How Many Au Nanoparticles Does It Take to Circle the Earth?

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Gold nanoparticles are used in a variety of applications, many pharmaceutical. The average size and the distribution play a crucial role in determining how well they work in a particular application. While TEM can show the shape of nanoparticles, it is not ideal for the statistical task of averaging the size and producing a distribution. Dynamic Light Scattering, DLS, is an ideal technique for doing size distribution measurements. This note shows results, discusses approximations made, and demonstrates difference between different distribution weightings.

Introduction

Let's answer the question first. To do so, we need to know the size of the Au particle and to assume it is monodisperse. In fact, one purpose of this application note is to explore the meaning of monodispersity, despite its literal definition, one size. We chose 5 nm diameter Au nanoparticles. Now the earth has an average circumference of 40,000 km or 4 x 10^{16} nm. So we need 8 x 10^{15} particles. That's a lot of particles. Yet, it corresponds to a total volume of just 5 x 10^{-4} cm^3, approximately. Gold's density is 19.3 g/cm^3. So we need about 10 mg of Au. Not much. Of course, given that high density, it will be hard to keep the particles from sinking into the oceans as we circumscribe the earth, not to mention the tiny tweezers required to manipulate the nanoparticles. But our main goal is to figure out if the size claimed is correct and if the distribution is one size.

Experimental Method

The Au was purchased from nanoComposix Inc.[1]. The NanoXact 5 nm diameter sample was selected with tannic acid used as the surface agent to provide stability. The concentration is 0.05 mg/mL and it was used without dilution. The accompanying literature claims monodispersity with a CV of 8-15% and a mean size within 2 nm of 5.0 nm. The TEM picture from the manufacturer is shown here as Fig. 1.

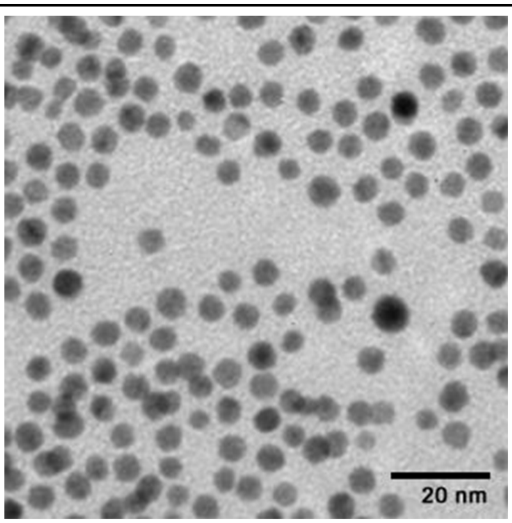

Figure 1: 5 nm Au from nanoComposix, Inc.

Notice there are less than 150 total primary particles. The majority are single primary particles. But some apparent doublets and even more apparent triplets are visible. But are they true aggregates or forced together during sample preparation for the picture? With so few particles, it is hard to tell. Likewise, it is hard to be precise about the mean diameter and CV with so few particles.

DLS was performed using the Brookhaven NanoBrook Omni with a nominal 35 mW diode laser at 658 nm wavelength. Ten measurements were made using the BI-SM50, a 50 µL disposable cell.

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Results

Table I shows results on nanoComposix 5 nm Au using the NanoBrook Omni.

Run	d_{eff} (nm)	PDI	P1 by Int in nm	% by Intensity	P2 by Int in nm	% by Intensity	P1 by Num in nm	% by Number
1	10.50	0.132	4.95	19	13.0	81	4.73	100
2	10.28	0.154	5.20	26	12.8	74	5.20	100
3	09.81	0.179	5.25	33	15.8	67	5.25	100
4	10.16	0.194	4.95	12	11.5	88	4.77	100
5	10.74	0.205	5.06	21	15.8	79	5.06	100
6	11.69	0.170	5.88	36	18.0	64	5.57	100
7	09.92	0.077	5.37	31	15.6	69	4.11	100
8	10.19	0.190	4.77	25	14.3	75	4.53	100
9	09.41	0.132	4.97	25	14.1	75	4.97	100
10	10.06	0.132	5.40	22	14.0	78	5.40	100
Ave	10.28±0.20	0.156±0.012	5.18±0.10	25±2.2	14.5±.6	75±2.2	4.96±0.14	100
CV	1.9%	7.7%	1.9%	8.8%	4.1%	2.9%	2.8%	

The average hydrodynamic diameter calculated from the cumulant fit[2] is (10.28 ± 1.9%) nm and it is very repeatable. Yet, the size is supposed to be 5 nm. Might this suggest that all the particles have formed doublets? The polydispersity index (PDI) is far from zero, indicating there is a width to this distribution. So a multimodal fit was performed using NNLS, non-negatively constrained least squares. The result is a bimodal with 25% of the light scattered coming from an average of (5.18 ± 1.9%) nm particles, in excellent agreement with the expected result and 75% of the light scattered coming from an average of (14.5 ± 4.1%) nm, about three times the size expected. After conversion from intensity to number weighting, the results are interesting. 100% of all the peaks occur at an average of (4.96 ± 1.8%) nm, in even better agreement with expectations.

