Simple direct observation of polarization changes of Rayleigh scattering on sugar solution at low concentration

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Abstract. Commonly, light scattering is observed and measured by its scattered light intensity. In this research, we use direct polarization changes in sugar solution using Rayleigh scattering to observe the dependence of polarization changes of scattered light on incident polarized light angle and sample concentration. Commercial sugar and pure sucrose diluted in aqueous solution were used as samples with concentrations in the range 0.01 g/ml – 0.1 g/ml, and were assumed to be homogeneous and having identical molecular size. Green pointer laser having wavelength of 532 nm was used which its polarization changes was measured by analyser. The result shows that the polarization changes of scattered light is linearly dependent both on polarizer angle of the incident light and the sample concentration (number of particles) showing polarization changes in commercial sugar solution greater than in sucrose solution. This indicates quality differences of the samples due to molecular size differences and additional impurities in the commercial sugar. The direct polarization changes measurement is able to show relative different of sugar quality, i.e. pure sucrose and commercial sugar and can further be developed as a simple measurement method in finding information of molecular size and number of particles.

Keywords: Rayleigh scattering, direct polarization changes, Sugar solution

1. Introduction
Light scattering is a well-known phenomenon, which its application is also developed in many wide areas. Today, the application of light scattering leads to Dynamic Light Scattering (DLS) method to obtain information of particle size and its dynamic motion [1, 2]. In Pharmaceutical area, nanoparticle impurity in sugar was also reported using DLS and Nanoparticle Tracking Analysis [2].

Rayleigh scattering is an elastic light scattering characterized by its very small particle size compared to the wavelength of incident light. The amplitude of electric field of light which is scattered by a spherical particle is given by:

$$E' = \frac{k^2D^2}{r} \left( \frac{\sin \theta}{\sin \phi} \right) E \sin \phi$$  \hspace{1cm} (1),

where $E'$ and $E$ represent the amplitude of scattered field and incoming field, respectively. The factor $k = 2\pi/\lambda$ is wave number, $r$ the distance between observer and the target, $D$ the size of the particle,
The number of the particle, \( N \), polarizability of molecular sample, \( \varepsilon_0 \), free space permittivity and \( \varphi \) the observation angle (angle between the direction of incoming light and observation).

Having used on air molecules, Rayleigh scattering is also used on water and sucrose molecules due to its sample transparent characteristics and its prospects in food and environment cases [3, 4]. On commercial sugar solutions, the scattered intensity of light scattering was measured to obtain its Rayleigh factor [5], and its optical activity was also detected on glucose using transmitted and reflected light [6].

Many previous studies commonly use the intensity of the scattered light to obtain the information of its targets particle. To our knowledge, there are no reports of any comprehensive discussion on direct measurement of polarization changes of scattered light. More over the use of direct observation of polarization changes in inelastic scattering such as fluorescence polarization [7, 8], leads to another new method for determination of various qualities from cooking oils, however it has still less attention from researchers.

Equation (1) can be used to determine the physical quantities related to the equation by measuring scattered and incoming field. The magnitude of scattered and incoming field can be described by changed linearly polarized angle \( \beta \) and \( \theta \), respectively. In this paper, we aim to study how the polarization changes (\( \beta \)) of the scattered light can be observed for various angle of linear polarized incident light (\( \theta \) and the number of particles (\( N \)) for commercial sugar and pure sucrose solution in aqueous solution.

2. Methods
In this research, we assumed that the Rayleigh scattering still holds for sugar solution which consists of mixing sucrose and water. Namely, the average size of a water molecule is 0.1 nm, and the size of a sucrose molecule is approximately 1 nm. By using green laser pointer with 532 nm, the ratio of size to the wavelength is set approximately to 0.002 to 0.002. When the light is linearly polarized, the incident electric field of light is divided into perpendicular \( E_\perp \) and parallel field \( E_\parallel \) in the direction of the polarizer and analyser axis. The model of observation is described by fig. 1.

![Diagram of polarization changes](image)

**Fig 1.** Model observation of polarization changes of the scattered light. The incoming light is linearly polarized using a polarizer with an angle \( \theta \), so that the electric field is divided into two components, i.e. \( E_\perp \) and \( E_\parallel \) relative to the plane of scattering. \( E'' \) and \( E'_\parallel \) represent as a transmitted and scattered field, respectively.
From fig. 1, the light is passed through a polarizer to get a linear polarized light with angle $\theta$, hence the angle can be varied to obtain various linear polarization of the incoming light, in which its incident field is divided into two components, i.e. perpendicular to the plane of scattering $E_{\perp}$ and parallel to the plane of scattering $E_{//}$. Experimentally, angle of observation $\phi$ was 90° in fig. 1, then $\sin \phi = 1$ meaning that only the component of fields $E_{\perp}$ will be observed in the scattered light direction. The scattered field is shifted to $E_{\perp}$ relatively to the analyser axis of angle $\beta$, known as polarization changes of the scattered light. The incoming electric field is linearly polarized to angle $\theta$, and the desired observation of polarization changes $\beta$ should be a function of $\theta$ and $N$ as:

$$\sin \beta = f N \sin \theta$$  

(2),

where $f = \left[(k^2 D^3 r)/(\alpha^3 \varepsilon_0)\right]$ is nearly constant under special condition, that $\lambda$, $D$, $r$, $\alpha$ and $\varepsilon_0$ are already known. Especially for homogeneous size of sugar molecule, $D$ was assumed approximately equal to 1 nm.

