Electronic Supplementary Material (ESI) for Chemical Science

SUPPLEMENTARY INFORMATION

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1. General materials and methods

Gold tetrachloroauric acid ($HAuCl_4$), ethylene glycol were purchased from Sigma-Aldrich, trisodium citrate from and borate buffer tablets (pH 9.2) from Fisher Scientific. All the chemicals were used as received without further purification. A 2 mM solution of $HAuCl_4$ (78.8 mg, 0.2 mmol, 100 mL) in ethyleneglycol was used as stock solution and diluted to the corresponding concentration employed in each experiment. Trisodium citrate was dissolved in miliQ water to yield a 4 mM solution. Borate buffer was prepared following standard procedures.

UV-Vis spectroscopy. On-line spectra were acquired employing a AvaSpec2048 spectrometer from Avantes, a DH-2000 light source from Ocean optics and a Z-shaped flow cell (10 mm pathlength). The solutions were also controlled off-line for consistency using a Jasco V670 spectrophotometer.

Dynamic Light Scattering. A Nano Zetasizer from Malvern equipped with a continuous-flow cell (ZEN0023) from Hellma Analytics was employed to characterise ‘on the fly’ the particle size distribution. Typically, 13 measurements were averaged in each measurement cycle. This process was repeated 3 times. The flow cell dimensions are 35x12.5x12.5 mm. At the flow rates employed for DLS measurement (0.5 mL min^{-1}), the linear velocity in the measurement point is 0.053 mm s^{-1}.

Transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) was performed on a FEI Tecnai TF20 instrument fitted with a field emission gun and operated at 200 keV. TEM samples were prepared by dropping the nanoparticle-containing ethylene glycol solution onto an amorphous carbon coated grid and allowing the solvent to evaporate. TEM data were obtained and processed using either Digital Micrograph or IMAGEJ 1.41 software.

2. Synthesis of nicotinamide derivatives

Isonicotinoyl chloride was purchased from Sigma Aldrich. Octylamine and Octadecylamine were purchased from Lancaster. All reagents were used as received. Isonicotinoyl chloride (2.5g, 141.5 g/mol, 0.018 mol) was suspended in 100 mL of $CHCl_3$. A solution of the corresponding amine (0.9 eq.) and Et_3N (4.5mL,0.032 mol, 1.8 eq.) in CH_3Cl was added dropwise at room temperature. After 3 hours stirring at room temperature the solution was filtered, washed with H_2O, dried over $MgSO_4$, evaporated and dried under and recrystallised in EtOAc. White needle shaped crystals were obtained.

N-octadecylisonicotinamide: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.67 (dd, *J* = 4.4, 1.7 Hz, 2H), 7.52 (dd, *J* = 4.4, 1.7 Hz, 2H), 6.21 – 5.97 (m, 1H), 3.39 (dd, *J* = 7.1, 1.2 Hz, 2H), 1.56 (s, 2H), 1.53 – 1.15 (m, 30H), 0.81 (t, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 165.50, 150.63, 141.89, 120.79, 40.30, 31.94, 29.70, 29.54, 29.37, 29.29, 26.97, 22.70, 14.13. ATR-IR: 663, 673, 716, 731, 758, 849, 868, 896, 993, 1065, 1132, 1155, 1220, 1231, 1281, 1312, 1347, 1373, 1409, 1473, 1493, 1537, 1598, 1633, 2845, 2861, 2871, 2928, 2954, 3060, 3304. Mass spec: $[M+H]^+$ 375.1. E. analysis calc. (%) C, 76.95; H, 11.30; N, 7.48. Found C, 78.33; H, 11.46; N, 7.55. m.p. 99 ˚C Isolated yield (34%).