How is the conversion performed? Let us look at one of the 10 runs and the intensity-weighted (G(d)) diameter values, Run #9. Below is the tabulated result in Table II showing two peaks, one at 4.97 nm (25% by intensity) and the other at 14.1 nm (75% by intensity). The third column, C(d), shows the cumulative undersize distribution by intensity. From this tabulated result it is easy to pick off the percent by intensity in the first peak: 24.8%, rounded to 25% in Table I above.

Table II: Run #9 using DLS showing diameter, d, differential intensity, $G_I(d)$, and cumulative percent by intensity, $C_I(d)$.

d(nm)	$G_I(d)$	$C_I(d)$	d(nm)	$G_I(d)$	$C_I(d)$
3.99	0.00	0.00	13.4	69.77	47.84
4.21	0.00	0.00	14.1	100.00	70.94
4.45	8.30	1.92	14.9	78.29	89.02
4.70	20.34	6.61	15.8	39.57	98.16
4.97	34.98	14.69	16.7	7.98	100.00
5.25	28.04	21.17	17.6	0.00	100.00
5.54	15.70	24.80	18.6	0.00	100.00
5.86	0.00	24.80			
12.0	0.00	24.80			
12.7	30.00	31.72			

$G_I(d)$ is the differential or relative amount by scattered intensity at diameter d. (To simplify, except for the first and last two rows, all others with zero for $G_I(d)$ were deleted.) To obtain the intensity-weighted mean diameter, one would use the following equation:

$$\langle d \rangle_I = \frac{\sum d_i \cdot G_i}{\sum G_i} = 11.99 \text{ nm} \qquad \text{Eq. (1)}$$

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This applies to the total distribution. Notice that this value is not the same as the apparent, also known as the effective diameter, in Table I. Though often confused, the intensity-weighted mean diameter, here 11.99 nm, is not the same as the diameter calculated from the intensity-weighted translational diffusion coefficient, the property initially obtained using cumulant analysis on the autocorrelation function from a DLS measurement. The intensity-weighted, average, translational diffusion coefficient, D_T, is obtained using this equation:

$$\langle D_T \rangle_I = \frac{\sum D_i \cdot G_i}{\sum G_i} \qquad \text{Eq. (2)}$$

Assuming spheres, the Stokes-Einstein equation can be substituted yielding:

$$\langle \frac{1}{d} \rangle_I = \frac{\sum \frac{1}{d_i} \cdot G_i}{\sum G_i} = 0.1023 \text{ nm}^{-1} \qquad \text{Eq. (3)}$$

Inverting this value results in 9.77 nm obtained using the NNLS result, close to 9.41 nm using cumulants. Note that it is often, yet erroneously stated, that this cumulant result is the z-average diameter. But a z-average is an intensity-weighted average. In this case, the z-average is 11.99 nm.

Comparison with a TEM result requires the number-weighted average. To obtain the number-weighted differential or relative amount by number, we need the relationship between scattered intensity and number, N, of particles at diameter d. This relationship is given by

$$G_N = \frac{G_I}{d^6 \cdot P} \qquad \text{Eq. (4)}$$

The factor P, sometimes referred to as the light scattering or angular factor is calculated from Mie theory[3] given the diameter, wavelength, scattering angle and refractive index of the particle and liquid in which it is suspended. For most non-absorbing particles like polystyrene latex, it is a real number. But for Au or other particles that absorb at the wavelength of interest, it is a complex number. The real part describes the usual bending of light and the imaginary part describes absorption. The values for Au are 0.165, 3.14 and were obtained by interpolation between reported wavelength values.[4]

A useful generalization is that for very small nanoparticles, called Rayleigh particles, P is unity up to a diameter of about 25 nm. But this is based on low density, organic particles like polystyrene latex with a real refractive index in the visible of 1.59 and zero for the imaginary part. At 90^o, P = 0.989 for 25 nm polystyrene in water at a wavelength of 658 nm and P = 0.979 at 180^o backscatter. Above 25 nm, P is continuing to decrease and it causes increasing errors to ignore it. For example, at 50 nm, P = 0.958 & 0.918 for 90^o and 180^o, respectively. However, due to gold's strong absorption, P remains within 1% of unit at 658 nm, at 90^o and 180^o, in water even at 50 nm.