In this research, the sample consisted of pure sucrose and commercial sugar. The measurement of the density gave the same value of 1.56±0.05 g/ml, and therefore assuming both had the same characteristics. The sample was diluted into water (aqueous solution) with various low concentration from range 0.01 g/ml to 0.1 g/ml, i.e. an amount of gram of sample in total volume of solution, which could be regarded as number of particles, $N$. The used incident light was green pointer laser with wavelength of 532 nm. The angle of linear polarized incoming light was adjusted using polarizer to obtain various $\theta$ from 0° to 180° (with increasing step of 10°) and the desired polarization changes of scattered light $\beta$ was measured using analyser. According to equation (2), for constant $f$, it was to be proven the relation $\sin \beta \sim \sin \theta$ and given value $N$, and then the relation of $\sin \beta \sim N$, for given value $\theta$.

3. Results and Discussion

Fig. 2 shows the polarization changes of the scattered light $\beta$ against polarization angle $\theta$ from 0 to 180° for both of sucrose and commercial sugar solution at 0.1 g/ml and 0.01 g/ml. The lowest graph in Fig. 2 shows the value of aqueous representing water molecules.

The symmetrical curves (fig. 2) from 0° to 90° and from 90° to 180° indicate the scattering of electric fields of light in the samples is good agreement with the Rayleigh scattering for single particle, since the electric fields of light oscillates, hence the physical meaning of the graphs is qualitatively
understandable. As \( \theta \) is close to 0° or 180°, small amplitude of perpendicular field will be scattered resulting to small value \( \beta \). And for \( \theta \) close to 90°, high amplitude of perpendicular field will be observed indicated by high value \( \beta \). The lowest value \( \beta \) in fig. 2 is belong to aqueous solution that represents to water molecule. This means that water molecules scatters light less intense than sugar molecules due to smaller molecular size compared to the sucrose or sugar. For the sucrose and commercial sugar at 0.01 g/ml, both of them have identical value \( \beta \), since the samples were at the low concentration and assumed to be homogeneous. At 0.1 g/ml of concentration, the value \( \beta \) between sucrose and commercial sugar is slightly distinguishable in the range \( \theta = 30° \) to 150°. The highest value \( \beta \) obtained by commercial sugar solution at concentration of 0.1 g/ml indicates that commercial sugar is denser than sucrose, i.e. there could be different molecular size and composition. Since we assumed that sucrose and commercial sugarsolution have an identical molecular size, so the value of \( f \) in equation (2) should be constant at that condition. Based on the result above, we suspect that \( f \) is not constant. Because, \( f = f(\lambda, r, D, \alpha) \) for given value of \( \lambda \) and \( r \), the different value \( \beta \) for commercial sugar from sucrose could be caused by different value \( D \) and \( \alpha \) simultaneously. It seemed that the commercial sugar consisted of non-identical molecular size suggesting its impurities.

According to equation (2) our experimental results provide the same linear relation between \( \sin \beta \) and \( \sin \theta \) as described in equation (2) for all concentration between 0.01 g/ml and 0.1 g/ml. The experimental result of the relation is shown in Fig. 3.

**Fig3.** The graphs of \( \sin \beta \) vs. \( \sin \theta \) of sucrose solution compared to aqueous solution (lowest graph). The pattern is almost identical for commercial sugar solution at the same concentration (not shown).

From the results (fig. 3), the best linear relation between \( \sin \beta \) and \( \sin \theta \) in equation (2) is still hold in the range \( \theta = 0° \) to 70°, i.e. \( \sin \beta - \sin \theta \), for both commercial sugar and sucrose solution so far the sample assumed to be homogeneous. However, in the range \( \theta = 80° \) to 90°, both of commercial sugar and sucrose solution show not linear relation. This could be caused by anisotropic characteristics in sugar and sucrose solution that leads to the contribution of additional component of polarizability \( \alpha \). The component of tensor \( \alpha \) will modulate a phase shift to \( \beta \) and might highly influence at high value \( \theta \). A different value \( \alpha \) could be caused by different molecular size or additional impurities in the sample. A comprehensive calculation and measurement about this complex scattering should be done to explain this finding in the next research.

**Fig4** shows the linear graphs of \( \sin \beta \) vs. \( N \) at \( \theta = 0° \), 30°, 60°, and 90° for sucrose solution. The similar results were also obtained for commercial sugar solution (not shown), so it is in agreement with equation (2).
**Fig 4.** The linear relationship between sinβ and N of sucrose solution at θ = 0°, 30°, 60°, and 90°. The linear curves were also obtained for commercial sugar.