N-octylisonicotinamide: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.77 (dd, *J* = 4.4, 1.7 Hz, 2H), 7.62 (dd, *J* = 4.4, 1.7 Hz, 2H), 6.21 (s, 1H), 3.50 (td, *J* = 7.2, 5.9 Hz, 2H), 1.66 (dt, *J* = 14.8, 7.4 Hz, 2H), 1.56 – 1.18 (m, 10H), 0.92 (dd, *J* = 9.2, 4.6 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 165.49, 150.63, 141.89, 120.78, 40.29, 31.77, 29.54, 29.24, 29.18, 26.96, 22.63, 14.07. ATR-IR: 673,716, 731, 758, 849, 896, 993, 1065, 1132, 1155, 1220,1281, 1312, 1347, 1409, 1473,1493, 1537,1598, 1633, 2845, 2861, 2871, 2928, 2954, 3060, 3304. Mass spec: $[M+ H]^+$ 235.07. E. analysis calc. (%)C, 71.76; H, 9.46; N, 11.95. Found C, 71.54; H, 9.53; N, 11.86. m.p. 70 ˚C. Isolated yield (28%).

3. Details of experimental set-up

Figure S1 shows the experimental rig employed in this work. A set of programmable syringe pumps (C3000 Tricontinent) were employed to flow the solutions through the system. A linear flow set-up was designed employing 1/8” FEP tubing and a 6-way connector from Omnifit fitted with check valves. After mixing, the fluid was passed through a CEM Discovery microwave chamber equipped with a flow cell. This was employed as a tubular reactor with U-shape (volume = 0.7 mL). A bubble trap was employed after the reactor. Afterwards was connected to a FIA-Z-SMA flow cell (Figure S2). A NanoZS DLS was equipped with a flow cell from Hellma Analytics. Finally, the products were automatically collected employing a Gilson FC204 fraction collector.

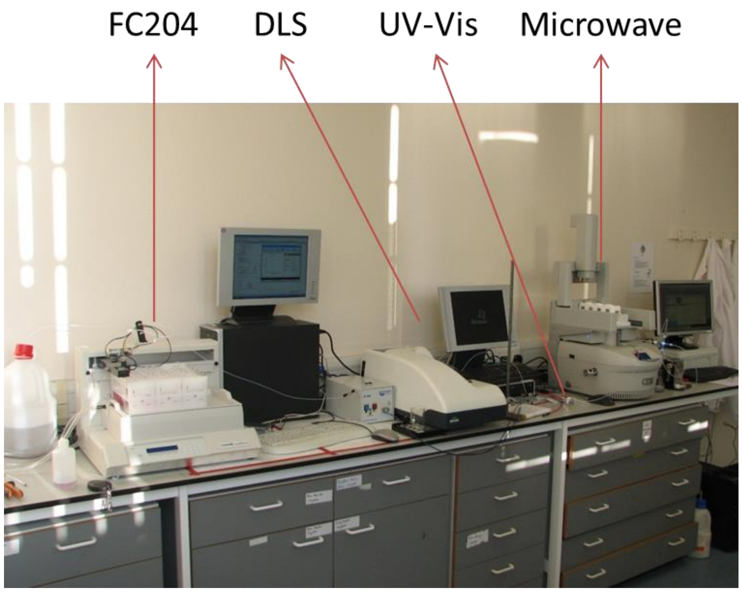
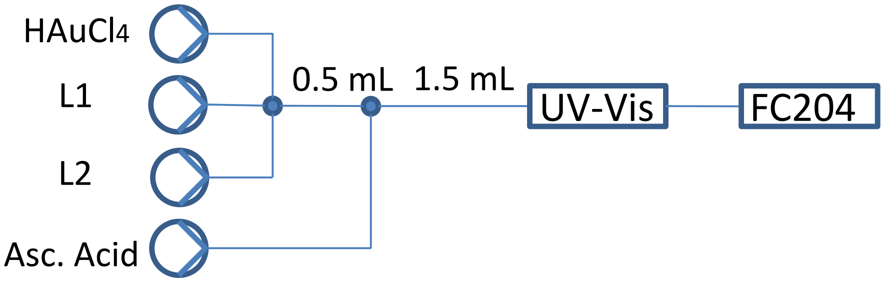


Figure S1. Image corresponding to the experimental set-up employed. From left to right it is shown the CEM Discovery microwave unit, UV-Vis flow-cell, DLS and fraction collector.

Figure S2. Detail of the UV-Vis and DLS flow cells.

