

Photopia Refractor Volumetric Scattering

Scattering Probability

The probability of scattering is determined by the Beer-Lambert Law:

https://en.wikipedia.org/wiki/Beer%E2%80%99s_Lambert_law

Since you will see many forms of this on the wiki page, the form we use for the case of uniform attenuation is:

$$T = e^{-\mu l}$$

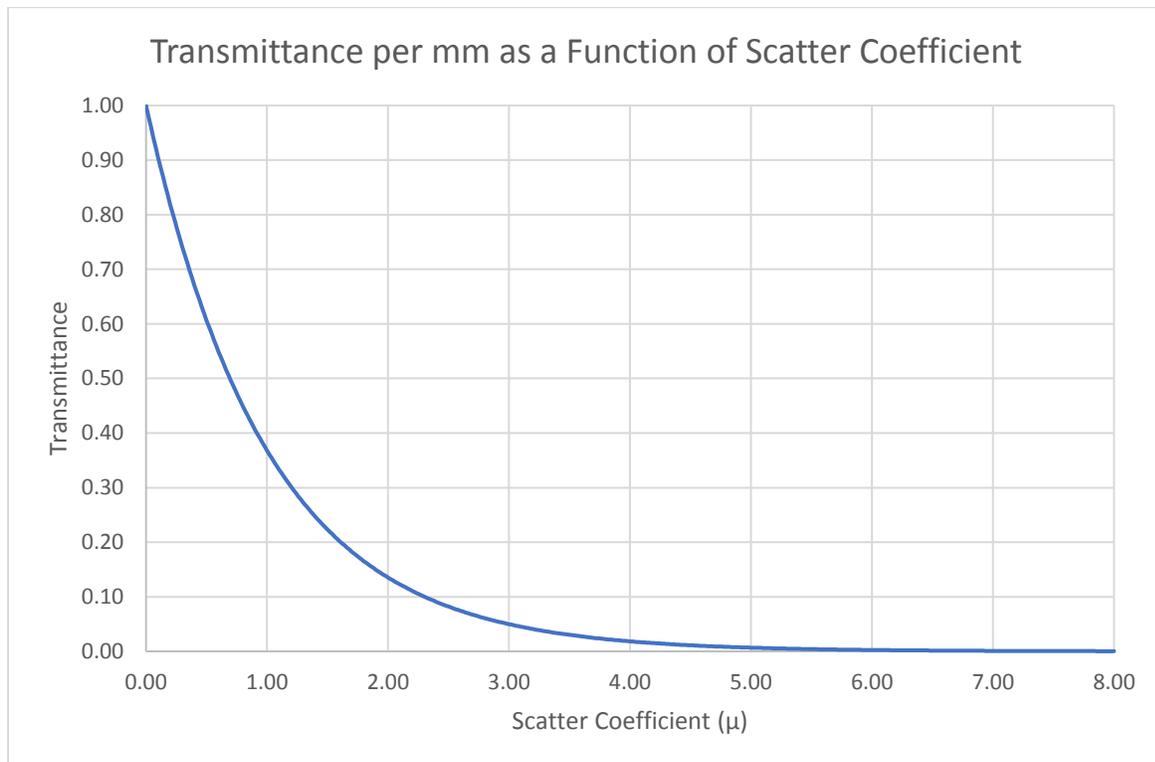
Where:

T = transmittance

μ = scatter coefficient

l = path length in mm

The transmittance is therefore exponentially related to the scatter coefficient. A scattering coefficient of 0.5 results in a transmittance through 1mm of material of about 60%. As you can see in the plot below, you can enter scatter coefficients greater than 1.



The higher the coefficient, the lower the transmittance and thus the higher the probability of scattering over 1mm. Keep in mind that with higher scatter coefficients, the more ray reactions there will be within a short distance, so you will also need to increase the # of Ray Reactions in Photopia's Raytrace Settings. That number may need to increase to 100 or 200 from the default of 25. If rays are still reacting within the material and reach the reaction limit, then the rays will be shown as red in Photopia and the amount of light lost due to reaching this reaction limit will be listed in the Anomalous Lumens section of the raytrace report.

