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Gustav Mie and the scattering and absorption of light by particles: Historic developments and basics

Helmuth Horvath *

Faculty of Physics, Aerosol- Bio- and Environmental Physics, University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria

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ABSTRACT

Gustav Mie was a professor of physics with a strong background in mathematics. After moving to the University of Greifswald in North-Eastern Germany he became acquainted with colloids, and one of his PhD students investigated the scattering and attenuation of light by gold colloids experimentally. Mie used his previously acquired knowledge of the Maxwell equations and solutions of very similar problems in the literature to concisely treat the theoretical problem of scattering and absorption of light by a small absorbing sphere. He also presented many numerical examples which completely explained all the effects that had been observed until then. Since all calculations were done by hand, Mie had to limit his theoretical results to three terms in infinite expansions, thus he only could treat particles smaller than 200 nm at visible wavelengths. Mie's paper had remained hardly noticed for the next 50 years, most likely because of the lack of computers. It experienced a revival later and up to now it has been referenced more than 4000 times, owing to the widespread use of Mie's approach in sciences such as astronomy, meteorology, fluid dynamics and many others.

Gustav Mie did not consider his work on scattering of light by small particles as very important, since he just tried to explain the effects which his students had observed. He concentrated on hot topics in theoretic physics, e.g., the theory of matter. He wrote several textbooks, e.g., on relativity, gravitation theory, and electromagnetism, and all of them had run into several editions.

1. Introduction

Gustav Mie (1868–1957), a German professor of physics, had specialized in electrodynamics and used his knowledge to rigorously solve the problem of scattering of light by a spherical particle made of an arbitrary material. He could give theoretically founded explanations of all optical phenomena which had been observed for colloids. After having found the solution and having explained the phenomena, he considered this work completed and looked for other interesting subjects such as the theory of gravitation as well as for more philosophical questions.

The 1908 paper by Mie [1] is the basis of aerosol optics and has been cited in virtually all textbooks on aerosol and atmospheric science. The interaction of electromagnetic waves with small spheres was in the air in the first decade of the 20th century. Several papers dealing with this subject had been published previously (see below). His work was a rigorous treatment of the interaction of light with a particle smaller than or comparable to the wavelength of light and combined theory with applications to a real practical case: the scattering and absorption of light, its polarization, and color

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* Tel.: +43 142 775 1177; fax: +43 142 779511.
E-mail address: Helmuth.Horvath@univie.ac.at

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phenomena observed for gold colloids. From the modern point of view everything is straightforward, but Mie entered a new terrain. For example, he assumed that optical constants of metals, which were obtained for bulk material, are also applicable to nanoparticles which were at least one order of magnitude smaller than the wavelength of light, and luckily this was almost right for the size, wavelength and material he considered. No computer was available in 1908, thus all calculations were performed by hand, and only a maximum of three terms in the infinite series could be considered. Therefore, the findings were limited to particles smaller than the wavelength. Mie [1] already realized that spherical particles are an oversimplification and that ellipsoidal particles should be considered. He did not pursue this, most likely because the computational effort was expected to be too overwhelming. It took more than 60 years to solve for scattering by spheroidal particles numerically. With the availability of large computers, also the scattering and absorption by particles of arbitrary shape can be determined using techniques such as the *T*-matrix, discrete dipole approximation, finite-difference time domain, etc. (see other papers in this special issue).

2. Fields of interest and early work on light scattering in the beginning of the 20th century

In the first decade of the 20th century the following subjects were of special interest to the physicists: relativity, radioactivity and its interaction with living matter, electromagnetic waves, electrons and ions, X-rays, acoustics, and colloids. This is also documented by the Nobel prizes that were awarded in these areas. Many papers on these subjects were published in the leading journals on physics. Mie worked on electromagnetic waves, both theoretically and experimentally, but also had interest in relativity. Likewise he knew a lot about colloids, since one of his students, Streubing, worked on a thesis on this subject [2]. Most influential was the scientific work by Zsigmondy (1865–1929), an Austrian chemist who moved to Germany and published a book on his extensive work on colloids [3]. Colloids were something new and unusual, and their properties were surprising. The Nobel prize was awarded to Zsigmondy in 1925.

With the formulation of the Maxwell equations[1] in 1861 (Maxwell 1861 [4], 1873 [5]) and the proposal of the electromagnetic light theory in 1864 by Maxwell, the interaction of light or electromagnetic waves with matter could be handled theoretically. Thomson published a 560-page book [6] treating theoretically every thinkable problem of electricity and magnetism (e.g., the motion of tubes in a steady magnetic field (p. 28), the action of a magnet on negative rays (p. 134), the propagation of waves along wires (p. 263), the time of oscillations of a cylindrical cavity (p. 344)), and obviously he also treated the interaction of electromagnetic waves with a sphere smaller than or comparable to the wavelength (electrical oscillations of a spherical conductor (p. 361)). From the point of mathematics the problem is almost identical to elastic vibrations of a sphere. This had already been solved by Rayleigh [7]. Thomson's solution had been derived for a perfectly conducting sphere. Hasenörl [8] correctly noted that this is not an adequate assumption for metal colloids and improved the theory by allowing non-zero conductance. Unfortunately his paper had the misleading title "*On the absorption of electromagnetic waves in a gas*" (the gas was understood as a suspension of particles). This paper actually already gives the full solution contained in Mie's later publication. Using the results of Hasenörl, Ehrenhaft [9] gave a rigorous treatment of the scattering of light by small absorbing spheres, which is even more elegant than Mie's work and gives some hints to observed effects, both with respect to color phenomena as well as polarization. But there seems to be a mistake in Ehrenhaft's calculations, since he finds a maximum polarization at 120° for the limiting case of the particle size approaching zero. Mie [1] found the correct value of 90°. A similar treatise was given by Debye [10], who claimed to provide a more elegant solution by utilizing two scalar potential functions.

Lorenz [11] completely solved for the scattering of light by small particles theoretically using the ether theory. The paper was published only in Danish, and thus is had been known only to a few persons. A French translation was published in 1898 [12]. It should also be mentioned that Clebsch [13] published a general solution of the elastic wave equation in terms of the vector wave functions. Both Lorenz [11] and Debye [10] used his work. A textbook on electrical and optical waves, also including Mie's solution, was written by Bateman [14] in 1915. On p. 44–60 Mie's solution was presented and Figs. 5–10 (electric and magnetic partial vibrations, actually radiating multipoles) and Figs. 25 (attenuation by gold suspensions) from [1] were reproduced. A survey of the early work was given by Logan [15]. An interesting analysis of the interrelations of the scientists working on the scattering and absorption of light by small particles, who might have known what, and which ideas stimulated the work is given by Kerker [16].

3. Experimental work on the optics of colloids

Colloidal gold could be produced by reducing a gold chloride solution [3], and the concentration of the gold particles could vary between 0.0005% and 0.05% by mass. Ehrenhaft [17] produced gold colloids by an arc discharge of low current between gold wires under water. The size of the gold colloid particles was far below the resolution limit of the light microscope (approx. 400 nm) and thus could not be determined directly. The electron microscope was invented 25 years later, the photon correlation method was first proposed in 1969, and thus a direct determination of the size was impossible. The gold particles could be made visible by the "ultramicroscope" developed by Siedentopf (he was awarded a Nobel prize for this invention together with Szigmondy in 1925). This instrument uses a concentrated solar light beam to illuminate the

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[1] The term "Maxwell equations" was coined independently by Heaviside and Gibbs in 1884.

