagnetic field is sufficient to produce a movement in both directions, if, as in the case of the author's laboratory in Vienna (Austria), the direction of the geomagnetic field is vertical and its intensity about 0.4 Gauss (the horizontal component was negligible because of the iron in the building). This movement could be annulled by an inverse magnetic field of the same strength. The movements of the particles are reversed if the magnetic field at sufficiently high strength is reversed. The photophoretic force is a linear function of the field if said field is weak (56). At higher fields saturation values were observed and the magneto-photophoretic velocity was independent of the magnetic field strength. There is therefore no dependency upon the history of the particle. A discussion of ferromagnetic particles in high fields is given in Ann. de Phys., p. 166 (53). Ferromagnetic particles reverse the direction of their movement with the reversal of the field with very few exceptions. Diamagnetic particles reverse the direction of their movement in high magnetic fields (39, p. 655, Statistic). In lower fields they do not follow the fields in all cases (sometimes the rate is 50 : 50) and in still smaller fields the spontaneous reversal of the direction of movement occurs so fast that it cannot be counted.

4. The Trembling-Effect.

This rapidly changing movement of diamagnetic particles in low fields cannot be confused with Brownian movement in gases, discovered by the author (1905) (60) because it is of another magnitude and kind. After the discovery of the Trembling effect by the author it was also observed by I. Parankiewicz, J. Mattauch (20), E. Reeger (39), B. Whytlaw-Grey and H. S. Patterson (42) (p. 122). The latter two independently working in Leeds (England). Those particles did not show any change of physical properties, if examined after they executed the Trembling-motion for a long period. It should be noted that this motion is also possible in the geomagnetic field.

5. Other Remarkable Facts.

Rising particles remain on the upper edge of the light beam and stay there. After a short while the whole upper edge of such a beam is filled with such particles. This was observed by the author, E. Reeger (39) (p. 651), E. Wilflinger (40) and Whytlaw-Grey and Patterson (42).

The fluctuations in the velocities of the electro-photophoresis was found to be much smaller in ultrared light than in natural light (43).

II. THE INADEQUACY OF THE EXISTING THEORIES TO EXPLAIN THE PHENOMENA.

At first the author tried to explain the phenomena as far as they were then known by light pressure and radiometer theories (1910) [(1), p. 836]. Later he had to recognize that those forces did not explain the facts (1918) (5). Other suggestions as made by F. Michaud (Paris) (16), P. Epstein (Pasadena) (17) and T. Terada (Tokyo) (18) did not give satisfactory explanations, any more than those of A. Rubinowicz (Munich) (22, 23, 24), G. Laski and F. Zerner (25, 26), O. Halpern (32) and others. After the discovery of electrophotophoresis and magnetophotophoresis the author and his pupils tried to apply the radiometer theory to explain the phenomena (13). The discovery of the photophoresis in liquids by Satiendra Nat Ray (25*a*, 34), W. W. Barkas (35) and G. Fachini (36) complicated the situation considerably.

The following are the main difficulties which are encountered in an explanation by radiometer forces.

(*a*) There are silver spheres which exhibit a tremendous light negative motion though, as the most strongly reflecting of all substances silver certainly ought to be most heated on the side toward the light (2, 4, 41).

(*b*) It is known that selenium spheres of equal size in hydrogen, nitrogen and argon, experience the same photophoretic negative force though the conduction of heat and the gas viscosity are very different in the three gases [(15), *Ann. der Physik*, p. 513].

(*c*) As above mentioned the photophoresis was also found in liquids, where radiometer forces are impossible because of the short mean free path of the molecules. W. W. Barkas working in the University College laboratory in London (directed by Porter and Andrade), has shown that single colloidal particles of the same kind (gold, silver, copper or oil) were both light positive and light negative, and that the forces are of the same order of magnitude as those which Ehrenhaft and others measured in gases (35).

(*d*) It does not seem possible to explain the reversibility of the particles by reversals of the (electric or magnetic) field on the basis of radiometer forces. Some particles could be reversed a hundred times and more. The field intensity E or H does not have a bearing on solely the orientation of the symmetrical or asymmetrical particles. The energy of H or E which is alone responsible for orientation is a quadratic function of the potentials. Therefore it cannot change when the potentials are reversed, i.e. E or H. However, the particles immediately do change their direction of motion.