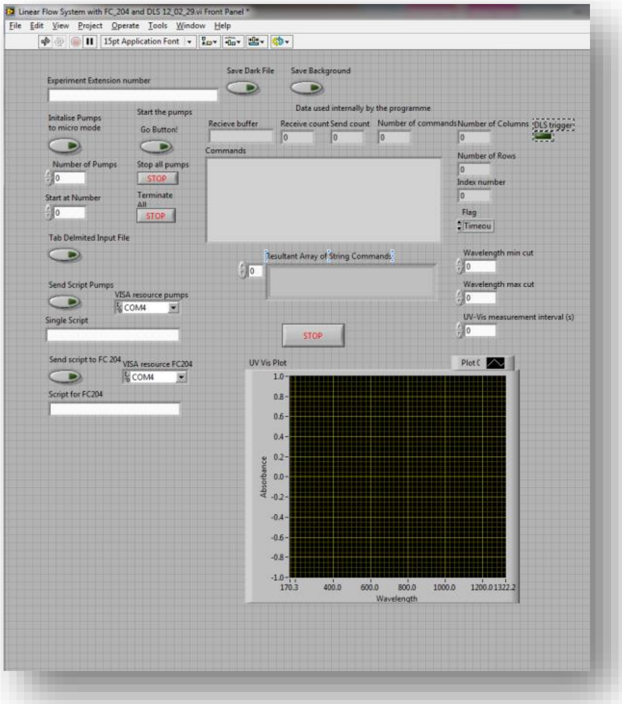
The set-up employed for the discovery of the hyperbranched nanoparticles was built employing PTFE tubing (1/16” OD, 1 mm ID) connected with standard fittings to the pumps and to a 4-way and 3-way manifold according to Scheme 1.



Scheme 1. Representation of the set-up employed for the discovery of hyperbranched Au nanostructures

4. LabView interface

The pumps, UV-Vis and fraction collector were controlled with LabView. DLS was triggered externally and the CEM Discovery was programmed with its own software. Figure S3 shows the in-house developed VI employed in this work.



Number of Pumps: 0
Start at Number: 0
VISA resource pumps: COM4
VISA resource FC204: COM4
Receive count: 0
Send count: 0
Number of commands: 0
Number of Columns: 0
Number of Rows: 0
Index number: 0
Flag: Timeou
Resultant Array of String Commands: 0
Wavelength min cut: 0
Wavelength max cut: 0
UV-Vis measurement interval (s): 0

Figure S3. LabView based programme developed in this work.

5. LSPR observed from an uncoated reactor

Initial results showed λ_{max} values between 550 and 560 nm and a high dispersion can be observed. After ca. 150 minutes , the plasmons of resonance observed dropped, suggesting the formation of a Au layer covering the surface of the tube. This extent was visually confirmed when the microwave chamber was open.

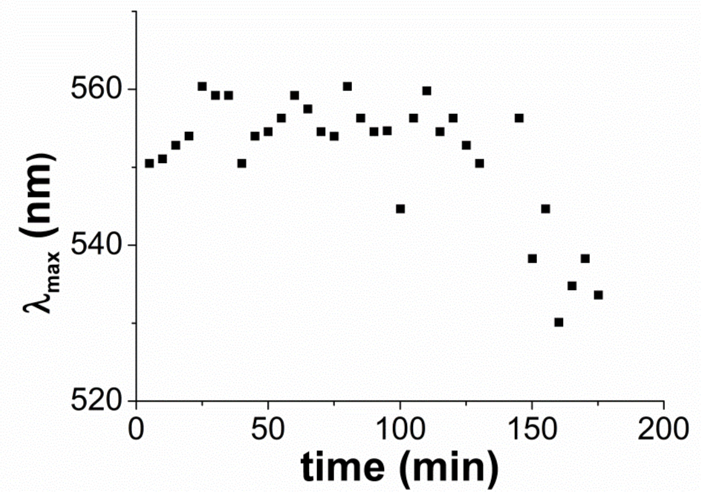


Figure S4. LSPR as a function of time in the synthesis of AuNPs under flow conditions emplying MW and an uncoated tube.