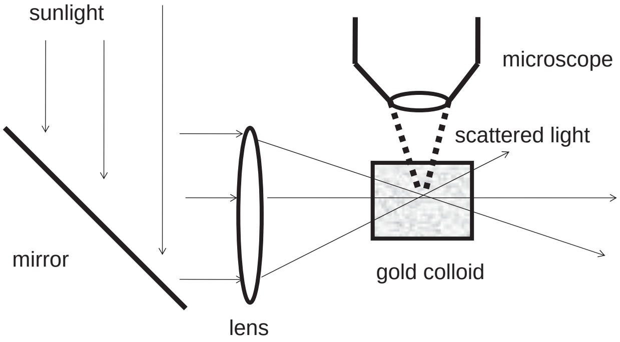

Fig. 1. Basic principle of the ultramicroscope. The colloid is illuminated by an intense beam of light, which then was the sunlight, directed into the instrument via a heliostatic mirror. Part of the light scattered by the particles is observed through a microscope. The light scattered by a particle produces a bright spot in the microscopic image. In today's nomenclature the illumination system would be called dark field illumination.

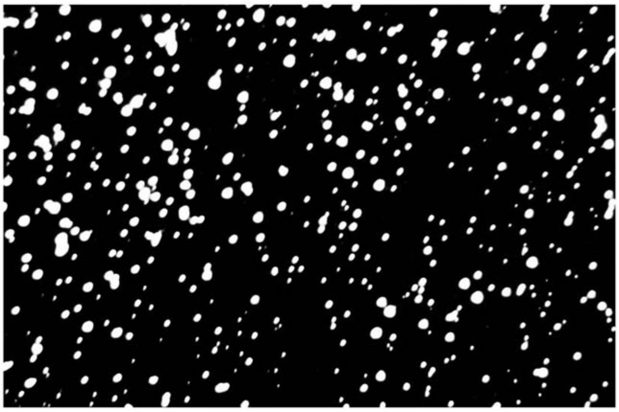

Fig. 2. Ultra-microscopic image of particles with sizes below the resolution limit. The particles appear as bright spots. Due to diffraction in the microscope, the spots are Airy disks. The size of the disks is not indicative of the size of the particle, i.e., seeing an Airy disk just signifies the presence of a particle.

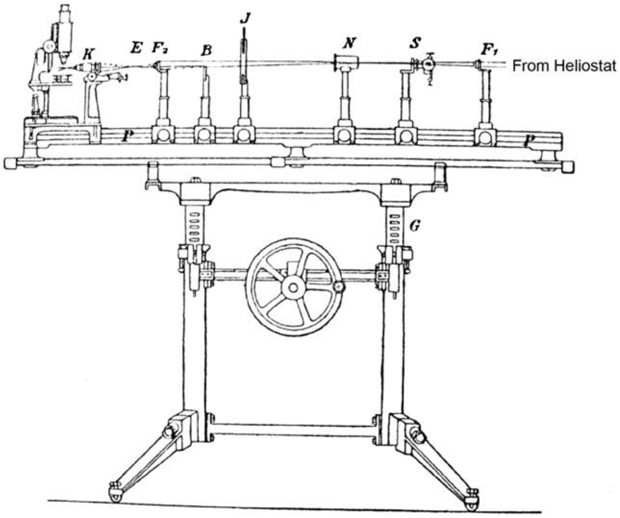

Fig. 3. Experimental setup for the observation of gold colloids developed by Siedentopf. G—rack, adjustible in height, P—prismatic optical bench, F1—telescope lens with a focal length $F = 100$ mm, S—slit, N—polarizer (Nicol prism), J—iris, B—rectangular adjustible stop, F2—telescope lens with $F = 80$ mm, E—location of image of slit, and K—microscope condenser (from Szigmondy [3], Fig. 2).

colloid perpendicular to the direction of observation (see Fig. 1 for the principle, Fig. 2 for an image, and Fig. 3 for the setup used by Szigmondy [3] and most likely also by Streubing [2]). Extreme care must be taken to avoid any sunlight to enter the observation microscope. The scattered light by the particles produces Airy disks, which can only be used to detect particles but not to size them. The lower detection limit is about 4 nm. The approximate size of the colloid particles could be determined by an elaborate microscopic counting of the particles in a given volume. With known concentration of the gold in the solution from which the gold particles were made, and assuming the density of the gold particles being the same as for the bulk material, the size could be derived. The size of the gold particles used by Szigmondy [3] and also produced by Streubing [2] and others was between 6 and 180 nm.

The gold colloids had interesting colors, usually brilliant red which was almost independent of size of the particles in the range 10–80 nm. As soon as the particle size exceeded 100 nm the color changed to blue, indigo and eventually to blue green at 180 nm. For larger sizes no color effects could be seen. The illuminated particles themselves had colors starting at green and becoming yellow and red with increasing particle size. A full description of instrumentation and optical effects can be found in Szigmondy [3]. Mie's student Streubing [2] repeated the experiments and found the same results as Szigmondy.

4. Explanations of the color effects of colloids before 1908

The complete explanation of the various color effects was not possible before Mie's 1908 publication. Some scientists speculated about various modifications of gold which could give the distinct colors, as it is the case for the different modifications of phosphorus (white, red, scarlet, and black phosphorus have distinctly different colors). This assumption could never been proven. Rayleigh scattering [18] would only give blue scattered light. Maxwell–Garnett [19] could demonstrate the red color of gold colloids by applying a theory for inhomogeneous media (as developed by Lorenz [20]). Unfortunately the blue and green colors which have also been observed could not be explained by this theory. Ehrenhaft [17] had investigated experimentally the color of many metal colloids (Au, Pt, Ag, Cu, Ni, Co). He observed strong absorption at distinct wavelengths and concluded that this could be due to resonances of the electric wave in the particles: the large amplitude of the wave in the particles causes a strong damping of the wave due to the conductance of the metal forming the particles. Using results for resonance frequencies of electromagnetic waves in spheres by Thomson [6] he determined the size of the particles as being between 30 and 50 nm, which is in the correct size range. Although the theory for the scattering of light by small spheres was already available, the authors were either satisfied by having found an elegant solution (e.g., Hasenörl [8]), or chose to give just one example which explained one experimentally detected effect (e.g., Ehrenhaft [9]). A comprehensive comparison of experimental results with theoretical findings had not been done until 1908.

5. Mie's approach

Mie had seen the need for a complete comparison of theoretical computations with the experimental results. Good laboratory data were available at his institute in Greifswald, Germany. For the theoretical solution he considered the following case: a plane electromagnetic wave hits a smooth spherical particle embedded in a medium with a real refractive index m_0. The particle can be metallic, thus it can be absorbing and its refractive index is, in general, a complex number: $m = \nu(1-i\kappa)$. The Maxwell equations must be fulfilled as well as the continuity relations at the surface.

Mie introduced spherical coordinates, (r, θ, ϕ), used the dimensionless size parameter $x = 2\pi rm/\lambda$, and $\alpha = 2\pi rm_0/\lambda$ on surface of particle. The electric and magnetic field strengths **E** and **M** are written as the product of time- and coordinate-dependent factors. The Maxwell equations are written in spherical coordinates, the tangential components of **E** and **M** must satisfy the continuity relations at the surface of the sphere. For finding a solution Mie used the method developed by Rayleigh [7]. Mie [1] explicitly mentioned (p. 382) that this is the method as used by Hasenörl [8]. The coordinate-dependent parts of **E** and **M** were written as products of functions depending only on r, θ, or ϕ, which yields differential equations for the coordinate-dependent $E_{r,\theta,\phi}$ and $M_{r,\theta,\phi}$ components. The solution can be represented by infinite sums containing Bessel and Hankel functions, as had been done by the aforementioned authors. At this point Mie's solution differs from that of the other authors: he developed simple recurrence relations for the solutions and indicated (p. 389) that these are more convenient for numerical calculations. He gave a simple argument why the series of partial waves should converge. For gold colloids the summation of three terms is usually sufficient. He also mentioned that the "rainbow problem" caused difficulties due to the large number of partial waves which were impossible to calculate at that time.

