DOI: 10.1478/AAPP.99S1A37

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 99, No. S1, A37 (2021)

WAVE-PARTICLE DUALISM DEVELOPMENT FROM THE FIRST SPECULATIONS ON LIGHT TO MODERN METHODS TO PROBE MATERIALS: AN OPPORTUNITY FOR A FLIPPED CLASSROOM APPROACH

PIETRO CALANDRA [a] *, VALERIA LA PAROLA [b], DOMENICO LOMBARDO [c], DAVIDE PEDDIS [d], CARMEN CRETU [e] AND ELISABETA ILDYKO SZERB [e]

ABSTRACT. It is always a big problem to explain students what radiation is and how it can help researchers in understanding the structure of materials in a clear and simple way. The exact comprehension of radiation has followed a very problematic historical excursus. The problem of understanding what light is started to be faced around the VI century B.C.; since that time, a continuous development of ideas and models has characterized the definition of radiation. After Maxwell's equation, the behaviour of light seemed to be well understood, although further enriched, afterwards, by the discoveries in quantum mechanics. Radiation can give rise to several phenomena when interacting with matter. Thus with a correct comprehension of its origin, radiation can constitute a powerful tool in modern science to probe the structure of materials down to the nano-scale and even lower. In this work, scattering phenomena will be considered as effective examples to propose to young students for probing the structure of materials, since these are usually characterized by hierarchical organization of self-assembled structures at different length scales, from atomic to macroscopic distances. In this complex framework, the concept of characteristic distances is pivotal in defining the structure of a material, and can be easily derived from scattering experiments. In this respect, the efforts made in the last century to understand the origin of radiation turned out to be useful in giving researchers the best tool to characterize a given material, at least from its structural point of view. For this reason, modern didactics must take into account for modern approaches to make people aware of these aspects. If bringing kids and young students closer to these arguments is easily achieved by a "learn by doing" approach, this work, structured from the historical point of view and reporting tickling aspects of the debates taken place among peoples over the centuries, represents an opportunity for an interdisciplinary flipped classroom approach.

1. Introduction

Understanding the nature of radiation and how researchers use it for investigating the structure of materials is highly challenging for a student. All age scholars should have a different approach of learning scientific concepts (Mynbayeva *et al.* 2018). The extent of the argument and the possibility to deepen the understanding of the subject with the age of the

learner made the radiation a subject perfect for a complete study path across all the academic or scholar courses of study. The younger students may retrace the process of discovering the characteristics of light by retrying the experiments made over the centuries, with the available means of the time. A typical flipped classroom approach may be used for the older students. The properly guided students can study the basics of theory at home, considering that given the importance of the topic many media and digital contributions are easily available. Project work at school can consolidate the knowledge and the understanding of the theory. Project works and interacting discussions would promote the critical thinking and the deduction skills of the young learners. Therefore herein the historical excursus from the first theories developed for the comprehension of radiation around the VI century B.C. until the nowadays elaborated ideas and models are presented in order to have a better view of the possible practical experiments to be elaborated for active participation of students in learning.

2. Historical excursus

2.1. VI century B.C. – 1000 A.D.. The long story which led to the definition of nature of light and to the laws governing the phenomena related to the light dates back to the VI century B.C. It is an interesting and fascinating path for the overlapping of conjectures, hypotheses, experiences, theories, sometimes to go back and re-propose ideas, adapt them, interpret them in coincidence with new phenomena or to examine already known phenomena. The perfection of these theories and the corresponding physical laws led to the development of many spectroscopic techniques, which are nowadays used in all field of science to reveal the nature and characteristic of matter.

In the ancient Greece, the popular understanding of the visual process consisted in the theory in which the eye emits a fire whose rays probe the surface of observed object. During the first three centuries of Greek philosophy there were many theories dealing with the perception of sight. In the first attempts to understand the ability of men to "see" objects the existence of "visual rays" was postulated by Pitagoric School. These rays were imagined as sticks, coming out of the eyes and physically probing space and objects. Euclid (ca. 300 B.C.), in his work *Ottica*, defines the visual rays as abstract geometric entities and applies to them his mathematical and geometric knowledge. Like segments traced from the eyes, the rays are half-lines which extend in a straight line towards the things seen forming a cone with vertex in the eye and base in the objects. The theory of visual rays is further developed by Tolomeo (II sec. A.D.) who states that the visual rays are not discrete, but fill the visual cone with continuity. Its studies on refraction, as testimony of ancient experimental method, provide refractive angles corresponding to various angles of incidence for some different media pairs (*i.e.* water-air, air-glass and water-glass) (Hentschel 2014).

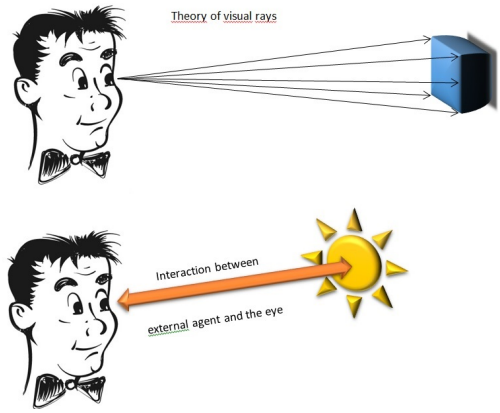

FIGURE 1. Upper panel: the theory of visual rays postulated by Pitagoric School. Defined by Euclid and further developed by Tolomeo, this theory considers light as continuous cones coming out from the observer and probing space and objects. Lower panel: the persistence of the image with closed eyes or the pain experienced in direct observation of the sun suggested the existence of an external physical agent directly interacting with the eye (from 1000 A.D. on). See text for details and discussion. The figure includes a .jpg image freely downloadable from https://publicdomainvectors.org/it/vettoriali-gratuiti/Abbozzo-delluomo-retr%C3%B2/81376.html. Many thanks are due to this website for sharing the image).