If you know the transmittance through 1mm of material (the likelihood the ray will not hit a particle), then you can compute the scattering coefficient with this equation:

$$\text{Scattering Coefficient} = -\text{LN}(\text{transmittance})$$

LN is the natural log function in Excel™.

Also keep in mind that Photopia separates the transmittance through refractors due to bulk absorption and scattering effects. The extinction coefficient that defines the absorption in the material is already defined as the 3rd value in the material .RFC file. That value is in 1/inches. The scattering coefficient is therefore limited to just the probability that the ray will interact with a particle. Note that both coefficients will be in units of 1mm in a future revision to the library files.

Non-spectral material .RFC file format:

Outside index, Inside index
Extinction coefficient (1/inches)

e.g.

1.000000 1.491000
0.006

Utilities

The "Beers Law.xlsx" spreadsheet shows the values in the above plot. It also computes the transmittance for any thickness material for the range of scatter coefficients.

The "Extinction Calculator.xls" spreadsheet computes extinction coefficients based on a known transmittance through a known material thickness, both with and without end effects from Fresnel's Reflections. So this spreadsheet can be helpful when defining material properties. Although this was originally created to help define the extinction coefficient values to put in the .RFC files, the same equation is used to define the transmittance from losses due to scattering instead of absorption. So if you know the transmittance through some specific length of your material where the reduction was all due to scattering, then this will compute the scattering coefficient for you. You will just need to convert the units to 1/mm or simply enter the length in mm and the results will be a coefficient in 1/mm. Keep in mind that rays interacting with particles can still add to the overall material transmittance. This is a function of the specific scattering reaction. Some rays will continue to go forward while others will exit or back scatter within the material.

These spreadsheets are available in the following folder:

C:\Users\Public\Documents\LTI Optics\Photopia\Utilities

A more general form of the Beer Lambert Law shows the exponent of exponential constant "e" as the addition of 2 terms, one being for extinction due to bulk absorption and the other for extinction due to scattering. So this is a good way to think of how these 2 effects combine to produce the directional transmittance through a material.

$$T = e^{(-\mu_a l - \mu_s l)}$$

Where:

T = transmittance in a given direction
 μ_a = bulk absorption coefficient
 μ_s = scatter coefficient
 l = path length

Particle Scattering Distributions

Particle scattering distributions are determined by different scattering regimes. The regime is a function of the particle size, wavelength of light and the particle refractive index. The particle size is generally defined by a non-dimensional size parameter, which is the particle circumference divided by the wavelength:

$$x = \frac{2\pi r}{\lambda}$$

Where:

x = size parameter

r = radius of a spherical particle

λ = wavelength of the light

The 3 scattering regimes are:

- 1) $X \ll 1$: Rayleigh scattering
- 2) $X \approx 1$: Mie scattering
- 3) $X \gg 1$: Geometric scattering

The scattering regimes for various particle sizes and ranges of spectrum are shown in the following diagram.

