Towards automation of the polyol process for the synthesis of silver nanoparticles

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Metal nanoparticles have a substantial impact across different fields of science, such as photochemistry, energy conversion, and medicine. Among the commonly used nanoparticles, silver nanoparticles are of special interest due to their antibacterial properties and applications in sensing and catalysis. However, many of the methods used to synthesize silver nanoparticles often do not result in well-defined products, the main obstacles being high polydispersity or a lack of particle size tunability. We describe an automated approach to on-demand synthesis of adjustable particles with mean radii of 3 and 5 nm using the polyol route. The polyol process is a promising route for silver nanoparticles e.g., to be used as reference materials. We characterised the as-synthesized nanoparticles using small-angle X-ray scattering, dynamic light scattering and further methods, showing that automated synthesis can yield colloids with reproducible and tuneable properties.

Metal nanoparticles (in the following abbreviated to NPs) find many applications in medicine and technology1,2. Generally, synthesis routes of NPs strive to achieve a high level of control over size, shape, polydispersity and at the same time try to limit the extent of aggregation or agglomeration. In addition, the long-term stability and the rheological properties of such dispersions are of importance2–5. Problems with reproducible particle synthesis and colloidal stability have limited the availability of nanoparticle-based reference materials to comparatively few, despite of repeatedly demanded provision of nanoscale reference materials for environmental, health and safety measurements for many years4. The physicochemical aspects of NPs constitute complex requirements, determining the usability for a particular application. The various NP systems, often conceptually related to each other, exhibit different and unique challenges, when it comes to their synthesis, and hence the expected results. In this regard, silver NPs (Ag NPs) are difficult to synthesize, especially if tunability, long-term stability, and reproducibility are required4,7,8. This contrasts with Au NPs, for instance, which have recently become a “poster child” for a controllable and straightforward synthesis5, a distinct size regulation and the realization of predicted nanoparticle sizes is state of the art6. Nevertheless, Ag NPs are in high demand due to their well-known anti-bacterial properties and their use in catalysis, photochemistry, sensing, and optoelectronics6–9. Therefore, synthesis routes for Ag NPs that deliver spherical particles of less than 20 nm in diameter and low polydispersity are of importance.

One such promising route, described by Kästner and Thünemann11, is based on a polyol process published by Hu et al.8. In this synthesis, Ag NPs are formed from the reduction of Ag+ ions in the presence of polyacrylic acid (PAA) in hot ethylene glycol (EG), where EG provides both the solvent and the reducing agent. This synthesis route delivers spherical NPs with a mean radius of 3.0 nm and a radii distribution width of 0.6 nm12. The nanoparticles are stabilized in an aqueous solution by adjusting the pH of the solution to 10, thereby creating a negatively charged PAA shell. Consequently, the particles remain unchanged in a suspension for over six months. Additionally, the polyacrylic acid changes the nucleation mechanism by preventing growing particles from agglomeration and fusion and thus restricts the growth solely to an incorporation of monomers from a solution8. These properties suggest that such Ag NPs could constitute potential reference materials (RMs) for the quantification of the size distribution and concentration of nanoparticles17. RMs need to fulfil the criterion of long-term stability14, normally verified by time-consuming experiments using procedures standardized internationally by ISO GUIDE 35, for example13. These entail storing samples for a certain amount of time (at least six month) and checking for deterioration over that period. For nanoparticle samples dispersed in a liquid phase, this criterion is especially hard to achieve due to sedimentation, potential biological activity, and aggregation. In

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the case of RMs, long term stability could constitute a severe issue if adjustments to the synthesis are required. For example, modification of particle size by a slight change in the procedure, could have adverse and unpredictable effects on the stability. Moreover, in practice RMs are often prepared in bulk quantities with the intention of long-term storage exceeding the period of six months, either by the supplier or customer. This creates a risk of an unintentional expiration of the material under variable and ill-defined storage conditions.

Faster development of reference materials and circumventing these problems could be enabled by rapid on demand synthesis by an automated platform. Such an approach should reduce the need for a long shelf-life. In addition, fast, automated, and controlled synthesis in small batches would allow for more targeted testing of physicochemical properties, and thereby faster convergence on desired properties. In a classical laboratory approach, it is far less time-consuming to create one large batch and perform a full characterization on this system, compared to preparing several small batches distributed over time. This is mainly because of the potential effort required to run multiple syntheses with the required precision and level of reproducibility (i.e. the human factor). Single, large batch synthesis is likely to be problematic if the sample stability is unknown, which could potentially lead to substantial amounts of expensive materials to be wasted if an out-of-specs product is produced. Also, smaller batches benefit from better mixing and less temperature gradients in the reaction solution potentially improving uniformity of acquired materials.