With this the problem of light absorption and scattering was solved completely. On the remaining 32 out of 67 pages application of the theoretical results to real cases are discussed. Mie was able to explain all observed effects. In that respect Mie's solution greatly differs from the previous publications which had mostly stated the solution of the problem and gave only one practical example, whereas Mie gave 10 examples. These will be discussed in the following.

5.1. Rayleigh scattering by gold particles

The light scattered by particles much smaller than the wavelength (such as air molecules or oil smoke) is blue, whereas the color of the Airy disks of gold particles observed through the ultramicroscope is green. The limit of Mie's solution with particle size approaching zero gives the amount of light scattered by N particles per unit volume (i.e., the scattering coefficient in units of m^{-1}) as

$$N\frac{24\pi^3}{\lambda^4}V^2\left|\frac{m^2-1}{m^2+2}\right|^2 \tag{1}$$

with V being the volume of the particle. For non-absorbing particles, the refractive index is a real number, and so Rayleigh's solution is obtained:

$$N\frac{24\pi^3}{\lambda^4}V^2\left(\frac{m^2-1}{m^2+2}\right)^2. \tag{2}$$

For transparent materials such as air or glass, the refractive index varies only by a few per cent between in the wavelength range 400–700 nm. Therefore, the wavelength dependence is dominated by the inverse of λ^4.

Gold is a conductor and thus has a complex refractive index. Mie used measured values of the reflection and transmission coefficients of bulk gold [21,22] to calculate the refractive index, which is shown in Fig. 4. Both the real and the imaginary part strongly depend on the wavelength of light. Whether the absorption and refraction values for the bulk material can be applied to particles having a size of only one-tenth of the wavelength was doubtful in 1908 since not much was known about the internal structure of solids. The surface plasmon resonances in small spherical particles [23] should have been considered. In particles of a few nanometers in size the mean free path of the conduction electrons is limited by the diameter of the particle, which interferes with the relaxation. This leads to increased absorption in a narrow wavelength range as was already postulated by Ehrenhaft in 1903 [17]. The imaginary part of the dielectric function, which is responsible for the absorption, increases by a factor of 10 compared to the bulk value for particles of 2.5 nm [24], thus using bulk values completely underestimates absorption. For increasing particle size the difference rapidly becomes smaller, e.g., for 20 nm particles the difference is a factor of 1.5–2, depending on wavelength. Furthermore it should be considered that Maxwell's theory postulates a discontinuity of the dielectric function at the surface of the particle. This does not hold within a few nanometers of the particle's surface, thus for particles of a size of a few nanometers other solutions have to be found.

Thus using bulk properties of the metal may not be adequate. Fortunately this is not very important for the wavelength range and size range considered by Mie, since the smallest size investigated by Mie was 20 nm, and he mainly concentrated on sizes between 40 nm and 180 nm. Obviously the limiting case of the particle size approaching zero would have needed the knowledge of plasmon resonances which was unavailable at Mie's times. Mie seems to have been aware that bulk

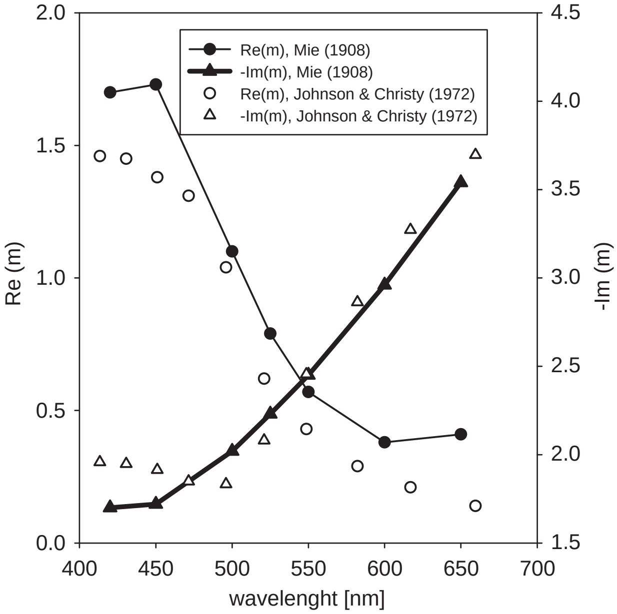

Fig. 4. Real and imaginary parts of the refractive index of gold as functions of wavelength taken from the unnumbered table on p. 417 of [1]. For comparison the values published by Johnson and Christy [26] are also plotted.

properties of metals may not be applicable to nanoparticles and correctly notes that it would be an interesting challenge to measure the optical properties of very fine particles down to those consisting only of a few atoms (p. 445 of [1]). In an experimental investigation Sönnichsen [25] measured the optical properties of gold particles having sizes between 20 and 150 nm for wavelengths between 450 and 700 nm. He compared his measurements with the calculated values, using measured bulk properties by Johnson and Christy [26]: the agreement is excellent. Therefore Sönnichsen concludes that the quantum treatment is not necessary in this case, since the dephasing of the collective oscillations is adequately described by single electron dephasing as given by Mie's solution. No contributions from surface effects such as surface scattering or chemical absorbate damping were observed either. Thus Mie's assumption to use bulk properties was fortunately the right one. In Fig. 4 nowadays accepted values of bulk optical properties of gold are plotted also. There is some difference to the historic values, but this does not change Mie's conclusions dramatically.

The amount of light scattered by very small gold particles calculated by Mie is shown in Fig. 5. Transparent or perfectly conducting particles exhibit the typical Rayleigh scattering. The light scattered by gold particles shows a distinct maximum at 550 nm, i.e., they appear as green spots in the ultramicroscope, as had also been observed. This is caused by the strong variation of the real and imaginary parts of the refractive index, see Fig. 4. Also in this size range the scattering of light by the absorbing particles is stronger by a factor of 4, which explains why these small particles are visible in the ultramicroscope.

5.2. *Particles with sizes between 20 and 200 nm*

Using the first three terms of the infinite series, Mie calculated the spectrum of the scattered light. For particles with sizes between 20 and 140 nm, almost independently of size, the scattered light is green to yellow, the largest amount of light is scattered by particles sized between 100 and 140 nm. Particles with sizes between 140 and 180 nm predominantly scatter orange to red light. Both theoretical findings are in agreement with observations.

5.3. *Polarization of the scattered light*

If particles are illuminated by unpolarized light, the scattered light is usually partly polarized. For particles smaller than 100 nm (Rayleigh scattering) the light scattered at 90°is completely polarized, which is also true for gold particles. For particles with sizes between 100 and 180 nm the degree of polarization diminishes rapidly with increasing particle size, again in agreement with the observations.

5.4. *Polar diagrams*

Each textbook on aerosol optics contains polar diagrams of the angular scattering of light by particles. Mie calculated and showed such polar diagrams for the first time. Due to computational limitations he only could do it up to a particle diameter of 180 nm. Three diagrams taken form Mie's publication are shown in Fig. 6 for a wavelength of 550 nm. Mie pointed out that with increasing particles size the forward scattering rapidly increases in comparison to the backscattering. He also noted that the proper choice of the refractive index is absolutely critical. Assuming the sphere to be perfectly conducting (a simplification frequently used for conductors) yields a polar diagram with predominant backscattering, which had never been observed (Fig. 20 in [1]). The polar diagram also makes possible to determine the degree of polarization. It is immediately evident, that complete polarization of the scattered light for particles below a diameter of 180 nm is not possible outside of the Rayleigh range no matter at what angle. Maximum polarization outside the Rayleigh range is attained for scattering angles between 110° and 120°.