2.2. From 1000 A.D. on: the lumen interacting with the eye. The theory of visual rays was very successful, and it was only around 1000 A.D. that it started to be questioned. In particular, the Arab scientist, Abu Ali Hasan Ibn al Haitham, known as Alhazen, (965-1040 A.D.) in his work *Ottica* refutes the existence of visual rays on the basis of the observation of some phenomena like persistence of the image with eyes closed or pain experienced in direct observation of the sun; these kind of effects presuppose an external agent that interacts with the eye. This agent must be physical and he called it *lumen*, while the resultant, i.e. the vision, was called *lux*. The work of Alhazen was elaborated in Europe by Roger Bacon (1214-1294 BC) and translated and rationalized by Vitellione (1120-1280). Three centuries later in 1604 Johannes Kepler writes a treatise on vision and analysis of the eye and its parts using the theory of Alhazen. For the first time the pupil is seen as a diaphragm implying that ray coming from a point of an object hit by the *lumen* produces a point in the retina. This phenomenon is repeated for all the points of the object observed and generates the whole picture in the retina (Baker 2016).

2.3. XVII century: attention is shifted to the nature and laws of the lumen. In the XVII century the focus shifts on the actual nature of *lumen* (*i.e.* the entity which is responsible for the process of visualization) and on the definition of its laws. For example the Dutch scientist Willebrord Snell (1580-1626) defines experimentally a law on refraction, while in the same period the theory underneath will be described by René Descartes (1596-1650). The law of Snell-Descartes describes the relations between the angle of incidence and

refraction of a beam passing between two different isotropic media. However, the problem related to the nature of light, whether it is motion or matter, remained open. Descartes believes that the light is an action or movement that obeys the same laws of local motion and that is transmitted in a full whole. However, it does not correspond to an actual motion but rather to a tendency to movement, to a pressure that instantly propagates from the light source to the observer's (Dioptrique 1824). Extremely critical on Descartes theory is Pierre de Fermat (1601-1665) who thinks is impossible for light to propagate instantly, and that light can be faster in water than in air. In 1662 Fermat will derive the refraction law which we know today to be correct. The starting point is "light travels between two points along the path that requires the least time, as compared to other nearby paths" (Laranjeiras *et al.* 2017). Fermat's ideas, accused by the Cartesians themselves of conducting non-causal but teleological demonstrations, however will not find acceptance in academic circles and the affirmation that the speed of light must increase in the densest media will dominate optical research for over two centuries. In the same period Francesco Maria Grimaldi (1613-1663) postulates other theories on the nature of light, which are posthumously published in 1663. The accepted way of propagation of light in straight line is able to explain the majority of phenomena. Anyway there are some phenomena which cannot be explained by this assumption. For example, in an attempt to experimentally establish the dimensions of a light beam, Grimaldi observed one of these phenomena which he defined as "diffraction". He hypothesized that light "at least sometimes" must propagate "even as a wave" (Sabra 1981; Cecchini and Pelosi 1990). Thus, alongside the idea of propagation for straight rays, the idea of rays with oscillations emerges. These rays would behave according to the principles of geometric optics but, depending on the nature and size of the obstacle, somehow would change in direction and intensity. Two different interpretative models start to shape: is light matter or motion? These two conceptions are commonly attributed one to Newton (1642-1727) and the other to Huygens (1629-1695).

According to Newton the light is composed of very small particles of matter emitted by luminous substances in all directions and in a straight line. The reflection is explained by the rebound of the particles at the moment of impact with a surface. The refraction is due to the forces that the molecules of a substance exert on the light particles by diverting their direction.

Cristiaan Huygens postulate the presence of a media, the ether, composed of identical particles with great elasticity and the motion of light is supposed to originate from the impacts between these particles and those of the luminous body. The light of a candle, for example, is the result of many elementary waves emitted by every single point of the flame. The movement of matter is local; what move in space is the wave that in its subsequent movement hits the particles of the ether and puts them in vibration. Furthermore, the wave production is regulated by the principle, now known as the "Huygens principle", according to which "each particle of the matter in which a wave travels communicates its motion not only to the neighbouring particle which is aligned with the light source, but necessarily also to the others with which it is in contact and who oppose its movement. So that around each particle a wave originates of which it is the centre". The secondary waves are effective only when they concur to form simultaneously the wave front which is therefore constituted by the envelope of all these elementary contributions; with this additive hypothesis Huygens explains the rectilinear propagation of light (Dijksterhuis 2004).

2.4. From XIX century to modern theories. A the beginning of XIX century Thomas Young (1773-1829) returned to Huygens' theory of undulated nature, which had been abandoned by the Newtonians for the benefit of corpuscular theory. He studied the phenomenon of optic interference. Through appropriate experiments and applying the theory of undulatory nature of light, he studied the interference of surface waves in a ripple tank noting that similar wave emitted by a two points oscillator could interfere both constructively and destructively. He then transferred this observations to the light going through a first slit and subsequently a double slit (Young 1801, 1803).

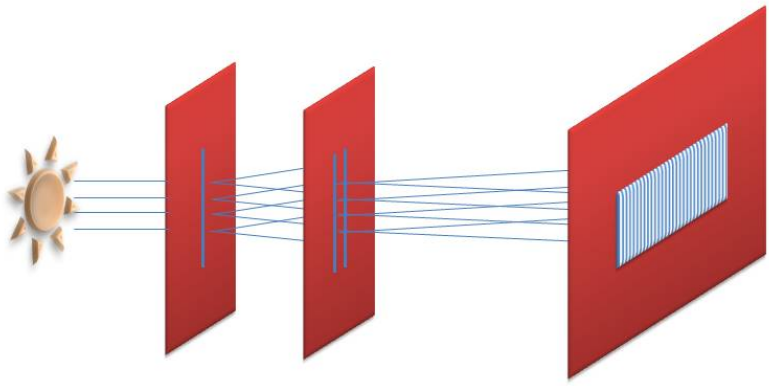

FIGURE 2. Scheme of the experiment showing interference from a light source.

Young's work was disparaged by most English scientists: any opposition to a Newton's theory was unthinkable. It was only with the work of the French physicists Augustin J. Fresnel (1788-1827) and the physicist François Arago (1786-1853) that Young's wave theory finally achieved acceptance in Europe. Fresnel starting point for his mathematical description of diffraction was Huygens principle stating that every point on a wave front can be considered a secondary source of spherical wavelets. The experiment that proved his theories was set up by Arago (Basdevant 2019). Fresnel introduced the notions of wavelength and the propagation of vibrations through the ether, with both spatial and temporal periodicity. His ideas were originally based on an analogy with pendular motion.

