Department of Physics
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Interdisciplinary Diffusion Lab

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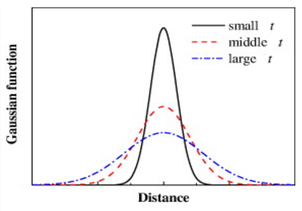
Abstract

Diffusion is a principle in Physics, Chemistry, and Biology. The rate of diffusion is affected by temperature, particle size, concentration, and material type. Students can model the rate of diffusion based on particle size by contrasting blue and yellow dyes. Two petri dishes containing agar-agar receive a drop of dye at the center. The radius of expansion is recorded over time. The variance of the distribution grows as $\sigma^2=4Dt$, where σ^2 is the variance, D is the diffusion constant, and t is time. Graphing variance versus time gives a slope of 4D. Diffusion constants vary by particle size, allowing for a size ratio comparison between blue and yellow dyes. Relating this to cells, students predict that smaller molecules diffuse into living cells, whereas larger molecules need some assistance from protein channels as in facilitated diffusion. In Physics and Chemistry, the data can be related to thermal energy.

Background



When a high-concentration dot of molecules is placed in a viscous fluid, the expansion of the dot due to diffusion may be modelled by a Gaussian with a variance that grows linearly with time.

Fig. 1: distribution of molecules

For 2-D diffusion, the variance of the distribution of particles grows as

$$\sigma^2=4Dt \qquad (1)$$

where D is the diffusion constant, σ is the standard deviation and σ^2 is the variance. A graph of σ^2 vs t should be a straight line with a slope equal to 4D. If the particle are small spheres, the diffusion constant, D, depends inversely on the radius, a, of the particles, i.e.,

$$D=\frac{k_B T}{6\pi\eta a}\propto\frac{1}{a} \quad \text{(Stokes Formula)} \quad (2)$$

Thus, if comparing the diffusion coefficients of two different sizes of particles,

$$\frac{a_2}{a_1}=\frac{D_1}{D_2} \qquad (3)$$

In other words, larger particles diffuse at a slower rate than smaller particles. The goal of this experiment is to measure the diffusion constants for two different food-coloring molecules Blue and Yellow and thus obtain the ratios of their "sizes".

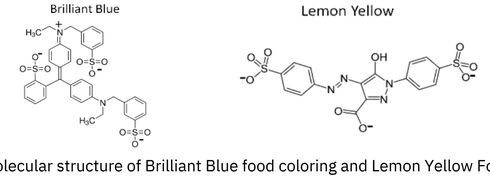


Fig. 2: the molecular structure of Brilliant Blue food coloring and Lemon Yellow Food coloring.

Methodology

Fig. 3: measuring the diameter of the central-spread of the blue and yellow dyes

Agar-agar plates are prepared by mixing a tablespoon of Agar-Agar with a half cup of water and then heated to a boil. This warm liquid is poured into two separate petri dishes to about 2-3 mm thickness. During the cooling process of the Agar-Agar, about 20 minutes at room temperature or 10 minutes in the refrigerator, the food coloring samples are prepared. A drop of glycerin is mixed into a drop of each food coloring sample.

Once the agar-agar has congealed, the tip of a pipette is used to create an indentation about half the agar's thickness in the center of the plate. This process is repeated for the second plate. With a timer and ruler accessible nearby, a small drop of the blue dye sample is added to the indentation in one of the plates via pipette. The yellow dye is added to the other plate. The diameters of the central-spread for each dye sample are recorded in a table at 20 minute intervals for the duration of the allotted class time, typically between one to three hours.

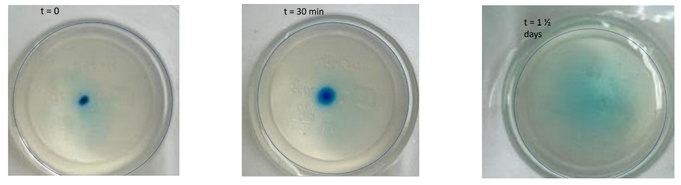


Fig. 4: the spread of the dye sample over time.

Results

Table 1: The central-spread diameters, radius and variance of the blue and yellow dyes samples. Data provided by Dave Carter.

Time (s)	d_{Blue} (m)	$\sigma_{Blue} = r_{Blue}$ (m)	σ^2_{Blue} (m^2)	d_{Yellow} (m)	$\sigma_{Yellow} = r_{Yellow}$ (m)	σ^2_{yellow} (m^2)
0	0.005	0.0025	0.00000625	0.005	0.0025	0.00000625
1200	0.0085	0.00425	1.80625E-05	0.01	0.005	0.000025
2400	0.01	0.005	0.000025	0.0115	0.00575	3.3063E-05
3600	0.011	0.0055	0.00003025	0.014	0.007	0.000049
4800	0.012	0.006	0.000036	0.015	0.0075	0.00005625
6000	0.0125	0.00625	3.90625E-05	0.0165	0.00825	6.8063E-05
7200	0.014	0.007	0.000049	0.018	0.009	0.000081
8400	0.0145	0.00725	5.25625E-05	0.018	0.009	0.000081
9600	0.0155	0.00775	6.00625E-05	0.0205	0.01025	0.00010506
10800	0.0165	0.00825	6.80625E-05	0.0205	0.01025	0.00010506
12000	0.017	0.0085	0.00007225	0.0212	0.0106	0.00011236
13200	0.018	0.009	0.000081	0.023	0.0115	0.00013225

The molar mass of Brilliant blue was 792.85 g/mol, where as the molar mass of Yellow was 534.3 g/mol. The ratio of the molar masses was 1.48.

Comparison of distributions

Based on Stokes formula a small spherical particle's diffusion constant is inversely related to the radius. Thus, the the radius of color distribution is approximately equal to the standard deviation of the distribution of the dye molecules.

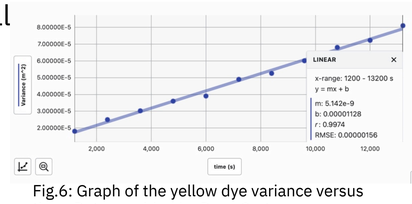


Fig.6: Graph of the yellow dye variance versus time. Data provided by Dave Carter.

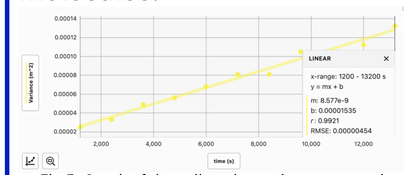


Fig.5: Graph of the yellow dye variance versus time. Data provided by Dave Carter

Since variance versus time gives a slope of 4D. The value of the diffusion constant is 1.28×10^{-9} m^2/s for the blue dye and 2.14×10^{-9} m^2/s for the yellow dye.

Conclusion

In order to understand the relationship between diffusion rate and particle size, the diameter of central-spread of each dye is measured for specific time intervals. Graphing variance versus time gives a slope of 4D. Comparing the diffusion constants allows students to understand that larger molecules will diffuse at a slower rate compared to smaller molecules. Relating this data to cells, students would recognize that diffusion alone would take a long time for larger molecules to pass through the cellular membrane. Thus, larger molecules would require assistance such as protein channels. The rate of diffusion can vary based on the concentration, material type, particle size and temperature. Students could conduct future experiments by changing these variables. Changing the temperature of the gel could be related to Kinetic energy.

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