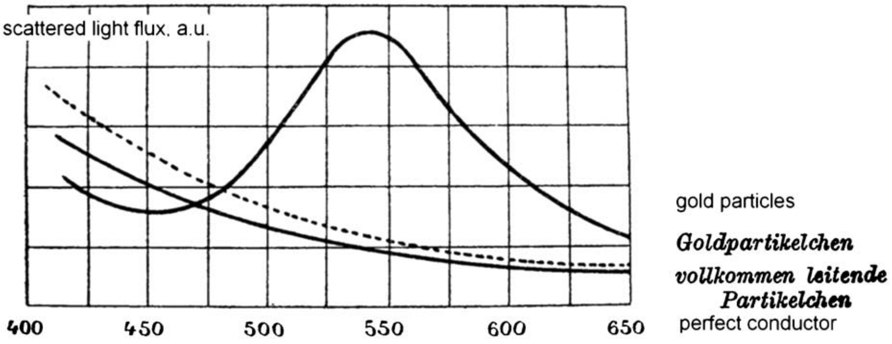

Fig. 5. Scattered radiation as a function of wavelength for particles of size approaching zero (Rayleigh scattering). The horizontal axis shows the wavelength (in nm), the vertical axis shows the amount of scattered light (in arbitrary units). Solid curve: the particle is made of a non-absorbing material; dashed curve: the particle is made of a perfectly conducting material; and solid curve with a maximum: the particle is made of gold (from [1], Fig. 11).

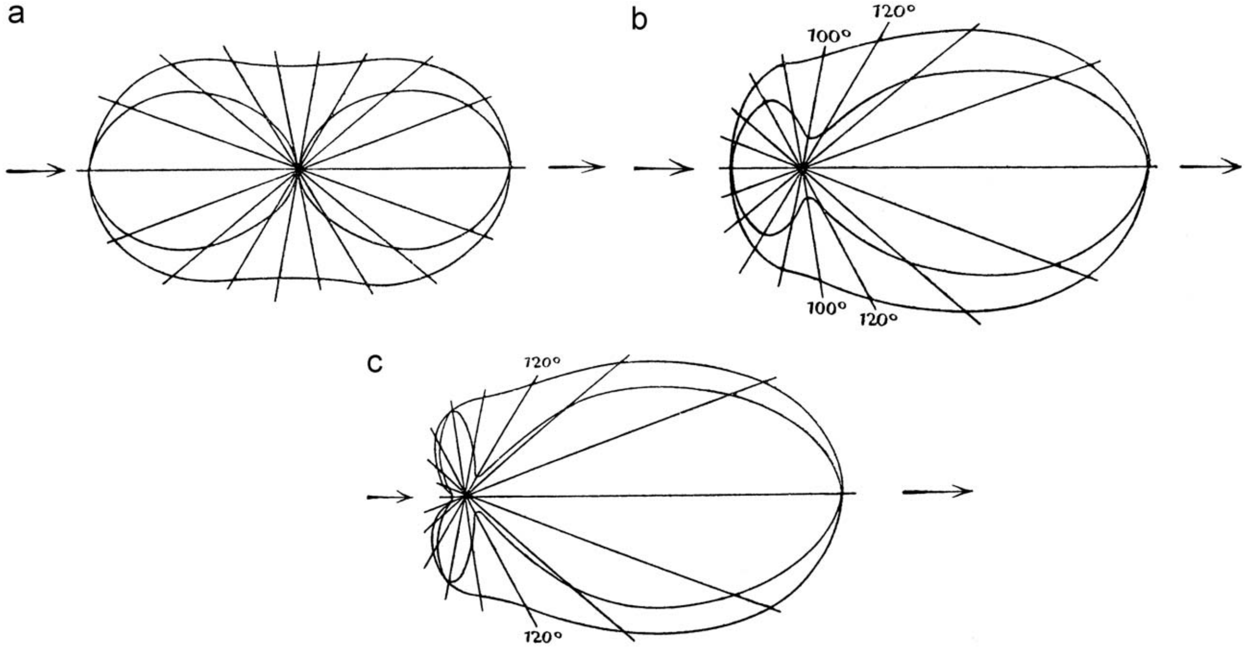

Fig. 6. Angular dependence of the scattered light with polarization parallel and perpendicular to the plane of observation for spherical gold particles. Left-hand panel: the limiting case of infinitely small particles. Right-hand panel: particles with a diameter of 160 nm. Central panel: particles with a diameter of 180 nm (from [1], Figs. 17–19).

5.5. *Light extinction (attenuation) by gold colloids*

Light passing through a gold colloid loses energy both due to scattering of the light and absorption inside the particles. Mie showed that for particles smaller than 10 nm the color seen through the suspension is independent of the particle size and is proportional to the mass of the suspended particles. The maximum attenuation is at 525 nm, the minimal one is in the red, and thus the colloid appears ruby red in transmission. For particle sizes between 20 and 100 nm the maximum of the attenuation slightly shifts to longer wavelengths, which still produces a red color in transmission. A graph of Mie's data of the light extinction (attenuation) coefficient (called "absorption" by Mie) is shown in Fig. 7. For sizes above 100 nm the wavelength-dependent attenuation changes significantly. The absorption maximum shifts towards longer wavelengths and the weakest attenuation is between 400 and 450 nm, causing the colloid to appear violet in transmission for particle sizes ~100 nm, deep blue for ~120 nm, indigo for ~160 nm, and green–blue for ~180 nm. All these theoretical predictions agree perfectly with observations.

5.6. *Light absorption by gold colloids*

The distinct colors of gold suspensions were surprising, and Mie investigated the physics behind this behavior. Mie also calculated the absorption coefficient (which he called pure absorption or "Reine Absorption"). This has a distinct maximum at 525 nm for sizes between almost zero and 80 nm, while for sizes between 100 and 180 nm the maximum is still at the same wavelength, but is less distinct (see Fig. 8). Thus the brilliant red colors of gold suspensions are mainly caused by the strong wavelength dependence of the complex refractive index of gold (see Fig. 4). The peak absorption seems to be a resonance phenomenon in the sphere. The absorption coefficient is at least three times larger than the particle geometric cross section. If the particles were assumed to be perfect conductors, these results could not be obtained.

All these results are a profound proof that the observed phenomena have a well founded theoretical basis. The good agreement between Mie's theoretical results and the experiments is a hint that the optical constants obtained by measurements on bulk samples with sizes several orders of magnitudes larger than the wavelength of light can be used for particles having the size of one twentieth of the wavelength. This was not obvious then. For very small sizes (a few nanometers) this issue still remains unresolved.

6. Conclusions

Gustav Mie introduced a completely new vision of the optics of small aerosol particles and pioneered a new field in aerosol science. Rightly his paper is referenced quite frequently, although nowadays other means to solve the same problems exist.

