Teacher's Guide

Sand and Multiple Light Scattering

Grade Level: High school

Subject area(s): Physics

Time required: (2) 50 minute class

Learning objectives: Through experimentation understand: 1. light refraction; 2. light scattering; 3. applications of nanotechnology

Summary: Nanoparticles and other nanoscale materials are often analyzed through the specialized use of light scattering. Several techniques use the light scattered from small particles to estimate their size distribution; these techniques employ light absorption, laser diffraction, and dynamic light scattering. This lab introduces concepts of particle light scattering, using somewhat larger particles that students can easily see. The lab is designed to allow students to explore the interaction of light with small particles of sand immersed in a medium; the latter includes air, water, toluene, and a mystery liquid (acetone is used here; alcohol or some other organic solvent can also be used). This lab introduces related concepts of refractive index and multiple light scattering. From this lab, students will be able to discuss how light refraction and scattering may be used in the detection and characterization of nanoparticles. In this lab, students will work with the light scattering properties of sand when wet versus dry, and the differences when the wetting agent is water versus a hydrocarbon.

Lesson Background: When light interacts with matter, it may be reflected (as with a mirror) or it may be absorbed. Some materials absorb light energy and then re-radiate that light at a longer (and lower energy) wavelength. More commonly, however, matter will absorb light and then immediately re-radiate the light with little change in wavelength. This is termed light scattering. Most objects that one sees are visible due to light scattering from their surfaces. This is our primary mechanism of physical observation.

Light scattering can be thought of as the deflection of a light ray from a straight path, for example by irregularities in the propagation medium, particles, or in the interface between two media. Scattering of light by matter depends on several things: 1) the wavelength or frequency of the light being scattered, 2) the physical size of the material doing the scattering, and 3) the optical properties of the matter and the medium it is in. The interaction of light with matter can provide important information about the structure and dynamics of the material being examined. This lab will use light scattering to explore the optical properties of small particles, namely, common sand when wetted with various liquids.

Sand is made of tiny particles of worn-down rock. Grains of sand range from 0.1 mm to 2 mm in size; when things get smaller than a fraction of a millimeter, it gets hard to see them with just your eyes. Sand is made of millions of individual particles, each of which will scatter light; such a

Development and distribution funded by the **National Science Foundation**

collection of particles is termed a multiple scatterer. As such, it increases the number of ways in which an incoming photon of light will interact with the sand particles and eventually reach our eyes.

Silica sand (Figure 1) is one of the most common varieties of sand found in the world. It is used for a wide range of applications and can be purchased from various suppliers. Silica sand is used in industrial processing, to make glass, as fill, and to create molds and castings. It is used in the nanotechnology field to make silicon wafers, the backbone of modern electronics. The most common mineral in the Earth's continental crust is quartz, and most silica sand is made up of broken-down quartz crystals. Silica is another name for silicon dioxide, SiO_2, of which quartz is a specific crystalline structure. So, silica sand is quartz that over the years, through weathering and erosion, has been broken down into tiny granules.

Figure 1. Silica sand. Image: wisegeek.org

While sand is made of mineral grains, sand itself is not a mineral; it is a sediment like clay, gravel, and silt. It is a granular material made up of particles in a wide size range. To describe particle size of sand, a sample is passed through a series of sieves with different size openings. This will establish how much of the sand particles lie in the largest size bin, how much in the next smaller size bin, and so on. According to the classification parameters normally used in industry, a collection of sand grains of which 50% or more of the particles are coarser than the #200 sieve (0.075 mm, 75 micrometers) but which 50% or more are finer than the #4 sieve (4.75 mm), is classified as sand. If there are large amounts of particles smaller than 75 microns, the material is called clay or silt. If there are large amounts of particles bigger than 4.75 mm, the material is called gravel.

The semiconducting properties of pure and doped silicon have placed it as a foundational element in the nanotechnology field, particular in nanoelectronics. In addition, silicon's optical properties have recently made it interesting as a "quantum dot" light source and as a light absorber for solar cells. Researchers continue to use silicon as they work to create smaller, more efficient, and reliable electronic devices. In this experiment, students will come to understand the ideas of a substance having different optical properties, and how those properties can be observed. Students will study the light scattering (Figure 2) of dry sand versus sand wetted with several types of liquids. In addition, students will work with different wetting agents which will likewise impact the light scatter being observed.