Experiments like the one of Armand Louis Fizeau (1819-1896) measuring light speed in water or the ones of Jean Léon Foucault (1819-1868) who demonstrated that light propagation rate in air is higher than in water, favoured the affirmation of the wave theory of light.

An important contribution to this theory was given by Clerk Maxwell (1831-1879) with his studies on electromagnetic fields. In his *"Treatise on Electricity and Magnetism"* (Maxwell 2010) formalizes and summarizes in some fundamental equations the unification of electrical and magnetic phenomena through the definition of the electromagnetic field. His theory was proved in 1886 by Heinrich Hertz (1857-1894) who was able to produce and detect the electromagnetic waves theorized by Maxwell. During his experiment Hertz

discovered the photoelectric effect. This effect gives rise to phenomena that cannot be explained by the wave theory. In particular, the phenomenon does not occur if the frequency of light is less than a minimum value, different from material to material. This led Albert Einstein (1879-1955) to rethink the theory of light. In 1905 he correctly proposed that light came in distinct packets of energy called photons. Photons of ultraviolet light have the right amount of energy to interact with electrons in metals, giving the electrons enough energy to escape from the metal (Einstein 1905). Einstein noted that the photoelectric effect depended on the wavelength, and hence the frequency of the light. At too low a frequency, even intense light produced no electrons. However, once a certain frequency was reached, even low intensity light produced electrons. He compared this to Planck's hypothesis (1858-1947) that light could be emitted only in packets of energy given by hf, where h is Planck's constant and f is the frequency. He then postulated that light travels in packets whose energy depends on the frequency, and therefore only light above a certain frequency would bring sufficient energy to liberate an electron. Einstein's explanation of the photoelectric effect was one of the key drivers in constructing an entirely new way of describing atomic-scale events – quantum physics.

The experiments of Arthur Compton (1892-1962) on X-rays permitted to explain the changes in wavelength of X-Ray when colliding metals. This effect (known as Compton effect) is caused by the transfer of energy from a photon to an electron and point out to a dual nature of electromagnetic radiation, which behave in some cases as a particle, while in other cases as a wave (Compton 1973). A further step forward was made by Louis de Broglie (1892-1987) who guesses that the dualism wave-corpuscle was not related to radiation only, but it could apply to all matter. That means that not only electrons behave as waves but all particles and objects are associated with matter waves. de Broglie calculated what the length of these matter waves associated with each particle would be depending on its velocity and mass. Thus, according to de Broglie, our whole world is quantum. The theory was subsequently fully confirmed by the discovery of electron diffraction by crystals in 1927 by Davisson (1881-1958) and Germer (1896-1971); they served as the basis for developing the general theory nowadays known by the name of *wave mechanics*, a theory which has utterly transformed our knowledge of physical phenomena on the atomic scale.

3. Complexity in material science

The aim of this last paragraph is to give some hints on the concept of "complex systems". Complex behavior is indeed typical in materials. Just to introduce the topic by an example, elementary particles are somehow assembled to form atoms, atoms are assembled to form molecules, salts or inorganic materials, different materials constitute objects and devices. In few words it is based on a hierarchical relationship between constituents and objects. This is depicted in Fig. 3.

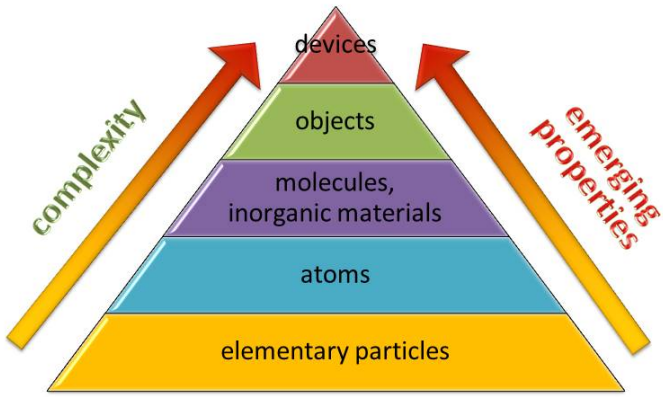

FIGURE 3. Increasing levels of complexity generate systems with emerging properties and novel functionalities.

Any "constituent" can assemble with other "constituent" to form a complex object which, in turn, can be one of the "constituents" of other supra-assemblies. So, when "constituents" are assembled to form a "bigger" object, a successive level of complexity is reached. The properties of a complex system cannot be traced back to those of its constituents because they are the consequence of novel emerging and unexpected properties that can arise when the constituents are interacting. Complex materials exhibit, therefore, spatial correlations between their constituents at different scales. Just to make an example, it is not rare that mixing two liquids with negligible conductivity, a liquid mixture with enhanced (several orders of magnitude higher) conductivity is obtained (Calandra *et al.* 2010a, 2012). This happens because a structural rearrangement usually takes place as a consequence of the intermolecular interactions (Yamada and Honma 2004; Kim and Honma 2005). The structural organization can give really unexpected mutually depending structural features and properties like 1D anomalous diffusion, anti-arrhenian behavior of conductivity (Calandra *et al.* 2013, 2015a), reaction to a magnetic field (Pochylski *et al.* 2016, 2019; Calandra 2020). These examples regard molecular liquids, but other interesting examples can be given by hybrid materials, where the organic and inorganic components are assembled to give very interesting properties (Lan *et al.* 2018), in nanocomposites (Calandra *et al.* 2010b; Ricciardi *et al.* 2017) in liquid crystals (Calandra *et al.* 2000; Cretu *et al.* 2018; Andelescu *et al.* 2020) and so on. In this ambit, general soft matter usually gives also other interesting examples (Likos 2001).

4. Probing Complexity by scattering

It is usually the term "structure" that is used to understand the localization and disposition of the constituents in a system. The term "structure" must be intended as strictly related to the spatial correlation between the constituents of the system. It is obvious that the study of material is advisable to involve non-invasive techniques. Scattering techniques does exactly this job. The structure factor is indeed inherently contained in the output of a scattering experiment which is its synthetic fingerprint. The "structure" involved in complexity is exactly defined in terms of the direct observable through scattering techniques, *i.e.*, the existence of preferred distances, *i.e.* the spatial correlations, among specific constituents of the system. This can take place at different length-scales (Glatter and Kratky 1982). Of course, there are other methods, used to investigate the structure; they are essentially microscopies (Atomic Force Microscopy - AFM, Scanning Electron Microscopy – SEM, fluorescence microscopy). However, AFM and SEM can probe essentially the surface and and fluorence microscopy is useless if the system has a component which is not fluorescent (Shirzad *et al.* 2016). Other vanguard technologies are available, like NMR, but scattering techniques directly probe the existence of preferred distances among constituents.