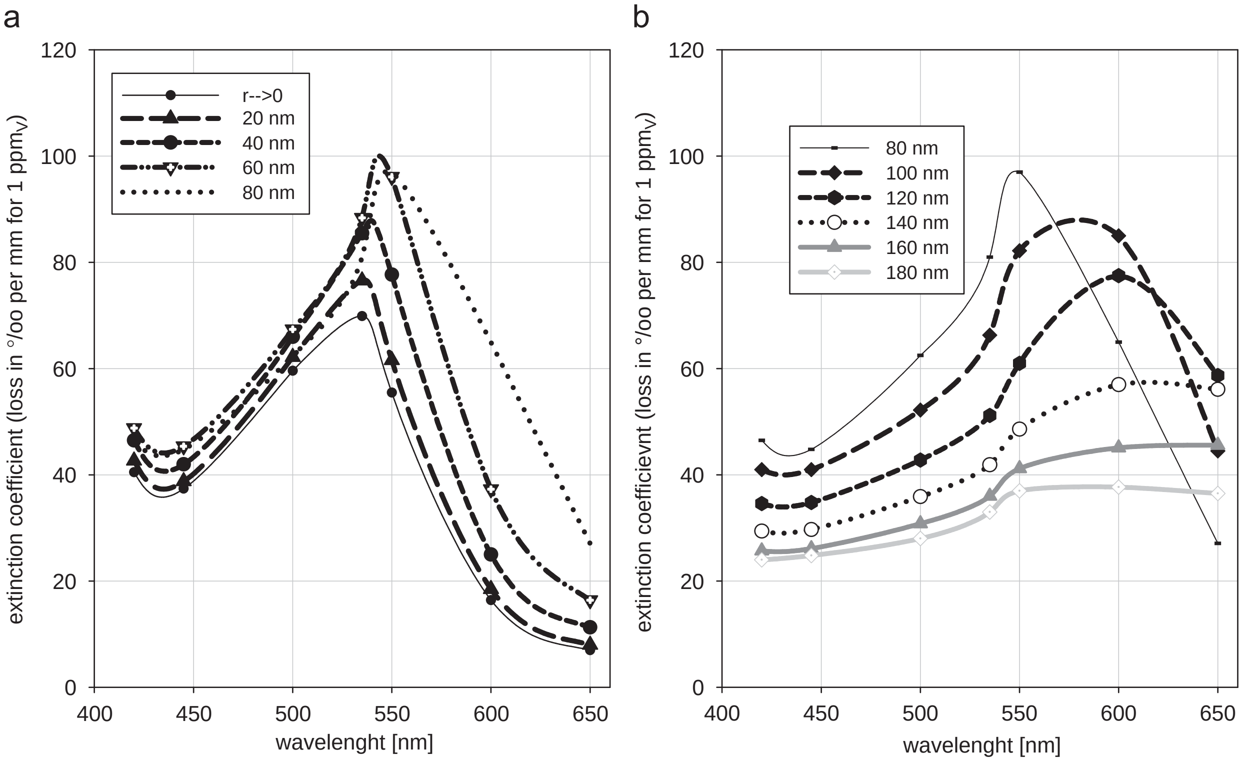

Fig. 7. Attenuation coefficient of gold suspensions with different particle sizes (data from the table on p. 438 of [1]).

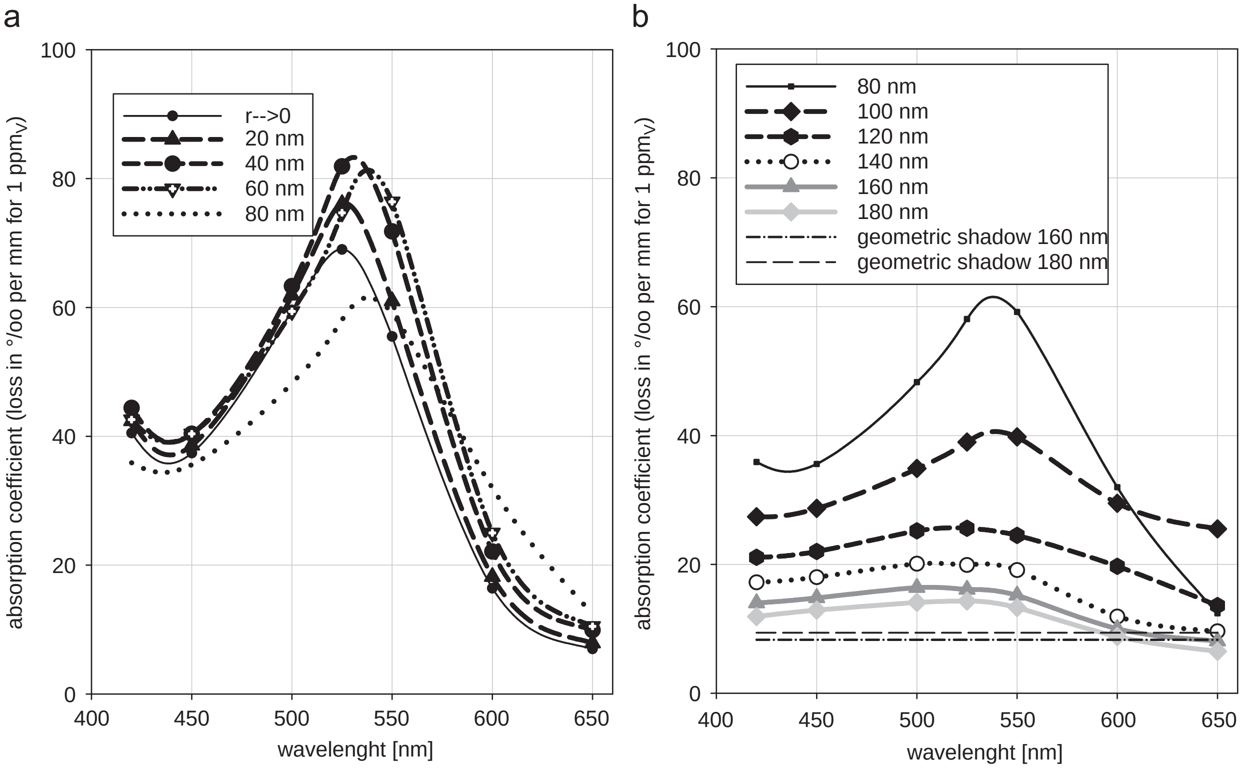

Fig. 8. Absorption coefficient of gold suspensions with different particles sizes (data from the table on p. 4 of [1]).

It is the profound Mie's merit that had provided a broad insight into the optics of turbid media. A theoretical solution for the interaction of electromagnetic waves with small spheres had already existed before Mie's publication of 1908. He used the methodology available in the literature to develop a mathematical solution which is well suited for numerical calculations. He devoted a major part of his paper to practical examples and theoretical explanations of observed effects. This is the great merit of Mie's paper. No other author had taken so much care of the interpretation of theoretical results. The traditional term "Mie theory" is somewhat misleading, since he was not the first one to derive a solution, but the first one to apply it to the scattering and absorption of metal spheres. A better term would be "Mie's solution" or better still "Mie's application". The Brockhaus Dictionary for Natural Sciences and Technology [27] as well as the Brockhaus Encyclopedia [28] call it the "Mie Effekt".

