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An Inexpensive Optical Absorption Experiment

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This optical absorption experiment can be put together in only a few minutes with materials found in most secondary or undergraduate stockrooms. The absorption material is the partly transparent flexible anti-static plastic material used to package solid-state devices. The detector is a hand-held photographic exposure meter of the type that was in common use before the advent of point-and-shoot cameras. A graph of the intensity of the transmitted light as a function of the number of sheets of the material is a decreasing exponential. The emphasis of the experiment is on the mathematical form.

The Experiment

The apparatus is shown in Fig. 1. The small pieces of thin plastic absorber are hard to handle, so I cut them into 24- x 36-mm rectangles and put them into 35-mm slide mounts. To try to keep the variation in the material to a minimum, all of the rectangles were cut from adjacent portions of the shipping bag. The light source was a light box (used to view transparencies) covered with a sheet of opaque cardboard with a square hole cut in it.

The absorbers are placed one by one on top of each other and the f-number indicated by the exposure meter noted as a function of the number of absorbers. The square of the f-number is then plotted versus the number of absorbers. The use of the square of the f-number as a measure of light intensity is discussed in the next section. To allow for differences in the effects of individual absorbers, several trials are made with the absorbers used in different, random orders.

Figure 2(a) shows a graph of the relative intensity, $I$, of the transmitted light as a function of the number of absorbers. An exponential function has been fitted to the data points using a standard curve-fitting program. Figure 2(b) is a graph of $\ln (I)$ as a function of the number of absorbers, and the straight line with a negative slope indicates the presence of exponential absorption. Graphs with data sets taken with the absorbers added in different orders show a similar scatter but at different points, suggesting that the sheet of plastic was not quite uniform.

The Decreasing Exponential

Why do we expect a decreasing exponential law in this case? For each slice of absorber, the decrease in the intensity, $\Delta I$, is proportional to the incident intensity $I$. This is expressed as:

$$\Delta I = -k \cdot I$$

where $k$ is a constant. Integrating this equation gives the intensity after $n$ absorbers as:

$$I_n = I_0 e^{-kn}$$

where $I_0$ is the initial intensity. This is a decreasing exponential law.

Fig. 1. Overall view of the absorbers and exposure meter laid out by the mask on the light table.
I and the thickness of the absorber $\Delta x$. We can then write $\Delta I = -B I \Delta x$, where $B$ is the constant of proportionality. This can be rewritten as

$$\frac{\Delta I}{\Delta x} = -B I,$$

which is the basic equation that predicts exponential decay. The standard solution for the intensity after passing through a thickness $x$ is

$$I(x) = A \exp(-Bx).$$

Since the overall thickness $x$ is an integral multiple, $m$, of the thickness $\Delta x$ of one sheet (all the absorbing sheets are identical) we can write

$$I(m) = I_0 \exp(-Km).$$

Note that $B$ and $K$ are constants. For easy analysis it is customary to take the natural logarithm of both sides, producing the linear relationship

$$\ln (m) = \ln (I_0) - K m.$$  

In addition to absorption, there is another effect involved in this experiment. Each front and rear surface of a single sheet of plastic film reflects a certain fraction of the incoming light beam. Glass plates with an index of refraction of 1.50 reflect 4% of the light incident on each surface, and the plastic has relatively similar numbers. A treatment of this effect can be found in Ref. 1. Note that a certain fraction of the incoming light is transmitted at each interface and that

![Graphs of transmitted intensity as a function of absorbers. Least-squares curve fitting techniques have been used to draw the lines.](image)
a certain fraction of the incoming light is transmitted by each layer of plastic. Thus the effect of the reflection of light is simply to add to the constant $K$.

**Using the Exposure Meter as a Photometer**

Experiments involving the intensity of light would be easy if we had the use of a photometer: an instrument to measure the intensity of an incoming optical signal. Unfortunately, these instruments are not commonly found in secondary and undergraduate physics laboratories. The photographic exposure meter, which is now cheap for both new and second-hand, has the necessary sensor and electrical output meter. Its calibration is designed to be used to give the correct exposure for photographic film and must be reinterpreted to be used as a photometer.

The sensitive photographic surface, either a matrix of silver halide grains or an array of pixels in a charge-coupled detector, requires that the number of photons per unit time per unit area (the photon flux) striking the surface varies over a relatively narrow range of values to give a proper exposure. Assuming that the shutter is always open for the same length of time, this is accomplished by placing a variable aperture iris in the image-forming system. If the photon flux approaching the lens is too large, the iris opening is decreased in area to reduce the photon flux impinging on the sensitive surface. Increasing the area of the iris opening compensates for a smaller external photon flux.

The critical dimension is the area of the iris, which is proportional to $D^2$, where $D$ is the diameter of the opening. This diameter is conventionally indicated by the $f$-number, $N$, defined by $D = f/N$, where $f$ is focal length of the lens. Thus, a camera using 35-mm film, equipped with the usual $f = 50$-mm lens, has an iris diameter of 25 mm at $f/2$.

The exposure meter’s scale gives pairs of shutter speeds and $f$-numbers that all deliver the same photon flux to the sensitive surface. Again, we assume that the shutter speed is a constant. The standard $f$-numbers go up in steps of $1/2$; each succeeding number gives half the iris area. Thus, there is a standard series of $f$-numbers, $f/4, f/5.6, f/8, f/11, f/16, \ldots$, each giving half the delivered photon flux as the one before it.

When the exposure meter is used as a photometer, we need to reinterpret its readings. Instead of keeping the exposures the same, we want to know the relative photon flux delivered to the instrument. Remembering that the exposure time on the exposure meter is assumed to be the same, a decreasing photon flux corresponds to larger iris areas and inversely smaller $f$-numbers on the exposure meter scale. Since the area is proportional to $D^2$, it can be seen that a measure of the photon flux is $1/D^2$, and that is proportional to $N^2$.

In most cases the exposure meter reading will not be on a standard (16, 11, 8, 5.6, 4, \ldots) value of $N$. To a first approximation linear interpolation between standard values will produce useful values of $N$.

**Coda**

During the course of the year, students are exposed to phenomena that are described by a variety of mathematical forms. I have always suspected that the decreasing exponential function is one of the most difficult to understand. Therefore, when I taught the noncalculus introductory course (mainly composed of pre-medical students) over the years, I have used a series of experiments that use the exponential function, including the decay in the height of a water column, capacitor discharge, absorption of gamma rays in increasing thicknesses of material, and real and simulated radioactive decay. This relatively quick experiment is an addition to this list.

**References**

3. We use the beta decay of neutron-activated silver isotopes. However, the situation can be modeled using the usual sort of dice-throwing experiment. (That is, a large number of dice are thrown, those with a certain number of spots are removed and the process is repeated until the statistics become poor.)

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