6. SAM coating of reactor walls

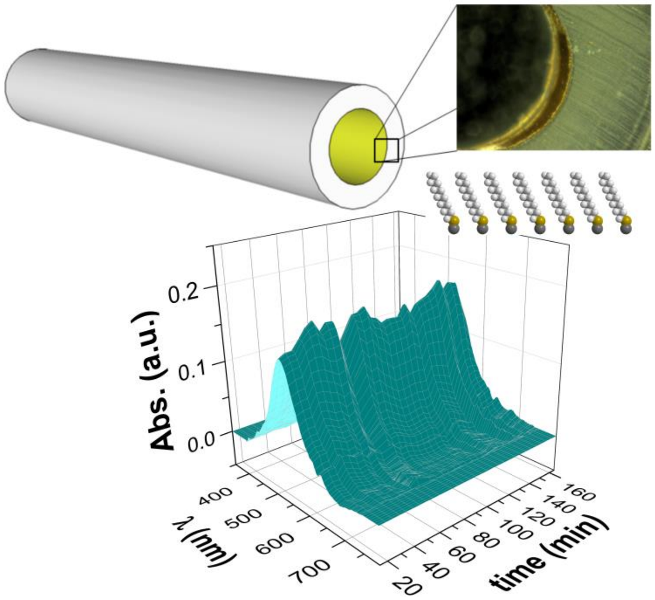


Figure S5. Coating of the reactor walls with a SAM based on dodecanethiol.

7. Comparison of particle size distribution by flow DLS and TEM.

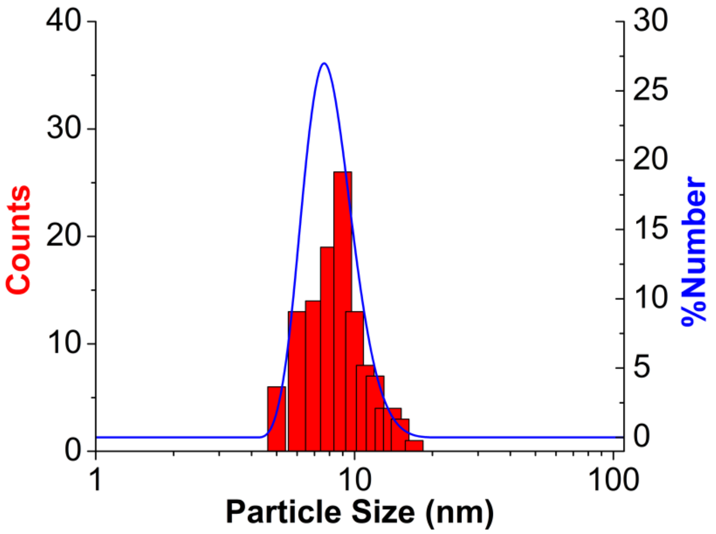


Figure S6. Comparison between the results obtained by flow DLS

8. Stability of nanoparticles

The nanoparticles synthesised under optimised conditions (F. rate 0.5 mL min^{-1}, residence time 1.4 min., T = 90 ℃) were stable for more than a month, as evidenced by the absence of change in the extinction spectra.

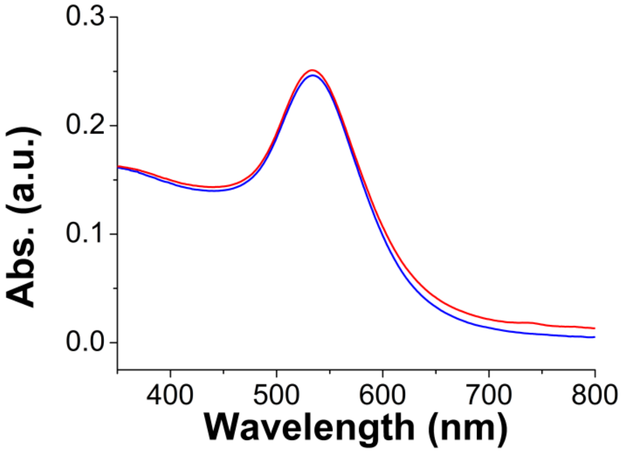


Figure S7. UV-Vis spectra corresponding to the synthesised nanoparticles. Red line correspond to the nanoparticles after the synthesis and blue line after one month stored at room temperature.

