

approximately 7.6. This corresponds to a DNA-SWCNT calibrated length, via equation (6) of 1090 nm. The average length measured via AFM (amplitude image shown) for this fraction is 960 nm with a standard deviation of the mean (SDOM) of 35 nm, indicating that length separation is both occurring, and that the lengths can be sufficiently described by the DNA-SWCNT calibration. The small discrepancy in length for this specific fraction may be due to the small amount of chirality sorting apparent in the spectra, which would enhance the apparent optical length. The imaged fraction was collected from the top layer of the separation. This layer includes all lengths that have traveled that distance as the meniscus prevents the longest SWCNTs from traveling farther. This effect is the primary source of the polydispersity visible in the AFM. The photograph shows the color of the solution for the spectra shown.

**[0085]** FIG. 6 shows the SWCNT length versus distance traveled for the investigation detailed in FIG. 3. The lines are calculated length versus distance curves for the SWCNTs using equation (4). The measured velocity indicates an effective diameter of approximately 6 to 13 nm for the SWCNT plus its surfactant shell, assuming that the effective buoyancy difference,  $\Delta\rho$ , is independent of the iodixanol concentration, and the equilibrium density value of  $1055 \text{ kg/m}^3$  is used for ( $\rho_{\text{SWCNT}}$ ). Such a value for the effective diameter could indicate that either the effective buoyancy of the SWCNTs varies with the iodixanol concentration, or that the presence of the iodixanol molecules increases the length scale of the surfactant structure around each SWCNT. A combination of the two effects is also a possibility. This finding may indicate that the iodixanol molecule is functional in producing the buoyant density shell around the nanotube. An interesting effect notable in FIG. 6 is the sharp sigmoidal shape of the data. This effect is not noted for short time separations (as seen in FIG. 4), and is not captured by the first order theory given above.

**[0086]** Specifically, referring to FIG. 6, the theoretical SWCNT displacement calculated as a function of the nanotube length is illustrated assuming a value of 4, 5, or 6 nm for the effective radius and the following parameters:  $\Delta\rho=83 \text{ kg/m}^3 \gg \Delta\rho_{\text{SWCNT}}$ ,  $\eta=0.002 \text{ kg/ms}$ , and  $G=40\,000 \text{ g}$ . Translational diffusion can be shown to be unimportant for this calculation. Error bars in length represent 10% of the of the projected length value due to uncertainty in the slope of equation (5). The uncertainty in the distance traveled is approximately equal to the point size. The curves likely do not overlap the data exactly due to unaccounted for phenomena, such as additional frictional drag from the sedimentation of the polymer, failure of the slender body approximation for shorter SWCNTs, possible relative alignment of longer SWCNTs due to motion or a sedimentation potential or surfactant driven effects (which could introduce a sigmoidal functionality to the theoretical curve), vibration driven mixing during the centrifugation, and the use of a non-optimal fixed angle rotor for the separation.

**[0087]** It is important to note that the length separation results presented here do not conflict with the results of Arnold et al. Given a proper density gradient above the injection layer, the separation will run to the point at which the tube densities approach the local density within the gradient. In this situation  $\Delta\rho_{\text{SWCNT}} = (\rho_{\text{SWCNT}}) - \rho_{\text{SWCNT},i}$  becomes important and the SWCNTs fractionate by chirality. For length separation, the key is to exploit the transient motion regime, not the regime in which buoyancy equilibrium is approached.

**[0088]** In summary, ultracentrifugation can be used to separate single wall carbon nanotubes by length. In this experiment, approximately 0.25 mg of dispersed CoMoCat SWCNTs were sorted by length in each of the identically prepared 15 mL centrifuge tubes, demonstrating that mg scale separation is easily obtainable. Additional investigations described below, explore a switch to a swinging bucket rotor to provide a theoretically optimal geometry for the separation, as well as additional parameters of the separation. As noted by Arnold et al., commercial centrifuges are available that can handle 0.5 L or more, while generating  $G>150\,000 \text{ g}$ , creating a strong potential for scale up.

**[0089]** In a second set of trials, the following were investigated.

**[0090]** Materials: Cobalt-molybdenum catalyst method (CoMoCat) (S-P95-02 Grade, Batch NI6-A001, Southwest nanotechnologies), SG grade CoMoCat (SG-000-0002, Southwest Nanotechnologies), high pressure carbon monoxide decomposition (HiPco) (Batch 286, Carbon Nanotechnologies Inc.), and laser ablation (NASA-JSC soot #338 and NanoPower Research Labs soot # NPRL-299) SWCNTs were dispersed in aqueous solution using 2% by mass sodium deoxycholate surfactant (Sigma). SWCNT preparation consisted of sonication (tip sonicator, 0.64 cm, Thomas Scientific) of the SWCNT powder loaded at  $(1.0 \pm 0.1) \text{ mg/mL}$  in the 2% surfactant solution for 1.5 h in approximately 32 mL batches immersed in an ice water bath and tightly covered at approximately 30 W of applied power.

**[0091]** Post-sonication: Each suspension was centrifuged at 21,000 g in 1.5 mL centrifuge tubes for 2 hours, or 35,000 g for 2 h in 13 mL centrifuge tubes, and the supernatant collected. The resulting rich black liquid contains primarily individually dispersed SWCNTs.

**[0092]** Density modified solutions were generated by mixing the appropriate surfactant or SWCNT solution with iodixanol, (5,5'-[(2-hydroxy-1-3 propanediyl)-bis(acetylamino)] bis [N,N'-bis(2,3dihydroxy)propyl-2,4,6-triiodo-1,3-benzenecarboxamide]), purchased as Opti-Prep™ (Sigma) and 2% by mass sodium deoxycholate solution; all percentages listed for iodixanol solutions are for percent mass. Appropriate dilutions were additionally made where specified. For the experiments, the density of the layers was chosen such that  $\Delta\rho \gg \Delta\rho_{\text{SWCNT}}$  in the starting layer and for 5 cm above. A dense underlayer was also included. These liquid layers were performed by careful layering in either (17 or 38.5) mL centrifuge tubes (Beckman-Coulter #344061, #355631 respectively), with the center of the SWCNT layer defined as  $z=0$ .

**[0093]** Ultracentrifugation: A Beckman-Coulter L80-XP ultracentrifuge with a swinging bucket SW.32 Ti rotor was used with either the SW-32 or the SW-32.1 bucket sets, depending on the experiment, for the length separation and post-fractionation concentration of like fractions; a VTi.50 vertical rotor was additionally used for concentration of some fractions and further purification by diameter. In length separation experiments, the total volume separated was scaled with the inner diameter of the chosen centrifuge tube, such that for either SW-32 (38 mL) or SW-32.1 (17 mL) buckets, equivalent separation and fractions based on the distance traveled were achieved and collected. In the larger buckets, the typical preparation contained 24 mL of liquid in four layers: 1 mL of 40% iodixanol, 1 mL of 30% iodixanol, 2 mL of 20% iodixanol containing the SWCNTs, and 20 mL of 18% iodixanol in the top layer. All layers contained 2%