Development and distribution funded by the **National Science Foundation**

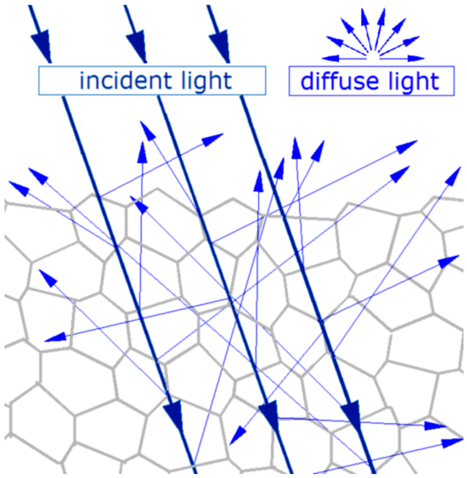


Figure 2. Light scattering by a multiple scattering system. Image en.wikipedia.org/wiki/Light_scattering

One of the most important optical properties of a material is its refractive index, or RI. The RI is a measure of how much a material slows down the light that passes through it. Water and glass both have RI values that differ from air; these different values of RI lead to the familiar light bending properties of glass lenses. Sand has an RI close to that of water and even closer to those of some organic solvents, like toluene. One way to explore this optical property is to recognize that the major component of glass is silica sand. If a clear drinking glass is placed into water, it becomes very difficult to see. This is due to the refractive index of water and glass being very close to each other. If a material has the same RI as its surrounding medium, no light will be scattered from the interface between the material and the medium; the material object will become invisible.

To understand what is happening when water or toluene is added to the sand, refer to Figure 3. An important parameter in light scattering is the scattering angle. The average scattering angle of a particle depends on its size. If a particle is large compared with the wavelength of the light illuminating it, the more it scatters forward; conversely, a particle that is much smaller than the wavelength of light striking it will scatter light in all directions.

Size, though, is not the only determinant of the average scattering angle. It also depends on the medium that surrounds the scatterers, especially if they are large compared with the wavelength. The refractive index of the medium that surrounds the sand will affect the light scattered from the particles, and will result in a darker or lighter appearance of the wetted samples. . The more closely the refractive index of the surrounding liquid matches those of the grains of sand, the smaller the average scattering angle will be. A small scattering angle means that the light bounces around inside the sample and some of the light is absorbed. When the light finally scatters out of the sand sample to our eyes, it looks darker because some light has been absorbed by the sand grains. Thus, if the refractive indices of the sand and its surrounding medium are nearly the same, the sand will appear darker.

The opposite is also true: if the refractive index of the surrounding liquid is much different than that of the sand grains, the average scattering angle will be larger. A large scattering angle means that the light is more likely to come back out of the sand sample, and doesn't bounce

Development and distribution funded by the **National Science Foundation**

around inside the sample as much, meaning less light is absorbed by the sand. When this light scatters out of the sand sample to our eyes, it looks less dark, although it is still darker than sand in air. Thus, if the surrounding medium has a lower refractive index, the sand will appear less dark than when the surrounding medium has a higher RI. Air has the lowest refractive index of the media we consider here, so the sand appears lightest when sitting in air alone (i.e., dry sand).

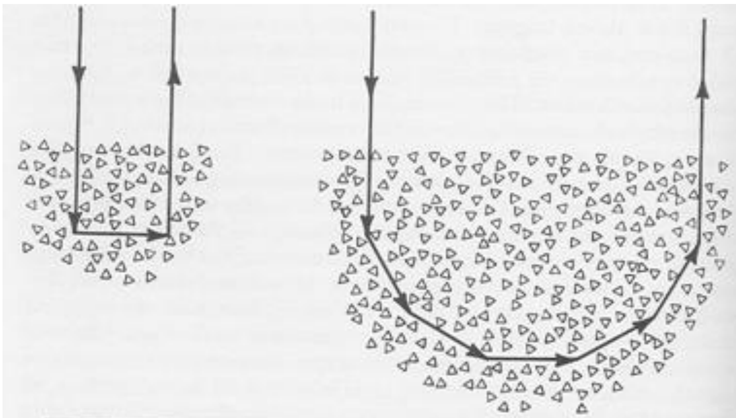


Figure 3. The shortest path taken by an incident photon before re-emerging from a collection of many scatters. On the left the average scattering angle is 90° and on the right it is 30°. Image from Bohren, 1987.