(*e*) Let us consider a symmetric or asymmetric particle at the lower edge of the beam, so that its upper part being inside the beam will be hotter than its lower part. Thus radiometer forces could only repulse such a particle from entering the beam. But it has actually been observed a number of times by the author as well as by others (37, 38, 39, 40, 42) independently of him that under the influence of E or H particles moved upwards and across the beam.

(*f*) The motion of particles of iron and nickel across the beam occurs frequently without an artificial vertical magnetic field. The explanation is given in the interesting dissertation of N. Judenberg 1938 on the basis of work done under the author's direction at the University of Vienna. The exact diagram of the arrangement has been published *Ann. de Phys.*, **13**, 161, 1940 (Paris). The direction of the geomagnetic field intensity of his laboratory room was vertical on account of iron in the building and was of a magnitude of 0.4 Gauss. *This geomagnetic field alone without any artificial field caused nickel particles to move upwards.* When this homogeneous field was compensated by an artificial field of the same size but of reverse direction the motion resulting from the geomagnetic field ceased instantly.

(*g*) The radiometer theory cannot explain the typical difference between the behavior of ferromagnetic and the diamagnetic substances in the condenser. Ferromagnetic particles almost always reverse their motion when the magnetic field is reversed, but diamagnetic particles very often change their direction of motion spontaneously. The number of spontaneous reversals with the magnetic field depends upon the strength of this field. If the magnetic field is of great intensity the spontaneous reversals do not occur, but they happen more often as the intensity of the field decreases until such spontaneous reversals are so numerous that they cannot be counted. This occurs sometimes at fields of about 3000 Gauss (8, 39) sometimes even in the geomagnetic field. It is known that a particle in the Ehrenhaft condenser cannot be charged if it is in a large electric field. The sudden changing of movements (Trembling-effect) occurs only in low magnetic fields. It seems almost impossible to explain the Trembling-effect as a mechanical thermal effect, especially since this effect occurs only in fields of a certain strength.

(*h*) The photophoretic force is a linear function of the field if it is weak. This applies to the electro- as well as to the magneto-photophoresis.

(*i*) It is well known that asymmetrical bodies will orientate themselves in E or H (in the case of H regardless of whether they are ferro-, para- or diamagnetic) so that the longest diameter comes to lie in the direction of the lines of force for well known energy reasons. Experiments show that for these bodies the direction of the electrophotophoretic force as well as the direction of the magneto-photophoretic force are entirely independent of the direction from which the light is coming (defined by its wave front normal): for this motion always follows the direction of the respective field. Were we dealing with radiometer forces either of the Crookes type or by assuming a dependency of the accommodation coefficient upon the magnitude of the field, than the direction of motion would still have to depend upon the direction of the incident light upon which, in turn, depends the distribution of temperature on particles whether symmetrical or asymmetrical. (E. Reeger (39), G. Placzek (37), P. Selner (38).)

(*j*) It seems worth while to mention that some particles start to move suddenly from rest. It was also observed that for other particles the photophoresis sometimes suddenly disappeared and sometimes decreased or increased gradually.

[(15) Parankiewicz] [(27, 28) Mattauch] Isser & Lustig (43), G. Placzek (37).

(*k*) The particles showed no changes of velocity in ultra-red light ($\lambda > 750$ mμ), but the same particles frequently showed changes in white light. If the phenomena could be explained by heat effects it is not clear why the white light should cause the effects but not the much hotter ultra-red light (Isser & Lustig (43)).

(*l*) Silver particles, which were analyzed for mechanical qualities and found to be the same differ in their behavior in the photophoresis. Some of them are light positive, some are light negative and some keep changing from the light negative movement to the light positive one and (41) vice versa.

(*m*) It is also very difficult to explain the fact that photophoresis can also be observed with X-rays.