4.1. Scattering: Principles and applications. Scattering probes the statistical ensemble of the nano-structures and deals with the diffusion of electromagnetic (or particle) waves by heterogeneities in material systems (Magazù *et al.* 2013). The fundamentals of scattering techniques are now given with the only scope to show how they are able to furnish the synthetic view of the material structure (Harroun *et al.* 2006; Lombardo 2014). Apart from the development of scattering techniques at the large-scale facilities, recent improvements in lab instrumentation and the related beam intensities have greatly enhanced the importance of scattering methods in the structural characterization of complex materials. The quality of the recorded spectra is becoming adequate to extract information even from complex systems as bitumen is. This also, allowed the development of suitable methods to understand the complex organization in complex, usually bio-related, materials (Kiselev *et al.* 2001) as well as their structural changes (Lesieur *et al.* 2000; Kiselev *et al.* 2013; Yen *et al.* 2016). A typical scattering geometry is reported in Figure 4: an incident beam from a given source (e.g., Neutrons, X-rays, visible light, electrons, etc.) with incident wavevector (k_0) impinges on the material system under investigation. It is important that the beam is monochromatic or monochromatized because the (k_0) value has to be unique. The sample scatters radiation and the scattered radiation intensity (I) is collected by a detector at a given scattering angle (2θ) with respect to the incident radiation direction. The difference between the scattered (k_F) and incident (k_0) wavevectors furnishes the scattering wavevector (q) defined as

$$q = |k_F - k_0| = (4\pi n/\lambda)\sin(\theta) \tag{1}$$

where n is the index of refraction of the medium and λ is the wavelength of the source radiation. The scheme of the experimental setup is shown in Fig. 4

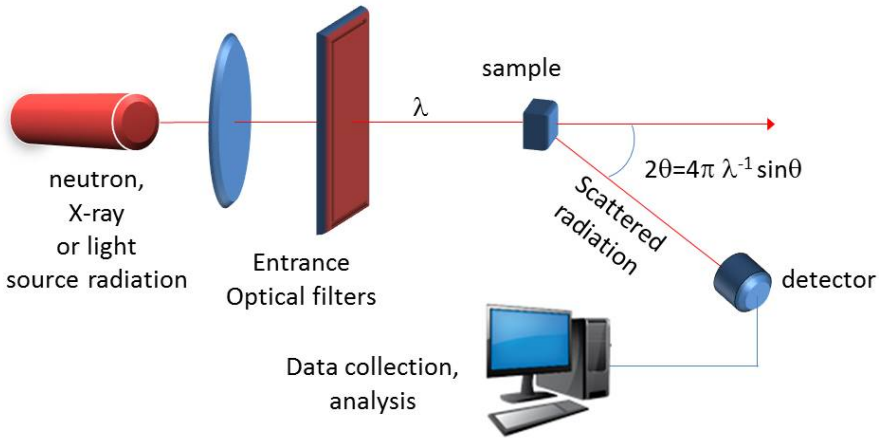

FIGURE 4. Scheme of the experimental apparatus for a scattering experiment.

Generally for X-rays and neutron n is very close to unit. It is worth noticing that a scattering experiment furnishes information over distances that are of the same order, or bigger, than the wavelength λ of the source radiation. The scattering is generally described as arising from the constructive interference coming from objects that are embedded in a continuum medium (treated as constant background) as shown in Fig. 4.

The interaction of radiations with materials is characterized then by a scattering length (b_i), of the i-th scattering center (usually atoms) and the scattering density $\rho(r) = \sum_i \rho_i(r) b_i$ where $\rho_i(r)$ is the local density of scatters of type I (Feigin and Svergun 1987; Belloni 1991). Of course, different radiation (particle) sources give different sub-techniques. Several cases are possible:

(i) neutron scattering arises through (short-range) nuclear interactions (or magnetically, if atoms have unpaired electron spins), while the scattering length depends on the nature of the nuclei of the reference atoms.
(ii) X-rays scattering comes from the interactions among all the electrons in the material under investigation. In this case, the scattering density can be traced back to the electron density.
(iii) in the case of Light photons, which have lower energy than X-rays ones, are scattered only by the outer part of the electronic cloud of an atom. In this case, the scattering length density is proportional to the polarizability of the materials.

Even if different techniques are possible by changing the radiation source, in the following it will be shown that different information can be derived from the various scattering angle ranges, which in turn give different methods of analysis.

4.2. Small angles. At small angles 2θ, according to the source several techniques are possible. The name of the technique is then characterized by the probe which is used: if the probe is made of X-rays, then SAXS is considered; if the probe is a flux of neutrons,

then SANS holds, etc. If the source is light, then it will obviously deal with light scattering. Light scattering is not to be confuse with dynamic light scattering (DLS) also known as photon correlation spectroscopy (PCS), is usually referred to (see below for details).

So, summarizing, the techniques are:

- Scattering of Neutrons (SANS)
- X-rays (SAXS)
- Light

In these cases, the (coherent) scattering intensity in the so-called "static approximation" is given by:

$$I(q) \propto \left[\sum_i b_i e^{iqR}\right]^2 \tag{2}$$

where b_i is the scattering length of the particle (chemical species) that occupy the position **R** in the material system.

For SANS experiments the scattering length density ρ_i of the sample is defined as:

$$\rho(r) = \sum_i n_i(r) b_i \tag{3}$$

where b_i is the scattering length of the nucleus of type i, while is the corresponding number density of such nuclei.

For X-ray scattering

$$\rho(r) = \left(\frac{e^2}{mc^2}\right) n_{el}(r) \tag{4}$$

where $\left(\frac{e^2}{mc^2}\right)$ represents the Thompson scattering length of the electron, and $n_{el}(r)$ is the electron number density.