At the end of this lab, students are asked to apply what they have learned about the interaction of light with small particles, and predict what color the sand will be if the refractive index of a new liquid more closely matches the refractive index of the sand; i.e. the refraction angle is greater than the critical angle. When the two match, little or no light will be scattered back to the eye. More of the light will remain within the sand and the liquid, and the sand sample will appear darker.

This lab develops student understanding of tools used to detect the chemical and physical properties of small particles. Refractive index is used to determine the size of very small particles in a given medium. An example of this particle size measurement is given in Figure 4, which shows the size distribution of particles measured in water, using an automated analyzer that employs light scattering.

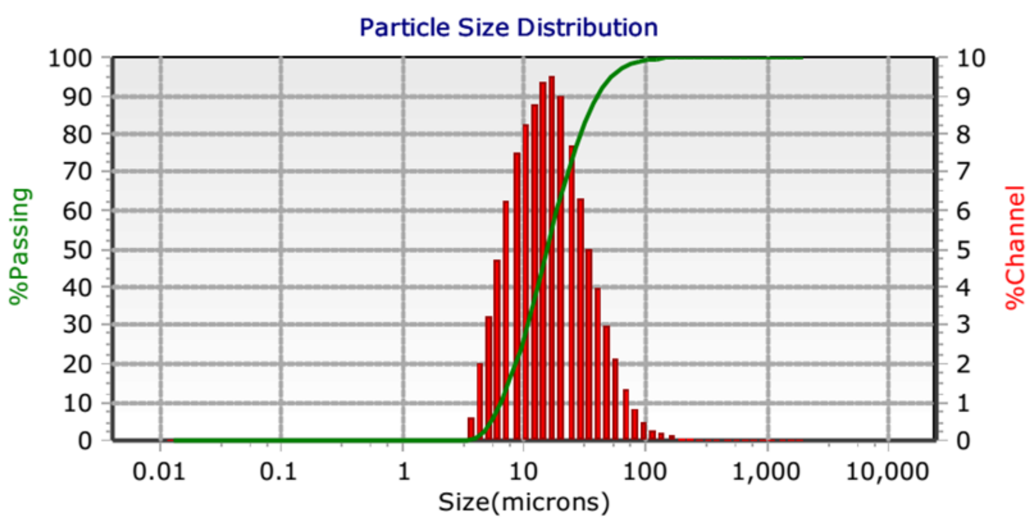


Figure 4. Size distribution of carbon nanoparticles, measured with dynamic light scattering. (Source: J. Marti, University of Minnesota Nano Center.)

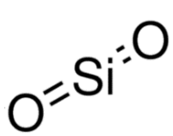
Sources:

1. "Advancing Resistive Memory to Improve Portable Electronics" University of California – Riverside. http://ucrtoday.ucr.edu/16951 August 2013
2. Bohren, C. F., Clouds in a Glass of Beer. John Wiley and Sons, Inc. 1987
3. "Microscope Activities – Sand Analysis" Microbus http://www.microscope-microscope.org/applications/sand/microscopic-sand.htm August 2013
4. Sand Atlas http://www.sandatlas.org/2011/10/what-is-sand-made-of/ August 2013
5. Sand Activities Nano-Activities for Kids, Penn State http://www.mrsec.psu.edu/education/nano-activities/sand/ August 2013
6. Size and Scale MRSEC Education Group University of Wisconsin – Madison http://education.mrsec.wisc.edu/36.htm
7. Optical Properties of Water http://misclab.umeoce.maine.edu/boss/classes/RT_Weizmann/Chapter3.pdf
8. Optical Properties http://www.utexas.edu/tmm/npl/mineralogy/science_of_minerals/optical_properties.html
9. Optical Properties http://web.mst.edu/~brow/PDF_optical.pdf

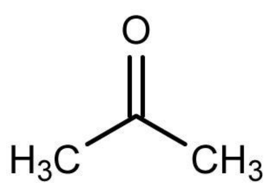
Pre-requisite Knowledge: Students should know how light interacts with matter, deflects, refracts, and wavelength and frequency.