According to equation (2), and from fig. 4, the relation of sinβ-N is still hold in the range θ = 0° to 180° (the curves were presented only for θ = 0°; 30°; 60° and 90°). Because of small value β, hence the sinβ=β and we can use also the linear relation β-N to analyse the difference between sucrose and sugar solution, and it is presented more clearly in fig. 5.

**Figure 5.** The graph of β vs. N for sucrose and commercial sugar solution at θ = 0°, 30°, 60°, and 90°. The linear curves are also the same as sinβ vs. N, because of β= sinβ.
The similarity of curves $\beta$-$N$ for sucrose and commercial sugar are taken place in the range 0-90°, however especially at $\theta = 90^\circ$ there is a slightly difference of the slope of the curves. To explain this difference, we refer back to the assumption of homogeneous sample for equation (2), that $f = f(\lambda, r, D, \alpha)$ is constant for given value $\lambda$ and $r$, for identical molecular size $D$, and a constant scalar $\alpha$. The properties of homogeneity of the samples should reflect in $\beta$-$N$, i.e. it results in the same gradient of the curves. In this discussion, we proposed that the homogeneous sample of sucrose and commercial sugar can be checked qualitatively using the gradient of value $\Delta\beta/\Delta N$. The difference of the gradient from samples can be caused by difference of single value $D$ or $\alpha$, or by both of value $D$ and $\alpha$ in the same time. For a bigger single molecule $D$, or a bigger single polarizability $\alpha$, individually it leads to higher gradient. However, for a bigger value $D$, usually it is accompanied by bigger value $\alpha$ simultaneously. Assuming that $D$ is hold constant, then any higher value $\alpha$ is highly possible caused by different composition, i.e. there is a small amount of additional impurities. By using these arguments, to check the similarity of the homogeneous sample from sucrose and commercial sugar, we determined all gradient of curves in the range $\theta = 0^\circ$ to 90°, and presented in fig 6.

Fig. 6 describes the value of the gradient of $\Delta\beta/\Delta N$ obtained from the linear curves $\beta$ vs. $N$ at $\theta$ from $0^\circ$ to 90°. Previously we mentioned that both commercial sugar and sucrose were assumed to behaving identical molecular size and homogeneous properties.

![Fig6](image-url)

**Fig6.** The gradient of polarization changes to the number of particle (°.ml/g) for sucrose and commercial sugar solution as function of $\theta$. In the range of value $\theta = 90^\circ$ to 180°, due to symmetrical consideration, so the value of the gradient is an average value in all range $\theta = 0^\circ$ to 180°.

Based on fig 6, the gradient value is relative constant for sucrose solution, which indicates identical size of particles. But for commercial sugar, the value increases almost linearly, which is strongly caused by higher $D$ and $\alpha$, than in sucrose solution. At this condition, we found that the characteristics of both samples are not similar. Referring to the discussion in fig. 5, the increasing gradient should be due by different value of $D$ and $\alpha$ simultaneously. It means that the molecular size distribution in commercial sugar is different from sucrose and there should be any additional small number of
impurities. Both of molecular size $D$ and impurities will influence also to the value $\alpha$ and the final value $\beta$.

This simple method so far has proven equation (2) and can explain the Rayleigh scattering by using direct polarization measurement at low concentration. The direct observation of polarization changes has made the interaction between light and particle easier and simpler to be studied than other method, such as DLS. The method can also qualitatively differentiate between pure sucrose and commercial sugar solution due to different molecular size and additional impurities. The actual size and composition further should be checked using other methods such as XRF or DLS.

In this limitation, we havenot yet measured the properties of the same sample with other methods such as DLS instrument. However we can compare in this time, at least, the capability of our method with a DLS instrument. In most previous works, the intensity of scattered light increases with increasing the number of target particle, in accordance with equation (2). The modest technique, i.e. DLS measurement results, is based on the fluctuation of intensity due to Brownian motion, and the molecular size is determined using Stokes-Einstein relationship. This previous technique can measure the size in the range of nano-particle and its size distribution relatively fast and accurate, however the most apparatus is already compact and very expensive. In our method, the direct polarization change measurement has some advantage, which is very simple to use, inexpensive, and provide wide level of students to understand the physically process of the light scattering. We propose that the method can be also used to measure molecular size at low concentration by using comparison of the size of water molecules to the sucrose molecule, including in finding molecular polarizability of samples relative to the water.

4. Conclusion

The direct measurement of polarization changes can be used to prove Rayleigh scattering at low concentration of sucrose and commercial sugar solution. The polarization changes of scattered light is linearly dependent on the polarization angle in the range $0^\circ$ to $70^\circ$, and linearly dependent on sample concentration (number of particles). This method is able to show sugar’s relative different quality, i.e. pure sucrose and commercial sugar due to different molecular size and additional impurities in the commercial sugar. The method is simpler and easier to study the interaction of light with matter for special condition. Additionally, for other known parameters, the method can be developed to obtain the molecular size and composition information of the sample using Rayleigh scattering.

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