III. THE INTERPRETATION OF THE EXPERIMENTS.

1. The Difference between Electricity and Magnetism.

The prevailing opinion is that within an arbitrarily chosen geometric surface a real quantity of either kind of electricity can be inclosed (div $E = \rho$), but no matter how the surface is chosen, it will always inclose the same amount of north and south magnetism (div $H = 0$). In other words there are true quantities of electricity of either sign, but not true magnetic quantities. Thus we have electric but not magnetic currents. The author and Dr. Leo Banet showed (59, 83) that the above mentioned assumption was based upon two so-called fundamental experiments:

A. The broken magnet gives two entire magnets with equal poles.

B. A magnet put into a vessel floating upon water shows direction and no motion. Therefore there can be no excess of charge. (Conf. J. C. Maxwell, "Treat. on Electr. & Magn.," 377–379.)

Ad experiment *A*: This experiment does not prove to be right. To see this one only has to take a piece of demagnetized iron wire and break it into two without using any tools. Often such pieces are then North or South magnetic at the broken ends while the other ends remain almost non-magnetic. The effect is the same when a nonelectrically glass or sulphur rod is broken and shows at the ends various kinds of electric charges. This phenomenon is easily explained since each breaking creates constriction. Each constriction however creates electricity and magnetism.

By means of such experiments it can not of course be proven that div H could not be zero on such pieces, but they undoubtedly indicate that experiment A is not conclusive. From experiment A cannot thus be concluded that div $H = 0$.

Ad experiment B: The historic facts are as follows: As early as 1269 Peter Peregrinus described the basic arrangement for experiment A as well as for experiment B (61). Later Robert Norman found that there is no motion of a floating magnet toward the rim of the vessel (62), as was also confirmed by W. Gilbert (63). Finally J. C. Maxwell concluded from the above mentioned experiments that div H is zero generally and under all circumstances. It can be easily seen that the mobility of the floating magnet (about 10°) is much too small to show small differences in the strength of magnetic poles. Just as small electric charges can be measured on small particles of great mobility (10^6 or more) in gases moving in a homogeneous electric field (Ehrenhaft condenser) (1) so the movement of submicroscopic particles (with a mobility of about (10^7) in a homogeneous magnetic Ehrenhaft condenser (7, 7*a*) enables us to have the most sensitive arrangement of the Peregrini-Maxwell experiment of a floating magnet in a homogeneous field. From this it should be clear that only by means of experiments of such a sensitivity could it be determined whether single magnetic poles (charges) exist or not. The fundamental experiments mentioned above are not sufficient to demonstrate that magnetic charges cannot exist. This had to be presupposed before an interpretation of the experiments of the photophoretic phenomena could be given.

2. The Interpretations of the Photophoresis.

In order to explain the phenomena of photophoresis one conclusion is drawn from the movement of the illuminated particles in the homogeneous electric and magnetic fields. The *light induces electric and magnetic charges* (*poles*) *upon the particles if they are illuminated by concentrated light pre-*

ponderantly shorter wave lengths. In the case of the electric charges it does not seem to be so strange since light ionizes the matter as is well-known. It is furthermore known that the ultraviolet part of the light is more active and that it changes the charges of single particles (Elementary photoelectric effect direct and inverse (64, 65, 66, 67, 68, 69, 70)). For the magnetic *charges this conclusion is new, but is justified because of the complete analogy of this phenomenon with the electric phenomenon.* This conclusion is not only justified because it gives a satisfactory simple explanation of all photophoretic phenomena as will be shown later but because it is also able to explain a various number of hitherto unexplained phenomena and allows the drawing of new conclusions which can be verified. This demonstrates the heuristic value of a theory in all cases.

It should be noted here that there are no empirical facts which contradict this conclusion as was shown above. The difficulties such an explanation encounters are not due to experimental facts but only to *theoretical* considerations which go back as far as Ampere who introduced the hypothesis of molecular currents and reduce the phenomena of magnetism to purely electrical phenomena.

3. Discussion of the Phenomena.

We shall now attempt to give the discussion of the phenomena as described in (*a*) to (*m*) but in another order.

To (*d*): It is obvious that the particles if they are charged have to follow the direction of the electric as well as magnetic field if these are reversed.

To (*e*): For the same reason as above the particles cross the beam upwards.

To (*f*): It is clear that the particles which were moved by the geomagnetic field across the beam had a magnetic charge since their movement could be compensated by an artificial magnetic field of the same strength but of opposite direction.