Materials: (per lab group of 2 students)

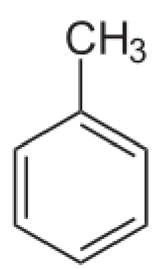
- Aquarium sand (silicon dioxide)– rinsed to remove the impurities and dried
- Petri dishes (3)
- Safety goggles
- Disposable gloves
- 10mL graduated cylinders (3)
- Sand - enough to fill Petri dishes
- Ruler to level sand in dish
- Distilled or deionized water (3mL)
- Toluene (3mL)
- Mystery liquid (3mL) – suggested acetone
- Black paper or cardstock
- 3x5 card
- Marker



Silicon dioxide, silica



Acetone – simplest of ketones; will mix with water



Toluene – clear, water-insoluble liquid

Safety Information: Use toluene and the other organic solvents a fume hood. Students should wear safety goggles and gloves when working with chemicals.

Toluene Precaution: Inhalation of toluene in low to moderate levels can cause tiredness, confusion, weakness, drunken-type actions, memory loss, nausea, loss of appetite, and hearing and color vision loss. These symptoms usually disappear when exposure is stopped. Inhaling high levels of toluene in a short time may cause light-headedness, nausea, or sleepiness. It can also cause unconsciousness, and even death. Refer to the MSDS for the chemicals used in the lesson.

Vocabulary and Definitions:

1. *Scatterer*: An object that scatters light.
2. *Sand*: is made of tiny particles of worn-down rock. Grains of sand range from 0.1 mm (100 micrometers) to 2 mm in size; when things get smaller than a millimeter, it gets hard to see them with just your eyes. Sand is a multiple light scatterer. As such, it increases the number of ways in which a photon may reach our eyes. The majority of sand is silica based.
3. *Optical Properties*: of a material describe how that material interacts with visible light. Commonly used optical properties include the index of refraction, the absorption coefficient (the degree to which light is absorbed per unit length of the material), and the volume scattering function.
4. *Air*: is a mixture of gases and water vapor. Its refractive index in close to 1.0.
5. *Water*: is a liquid with refractive index of 1.33.
6. *Toluene*: is a clear, water-insoluble liquid. It is an aromatic hydrocarbon, of 7 carbon and 8 hydrogen atoms, with the typical smell of paint thinners. Its refractive index is about 1.5. Inhaling toluene has the potential to cause severe neurological harm.
7. *Acetone*: (mystery liquid) is miscible with water, colorless and flammable. Its chemical formula is $(CH_3)_2CO$. It is an important solvent; your students maybe more familiar with its use in nail polish remover. Its refractive index is about 1.36. It is produced and disposed of in the human body through normal metabolic processes. It is normally present in blood and urine. People with diabetes produce it in larger amounts. Reproductive toxicity tests show that it has low potential to cause reproductive problems.
8. *Refractive index*: measure of the bending of a ray (path) of light (refracted) when passing from one medium into another.
9. *Nanoscale*: measured in nanometers; typically referring to materials between 1 and 100 nm but others use up to several hundred nanometers.
10. *Nanometer*: $1x10^{-9}$ or one billionth of a meter.
11. *Nanoparticle*: a small particle that ranges in size from 1 to 100nm.
12. *Nanotechnology*: Nanotechnology is science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers. It is the study and application of extremely small things and can be used across all the other science fields, such as chemistry, biology, physics, materials science, and engineering.

Development and distribution funded by the **National Science Foundation**

Advance Preparation:
To prepare students for this next step in learning, they need to develop an understanding of nanoparticles in their world, it is suggested that prior to this lesson, students research and present on the topic. Possible topics and articles to research include the ones listed below. These are not all inclusive and serve as a starting point.