By replacing b_i by a locally averaged scattering length density $\rho_i(r)$, (where r is a variable position vector), it is possible to perform an integration over the sample volume, V:

$$I(q) \propto \left[\int_V \rho(r) e^{iqR} d^3 r\right]^2 \tag{5}$$

If isotropic samples are considered (*i.e.*, where the orientation effects are averaged, due to the radial symmetry), the scattering intensity $I(q)$ can be expressed as:

$$I(q) \propto \int_0^\infty (\rho(r))^2 \frac{\sin qr}{qr} 4\pi r^2 dr \tag{6}$$

Usually, it is a complex matter to obtain direct information about the $\rho(r)$ function by inverse transform methods from the experimental Small Angle Scattering (SAS) intensity profile.

In this case, SAS interpretation is based on the choice of suitable models expressed in terms of specified functions, which are capable of furnishing information on specific parameters connected to particular properties of the material system under consideration (Calandra *et al.* 2004a). However, since the clues are clearly model-dependent, a critical

comparison among the clues obtained from different models is advisable (Calandra *et al.* 2004b).

However, it must be noticed that, when dealing with light scattering, another technique, called dynamic light scattering (DLS) also known as photon correlation spectroscopy (PCS), is usually referred to. In such a method, time fluctuations of the scattering intensity as a consequence of the Brownian motion of nano-scatters in a solution are recorded. Then, a time-dependent scattering function is derived to the diffusion coefficient of the particles (the scatters) dispersed in the liquid phase (Berne and Pecora 1976; Brown 1996). In contrast to this (more widely known) technique, the static light scattering (SLS) configuration resembles the typical scattering apparatus.

4.3. Wide angles. In the case of wide-angle scattering, higher q values are considered, which means that short distances are explored. In a typical Wide-Angle Scattering experiment, which can use in principle the same sources as small-angle, usually, the scatters are the atoms themselves. Typical interatomic distances are, therefore, probed: in the case of pure crystals, where positional order is dominant, this gives the famous Bragg law:

$$2\sin\theta = n\lambda \tag{7}$$

where n is an integer and d is the characteristic distance of reticular planes.

However, when the order is weak, the principle still holds, and wide-angle scattering can also be used for amorphous materials as in the case of bitumen. In this case, typical interatomic distances are unveiled: the interatomic first shell (which is often associated to the interatomic spacing typical of the liquid phase (Gowda *et al.* 2004)) and other eventual longer-range peaks sometimes occurring as a consequence of intermolecular interactions (Lindner and Zemb 1991).

In this situation, no sharp peak is observed, due to the disordered nature of the system. This disorder can be due to two effects:

(i) a polydispersion of the value of the interatomic distance represented by the peak. The intrinsically-disordered nature of the system (fluid) gives a peak broadening whose width gives the distance polydispersion. The order is partially lost at any distance.

(ii) Reduced size of the domain. The band broadening is due to the fact that the specific interatomic distance is only help at a certain length, called the correlation length. The order is lost beyond this length. The scattering domain size can be derived by the full width at half maximum (FWHM) of the band through the Debye-Sherrer formula:

$$\Delta = \frac{K\lambda}{FWHM\cos\theta} \tag{8}$$

where Δ is the average scattering domain size θ is the Bragg angle, λ is the wavelength of the incident beam, the FWHM (is expressed in radians and must be corrected for instrumental broadening, and K is a factor, approximately equal to unity, related to the domain shape (Kumar *et al.* 2001).

This approach has proved to be effective in the structural analysis of structured molecular fluids (Calandra *et al.* 2015b), ionic liquids (Liveri *et al.* 2018), fluids responsive to magnetic field (Calandra 2020) and recently also bitumens (Calandra *et al.* 2018).

5. Perspectives and conclusions

Understanding the behavior and the origin of the light involved the studies of several scientists for many centuries. Since VI century B.C. many ideas, continuously developing, have arisen as well as different models. What is surprising from a didactical point of view is that the various theories, although very different to each other, essentially swapped continuously from somehow corpuscular to undulatory models, in various forms. This is why the development of radiation understanding constitutes an excellent example for developing innovative teaching methods in science. The development of the theories from the beginning until nowadays may be nicely exemplified with different approaches for all age classes. Indeed, the extent of the argument and the possibility to deepening the understanding of the subject with the age of the learner made this argument perfect for a complete study path across all the academic scholar development.

Now, the origin of light is well understood and it is now clear that light is just an electromagnetic radiation of certain frequency with no difference but the frequency with all the others radiations (microwaves, X-rays etc), all sharing a lot of phenomena (absorption, scattering...). Also, and this is probably the most important and more recent discovery, it is now clear that due to the corpuscular-undulatory dualism, many phenomena can be shared also by travelling particles. This big discovery allowed scientist to widely enlarge the probes for investigating matter and materials. Scattering in fact is the diffusion of a wave (radiation, particles) in several directions as a consequence of its interaction with matter. So, the analysis of the scattered intensity profiles can give detailed information on the structure of a material in terms of preferential (characteristic) distances among scattering centres. If the probe is an electromagnetic radiation the scattering originates from electron density, if the probe is a beam of neutrons, the scattering centres are atomic nuclei, and so on. Different techniques and different angles of scattering give different information, but complementary. So, complementary size and energy ranges can be obtained by the suitable combination of different scattering methods, including small angle (X-rays and Neutron) scattering, and light scattering investigations (Phillies 2000; Lombardo *et al.* 2004, 2020b). Moreover the combination of scattering methods with other experimental approaches, such as the spectroscopic, resonance and dielectric techniques, which have proven to be powerful to highlight structural and dynamical aspects in complex materials (Caccamo *et al.* 2020; Calandra *et al.* 2021) can greatly help in the understanding of the system from different and complementary points of view, for an interdisciplinary (Lombardo *et al.* 2020a) and integrated (Lombardo *et al.* 2019) approach, which allows also the identification of the key properties that primarily influence the structural and dynamic properties of complex materials (Anitas 2019). Moreover, as future research in nanoscience will move toward the study of increasingly complex, supramolecular matter the use of combined theoretical and experimental methods will become imperative. Combined theoretical-experimental approaches has been recently applied in an increasing number of soft materials investigations with the aim to elucidate the design rules for the complex self-assembled nanostructured systems (Guala 2002; Lin 2010). In this respect, the direct comparison of the crucial parameters obtained from theoretical and experimental approaches request the employment of suitable mathematical models and novel computational efforts, while the molecular

interactions can be directly inferred from the best adaptation with proposed molecular models (Olafsen 2010; Lombardo *et al.* 2016, 2018).