To (*g*): A change of direction of movement in the electric or magnetic field must be due to changes of the charge of the particle. Such changes can occur spontaneously while a low field is applied or when the field is reversed since in that case for a certain time no field acts on the particle. As it is well-known particles in high fields do not change their electric charge but they do so under low or neutral fields. The phenomena in the electro- and magneto-photophoresis occur in the same way. Therefore we can understand why changes of direction occur only in low and neutral fields, sometimes so frequently that they cannot be counted. This phenomenon has been called by the author the Trembling-effect. *The Trembling-effect is thus a very frequent change of magnetic poles in the intense beam of light and the magnetic field.* It can occur even in the geomagnetic field.

To (*h*): It should be noted that it is only a primary effect that is characterized precisely by a linear relationship between its elements. The origin of this concept is the law of Hooke: Ut tensio sic vis. The same concept was used later in the development of the electromagnetic theories, by J. C. Maxwell expressed in the equations $D = \epsilon E$, $B = \mu H$, which equations were true only in certain cases and for small values of E and H. We have found that the electro- and magnetophotophoretic forces are linear functions of the electric or magnetic field (E or H), if these are weak. This indicates that the photophoresis is a primary effect.

To (*i*): It seems clear that it does not depend on the direction from which an electric or magnetic charge is induced. The particle always follows the applied field. On the other hand it seems impossible to explain this phenomenon by any theory which deals with differences of temperature of the bodies.

To (*j*): These phenomena show an exact analogy to the phenomena of sudden and slowly charging of electric particles as observed during the determinations of electric charges.

To (*k*): It is striking that ultrared light which produces a much greater heating effect has not as much influence as light of shorter wave-lengths. The violet part of the light seems to induce these charges to a greater extent.

Since light makes particles of matter unipolar with respect to homogeneous electric and magnetic fields and since, when no such fields act, it makes them move in or against its wave front normal and since, as has been shown above, radiometer forces cannot account for this movement, we are driven to suppose, that the light brings into play upon the particles forces which are perpendicular to its wave front normal. It is the belief of the writer that these forces are of the nature of electric and magnetic fields, which exist as part of the whole ensemble of light, surrounding medium and particles within the chamber of observation. It must, however, be stated here that, as will be shown later, the forces exist under all observed conditions, such as different gas pressures down to 4 mm mercury pressure, in liquids and in condensers and chambers of observation of different kinds and sizes. (83, Fig. 1). S. Patterson and R. Whytlaw Gray (30a) (42), for instance, observed light positive and light negative photophoresis with velocities up to 1 cm sec in the center of a vessel containing one liter, using a microscope of low aperture.

Such an idea touches upon the basic problems of light. May I recall here what Ernest Mach said (Erkenntnis und Irrtum, Leipzig, 1905, p. 241): "In the theory of optics one speaks about light waves while only the periodicity is required for the understanding of the facts. These accessorial elements which go beyond the necessity are the elements which are changed by the interconnection between thinking and experience." In order to perceive the periodicity, i.e. the oscillating components, of the light it is necessary to study its effects upon matter. If one talks about the oscillating components in empty space, it is a question of an extrapolation (i.e. carrying over conditions from the observable to the unobservable). One can observe in the experiments of photophoresis that particles of the same kind and size move simultaneously toward and against the propagation of the light and that they move in or against the direction of homogeneous electric and magnetic fields. Thus we need in the above case also matter to find the essence of the light beam. The movement of matter in or against the direction of the wave front normal has also been observed in liquids (34, 35, 36). It is known that spherical particles of equal size experience the same photophoretic force in (15) hydrogen, nitrogen and argon. Furthermore, all experimenters working in this field have found many particles whose photophoretic force, perpendicularly to the wave front normal, has been independent of the gas pressure to a very high extent (28, 4, 15). Such experiments were carried out down to pressures of 22 millimeter mercury (28). At these pressures the mean free path of the molecules is already large compared with the size of the particle itself. And even at pressures of 4 millim. mercury, where the vacuum can be considered as very good for testing bodies of a size of about 1.5×10^{-5} cm a distinct movement was observed toward the light by Mattauch and Ehrenhaft (28). If one says that the electromagnetic waves have longitudinal stationary components of E and H and potential differences along two points of a beam, this means only, according to Mach, an economical description of observable facts.