1. Nanoparticles in Food: http://www.scientificamerican.com/article.cfm?id=do-nanoparticles-in-food-pose-health-risk
2. Detecting Nanoparticles: http://www.sciencedaily.com/releases/2013/08/130822194530.htm
3. Nanoparticles in Clothes: https://www.greenamerica.org/detox-your-closet-search-less-toxic-clothes/trouble-nano-fabrics
4. Nanoparticles in Food: http://www.cnn.com/2013/02/14/opinion/behar-food-nanoparticles/index.html
5. Nanoparticles in Sunscreen: http://phys.org/news/2012-07-nanoparticles-big-potential-threat.html
6. Nanoparticles Overview and Research: http://www.jnanobiotechnology.com/content/2/1/3
7. The Project on Emerging Technologies (numerous reports on nanotechnology): https://www.nanotechproject.tech/publications/
8. Nanoparticles in Medicine: http://www.stanford.edu/group/mota/education/Physics%2087N%20Final%20Projects/Group%20Beta/index.htm
9. Properties of Nanoparticles: http://www.sigmaaldrich.com/materials-science/nanomaterials/silver-nanoparticles.html

Other nanoparticle lessons on the NNCI Resources for Educators page that you may want to explore include:

- Spectrophotometry with Metal Nanoparticles https://nnci.net/node/6016
- Light Extraction by Changing Composition of Material https://nnci.net/node/5675

Suggested Teaching Strategies: This lab relies on observation; as such it is most easily completed in small (2-3 students) groups or individually. Students should complete individual lab write ups. Use the vocabulary to begin a discussion of the lab and to determine what students know or have misconceptions of.

Time	Activity	Goal
Day 1	**The day before the lab**	
45 min	Introduce students to the topic of light scatter. Students explore, observe, draw pictures and develop the concept of light scatter by shining a laser at the back of a CD, onto a mirror, onto a window, into water in a tank/glass container, onto a textbook and onto other objects about the room.	To prepare students to understand the idea of light scatter

Development and distribution funded by the **National Science Foundation**

Day 2	The day of the student lab	
10 min	Students answer warm-up questions. Place a clear glass into a tank of water.	To ensure students understand, they will observe that the glass is very difficult to see. Explain that this is due to the optical properties of glass which are close to those of water.
30 min	Distribute *Student Worksheets* to students. Students follow procedures.	To help students understand optical properties of different liquids, and to predict the identity of a mystery liquid based on its optical properties.
10 min	Clean up.	To prepare workspace for next class.

Directions for the Activity: See the Student Guide for the Directions. Ask students questions to provoke thought and review what they already know:

1. What happens during a *chemical reaction? Chemical reactions occur when the reactants (particles) come into contact with each other and form new products.*
2. Why are you able to see an object when a light is shone on it? *Light bounces off (reflects) the object back to your eye.*
3. Does the light reflect from the object in a straight line (path)? *Yes, but due to variations within the object the light may bounce around at different angles, resulting in not all the light hitting our eyes.*

Procedure:

1. Have each student or team place some sand in three Petri dishes. They will place the dishes on a black paper background, and label them 1 – 3.
2. Students add a small amount (3 ml) of water to the sand in one half of dish #1. They should use a graduated cylinder to measure the liquids, adding just enough to wet the sand—do not add so much that the liquid pools in the sand.
3. Students describe and record the different appearance between the dry and water-wetted sides. An example is shown in Figure 5.

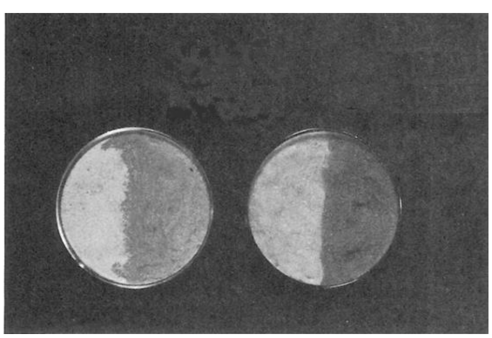


Figure 5 Left: Comparison of sand in air to sand in the mystery liquid. Right: Comparison of sand in water to sand in toluene