Acknowledgments

Financial support from the CNR-RA Romania bilateral project 2020–2022 (proposal n. 4657/2019) is acknowledged. It permitted fruitful discussions.

References

Andelescu, A., Heinrich, B., Spirache, M., Voirin, E., La Deda, M., Maio, G., Szerb, E., Donnio, B., and Costisor, O. (2020). "Playing with Pt II and Zn II Coordination to Obtain Luminescent Metallomesogens". *Chemistry* **26**, 4850–60. DOI: 10.1002/chem.202000124.

Anitas, E. (2019). *Small-Angle Scattering (Neutrons, X-Rays, Light) from Complex Systems: Fractal and Multifractal Models for Interpretation of Experimental Data*. DOI: 10.1007/978-3-030-26612-7.

Baker, T. (2016). "Essay review". *Studies in History and Philosophy of Science Part A* **59**, 89–115. DOI: 10.1016/j.shpsa.2016.03.002.

Basdevant, J.-L. (2019). "Famous optician: Augustin Fresnel and the wave theory of light". *Photoniques*, 18–22. DOI: 10.1051/photon/2019S418.

Belloni, L. (1991). "Interacting monodisperse and polydisperse spheres". In: *Neutron X-ray and Light Scattering*. Ed. by P. Lindner and T. Zemb. New York: Elsevier Science Publishers.

Berne, B. and Pecora, R. (1976). *Dynamic Light Scattering 1st ed.* Wiley-Interscience: New York, NY, USA.

Brown, W. (1996). *Light Scattering: Principles and Development, 1st ed.* Clarendon: Oxford, UK.

Caccamo, M. T., Mavilia, G., Mavilia, L., Calandra, P., Lombardo, D., and Magazù, S. (2020). "Thermal investigation of montmorillonite/BSA by fourier transform infrared spectroscopy measurements". *AIMS Biophysics* **7**(4), 248–266. DOI: 10.3934/biophy.2020019.

Calandra, P. (2020). "On the physico-chemical basis of self-nanosegregation giving magnetically-induced birefringence in dibutyl phosphate/bis(2-ethylhexyl) amine systems". *Journal of Molecular Liquids* **310**, 113186. DOI: 10.1016/j.molliq.2020.113186.

Calandra, P., Turco Liveri, V., Proietti, N., Capitani, D., Lombardo, D., Gainaru, C., Böhmer, R., Kozak, M., Dobies, M., Fojud, Z., and Pochylski, M. (2021). "Non-ideal mixing behavior in dibutyl phosphate-propylamine binary liquids: Dielectric and nuclear magnetic resonance investigations". *Journal of Molecular Liquids* **323**, 114963. DOI: 10.1016/j.molliq.2020.114963.

Calandra, P., Caponetti, E., Chillura Martino, D., D'Angelo, P., Minore, A., and Liveri, V. (2000). "FT-IR and dielectric study of water/AOT liquid crystals". *Journal of Molecular Structure* **522**, 165–178. DOI: 10.1016/S0022-2860(99)00351-8.

Calandra, P., Caputo, P., De Santo, M., Todaro, L., Liveri, V., and Oliviero, C. (2018). "Effect of additives on the structural organization of asphaltene aggregates in bitumen". *Construction and Building Materials* **199**, 288–297. DOI: 10.1016/j.conbuildmat.2018.11.277.

Calandra, P., Giordano, C., Ruggirello, A., and Liveri, V. (2004a). "Physicochemical investigation of acrylamide solubilization in sodium bis(2-ethylhexyl)sulfosuccinate and lecithin reversed micelles". *Journal of colloid and interface science* **277**, 206–14. DOI: 10.1016/j.jcis.2004.04.021.

Calandra, P., Liveri, V., Riello, P., Freris, I., and Mandanici, A. (2012). "Self-assembly in surfactant-based liquid mixtures: Octanoic acid/Bis(2-ethylhexyl)amine systems". *Journal of colloid and interface science* **367**, 280–285. DOI: 10.1016/j.jcis.2011.10.015.

Calandra, P., Liveri, V., Ruggirello, A., Licciardi, M., Lombardo, D., and Mandanici, A. (2015a). "Anti-Arrhenian behaviour of conductivity in Octanoic acid/bis(2-ethylhexyl) amine systems: a physico-chemical study". *Journal of Material Chemistry C* **3**. DOI: 10.1039/C4TC02500H.

Calandra, P., Liveri, V., Ruggirello, A., Licciardi, M., Lombardo, D., and Mandanici, A. (2015b). "Anti-Arrhenian behaviour of conductivity in Octanoic acid/bis(2-ethylhexyl) amine systems: a physico-chemical study". *Journal of Material Chemistry C* **3**, 3198–3210. DOI: 10.1039/C4TC02500H.

Calandra, P., Longo, A., Ruggirello, A., and Liveri, V. (2004b). "Physico-Chemical Investigation of the State of Cyanamide Confined in AOT and Lecithin Reversed Micelles". *Journal of Physical Chemistry B - J PHYS CHEM B* **108**. DOI: 10.1021/jp0492422.

Calandra, P., Nicotera, I., Oliviero, C., and Liveri, V. (2013). "Dynamical Properties of Self-Assembled Surfactant-Based Mixtures: Triggering of One-Dimensional Anomalous Diffusion in Bis(2-ethylhexyl)phosphoric Acid/n-Octylamine Systems". *Langmuir : the ACS journal of surfaces and colloids* **29**, 14848–54. DOI: 10.1021/la403522q.

Calandra, P., Ruggirello, A., Mele, A., and Liveri, V. (2010a). "Self-assembly in surfactant-based liquid mixtures: Bis(2-ethylhexyl)phosphoric acid/bis(2-ethylhexyl)amine systems". *Journal of colloid and interface science* **348**, 183–8. DOI: 10.1016/j.jcis.2010.04.031.