Combining the values for the intensity-weighted size distribution in Table II with Equation (4), the values for the number-weighted size distribution are shown in Table III for Run #9. Here $G_N(d)$ is the differential or relative amount by number at diameter d and $C_N(d)$ is the cumulative distribution by number. Using the values in the table, the calculated CV is 6.3%, a little smaller than the batch-to-batch range given by the manufacturer of 8-15%.

Table III: Run #9 using DLS showing diameter, d, differential number, GN(d), and cumulative percent by number, CN(d).

d(nm)	$G_N(d)$	$C_N(d)$
3.99	0.00	0.00
4.21	0.00	0.00
4.45	45.90	14.92
4.70	80.88	41.21
4.97	100.00	73.72
5.25	57.63	92.46
5.54	23.20	100.00
5.86	0.00	100.00
6.19	0.00	100.00

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In Figures 2 & 3 are shown the plots of differential intensity & number, respectively, for Run #9.

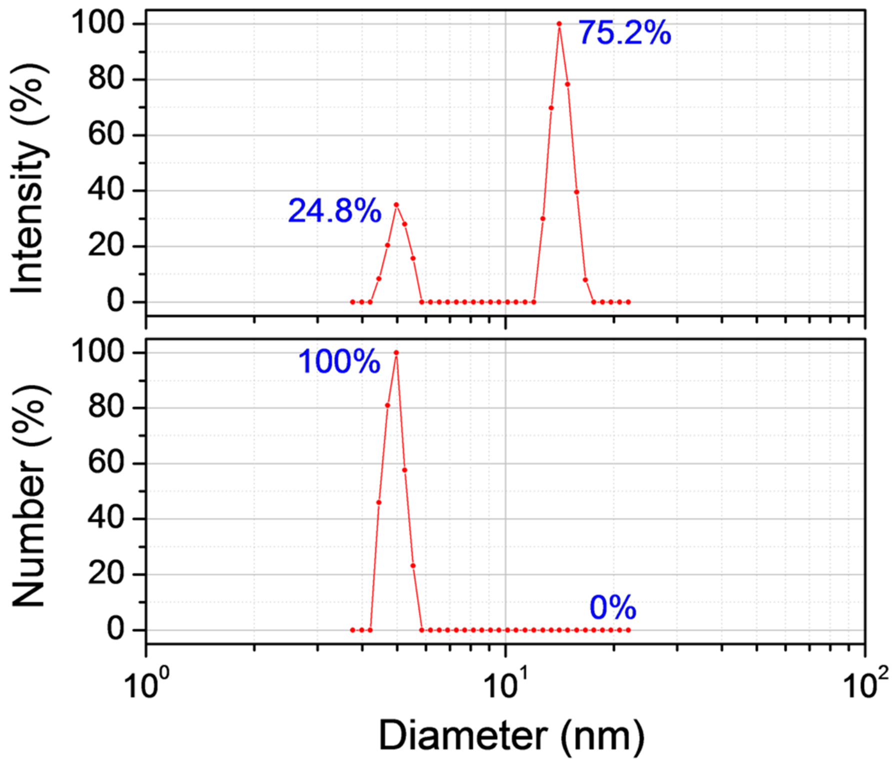

Figure 2: 5 nm Au Run#9, intensity-weighted

Figure 3: 5 nm Au Run#9, number-weighted

Summary

While image analysis like TEM is okay for determining particle shape, it is not good at the statistics needed for particle size distribution analysis. DLS looks at tens of thousands of particles and more in the scattering volume and avoids the statistical problem inherent in single particle counters. Furthermore, even a relative few multiplets such as the trimers in this Au nanoparticle sample are evident in the intensity-weighted size distribution but represent so few by number that the single peak at 5 nm left in the number-weighted distribution is in excellent agreement with expectations.

References

[1] nanoComposix Inc., 4878 Ronson Court, Suite K, San Diego, California 92111, USA, info@nanocomposix.com.
[2] D.E. Koppel, *J. Chem. Phys.*, **57**, 4814, 1972
[3] Craig F. Bohren & Donald R. Huffman "Absorption and Scattering of Light by Small Particles", Wiley, 1998
[4] "Handbook of Optical Constants of Solids", E.D. Palik, editor, Academic Press, 1985, page 294.

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