In his paper ([1], p. 443–445) Mie drew the following conclusions for the gold colloids in the size range he investigated:

- He treated the highly diluted suspension of smooth spherical gold particles.
- The light scattered by the particles can be represented as a sum of partial waves.
- Considering the particles as perfect conductors leads to erroneous results.
- Light scattered sideways is always linearly polarized. Elliptic polarization does not occur.
- Up to a particle diameter of 100 nm the scattered light behaves according to the Rayleigh scattering law and has a maximum polarization at 90°. With increasing particle size the maximum of polarization moves to 120°, while the forward scattering increases.
- For a constant concentration of particles the diffuse scattering is proportional to the volume of the particles provided that they are very small. Maximal scattering is attained for particle sizes between one quarter and one third of the wavelength.
- The light diffusely scattered by small spheres of a non absorbing material follows the Rayleigh law and is blue to violet, while for larger particles it is white with some weak color. Optical resonances enhancing scattering and absorption in one narrow wavelength range are not possible. Now we know, that this is possible due to plasmon resonances, but then the particles size needs to be far less than 20 nm, and thus is outside the range of Mie's investigation.
- Gold spheres scatter light more efficiently than their non-absorbing counterparts. Very small spheres mainly scatter green light due to the distinct wavelength dependence of the complex refractive index of gold. With increasing particles size the color of the scattered light changes to yellow.
- The attenuation of light by very small gold particles has a characteristic pattern with respect to wavelength, which is independent of size. It only depends on the mass of the suspended metal.
- The intensity of light transmitted through a suspension of fine gold particles (absorption dominates) has a minimum in green light, a maximum in red light and intermediate values in the blue; thus the suspension appears ruby red. With increasing particles size (scattering becomes important) the color changes to blue.
- Mie was aware of the fact that gold particles were not spherical, and so spherical particles could only be considered as a first approximation. A small discrepancy between the measured and observed polarization was interpreted by Mie as an effect of non-sphericity of the gold particles and he wrote in the final sentence of his paper: "For completeness of the theory it is absolutely necessary to also investigate the properties of ellipsoidal particles." This had not been accomplished until 60 years later.

All Mie's conclusions remain valid now, 100 years after the publication of his paper.

7. Epilogue

With the publication of his paper Mie considered the work done. He had found a solution for the theoretical problem and he had explained all known effects. He had not pursued the problem any further and devoted his energy to modern theoretical physics such as relativity and the theory of matter.

8. Outline of Mie's curriculum vitae

Mie's curriculum vitae also provides insight into the background of his 1908 publication and many other aspects of his research. An outline of his life and achievements can be found in Spehl [29] as well as in Lilienfeld [30]. A short summary will be given below.

Gustav Adolf Feodor Wilhelm Ludwig Mie was born on September 29, 1868 in Rostock, a city on the North–East coast of Germany. The family name Mie is not very common in Germany, and many associate it with Chinese. In fact, the Mie's family name originated from the Hugenots in the 16th century France. His ancestors avoided religious persecution by moving to Germany where reformation allowed more freedom of belief. Mie's family was very religious, his grandfathers were protestant pastors, as was his brother. His father was a businessman, a merchant. Gustav Mie attended a primary and secondary school in Rostock, and his school education was oriented towards the study of theology. He also was excellent in natural sciences. His graduation diploma from the school ("Große Stadtschule") in Rostock in 1886 stated

> In Mathematics he has shown above average to excellent knowledge in all fields. Solving problems was never a problem for him. The written examination was excellent, therefore an oral examination was waived, Grade A", "He has always been lively interested in Physics, he has a good understanding of the phenomena, and an excellent knowledge of the laws of physics, Grade B" and "He has participated in a 6-semester curriculum in general Chemistry, always with interest, enthusiasm and good success, Grade B.

Therefore, after graduation from school, it was straightforward for Mie to study natural sciences at a university. He started at the University of Rostock, his home town, in 1886. The sciences he began to study were mineralogy, geology, mathematics, physics, and chemistry. He also learned Hebrew. In 1888, after two years of successful studies in Rostock, he wanted to broaden his scientific horizon and transferred to the renown University of Heidelberg. In 1889 he got an award from the physics laboratory for excellent work. In 1890 he applied for the "Staatsexamen" (state examination) for Mathematics, Physics, Mineralogy, and Chemistry which took place in Karlsruhe in the spring of 1891. His examination work was on "Die Theorie der Dynamomaschinen" (the theory of electrical generators). This state examination enabled him to teach natural sciences as well as theology in schools, the latter being a family tradition. The topic of his thesis in Heidelberg was on a "very abstract problem of partial differential equations". Mie obtained his doctorate from the University of Heidelberg in July 1892. From 1889 to 1892 he held the position of an "Assistent" (assistant) at the Institute of Mineralogy in Heidelberg. His thesis [31] and subsequent work resulted in three papers [32–34].

After obtaining his PhD he taught for some time at a school in Dresden. He stayed in contact with the University of Karlsruhe and based on his thesis Professor Lehmann offered him a position as an assistant. He was in charge of the "Physikalisches Praktikum" (physics laboratory training for students). Obviously he acquired considerable experimental skills that way. Lehmann worked on liquid crystals, and Mie participated in this research. In all German universities lectures in experimental physics were accompanied by impressive demonstration experiments. Mie also helped with this. A few years earlier the propagation of electromagnetic waves along parallel wired had been detected by Lecher in 1889 [35]. Lecher started his work in Karlsruhe in 1886. After moving to Bonn in 1889 he could take his original equipment with him only after having built a copy to remain in Karlsruhe. Mie built a demonstration experiment using the equipment of Lecher available in the institute. He also published a sound theoretical basis for the propagation of electromagnetic waves along wires [36]. The "*Habilitation*" (lectureship) is an important step in the career at any university. The theoretical scientific work on energy transmission [37] presented by him as a Habilitation thesis was obviously stimulated by his experimental work. Other publications during this period were on DC generators [38], the Poynting theorem [39] and possible motions of the ether [40].

In 1901, he married Bertha Hess (1875–1954) whom he met during his studies in Heidelberg. A year later they moved to the University of Greifswald, which was close to his home town Rostock, where he obtained a position as an "*Extraordinarius*" (associate professor). In 1905 he became an "*Ordinarius*" (full professor) and director of the Physics Institute. From 1916 to 1917 he was "Rektor" (rector) of the university. At this university the optical properties of colloids and other substances were intensively investigated. Under the direction of Professor König, two dissertations dealing with metal colloids and the polarization of reflected light were prepared [41,42], and apparently Mie joined this team. His student Walter Streubing did an experimental PhD thesis on gold colloids [2]. Since Mie had vast experience in the electromagnetic theory and differential equations, he developed a rigorous theoretical treatment based on the Maxwell equations and explained all of the observed phenomena. A portrait of Gustav Mie taken during the work on his 1908 paper is shown in Fig. 9. With all his experience in electromagnetism Mie wrote a textbook on this subject [43]. Mie was very proud of using no mathematic formalisms for the Maxwell equations. It was his intention to promote Faraday's and Maxwell's ways of thinking in Germany. This book was republished several times, the last edition in 1948, thus it had been on the market for more than 40 years.

But Mie's 1908 paper on light scattering and absorption by small particles was considered by him only as a small offshoot. It is not even mentioned in his own memoirs [58]. His main interest was in the theory of matter and relativity, and he published several papers and two books on this subject [44–48]. He can be considered as a co-founder of the unified field theory.

Fig. 9. Photograph of Gustav Mie circa 1905 in his home town Greifswald. At this time he worked on his light scattering paper (courtesy of Fritz Mie).

The 15 years between 1902 and 1917 were very productive. Although Mie had already had a chair at the University of Greifswald, he accepted an offer to become a full professor at the University of Halle. This must have been a very attractive offer, since his prominent competitors were Debye and von Laue. Halle was a much bigger town than Greifswald (230 000 compared to 54 000 inhabitants) and at that time was considered to be the most cultural town in the Eastern Germany. Fig. 10 shows a photograph of Mie taken at that time. Also the proximity to memorial places of Luther may have been a decisive factor for him. Another decisive factor obviously was the higher salary in Halle (6600 compared to 4000 Mark). Unfortunately, the timing was not perfect, since turbulent years started after the end of World War I in 1918. Social unrest like revolts, military takeovers, and inflation made life in a bigger city unpleasant. Although in Halle he found the interdisciplinary cross fertilization very stimulating intellectually, Mie accepted an offer from the University of Freiburg im Breisgau in South-Western Germany where he taught and worked from 1924 until his retirement in 1935. Like in Greifswald, the experimental group was also headed by a theoretically oriented professor of physics. One of the results of his 1908 paper was the strong increase in forward scattering with increasing size. Having this in mind he used small angle scattering for the structural analysis of macromolecules with X-rays. Together with the eventual Nobel laureate Mie published a paper on the results of X-ray diffraction analyses of the structure of polymer formaldehyde. That team was the first to identify a fiber structure of the material under investigation [49]. This result was decisive for the development of future synthetic materials such as nylon. Besides supporting research by his theoretical and mathematical knowledge, Mie wrote a textbook on electrodynamics [50].