9. Aggregation of nanoparticles

The reduction in the thickness of the stabilizing double layer produces the aggregation of the synthesised nanoparticles. This was characterised by means of UV-Vis, DLS and verified by TEM. Figure S5 shows a typical UV-Vis obtained, where the extinction spectra from the nanoparticles at 530 nm is strongly reduced, while a new broad band appears at 712 nm.

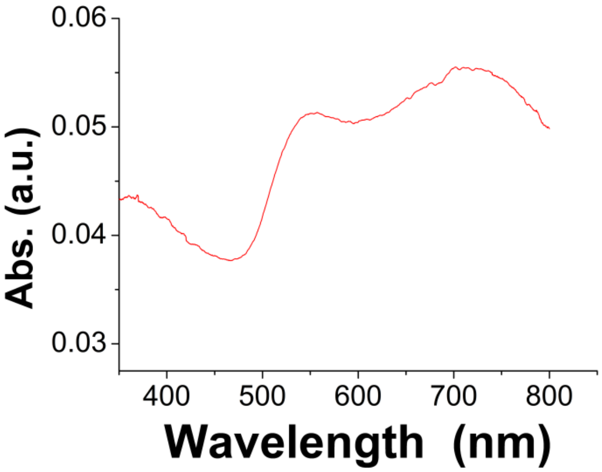


Figure S8. UV-Vis spectrum of the synthesis of AuNPs in a high ionic strength medium. Extinction at 532 nm is strongly reduced and a new mode appears at 712 nm.

TEM confirmed the presence of aggregates in the solutions.

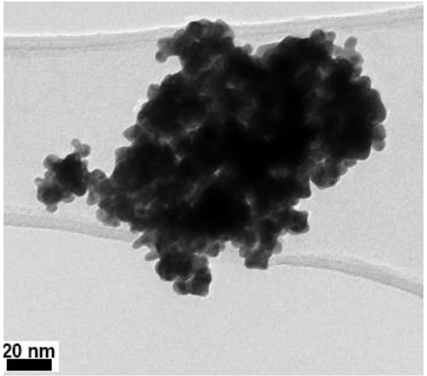


Figure S9. TEM confirms the presence of aggregates.

10. Flow rate effect and non-equilibrium synthesis

A variation in the flow rate has a profound impact on the nanoparticles formed. Figure S10 shows the maximum of absorbance as a function of the residence time in the in-line measurement and 2 hours after fthe synthesis. S11 left shows the extinction spectra of the nanoparticle solutions obtained at different flow rates, ranging from 0.25 to 1.5 mL min^{-1}.

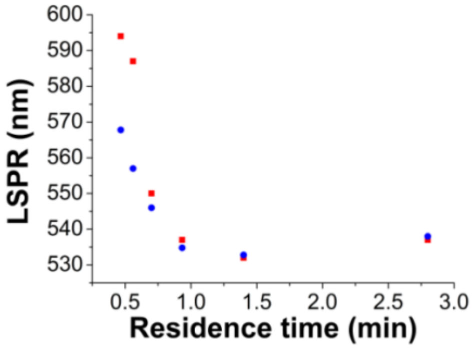


Figure S10. Non-equilibrium conditions in the synthesis of nanoparticles at low residence times. Red squares correspond to the in-line measured spectra. Blue circles correspond to the spectra acquired 2 hours after the end of the experiment.