This result can be supported by the older theories of light. The electron theory (Paul Drude, Woldemar Voigt) applied to light demonstrates from the phenomena of absorption and dispersion that an electrostatic field exists in the direction of propagation of a stationary beam of light. (Festschrift Heinrich Weber 1912.)

From similar experiments of photophoresis it can be concluded that stationary magnetic fields exist in the beam of light since superposed magnetic fields accelerate or retard the longitudinal photophoresis.

It therefore seems to the author that the longitudinal photophoresis is an electromagnetic phenomenon. The movement of particles in a concentrated beam of light is completely analogous to the movement of the particles in an electric or magnetic field. Therefore the phenomena *a*, *b*, *c*, *l*, *m* can be explained as follows:

(*a*): Since the movement of a silver particle as well as that of any other kind depends upon its charge it can be understood why light positive and light negative silver particles are found.

(*b*): Since the force is an electromagnetic one it does not depend upon the conduction of heat or gas-viscosity.

(*c*): The movement of particles of the same kind in liquids can be understood as produced by poles and fields.

(*l*): Both slow and fast changes of direction of movement of silver particles are due to change of charge.

(*m*): Since the X-rays constitute electromagnetic waves of very short wave-lengths it can be understood that X-rays show similar phenomena as light.

IV. CONSEQUENCES.

1. The Charge of the Magnetic Ions.

Using the complete analogy of Coulomb's law of electric and magnetic forces it is now possible to determine the pole strength (charge) of a single magnetic ion. If P denotes the force acting on the particle due to the magneto-photophoretic effect, e_m the absolute magnetic pole strength for a certain intensity and wave-length of light and H the magnetic field intensity, then

$$P = e_m \times H.$$

The magnetophotophoretic velocity of the motion in a viscous medium is proportional to the magnetophotophoretic force. Thus we have $v_m = PB$ where B is the mobility. Furthermore for the velocity of fall in diffused light (due to gravity alone) we have $v_t = mg \times B$ where m is the mass of the particle and g the acceleration due to gravity. Then we derive for the magnetic pole strength (charge of the magnetic ion)

$$e_m = \frac{v_m}{v_t} \times \frac{mg}{H} \cdot$$

The weight of spherical particles whose density is known can be determined by using Stokes law and its corrections. The author's method of precipitating the particles to be measured in the condenser and placing them under a microscope to determine their size can also be used (54, 56, 82). As examples a few figures for "the true magnetic charges" are given here, as obtained from successive points using different values of H and assuming the sphericity of the particles. (See JOUR. FRANK. INST., Sept., 1940, Fig. 8, -1, 2, 3.) Evidently in these curves constant slopes indicate constant charges, every change of slope indicates a change of charge. The result of this computation is given in the following table:

No.	Radius	Magnetic charge
28	0.79×10^{-5} cm.	-0.29×10^{-10} m.s.u.
32	0.86×10^{-5} cm.	-0.52×10^{-10} m.s.u.
33	1.02×10^{-5} cm.	$+3.21 \times 10^{-10}$ m.s.u.

The following values were used for the constants: the constant A of Stokes-Cunningham's law was 0.8, the mean free path of the gas molecules 1×10^{-5} cm., the coefficient of viscosity 1.76×10^{-4} g./cm. sec., and the density of Ni 8.5 g./cm.^{3}.

Let us compare these magnetic charges of single nickel particles with the electric charges of single small spheres as determined by the author, using his method formerly described. His most recent determinations, described in "The Microcoulomb Experiment" (Charges Smaller Than The Electronic Charge) (82) (p. 4) gave such values, f.i. 4.38, 8.50, 3.34, 2.9×10^{-10} e.s.u.

This shows the remarkable fact that the numerical value of the magnetic charge on a particle is about the same as that of the electric charge on particles of the same size. It should be mentioned here that the applicability of the Stokes-Cunningham law which requires that the particles have the same density as larger bodies and that their shape is spherical, had to be assumed in the calculation of the magnetic charge. In case of the electric charge it has been proved (82) that this assumption was justified. For this purpose the velocities of rise and fall had to be measured at various gas pressures up to 20 atmospheres, the test particle being caught and precipitated on a small quartz plate, and a new optical procedure had to be worked out to determine the actual shape, size and density of each individual particle.