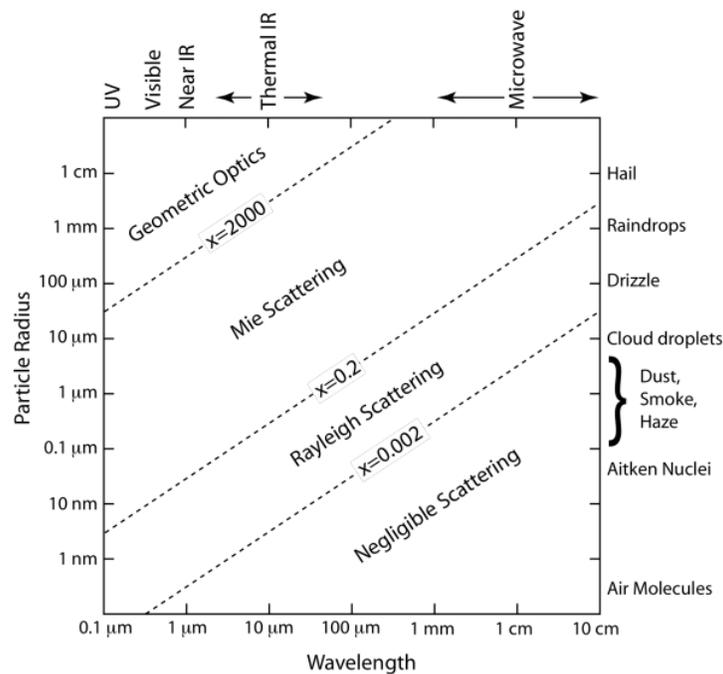
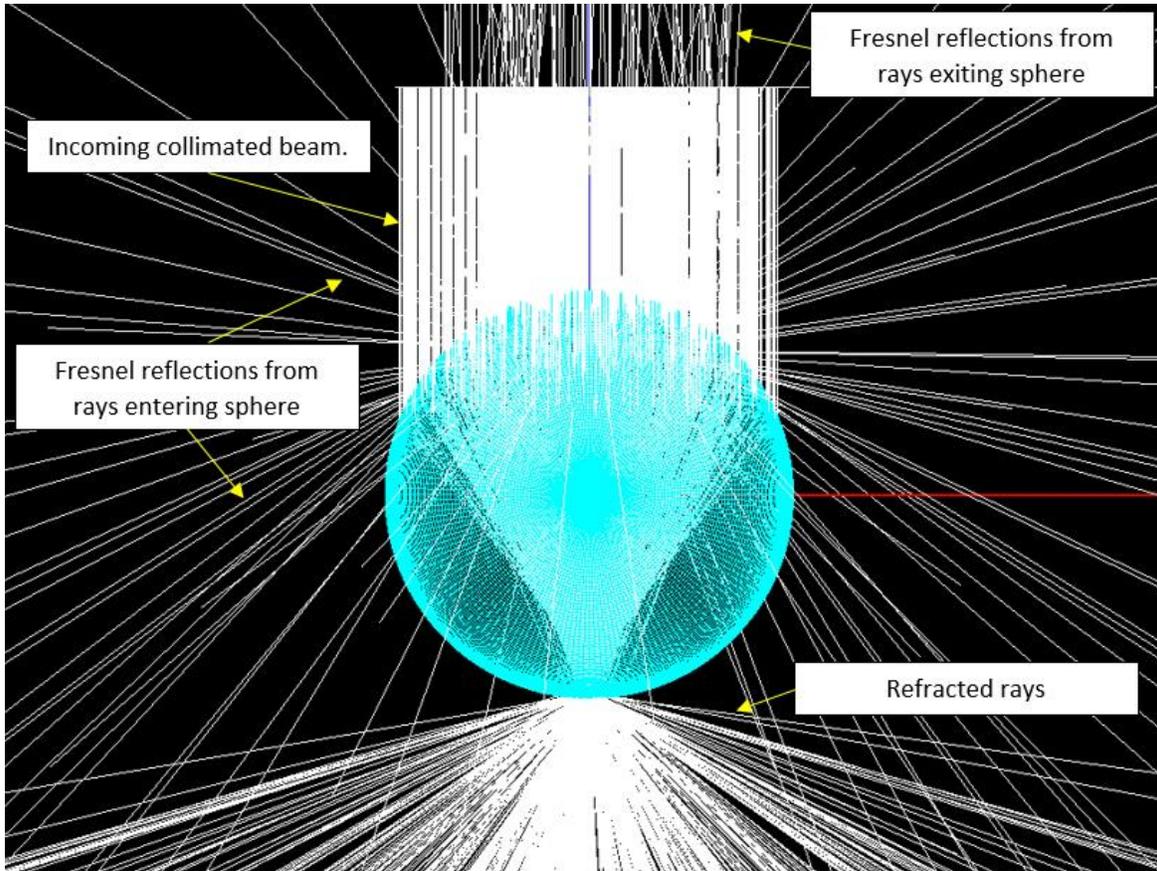
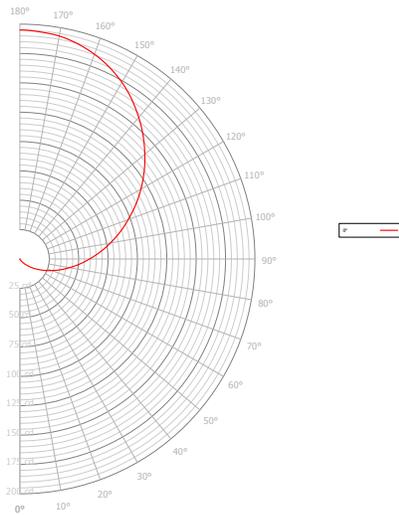


Diagram of scattering regimes. Diagram from Michigan Technology University (MTU), GE4250 scattering lecture.