Here, we conceptualize and implement an automated synthesis of Ag NPs using the polyol route to produce colloidally stable silver. In pursuing the automated synthesis of nanoparticles, the capabilities of the “Chemputer” are deployed, for the first time, into the field of inorganic chemistry. The Chemputer is a modular, automated platform developed by the Cronin group for execution of multi-step, solution based organic synthesis, including purifications. Liquids can be transferred across a backbone, constructed from HPLC selection valves and syringe pumps. The Chemputer operates in a batch mode, common laboratory devices, such as heaters and glassware like round bottom flasks, are connected to the backbone, forming reaction modules. Solutions can be manipulated in these modules, and as all operations are controlled through a software script, reproducibility among individual syntheses is high. Likewise, any adjustments of the synthesis conditions, if required, are straightforward to implement and are documented in the reaction log file and a code versioning system.

Methods

Synthesis—general considerations. The synthesis of the silver nanoparticles was performed using a Chemputer platform. All chemicals were used as received: AgNO₃ (PanReac, for analysis), ethylene glycol (PanReac, puriss), polyacrylic acid (Sigma-Aldrich, molar mass \( M_w = 1800 \) g/mol, ca. 25 monomer units per polymer chain), NaOH (Sigma-Aldrich), deionised water was taken from in-house Milli-Q system. The synthesis was adapted from Ref. 11. Prior to synthesis, all glassware and PTFE-coated stirring bars were thoroughly cleaned with aqueous nitric acid (30% wt.) and rinsed with deionised water (DI, MilliQ, 18 MΩ). Unless stated otherwise, all steps were conducted in a fully automated manner using the Chemputer. An overview of the synthesis and purification steps can be found in Fig. 1. Before the start of the synthesis, the elements of the Chemputer’s backbone (syringes, valves, and tubing) were cleaned with 5 mL of nitric acid (30% wt.) by pumping it through the transfer paths and the reactor (round bottom flask), followed by 6 transfers of water (5 mL for each transfer) to remove any remaining acid. We also note here that nitric acid should be disposed of into a separate waste container to avoid contact with organic solvents. The transfer paths were subsequently dried by pumping volumes of 5 mL of dry air five times to remove acetone. In our experiments, we had target radii of ~3 and 5 nm for which we used silver nitrate precursor concentrations of 33.4 mg/mL and 136.6 mg/mL, respectively. The specific reaction conditions are summarised in Table 1. A solution of polyacrylic acid in ethylene glycol (12.5 mL) was transferred within ~ 120 s to a 3-necked flask equipped with a PTFE stirring bar. Under stirring (400 rpm), the solution was heated to 210 °C. When the temperature was reached, a solution of AgNO₃ in ethylene glycol (2.5 mL, for concentration see Table 1) was, due to its viscosity, slowly aspirated, transferred and then added rapidly (3 s) to the heated solution together with

![Figure 1. Schematics of the overall synthesis and purification processes of herein described silver nanoparticles.](https://example.com/fig1.png)
air (7 mL) to ensure quantitative addition (accounting for the tubings’ dead volume). After 5 min, the colour of the solution had turned amber, changing to a deep brown over the following minutes. 15 min after addition, the heating was stopped, and the solution was left to cool to room temperature (25 °C), as was measured by a Pt100 thermocouple. After ambient temperature was reached (~1 h), water (34 mL) was added, and the stirring stopped. The nanoparticle synthesis on the Chemputer took 4 days per batch. It should be noted that the synthesis takes 5 h, while the rest of time was spent on decanting in 24-h-intervals. This long waiting interval was necessary due to slow sedimentation. The contents of the flask were transferred to narrow beakers (50 mL, 4 cm diameter) and left to sediment. After 24 h, the supernatant was manually removed, the beaker refilled with 34 mL of DI water, and the sediment was redispersed. This routine was repeated two times, and after decanting for the third time we refilled the beaker with only little water (6.4 mL). Finally, an aqueous solution of NaOH (0.4 mL, 1% wt.) was added. After mixing, the opaque, brown suspension cleared to a dark, greenish-black solution.

The as-obtained nanoparticles were further characterized by transmission electron microscopy, X-ray and light scattering methods, as described below.