Development and distribution funded by the **National Science Foundation**

4. In dish #2, students add a small amount (about 3 ml) of toluene to the sand in one half of the dish. They describe the different appearance between the dry and toluene-wetted sides.
5. Students then compare the appearance of the dry sand with the water-wetted and toluene-wetted sand samples; compare the observation results with the index of refraction information they have gathered (below); and explain the different appearances of the sand samples in terms of the index of refraction of sand versus the surrounding material.
6. Give the students the "mystery liquid" (acetone). They add 3 ml of this liquid to the sand in one half of dish #3, and describe the different appearance between the dry and liquid-wetted sides.
7. Based on their observations, students then estimate the value of the index of refraction of the mystery liquid.

Material	**Index of Refraction**
Air	1.0003
Water	1.33
Toluene	1.4969 at 20°C
Acetone	1.35916 at 20°C
Silica sand	1.54427

Cleanup:
Sand wetted with water or the solvents can be dried and re-used. Allow the solvent-wetted sand to dry in a fume hood. Extra organic solvents should be collected as solvent waste and disposed of in compliance with your school's hazardous waste procedures.

Review the findings with students: In this lab, the toluene has optical properties (that is, refractive index) most closely aligned to the sand. Note the following refractive indices. Toluene: 1.4969 at 20°C; acetone: 1.35916 at 20°C; sand: 1.54427; air: 1.0003; water: 1.33; diamond = 2.42 (for interest).
Applied: With a sand-in-toluene sample, less light is scattered back to the eye, making this mixture appear darker. Each liquid gives a different scatter pattern of dark or lighter shades of the sand. These properties can be used in labs to determine the identity of a given material.

Discussion after the Lab:
1. Where else do you see this phenomenon of a shade differences in wetted materials? *Clothing wetted with water will often change to a darker shade.*
2. If we wanted to build a machine to detect the color variation as our eye does, how would be go about building it? *The machine would need to be able to detect light waves and distinguish differences in light wavelength and intensity.*
3. After the water evaporates, what color will the sand be? *The sand will go back to the color it was when dry. No permanent changes were made to the sand.*
4. How is the refractive index an indicator of the chemical you are working with? *Different materials have different refractive indices. Thus these indices can be used as a fingerprint for the chemical being studied.*

Development and distribution funded by the **National Science Foundation**

5. Did a chemical reaction occur during this lab? *No. We know this because when the liquid evaporates from the sand, the sand retains its original color. Note: we did not look for other property changes so we are limiting our observations to just the impact on the light and our personal observation.*
6. Absorption and re-emission are other optical properties based on wavelength. These properties can be used to characterize nanoparticles in a way that becomes visible to the unaided human eye. Why is it important that we have tools to characterize a given material at the nano scale? *The use of nanoparticles in an ever increasing number of products and food items makes it a critical area of concern for the consumer but also for those working with the nanoparticles. Given this importance and prevalence in varied aspects of our lives, it is important to have a reliable, easy to perform and economically feasible method to detect and characterize these particles.*

Assessment: Students should be able to discuss the optical properties of various liquids as they compare to sand and to each other. They should further be able to discuss the reasons why this can be used as a form of detection and characterization of nanoparticles.

Additional Resources:

- Bohren, C. F., Clouds in a Glass of Beer. John Wiley and Sons, Inc. 1987
- Optical Properties of Water, University of Maine 2013. http://misclab.umeoce.maine.edu/boss/classes/RT_Weizmann/Chapter3.pdf
- Light Scattering. Vendantu Learn Live Online. accessed at: https://www.vedantu.com/physics/scattering-of-light
- Introduction to Dynamic Light Scattering Analysis. Accessed at: https://www.youtube.com/watch?v=ET6S03GeMKE

Next Generation of Science Standards:

- HS-PS1.A Structure and properties of matter
- HS-PS2.6 Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.
- HS-PS4.1 Use mathematical representation to support a claim regrading relationship among the frequency, wavelength and speed of waves traveling in various media.

Contributors: Denise Kapler, NNCI RET at the University of Minnesota

Supporting Programs: NNCI RET at the University of Minnesota NSF EEC 1200925 and National Nanotechnology Coordinated Infrastructure NSF ECCS 1626153