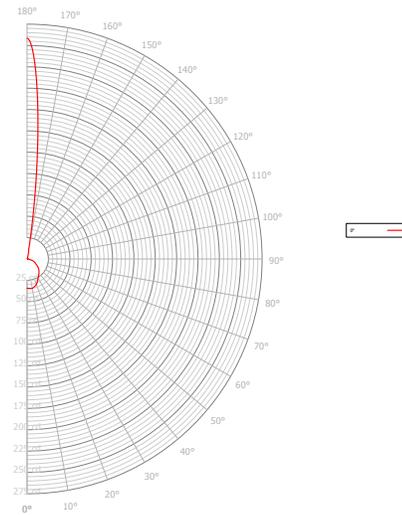
Photopia currently only supports geometric scattering, thus supporting the relatively larger particle sizes. The geometric scattering distribution is flexible and can be defined in the material properties. The typical way the geometric distribution is defined is to model a collimated beam of light directed onto a sphere that has been assigned appropriate material properties. For example, if the particle is an opaque white diffuse material, then the sphere could be assigned any of the perfectly diffuse reflectance materials in the library. If the particle is titanium dioxide suspended in acrylic (PMMA), a common whitening material added to clear plastics, then the sphere is assigned a refractive material that defines the refractive index of TiO_2 on the inside and acrylic on the outside. Although TiO_2 particles make materials appear white, they are actually clear particles with a relatively high index of refraction ranging from about 2.5 to 2.7. The following image illustrates a particle model for TiO_2 in acrylic.



Candela Polar Plot



Candela Polar Plot



The intensity distribution on the left results from a collimated beam directed onto a diffuse reflecting sphere. The incoming beam is directed toward 0° in the distribution, so the intensity in that direction is completely blocked. Some light still scatters forward as it reflects off the side of the sphere. The image on the right shows the distribution of a titanium dioxide (TiO_2) sphere in acrylic. TiO_2 is a clear, high index ($n=2.73$) material commonly used in white paints and diffusers.

The particle shape doesn't have to be sphere, as any particle shape could be modeled.

Matrix showing the totals of each row.

	400	450	500	550	600	650	700	750	800	Total
400	1	0	0	0	0	0	0	0	0	1
450	0	0.35	0.1	0.7	1	0.6	0.15	0.05	0	2.95
500	0	0	1	0	0	0	0	0	0	1
550	0	0	0	1	0	0	0	0	0	1
600	0	0	0	0	1	0	0	0	0	1
650	0	0	0	0	0	1	0	0	0	1
700	0	0	0	0	0	0	1	0	0	1
750	0	0	0	0	0	0	0	1	0	1
800	0	0	0	0	0	0	0	0	1	1

Matrix showing all values divided by the row totals. These are the probabilities that the ray reactions will emit at the given output wavelengths.

	400	450	500	550	600	650	700	750	800
400	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
450	0.000	0.119	0.034	0.237	0.339	0.203	0.051	0.017	0.000
500	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
550	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
600	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
650	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
700	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000
750	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000
800	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000

Each row stands on its own and shows relative values at each output wavelength. Since the values are all relative to each other in a single row, the units are irrelevant. If the absorption of the phosphor at a given input wavelength is low and the ray is more likely to just reflect off of the particle, then specify a higher value at the output wavelength matching the input wavelength. For example, if the absorption is only 10%, then make the value at the matching output wavelength 90% of the total of all values in that row. In the sample data set above, the chances that a 450nm ray will not convert to a different wavelength is 11.9%.