**Synthesis—software and hardware implementations.** The nanoparticle synthesis diagram required by the Chemputer is presented in Fig. 2. The diagram is directly rendered from a GraphML file (XML-based, see SI: file included). The file represents all the reactant solutions, glassware, devices etc. and their topology/connections indicated by arrows. Each object depicted in Fig. 2 contains metadata, which are read by the Python API (the “Chempiler”) to run the Chemputer (Fig. 2). The synthesis conditions are defined in the previous section and Table 1, based on which we present their implementation in the code (steps I–VI). Below, we describe the consecutive functional steps, while the actual Python code snippets are shown in the SI.

Step (I) Before the synthesis, tubing connecting reservoirs and pumps must be filled with reagents, to guarantee reproducible volume transfers. Potential glycol and acetone residues are then washed away with water thoroughly, followed by washing the backbone tubing with nitric acid (30%). Nitric acid residues are washed away with water, water is washed away with acetone and acetone is dried of with air transfers (SI: Snippet 1).

Step (II) The as-prepared platform can be used for synthesis. First transferring polyacrylic acid in glycol to the reactor, followed by transferring air to empty the tubing path. The backbone is cleaned again as described above, heating and stirring of the reactor is started, and once the temperature is reached, the solution of silver nitrate in glycol is added (SI: Snippet 2).

Step (III) To ensure quick and complete addition in one portion, the reactor syringe is charged with the solution and additional 7 mL of air as headspace. The syringe then is discharged into the reactor at maximum speed (3 s for the 2.5 mL of solution) (SI: Snippet 3).

Step (IV) After a waiting time of 15 min, the heating is stopped, and the reactor left for cooling to room temperature (SI: Snippet 4).

Step (V) Upon reaching room temperature, a specific volume of water is added, and the same volume removed after 24 h, decanting facilitated by adjusting the level of the tubing end (SI: Snippet 5).

Step (VI) The resulting suspension is diluted with water and the pH manually adjusted by adding NaOH (SI: Snippet 6).

**Characterisation.** Small- and wide-angle X-ray scattering (SAXS/WAXS) measurements were conducted using the MOUSE (Methodology Optimization for Ultrafine Structure Exploration) instrument. X-rays were generated from a microfocus X-ray tube, followed by multilayer optics to parallelize and monochromatize the X-ray beams to a wavelength of Cu Ka (λ = 0.154 nm). Scattered radiation was detected on an in vacuum Eiger 1 M detector (Dectris, Switzerland), which was placed at multiple distances between 137 and 2507 mm from the sample. Samples and backgrounds were measured in flow-through capillaries. The resulting data were processed and scaled to absolute intensity using the DAWN software package in a standardized complete 2D correction pipeline with uncertainty propagation. The data was fitted and analysed using the program McSAS, a Monte Carlo method for fitting SAXS data (Table 2; SI). We used the assumption that the Ag particles were spherical in shape, and the scattering length densities (SLDs) used for the fits were SLDwater = 9.4691 × 10−6 Å−2, SLDag = 7.7854 × 10−5 Å−2. As the intensity is expressed in absolute units, the resulting size distributions are also absolute in terms of calculated volume fractions.

Dynamic Light scattering (DLS) was measured on a Malvern Instruments Zetasizer. Sample solution (10 µL) was diluted with an aqueous solution of NaOH (pH 10) to 1 mL. Measurement was performed at 25 °C in

| Experiment code | cAgNO3 (mg/mL) | VAg,thermol (µL) | cPA A (mg/mL) | Target radius (nm) |
|-----------------|----------------|-----------------|---------------|-------------------|
| NP3_I           |                |                 |               |                   |
| NP3_II          | 33.4           | 5.06            | 53.8          | 3                 |
| NP3_III         | 133.6          | 20.21           | 3            | 5                 |

Table 1. Synthesis conditions and values of the radii for the Ag nanoparticles.
ZEN0040 disposable cuvettes (Malvern Instruments) after an equilibration time of 120 s under a scattering angle of 173° (backscatter condition), automatic measurement duration, 5 measurements and 1 s inter measurement delay time. The data were collected and automatically processed using Zetasizer Software version 8.

For TEM measurements, 1 mL of sample, directly after synthesis and before pH adjustment was sedimented with a small benchtop centrifuge (a = 100 G), 0.9 mL of the supernatant was removed, 0.9 mL of water was added, and the sediment was redispersed. This was repeated for 7 times to remove ethylene glycol and other solutes. The sample was diluted with 4 mL of Milli-Q water, 10 µL added onto the copper grid (3 mm holey carbon-coated Cu-grid (Lacey Carbon, 400 mesh)) and after drying, cleaned in a plasma cleaner for 15 s. Bright field electron microscopy (TEM) images were obtained on a Talos F200S Microscope (Thermo Fisher Scientific) operating at 200 kV equipped with a Ceta 16 M camera.