Calandra, P., Ruggirello, A., Pistone, A., and Liveri, V. (2010b). "Structural and Optical Properties of Novel Surfactant Coated TiO2–Ag Based Nanoparticles". *Journal of Cluster Science* **21**, 767–778. DOI: 10.1007/s10876-010-0330-x.

Cecchini, R. and Pelosi, G. (1990). "Diffraction: the first recorded observation". *IEEE Antennas and Propagation Magazine* **32**, 27–30.

Compton, A. (1973). *Scientific Papers of Arthur Holly Compton: X-Ray and Other Studies*. University of Chicago Press.

Cretu, C., Andelescu, A., Candreva, A., Crispini, A., Szerb, E., and La Deda, M. (2018). "Bisubstituted-Biquinoline Cu(I) complexes: synthesis, mesomorphism and photophysical studies in solution and condensed states". *Journal of Materials Chemistry C* **6**, 10073–10082. DOI: 10.1039/C8TC02999G.

Dijksterhuis, F. (2004). *Lenses and Waves, Christiaan Huygens and the Mathematical Science of Optics in the Seventeenth Century*.

Dioptrique, V. (1824). *Œuvres de Descartes, cap.1 p.6*. Paris, Levrault.

Einstein, A. (1905). "Concerning an Heuristic Point of View Toward the Emission and Transformation of Light". *Journal of Colloid and Interface Science* **17**, 132 [15 pages]. DOI: 10.1016/j.jcis.2010.04.031.

Feigin, L. and Svergun, D. (1987). *Structure Analysis by Small-Angle X-Ray and Neutron Scattering*. Plenum Press: New York, NY, USA.

Glatter, O. and Kratky, O. (1982). *Small-Angle X-ray Scattering*. Academic Press: London, UK.

Gowda, N., Chen, H., Khetrapal, C., and Weiss, R. (2004). "Amphotropic Ionic Liquid Crystals with Low Order Parameters†". *Chemistry of Materials - CHEM MATER* **16**, 2101–06. DOI: 10.1021/cm034963j.

Guala, F. (2002). "Model-Based Reasoning". DOI: 10.1007/978-1-4615-0605-8_4.

Harroun, T., Wignall, G., Fitter, J., Gutberlet, T., and Katsaras, J. (2006). "Neutron Scattering for Biology". In: pp. 1–18. DOI: 10.1007/3-540-29111-3_1.

Hentschel, K. (2014). "A History of Optics from Greek Antiquity to the Nineteenth Century". *Annals of Science* **71**. DOI: 10.1080/00033790.2012.722682.

Kim, J.-D. and Honma, I. (2005). "Anhydrous solid state proton conductor based on benzimidazole/monododecyl phosphate molecular hybrids". *Solid State Ionics* **176**, 979–984. DOI: 10.1016/j.ssi.2004.11.015.

Kiselev, M., Janich, M., Hildebrand, A., Strunz, P., Neubert, R., and Lombardo, D. (2013). "Structural transition in aqueous lipid/bile salt [DPPC/NaDC] supramolecular aggregates: SANS and DLS study". *Chemical Physics* **424**, 93–99. DOI: 10.1016/j.chemphys.2013.05.014.

Kiselev, M., Lesieur, P., Kisselev, A., Lombardo, D., Killany, M., and S, S. (2001). "Sucrose Solutions as Prospective Medium to Study the Vesicle Structure: SAXS and SANS study". *Journal of Alloys and Compounds* **328**, 71–76. DOI: 10.1016/S0925-8388(01)01348-2.

Kumar, A., Kunieda, H., Vázquez-Vázquez, C., and López-Quintela, M. (2001). "Studies of Domain Size of Hexagonal Liquid Crystals in C 12 EO 8 /Water/Alcohol Systems". *Langmuir* **17**, 7245–7250. DOI: 10.1021/la010615p.

Lan, Y., Wang, X., Wang, C., and Zebarjadi, M. (2018). "Organic/Inorganic Hybrid Nanostructured Materials for Thermoelectric Energy Conversion". In: pp. 445–484. DOI: 10.1002/9783527807369.ch12.

Laranjeiras, C., Silva, J., and Chiappin, J. (2017). "The heuristics of representation in science: The mechanisms and mathematical principles in physics of Descartes and Fermat". *Revista Brasileira de Ensino de Física* **39**. DOI: 10.1590/1806-9126-RBEF-2017-0025.

Lesieur, P., Kiselev, M., Barsukov, L., and Lombardo, D. (2000). "Temperature-induced micelle to vesicle transition: Kinetic effects in the DMPC/NaC system". *Journal of Applied Crystallography* **33**, 623–627. DOI: 10.1107/S0021889899012765.

Likos, C. (2001). "Effective interactions in soft condensed matter physics". *Physics Reports-review Section of Physics Letters - PHYS REP-REV SECT PHYS LETT* **348**, 267–439. DOI: 10.1016/S0370-1573(00)00141-1.

Lin, Z. (2010). "Interplay between Theory and Experiment: Computational Organometallic and Transition Metal Chemistry". *Accounts of chemical research* **43**, 602–11. DOI: 10.1021/ar9002027.

Lindner, P. and Zemb, T. (1991). *Neutron X-ray and Light Scattering*. Elsevier Science Publishers B.V., New York.

Liveri, V., Lombardo, D., Pochylski, M., and Calandra, P. (2018). "Molecular association of small amphiphiles: Origin of ionic liquid properties in dibutyl phosphate/propylamine binary mixtures". *Journal of Molecular Liquids* **263**, 274–281. DOI: 10.1016/j.molliq.2018.05.003.

Lombardo, D., Calandra, P., Caccamo, M. T., Magazù, S., and Kiselev, M. (2019). "Colloidal stability of liposomes". *AIMS Materials Science* **6**(2), 200–213. DOI: 10.3934/matersci.2019.2.200.

Lombardo, D., Calandra, P., Caccamo, M. T., Magazù, S., Pasqua, L., and Kiselev, M. (2020a). "Interdisciplinary approaches to the study of biological membranes". *AIMS Biophysics* **7**(4), 267–290. DOI: 10.3934/biophy.2020020.

Lombardo, D. (2014). "Modeling Dendrimers Charge Interaction in Solution: Relevance in Biosystems". *Biochemistry research international* **2014**, 837651. DOI: 10.1155/2014/837651.