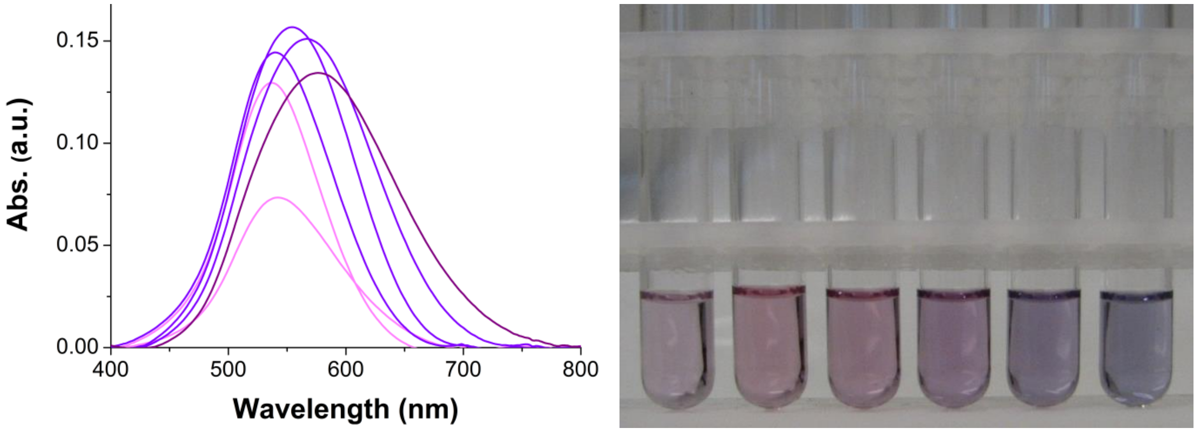


Figure S11. Left: Plot of the UV-Vis spectra obtained at different flow rates. Right: Image corresponding to the collected samples.

As the flow rate increases, the residence time decrease. The differences can be visually observed, with a colour change from light pink to violet as residence time increases (Figure S11, right).

11. Morphology of synthesised nanoparticles.

The nanoparticles were of crystalline nature, as evidenced by HRTEM. Figure S12 shows details about the polycristallinity of the synthesised nanomaterials.

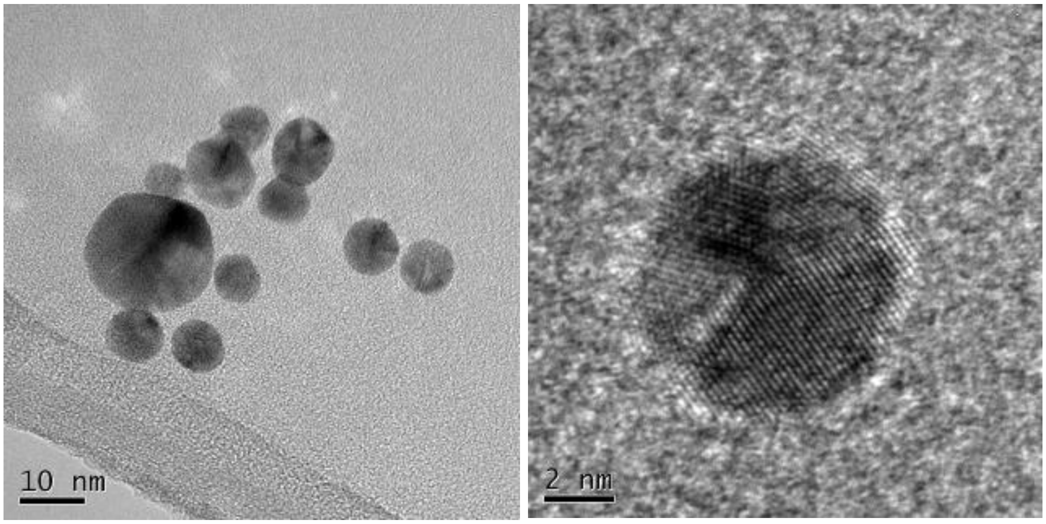


Figure S12. a) TEM image of spherical particles b) HRTEM image of a spherical particle, showing crystal defects.

12. Temporal stability of hyperbranched nanostructures

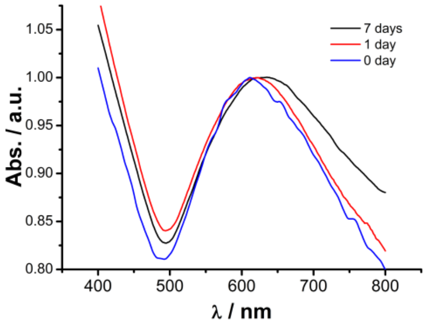


Figure S12. Extinction spectra of hyperbranched nanoparticles as a function of time.