Powder X-ray diffraction (XRD) patterns from dried NP3_I and NP5_I samples were collected on a D8 Bruker Diffractometer equipped with a LYNXEYE XE-T detector operating in a Bragg–Brentano geometry (reflection

| Experiment code | R (nm)       | S (nm)       | f            | C (mg/mL)   | Rg (nm)      | sh (nm)     | Yield       |
|-----------------|--------------|--------------|--------------|-------------|--------------|-------------|-------------|
| NP3_I           | 3.34 ± 0.01  | 0.81 ± 0.20  | 2.0 x 10^−4 | 2.09 ± 0.054| 7.59 ± 0.83 | 2.33 ± 0.73 | 0.3153      |
| NP3_II          | 3.37 ± 0.01  | 0.83 ± 0.21  | 2.2 x 10^−4 | 2.30 ± 0.060| 8.80 ± 0.92 | 2.92 ± 0.83 | 0.3463      |
| NP3_III         | 3.36 ± 0.01  | 0.85 ± 0.25  | 2.2 x 10^−4 | 2.35 ± 0.061| 7.82 ± 0.64 | 2.55 ± 0.49 | 0.3547      |
| NP3_IV          | 3.52 ± 0.01  | 0.99 ± 0.25  | 2.1 x 10^−4 | 2.18 ± 0.057| 6.91 ± 0.83 | 1.89 ± 0.52 | 0.3286      |
| NP5_I           | 5.26 ± 0.01  | 1.33 ± 0.17  | 1.2 x 10^−4 | 12.50 ± 0.325| 11.39 ± 0.40| 3.99 ± 0.38 | 0.4709      |
| NP5_II          | 5.35 ± 0.01  | 1.65 ± 0.13  | 1.1 x 10^−3 | 10.99 ± 0.29 | 12.75 ± 0.69| 5.44 ± 0.49 | 0.4147      |
| NP5_III         | 5.33 ± 0.01  | 2.13 ± 0.35  | 1.4 x 10^−3 | 14.27 ± 0.37 | 15.79 ± 1.31| 9.05 ± 1.25 | 0.5381      |
The as-derived volume-weighted radii are an average from, typically, > 10 measurements collected over several
ences among the samples are minor (see the overlapping curves from NP3-series in Fig. 3H), which confirms a
within the experimental uncertainties (Fig. 3A–D). This clearly indicates that the statistically significant differ-
size-distributions were obtained under the assumption that particles were represented by simple spherical form
factors, which we based on TEM images (see SI: Fig. S1). In this regard TEM imaging does not provide sufficiently

to extract the size distributions of Ag NPs, but is necessary to confirm their shape, which is an
important assumption for SAXS data fitting. The scattering patterns from all four runs exhibit a very small spread
in Ref. 20), it turns out that the upturn is expected, due to the instrumental background at these levels of intensity.
the data points have relatively small uncertainties for the NP5 series. These upturns might therefore superfi-
by a factor of > 2. DLS measures hydrodynamic size of particles, which in our case includes the size of Ag NPs
and a standard deviation of the distribution of ~ 0.8 nm, where the total volume fraction of particles is ~ 0.2%
(Table 2; complete reports generated by the McSAS are included in the SI: Supporting Files). The distributions
are overlaid in SI: Fig. S2 for a better comparison.

In the second series of experiments (Tables 1 and 2; NP5: I-III) our goal was to modify the synthesis so
that ~ 5 nm NPs would be obtained. We chose the value of 5 nm to check how accurately we could control the
reaction. Under the assumption that all the other reaction conditions were kept constant, the ~ (5/3) increase
in radius implied the cubic increase in the required concentration of silver (Table 1; ~ 4.2 times). Please note
that these were approximate conditions since we had not known the size distributions of our NP3 series a
priori. Under these assumptions, we performed three syntheses, and the resulting scattering curves are shown in
Fig. 3E–G. As in the case of NP3, the resulting NPs were unaggregated, but exhibited relatively higher polydispers-
ity (SI: Fig. S2). On average the particle mean radius was ~ 5.3 nm, but a standard deviation of the distribution
 ranged from ~ 1.3 to 2.1 nm, depending on a run (Table 2; Fig. 3; NP5). It is important to note, that both the NP3
(Fig. 3A–D) and NP5 series SAXS curves (Fig. 3E–G) exhibit upturns in the profiles for q < 0.04 nm⁻¹, where
the data points have relatively small uncertainties for the NP5 series. These upturns might therefore superfici-
ally point to the presence of very minor populations of larger species or aggregation. However, if we compare the
measured intensities against the low-q instrumental background level of our SAXS instrument (see Fig. 4
in Ref. 20), it turns out that the upturn is expected, due to the instrumental background at these levels of intensity.