As it is the case with many theoretical physicists who have deeply investigated the very basis of their science, Mie turned to more philosophical and theological matters towards the end of his career and life. He was a co-founder of the scholarly society "Pentathlon" (five faculties in Freiburg) intended to cultivate the contact between the different disciplines of science. Unfortunately this society was dissolved by the Nazi regime since it had Jewish members. Shortly after his retirement in 1935 Mie published a paper on the ways of thinking in physics [51]. He advocated the strict causality of modern thinking, but he also admitted that there was still enough space for God's ruling. Other papers and lectures dealt with the basics of quantum theory [52], the problem of matter [53], the intellectual structure of physics [54], natural sciences and theology [55], and the divine order of nature [56]. Fig. 11 shows a portrait of Mie at the end of his career at the University of Freiburg.

While being professor emeritus after 1935, Mie was still active in the scientific community. His textbook on electricity and magnetism ran into a revised edition in 1948. In 1950 he published a textbook on the basics of mechanics [57]. His philosophical and religious ideas could not be published during the Nazi regime and thus appeared after the war [55]. In these papers he tried to work out a coexistence between Christian beliefs and natural sciences. On February 13, 1957. Mie died in Freiburg im Breisgau, Germany.

Mie's scientific achievements were honored by various prizes and awards. He was elected as a member of two learning societies: "Gesellschaft der Wissenschaften in Göttingen" (1921) and "Kaiserlich Leopoldinisch-Carolinische Deutsche Akademie der Naturforscher in Halle" (1921). In 1925 Mie became honorary doctor of the Technical University of Karlsruhe. In 1938 he was elected honorary member of the German Physics Society, and in 1943 he was awarded the Goethe Medal for arts and science. The Faculty of Physics of the University of Freiburg bestows the Mie Award since 1989.

Fig. 10. Photograph of Gustav Mie circa 1917, the time when he moved from the University of Greifswald to the University of Halle (courtesy of Fritz Mie).

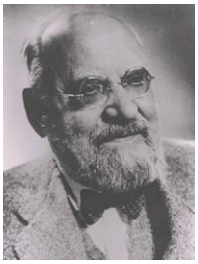

Fig. 11. Photograph of Gustav Mie circa 1940, shortly after his retirement from the University of Freiburg im Breisgau (courtesy of Fritz Mie).

Gustav Mie was an excellent scientist well recognized by his peers. He had contacts with scientists all over Europe. He was an expert on the application of Maxwell's equations to many problems such as small spheres, dielectric constants and anomalous dispersion. He worked on a unified field theory, and definitely stimulated further research, he interpreted X-ray crystallographic studies, worked theoretically on electrical machines, and made other scientific contributions. He wrote textbooks revised versions of which have run into several editions, and in the last part of his life gave deep thoughts to natural science and Christian beliefs. He liked music and emotionally followed it, for example, he had tears in his eyes when listening to the crucifixion of Bach's St. Mathew Passion. According to his friends he was easy to get along with, and preferred to stay in the background. This is best characterized by his writing in the introduction to his autobiography [58]:

> Wenn ich Ihnen etwas aus meinem Leben erzähle, so bitte ich Sie von vornherein nicht enttäuscht zu sein, wenn sie wenig aufregendes zu hören bekommen. Mein Leben ist sehr einfach und schlicht verlaufen, aber gerade darin sehe ich Gottes besondere Fügung, daß er mir nicht mehr zugemutet hat als ich tragen konnte. (When telling you something of my life, I ask you not to be disappointed right ahead for not hearing exciting things. My life was simple and plain, but in this I see an act of God's providence, because He has not exposed me to a larger load than I could bear.)

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References

[1] Mie G. Beiträge zur Optik trüber Medien speziell kolloidaler Goldlösungen (contributions to the optics of diffuse media, especially colloid metal solutions). Ann Phys 1908;25:377–445. This paper, including an English translation, as well as other historic papers on light scattering and absorption can be found at 〈www.iwt-bremen.de/vt/laser/wriedt/index_ns.html〉.
[2] Streubing W. Über die optische Eigenschaften von kolloidalen Gold Lösungen (on the optical properties of gold colloids). Ann Phys 1908;26:329–71.
[3] Szigmondy R. Zur Erkenntnis der Kolloide—Über irreversible Hydrosole and Ultramikroskopie (insights into colloids—on irreversible hydrosols and ultra microscopy). Jena: Gustav Fischer; 1905.
[4] Maxwell JC. On physical lines of force. Phil Mag 1861;21:161–75, 281–91, 338–48; 23:12–24, 85–95.
[5] Maxwell JC. A treatise on electricity and magnetism. Oxford: Clarendon Press; 1873.
[6] Thomson JJ. Notes on recent research on electricity and magnetism intended as a sequel to professor Clerk–Maxwell's treatise on electricity and magnetism. Oxford: Clarendon Press; 1893.
[7] Rayleigh L, Strutt JW. The theory of sound. vols. 1–2, London: Macmillan; 1877.
[8] Hasenörl F. Über die Absorption elektrischer Wellen in einem Gas (on the absorption of electric waves in a gas). Sitzungsberichte der mathematisch-naturwissenschaftlichen Klasse der Kaiserlichen Akademie der Wissenschaften ("Wiener Sitzungsberichte") 1902;111:1229–63.
[9] Ehrenhaft F. Die diffuse Zerstreuung des Lichts an kleinen Kugeln. Sitzungsberichte der mathematisch-naturwissenschaftlichen Klasse der Kaiserlichen Akademie der Wissenschaften ("Wiener Sitzungsberichte") 1905;114:1115–41.
[10] Debye P. Der Lichtdruck auf Kugeln von beliebigem Material (light pressure on spheres of arbitrary material). Ann Phys 1909;30:57–136.
[11] Lorenz L. Lysbevaegelsen i og uden for en af plane Lysbolger belyst Kugle. Det Kongelige Danske Videnskabernes Selskabs Skrifter1880; 6. Raekke, 6 Bind: 1–62.
[12] Lorenz L. Sur la lumière réfléchie et réfractée par une sphère (surface) transparente. in Oeuvres scientifiques de L. Lorenz. revues et annotées par H. Valentiner. Tome Premier, Libraire Lehmann & Stage, Copenhague, 1898, 403–529. This paper, as well as other historic papers on light scattering and absorption can befound at 〈www.iwt-bremen.de/vt/laser/wriedt/index_ns.html〉.
[13] Clebsch A. Concerning reflection on a spherical particle. Crelle's J 1863;61:195.
[14] Bateman H. The mathematical analysis of electrical and optical wave motion on the basis of Maxwell's equations. Cambridge: Cambridge University Press; 1915. 159p.
[15] Logan NA. Survey of some early studies of the scattering of plane waves by a sphere. Proc IEEE 1965;53:773–85.
[16] Kerker M. The scattering of light and other electromagnetic radiation. New York: Academic press; 1969. p. 54–59.
[17] Ehrenhaft F. Das optische Verhalten der Metallkoloide und deren Teilchengröße (The optical properties of metal colloids and their size). Sitzungsberichte der mathematisch-naturwissenschaftlichen Klasse der Kaiserlichen Akademie der Wissenschaften ("Wiener Sitzungsberichte") 1903;112:181–209.
[18] Rayleigh L, Strutt JW. On the transmission of light through the atmosphere containing small particles in suspension and on the origin of the blue sky. Phil Mag 1909;47:375–84.
[19] Maxwell-Garnett JC. Colours in metallic glasses and in metallic films. Phil Trans R Soc 1904;203:385–420.
[20] Lorenz L. Über die Refraktionsconstante (on the constant of refraction). Wiedmanns Ann Phys Chem 1880;11:70–103.
[21] Hagen E, Rubens H. Das Reflexionsvermögen einiger Metalle für ultraviolette und ultrarote Strahlen (the reflectivity of some metals for UV and IR adiation). Ann Phys 1902;8:1–21 This paper is wrongly referenced in [1].
[22] Hagen E, Rubens H. Die Absorption ultravioletter, sichtabarer und ultraroter Strahlung in dünnen Metallschichten (the absorption of ultraviolet, visible and infrared radiation in thin metal layers). Ann Phys 1902;8:432–54 [This paper is wrongly referenced in [1]].
[23] Kreibig U, Genzel L. Optical absorption of small metallic particles. Surf Sci 1985;156:678–700.
[24] Kreibig U. Hundert Jahre Mie Theorie (one hundred years of Mie theory). Phys Unserer Zeit 2008;39:281–7.
[25] Sönnichsen C. Plasmons in metal structures. PhD dissertation, Ludwig Maximilan Universität, München, Germany; 2001. 134 p.
[26] Johnson P, Christy R. Optical constants of the noble metals. Phys Rev B 1972;6:4370–9.
[27] Brockhaus Enzyklopädie, 19th printing. Mannheim: Brockhaus; 1991. vol 14, p. 573.
[28] Brockhaus Naturwissenschaft und Technik. Mannheim: Brockhaus; 1989. vol 3, p. 260.
[29] Spehl H. Mie, Gustav Adolf Feodor Wilhelm Ludwig, Physiker. In: B Ottnad, editor. Badische Biographien, neue Folge, vol. III. Stuttgart: W. Kohlhammer Verlag. 1990; p. 186–90.
[30] Lilienfeld P. Gustav Mie: the person. Appl Opt 1991;30:4696–8.