When modeling phosphors, it is reasonable to assume that the wavelength converted rays have an equal likelihood of emitting in all directions. Essentially, the phosphor particles are iso-radiant emitters. So a scatter distribution with equal values at all angles can be specified. However, when rays interact with the phosphor particles but are not absorbed and converted to a new wavelength, then the rays likely just reflect. In order to accommodate both types of scatter distributions (iso-radiant and reflections), Photopia has the capability to specify unique scattering intensity distributions based on the input and output wavelength ranges. The example file below includes a default scattering intensity distribution based on a ray reflecting off of a diffuse sphere, like shown in the left intensity plot above. An iso-radiant intensity distribution is then defined for the specific input wavelengths that are absorbed by the phosphor and then re-emitted into the longer wavelengths.

Material Library Files

The following shows the format of the .material XML file.

We recommend editing this file in Notepad++ (free to download) since it automatically formats the various sections of the xml files.

File content description:

First 2 lines are required to define the file format.

Meta labels:

id = material filename prefix

name = material name

description = material description

volumetric-scatter coefficient = the scatter coefficient exponent in the Beer Lambert Law equation (μ)

distribution = The scattered ray relative intensity distribution. The distribution is assumed to be axially symmetric and go from 0° to 180°. 0° is in line with the incident ray direction. 180° is therefore a retro-reflection. The “x” value is the vertical angular increment. If x=10, then 19 intensity values need to be specified. The magnitude of the distribution is irrelevant. Only the shape of the distribution matters.

(Optional) distribution rangekey = An additional scattered ray relative intensity distribution for a specific range of input and output wavelengths. The first 2 values of the rangekey attribute define the input wavelength range. The last 2 values define the output wavelength range. So in the example file below, this scattering intensity distribution will override the default distribution when the input wavelength is 450nm and the output wavelengths range from 500 to 800nm. There is no limit to the number of distribution rangekeys that can be defined.

(Optional) matrix = The wavelength conversion matrix. The “dimensions” are wavelength values in nm defining the start, end and increment in the distribution. This is then followed by the matrix of data that must be square and define the full range of the specified dimensions. If this data is excluded, then the particle reactions will not convert wavelengths.

refraction file = The .RFC or .SPDRFC refactor filename for this material.

Sample file for a phosphor:

```
<?xml version="1.0" encoding="UTF-8"?>
<material xmlns="http://www.ltioptics.com/material" >
  <meta label="id" value="PHOSPHOR-3000K-80CRISPD380-780" />
  <meta label="name" value="PHOSPHOR-3000K-80CRISPD380-780" />
  <meta label="description" value="SPD 380-780nm - Phosphor 3000K 80CRI" />
  <volumetric-scatter coefficient=".1" >
    <distribution x="10">0.00 0.00 0.05 1.03 4.03 9.44 17.70 28.82 42.73 59.25 78.13 98.08
118.86 138.76 157.34 173.66 185.54 192.81 195.04</distribution>
    <distribution rangekey="450 450 500 800" x="10">1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0</distribution>
    <matrix dimensions="400 800 50">
      1      0      0      0      0      0      0      0      0
      0      0.35  0.1  0.7  1      0.6  0.15  0.05  0
      0      0      1      0      0      0      0      0      0
      0      0      0      1      0      0      0      0      0
      0      0      0      0      1      0      0      0      0
      0      0      0      0      0      1      0      0      0
      0      0      0      0      0      0      1      0      0
      0      0      0      0      0      0      0      1      0
      0      0      0      0      0      0      0      0      1
    </matrix>
  </volumetric-scatter>
  <refraction file="PHOSPHOR-3000K-80CRISPD380-780.RFC" />
  <refraction file="PHOSPHOR-3000K-80CRISPD380-780.SPDRFC" />
</material>
```

A refractor material with scattering that does not have wavelength conversion requires the following files:

FileName.RFC
FileName.material

A refractor material with scattering that does have wavelength conversion requires the following files:

FileName.RFC
FileName.SPDRFC
FileName.material

All of the material files go into the material library folder:

C:\ProgramData\LTI Optics\Library\Materials

When adding a new material to the library, you just also add it to a Refract.lib file. This file provides the list of materials shown in Photopia. Create a custom Refract.lib file by copying the original and renaming it to Refract_YourCompanyName.lib. Photopia will read all the files beginning with "Refract" in their filename when creating the list to display. Creating your own file is important since the default file is overwritten with each update installation. This is an ASCII file you can open and edit in Notepad. Open the file and modify the data in the first line as you require. There are 5 entries on each line, with each piece of data separated by a TAB character. In order, the data is: manufacturer, designation, description, index of refraction, and material filename prefix. The first time you create and edit this file, delete the rest of the lines showing the standard materials.

When running a project with particles that shift the wavelength of light, you must choose the "Power Distribution Raytrace" under the "Advanced Raytrace Parameters." You will also specify the wavelength resolution in this setting, so choose a value based on the resolution of your matrix.

For more refractor scattering sample data files including both with and without wavelength conversion, see the following files in the material library folder:

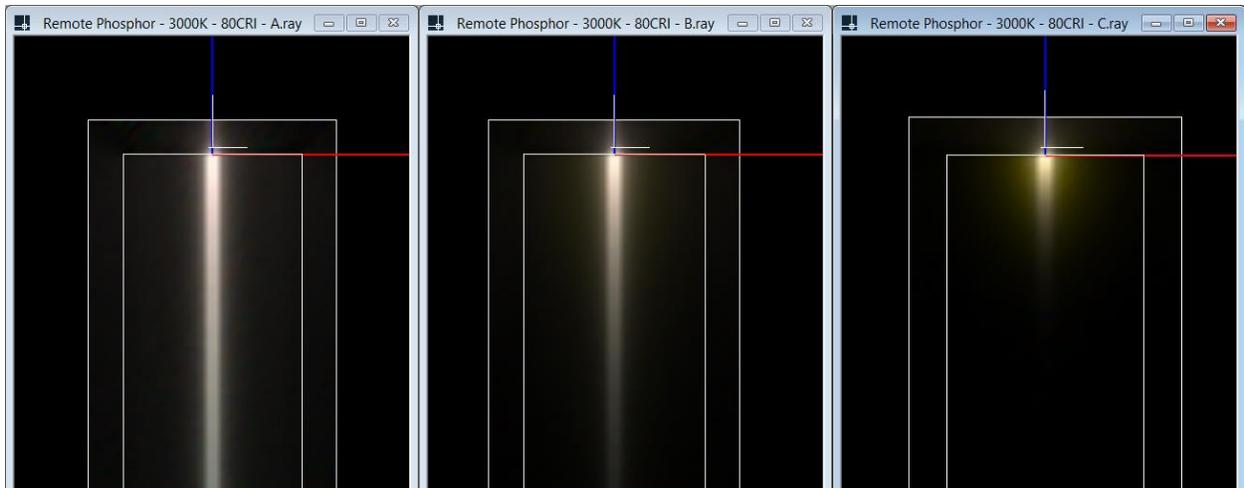
PHOSPHOR-3000K-80CRI-ACRYLIC-SPD380-780
EVONIK-0E011
EVONIK-0E012
EVONIK-0E013

Sample Results

Three sample projects were setup that used a blue laser lamp model directed into an acrylic light guide containing phosphor particles. These projects were all run with the same phosphor particle material in acrylic, but with scatter coefficients in the 3 projects A, B and C, set to the following values, respectively:

0.01, 0.1, 0.5

The images show the light pattern on a vertical illuminance plane in the light guide, where the laser is on top, directed downward. The image with the lowest scatter coefficient on the left shows the laser progressing farthest into the material while the highest coefficient on the right scatters the light more quickly. The color of the scattered light also becomes warmer as more light interacts with the phosphor.



To view one of these projects, choose Help / Open Sample Project in Photopia and then look for the following project in the "Phosphor Particle Scattering" sub-folder.

Phosphor Infused Light Guide - 3000K - 80CRI - B.ray

You will also see a project in this folder that can be used to determine a particle's scattering distribution using a laser directed onto a sphere that can be assigned any material properties you require.