All the particles from NP3 and NP5 series were also characterised using DLS (Table 2; Fig. 4; SI: Fig. S3).
The as-derived volume-weighted radii are an average from, typically, > 10 measurements collected over several
days (up to 6 days) on samples extracted from each batch. The DLS data, in general, correlate with those from
SAXS, but the measured radii from light scattering are systematically larger than those measured by the X-rays,
by a factor of > 2. DLS measures hydrodynamic size of particles, which in our case includes the size of Ag NPs
as well as the PAA shell which provides colloidal stability. Hence, the DLS measurements indicate that we deal
with core–shell NPs of sorts. The absence of this shell in SAXS and TEM (SI: Fig. S1) indicates that it is possibly
highly hydrated and hence of very low electron density and not persistent upon drying and in the case of TEM,
plasma cleaning (see Methods). Arguably, depending on a point of view, such a PAA shell may not be considered
a shell (in the sense of core–shell NPs), as it has a possible liquid-like dynamic character and is not an integral
part of the NPs. This PAA coating, however, is crucial for providing long-term colloidal stability of the NP5s.

Regardless of the physicochemical classification of the “shell” we can still evaluate the thickness of the PAA layer
at the surface of the NPs, from the juxtaposition of the mean values of the hydrodynamic radii from DLS and
NP5’s radii from SAXS (Table 2). In the case of the NP3 series the PAA layer was 4.4 ± 0.8 nm thick, while for the
NP5 series it was 8.0 ± 2.2 nm. The measured values of the shell thickness for the NP3 series are lower than those
reported for the analogous series in Ref. 11, where the layer was found to be ~ 7 nm. However, considering the
widths of the size distributions (i.e. standard deviations in Table 2) the difference is quite insignificant.

Two selected samples from each series, NP3_I and NP5_I were also characterised with XRD. In this case
the samples were deposited and dried on silicon wafer holders and formed thick films. The diffraction patterns
are shown in the SI (Fig. S4). The XRD confirmed that the NPs were crystalline, and that elemental Ag was the
only crystalline phase present. The size of the NPs is clearly manifested by peak broadening (FWHM), where
5.3 nm NPs yield narrower reflections in comparison with the 3.3 nm counterparts (see for instance 111 peak
in SI: Fig. S4). From the fitted peak profiles we evaluated crystallite size, which were 2.2 ± 1.0 nm for NP3_I, and
5.6 ± 3.8 nm for NP5_I. These values correctly represent the expected trends and agree within the uncertainties
with the SAXS data. This indicates that the NPs are single-crystalline in nature.

In overall, from the presented measurements it is evident that the automated synthesis with the Chemputer
delivers NPs of expected specifications in terms of size distributions. Since all the SAXS measurements are scaled
Figure 3. SAXS scattering profiles from NP3 and NP5 (see also Tables 1 and 2). Scattering profiles and selected fits using a polydisperse sphere model, where the corresponding size distributions were derived using a Monte Carlo method implemented in McSAS; (A)–(D) NP3_I-IV; (E)–(G) NP5_I-III; (H) comparison of all the profiles from NP3 and NP5 series on an absolute intensity scale.
to absolute units, the resulting volume-weighted size distributions are also absolute. Hence, the total volume fractions of Ag NPs can be easily expressed as a concentration of silver in the analysed samples (Table 2). By finding the ratio of these measured concentration values and the initial reactant concentrations (Table 1), we calculated the overall yields of each run (Table 2). Based on these data, one can see that for NP3 series the yields were from 30 to 35%, while for the NP5 series the values were higher ranging from 41 to 53%. The spreads of yields within and the different ranges of yields between the series, resulted from the decanting procedure (see Methods: Synthesis—software and hardware implementations, Step 5; SI: Snippet 5). This step involved removal of the supernatant from above of the sedimented suspension of the NPs. Although it was performed with the Chemputer, it involved estimation of the position of the interface between the two phases. The simplest approach to automated decanting was to adjust the PTFE tubing to be suspended above the level of sedimented particles (~ 5 mm). For determining the tubing level, at least one synthesis should be performed and the tubing visually adjusted. The lack of feedback on potential particle removal was, however, problematic as is evident from the values of yield. Approaches more amenable to automation like ultrafiltration could be included, potentially improving this purification step. Moreover, the automated titration with NaOH could be possible, however the Chemputer is tailored towards larger volumes > > 1 mL and working with smaller volumes would require further modification of the setup. We must point out, however, that the described above limitation is not so much relevant for the automated synthesis of reference materials in which the size distribution and long-term stability are the major quality criteria. Presented automated synthesis could also help in investigations of antibacterial and antifungal properties of silver nanoparticles. As has been shown already for this synthesis, the particles provide access to a ‘blank’ silver surface, one of the prerequisites for antibacterial properties. Thanks to an extensive and standardized purification, there are hardly any free silver ions present, which restricts the antibacterial activity to the particles themselves. In combination with the size control and reproducible synthesis this could enable cross-checking of the results and allow for studying of antimicrobial properties in a more comparable fashion.