[31] Mie G. Zum Fundamentalsatz über die Existenz von Integralen partieller Differentialgleichungen. Inaugural-Dissertation zur Erlangung der Doctorwürde, vol. 42, Dresden: B.G. Teubner; 1892.
[32] Mie G. Fundamentalsatz über die Existenz von Integralen partieller Differentialgleichungen (fundamental theorem for the existence of integrals of partial differential equations). Z Math 1892;37:151–70.
[33] Mie G. Fundamentalsatz über die Existenz von Integralen partieller Differentialgleichungen (fundamental theorem for the existence of integrals of partial differential equations). Z Math 1892;37:193–211.
[34] Mie G. Beweis der Integrirbarkeit gewöhnlicher Differentialgleichungen nach Peano. Math Ann 1893;43:553–68.
[35] Lecher E. Eine Studie über elektrische Resonanzerscheinungen (a study on electrical resonance phenomena). Wiedemanns Ann Phys Chem 1890;41:850–70.
[36] Mie G. Elektrische Wellen an zwei parallelen Drähten (electrical waves on two parralel wires). Ann Phys 1900;2:201–49.
[37] Mie G. Entwurf einer allgemeinen Theorie der Energieübertragung (design of a generalized theory for tranmission of energy). Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften in Wien, Mathematisch Naturwissenschaftliche Klasse 1898;107:1113–80.
[38] Mie G, Arnold E. Über den Kurzschluß der Spulen und die Kommuation des Stromes eines Gleichstromankers (on the short circuit in coils and the commutation of currents in a DC armature). Elektrotechnische Z 1899;#5:97–101; #7:136–8; #8:150–2 [Copyeditor: each issue has its own pagination].
[39] Mie G. Ein Beispiel für Poyntings Theorem (some examples for Poynting's Theorem). Z Phys Chem 1900;43:522–6.
[40] Mie G. Über mögliche Ätherbewegungen (on possible movements of the ether). Ann Phys 1899;68:129–34.
[41] Degen K. Beiträge zur Kenntnis kolloidaler Metallösungen (contributions to the knowledge on colloidal metal solutions. König W, Referent Prof., PhD dissertation, May 2, 1903, Greifswald: Julius Abel; 1903.
[42] Lischner E. Über die elliptische Polarisation des Lichtes bei der Reflexion an Lösungen von Körpern mit Obeflächenfarben (on the elliptical polarization of light reflected on solutions of substances with surface colors). Ann Phys 1903;12:964–83.
[43] Mie G. Lehrbuch der Elektriztät und Magnetisms (textbook on electricity and magnetism). Stuttgart: F. Enke; 1920. 736 p. [2nd revised edition: 1941, 638 p.; 3rd revised edition: 1948, 666 p.]
[44] Mie G. Moleküle, Atome, Weltäther (molecules, atoms, ether). Leipzig: Teubner, 1904. 141 p. [2nd and 3rd editions in 1907 and 1911.]
[45] Mie G. Grundlagen einer Theorie der Materie erste Mitteilung (basics of a theory of matter, first part). Ann Phys 1912;37:511–34.
[46] Mie G. Grundlagen einer Theorie der Materie zweite Mitteilung (basics of a theory of matter, second part). Ann Phys 1912;39:1–40.
[47] Mie G. Grundlagen einer Theorie der Materie, dritte Mitteilung, Schluß (basics of a theory of matter, third and final part). Ann Phys 1913;40:1–66.
[48] Mie G. Elektrodynamik Die Einsteinsche Graviatationstheorie, Versuch einer allgemein verständlichen Darstellung der Theorie (Einstein's theory of gravitation, an attempt to make the theory easy to understand), vol. 69. Leipzig: S Hirzel; 1923.
[49] Staudinger H, Johner H, Singer G, Mie G, Hengstenberg J. Der polymere Formaldehyd, ein Modell der Zellulose (polymersized formaldehyde, a model of cellulose). Z Phys Chem 1926;126:425–48.
[50] Mie G. Elektrodynamik, vol. 502. Leipzig: Akademische Verlagsgesellschaft; 1932.
[51] Mie G. Die Denkweise der Physik und ihr Einfluß auf die geistige Einstellung des heutigen Menschen (the ways of thinking in physics and their influence on today's attitudes of men), vol. 37. Stuttgart: Ferdinand Enke; 1937.
[52] Mie G. Die Grundlagen der Quantentheorie (the basis of quantum theory), vol. 38. Freiburg: Speyer Kaerner; 1926.
[53] Mie G. Das Problem der Materie (the problem of matter). Antrittsrede (inaugural speech), University of Freiburg, 1925.
[54] Mie G. Die geistige Struktur der Physik (the intellectual structure of physics), vol. 36. Gütersloh: Bertelsmann; 1934.
[55] Mie G. Naturwissenschaft und Theologie (natural sciences and theology), vol. 39. Leipzig: Akademische Verlagsgesellschaft; 1932.
[56] Mie G. Die Göttliche Ordnung der Natur, 3 Aufsätze;Das christliche Deutschland 1933 bis 1945 (the divine order of nature, three papers, the Christian Germany 1933 to 1945). Thübungen: Furche Verlag. 1946;31
[57] Mie G. Die Grundlagen der Mechanik (the basics of mechanics), vol. 80. Stuttgart: Ferdinand Enke; 1950.
[58] Mie G. Aus meinem Leben (from my life). Zeitwende 1947;19:733–43.