2. The Magnetization of Matter by Light.

After the author concluded that there are stationary magnetic fields in a beam of light with accompanying potential differences and that light induces magnetic charges, he concluded that the light must have a magnetizing effect and stated in his paper (59) that the charge of a magnet could be changed by light. He asked his former pupil and now co-worker Dr. Banet to study the literature on this subject (58, 59). Thereupon Banet found the following facts:

Even before the time of Oerstedt's experiments Domenico Morichini (1812) (71) magnetized compass needles by means of the ultraviolet portion of a sunlight spectrum as used by

Herschel. His experiments were verified by M. Sommerville (72), F. Zantedeschi (73), von Baumgartner (74) and others.

The author therefore together with Dr. Banet undertook to test the photomagnetic effect also on larger bodies (58). The experiments were successful with compass needles as indicators and a beam of light which was rich in ultraviolet radiation. Magnetic charges were induced on various unmagnetized annealed pieces of iron (paperclips, nails, little iron rods) which were placed normal to the geomagnetic field and which were irradiated for periods varying from minutes to several hours. The poles were mainly north magnetic (as mentioned already a century ago by von Baumgartner, Vienna) and were still present in many specimens after several days. Some were discharged almost instantly. After short periods of irradiation of iron wires it was found that the effect was only on the irradiated side and on the surface. After longer irradiation periods saturation values were obtained. Naturally, the magnetization was dependent to a high degree on the material, its surface and its history. This can be easily understood from the enormous differences in the various sorts of iron. Sometimes the magnetization could not be found at all for these or other reasons. We can now understand why Riess and Moser (75) (1829) and recently Charles M. Focken (Nature 148, 1941, 438) did not succeed to magnetize iron and therefore discredited the experiments of Morichini and others. In later experiments the author and Dr. Banet convinced themselves by means of an amplifier and oscillograph in the laboratory of the Amplifier Company of America that the characteristic of an induction coil with an iron core was changed by ultraviolet irradiation. We remind here that from a swarm of colloidal particles of iron and nickel only one part gets magnetized by light. This proved the author's belief that the magnetization is a general phenomenon as was observed in the magnetophotophoresis and that the magnetization of iron is only a special case. *Light thus magnetizes matter.*

3. The Influence of Light on Brownian Movement and on Diffusion.

Before the theory of Brownian movement was given by A. Einstein and Maryan von Smoluchowsky it had been observed by almost all experimenters that an influence of light upon Brownian movements in liquids existed. As is well known the theory of Brownian movements considers only the statistical movement of molecules and does not account for any such influence. It should be noted that V. Pospisil when observing (1930) carbon particles in liquids in polarized light found that the motion is amplified in the direction of the magnetic vector. R. Fuerth and his school found that the movements of gold particles in liquids diminished in the direction of the electric vector. From other quarters, also independently from the author, the influence of photophoresis was rightly suggested as the cause. (Cf. *Phys. Zeitschr.*, **39**, 194 and 198, 1938.) The author after his discovery of Brownian movements in gases (59) has repeatedly stated that the statistical theory of Einstein and Smoluchowsky does not suffice to explain the phenomena (76, 77, 78). He showed, in a letter to the editor of the *Physical Review* (79) regarding Diffusion, Brownian movement, Loschmidt Avogadro's number and light in connection with magnetophotophoresis that to the statistical fluctuations the movement caused by photophoresis of any kind had to be added. Particles with induced magnetic poles have to move in the direction of the geomagnetic field. *Furthermore the diffusion itself must depend upon the light if observed in light.*

It is obvious that this knowledge is of great interest to the medical and biological science as well as to physiologists and others.