Lombardo, D., Calandra, P., Bellocco, E., Lagana, G., Barreca, D., magazù, S., Wanderlingh, U., and Kiselev, M. (2016). "Effect of anionic and cationic polyamidoamine (PAMAM) dendrimers on a model lipid membrane". *Biochimica et Biophysica Acta (BBA) - Biomembranes* **1858**, 2769–77. DOI: 10.1016/j.bbamem.2016.08.001.

Lombardo, D., Calandra, P., and Kiselev, M. A. (2020b). "Structural Characterization of Biomaterials by Means of Small Angle X-rays and Neutron Scattering (SAXS and SANS), and Light Scattering Experiments". *Molecules* **25**(23), 5624. DOI: 10.3390/molecules25235624.

Lombardo, D., Calandra, P., Magazù, S., Wanderlingh, U., Barreca, D., and Kiselev, M. (2018). "Soft nanoparticles charge expression within lipid membranes: The case of amino terminated dendrimers in bilayers vesicles". *Colloids and Surfaces B: Biointerfaces* **170**. DOI: 10.1016/j.colsurfb.2018.06.031.

Lombardo, D., Micali, N., Villari, V., and Kiselev, M. (2004). "Large structures in diblock copolymer micellar solution". *Physical review. E, Statistical, nonlinear, and soft matter physics* **70**, 021402. DOI: 10.1103/PhysRevE.70.021402.

Magazù, S., Migliardo, F., Benedetto, A., Calabrò, E., La Torre, R., and Caccamo, M. T. (2013). "Sucrose: Properties, Biosynthesis and Health Implications". In: *Bioprotective effects of sucrose*

and trehalose on proteins. Ed. by S. Magazù. Biochemistry Research Trends. Hauppauge, New York: Nova Science Publisher, pp. 35–46.

Maxwell, J. C. (2010). *A Treatise on Electricity and Magnetism*. Vol. 2. Cambridge Library Collection - Physical Sciences. Cambridge University Press. DOI: 10.1017/CBO9780511709340.

Mynbayeva, A., Sadvakassova, Z., and Akshalova, B. (2018). *Pedagogy of the Twenty-First Century: Innovative Teaching Methods*. DOI: 10.5772/intechopen.72341.

Olafsen, J. (2010). "Experimental and Computational Techniques in Soft Condensed Matter Physics". *Experimental and Computational Techniques in Soft Condensed Matter Physics, by Jeffrey Olafsen, Cambridge, UK: Cambridge University Press, 2010*. DOI: 10.1017/CBO9780511760549.

Phillies, G. (2000). *Scattering of Light, Neutrons, X-Rays, and Other Radiation*. New York: Springer.

Pochylski, M., Lombardo, D., and Calandra, P. (2019). "Optical Birefringence Growth Driven by Magnetic Field in Liquids: The Case of Dibutyl Phosphate/Propylamine System". *Applied Sciences* **10**, 164. DOI: 10.3390/app10010164.

Pochylski, M., Oliviero, C., Nicotera, I., Liveri, V., and Calandra, P. (2016). "Nano-demixing as a novel strategy for magnetic field responsive systems: the case of Dibutyl phosphate/bis(2-ethylhexyl) amine systems". *RSC Advance* **6**. DOI: 10.1039/C6RA02386J.

Ricciardi, L., Sancey, L., Palermo, G., Termine, R., Luca, A., Szerb, E., Aiello, I., Ghedini, M., Strangi, G., and La Deda, M. (2017). "Plasmon-mediated cancer phototherapy: The combined effect of thermal and photodynamic processes". *Nanoscale* **9**, 19279–89. DOI: 10.1039/C7NR05522F.

Sabra, A. (1981). *Theories of LIgth: From Descartes to Newton*. Cambridge University.

Shirzad, S., Hassan, M., Aguirre, M., Mohammad, L., and Daly, W. (2016). "Evaluation of Sunflower Oil as a Rejuvenator and Its Microencapsulation as a Healing Agent". *Journal of Materials in Civil Engineering* **28**, 04016116. DOI: 10.1061/(ASCE)MT.1943-5533.0001625.

Yamada, M. and Honma, I. (2004). "Anhydrous Protonic Conductivity of a Self-Assembled Acid-Base Composite Material". *Journal of Physical Chemistry B* **108**, 5522–6. DOI: 10.1021/jp030767o.

Yen, K., Chaiprapa, J., Zeng, X., Yongsong, L., Cseh, L., Mehl, G., and Ungar, G. (2016). "Added Alkane Allows Thermal Thinning of Supramolecular Columns by Forming Superlattice-An X-ray and Neutron Study". *Journal of the American Chemical Society* **138**. DOI: 10.1021/jacs.6b01172.

Young, T. (1801). "The Bakerian Lecture. On the theory of light and colours". DOI: 10.1098/rstl.1802.0004.

Young, T. (1803). "The Bakerian Lecture, Experimentts and Calculatio relative to physical Optical". DOI: 10.1098/rstl.1804.0001.

[a] Consiglio Nazionale delle Ricerche (CNR)
Istituto per lo Studio dei Materiali Nanostrutturati (ISMN)
Via Salaria km 29.300, 00015 Monterotondo Stazione (RM), Italy

[b] Consiglio Nazionale delle Ricerche (CNR)
Istituto per lo Studio dei Materiali Nanostrutturati (ISMN)
Via Ugo la Malfa, 90100 Palermo, Italy

[c] Consiglio Nazionale delle Ricerche (CNR)
Istituto per i Processi Chimico-Fisici (IPCF)
Viale F. Stagno d'Alcontres, 98158 Messina, Italy

[d] Consiglio Nazionale delle Ricerche (CNR)
Istituto di Struttura della Materia (ISM)
Via Salaria km 29.300, 00015 Monterotondo Stazione (RM), Italy

[e] Romanian Academy
"Coriolan Drăgulescu" Institute of Chemistry
24 Mihai Viteazu Bvd., 300223-Timişoara, Romania

[*] To whom correspondence should be addressed | email: pietro.calandra@cnr.it

Paper contributed to the international workshop entitled "New Horizons in Teaching Science", which was held in Messina, Italy (18–19 november 2018), under the patronage of the *Accademia Peloritana dei Pericolanti*
Manuscript received 26 May 2020; published online 30 September 2021