Outlook. The used process employs a polyol, such as ethylene glycol, as solvent and reductant at the same time. By heating the polyol and injecting silver ions dissolved in ethylene glycol, polyol is oxidized to aldehydes and carboxylic acids, reducing the silver ions to Ag in turn. Parameters such as the reaction time, polyol viscosity or temperature are variables that control synthesis and the final properties of Ag NP, most notably, shape, size, and their distributions. For instance, an increase in reaction time also broadens the size distribution of the particles, which essentially is not desirable. Similarly, another possibility is to tune the viscosity, by either employing a more viscous polyol or by polymeric additives. The herein employed synthesis used polyacrylic acid of defined molecular weight as a polymeric additive, which also stabilizes the as-obtained colloid by charged surface capping the particles. Viscosity tuning, however, requires changing reactants, which may affect the mechanisms of NP formation, and in the case of automated synthesis requires different stock solutions and adjustment of synthetic procedures for the custom target.

In our approach we followed the hypothesis that size is controlled by availability of silver ions. Under this assumption, particle size follows a cubic relationship to the amount of reduced silver. This is approximated, because of the possible reverse oxidation of silver from Ag. Therefore, under this assumption, e.g. to double the radius of the NPs, the dissolved silver concentration would need to be increased eight-fold. In experimental terms, we injected 2.5 mL of Ag-bearing EG solution into 12.5 mL of hot EG with PAA (see Methods), hence the increase in silver concentration could be effectively achieved either by increasing the concentration of the silver solution, or, as a compromise, by increasing the volume of this solution. Both approaches have their advantages and disadvantages. On the one hand an increase in the concentration may be limited by the solubility of silver.
nitrate in EG, but at the same time it reduces the need for the direct addition of large volumes of silver-bearing solutions, which are added to the large volume of hot EG. Larger addition volumes could negatively impact the stability of temperature (210 °C) of the reaction solution, broadening the time range of seed creation, effecting the resulting NP size distribution. On the other hand, the increase in silver concentration (i.e., a fixed volume) also increases the kinetic rates of the reaction and consequently increases the nucleation and growth rates. As a result, the NPs are larger, but they also exhibit broader size distributions, in comparison with their smaller counterparts. This is indeed what we observed for the NP3 and NP5 series (Tables 1 and 2; Figs. 3 and 4) in which the concentration of silver was a variable. Hence, for either of the strategies, we would expect a broader size distribution for larger NPs, but the extent of this effect may differ. Moreover, the ratio of the concentration of the polymer to silver ions is one of the most important factors determining the size distribution of the nanoparticles. Therefore, the increase in nanoparticle size cannot solely be attributed to an increased concentration of silver ions but is also connected with a lower ratio of the surfactant to silver ions.

Conclusions
In conclusion, we described an automated synthesis of silver nanoparticles to produce adjustable monodisperse particles. The nanoparticles where thoroughly characterized by SAXS, DLS, TEM and XRD. The approach is an important first step towards the automation of nanoparticle syntheses in a modular, multipurpose automation platform. The modularity of the Chemputer opens many possibilities for the synthesis of a variety of different nanoparticle morphologies and sizes and potentially more complex structures. These advances and further work can help in the general investigations of silver nanoparticles by supplying a reliable and reproducible method of their synthesis and removing tacit knowledge by significantly reducing the experimental bias.

Data availability
All the data are included in the main, the Supplementary Information and at Zenodo.org.

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