Since the fluctuations of Brownian movement were thus increased by photophoretic movement the determination of the Loschmidt-Avogadro number of molecules by this method gave too small values. *One should therefore make measurement of Brownian movement and diffusion without illumination or with checking light sparks.*

4. The Coagulation of Matter in Light.

The author observed in his condenser that particles coagulated faster when more light is applied. This has to be explained by the fact that the induced poles attract each other. It should be mentioned here that Fachini (36) who also observed photophoresis in liquids also found such coagulations. Furthermore, it is well known that light of short wave-lengths increases particle size of colloids more rapidly than light of long wave-lengths (81).

It is obvious that these phenomena will also interest biologists and astronomers.

5. The Growth of Crystals Toward Light.

A pupil under the direction of the authors after observing photophoresis gathered the light negative and the light positive particles of tellurium separately and precipitated the single particles on quartz lamelle (for the method confer (54, 82). It appeared then that the light positive particles were amorphous spheres while the light negative ones were crystals. On the surrounding glass of the condenser precipitation took place on both sides of the surrounding glass, toward the light and away from the light. This is a clear example (statistics of more than 50 particles were made) of a case where crystals grow toward the light. It was observed (80) that precipitation takes place on those sides of glass windows of a vessel with fast sublimizing substances such as camphor and iodine, where the light comes in and not as should be expected on the darker and thus colder walls which were protected from the light. *This indicates that the photophoretic force is not due to heating effects.* This should be of interest to mineralogists.

6. The Ponderomotive Forces upon Matter.

If light induces electric and magnetic charges upon matter and if as under the conditions of the experiments, there are also electric and magnetic fields in beams of light (57) besides the well-known oscillating ones it follows that there are ponderomotive forces besides the light pressure which are produced by those stationary components and induced charges. *These forces have attracting as well as repelling effects.*

V. CONCLUSION.

Particles of matter irradiated by light between electrodes behave as if they carry positive or negative electric charges. Therefore we can say that through the action of the light uncharged particles obtain unipolar charges, either negative or positive.

Particles of matter, sufficiently irradiated by light between magnetrodes behave as if they carry single south or north magnetic poles (charges). Light therefore produces unipolar magnets (magnetic ions, charges). Unipolar particles flow in homogeneous fields E or H in the direction of the field and reverse their movement with the field. Such a flow of particles simultaneously in both directions can be observed directly by means of a microscope (dark field). One can actually see the flow of an electric current in the above mentioned arrangement. It is very remarkable that the same picture appears if the magnetic field is applied as if the electric field is applied. From the visual appearance it is impossible to determine when an electric and when a magnetic field is applied. The generality of this effect is not diminished by the necessity of using light to produce magnetic ions. It will be a question of further investigation to find out if magnetic ions exist also without light. It should be remembered that when electric currents were discovered, dissociation in the voltaic cell was considered all important, but nobody could explain it. No model to picture what happens in a voltaic cell was known to aid ones imagination and in the same way the author does not attempt to use a model to explain the mechanism of the production of the magnetic ions. . . .

It is evident that a great number of problems are suggested by the conclusions described above. Thus, for instance, one may think of the existence of conductors of magnetic ions, of the heat created by the flow of magnetic ions, etc.

In this paper, the attempt has been made to show that a beam of light causes or induces not only heat and electricity but also magnetism at the same time.

Although an attempt has been made to separate the thermal and mechanical forces from the electric and magnetic ones one cannot be certain, from a general point of view, whether this is entirely possible in the observation of physical phenomena.

NOTE MADE WHILE CORRECTING THE PAPER (DECEMBER 14, 1941).

THE PERMANENT MAGNETIC ION.

The author succeeded recently together with Dr. Leo Banet to observe magnetic ions (single magnetic poles, magnetic charges) which were not created by light.

(1) In a completely homogeneous vertical condenser particles of finest iron powder move from the center of one Magnetrode to the center of the other one, while one part of the particles is at rest.

(2) Colloidal nickel particles which were suspended in water move in the dark between homogeneous (gold plated) Magnetrodes of iron in such a way that one part goes to the North and one part to the South Magnetrode. There is a *Magnetophoresis* in the dark.

The deposits could also be preserved in a number of cases on photographic plates.

Further facts will be reported later.

It seems clear that the above described magnetic ions which were created by light represent only a special case of the "Magnetic Ions" in general.

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350 WEST 58TH STREET,
NEW YORK, N. Y.,
March, 1941.

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