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Pd$_{12}$M$_n$L$_{24}$ (for $n = 6, 8, 12$) nanospheres by post-assembly modification of Pd$_{12}$L$_{24}$ spheres†

Eduard. O. Bobylev, Leonardo Passerini, Felix J. de Zwart, David A. Poole, Simon Mathew, Martina Huber, Bas de Bruin and Joost N. H. Reek

In this contribution, we describe a post-assembly modification approach to selectively coordinate transition metals in Pd$_{12}$L$_{24}$ cuboctahedra. The herein reported approach involves the preparation of Pd$_{12}$L$_{24}$ nanospheres with protonated nitrogen donor ligands that are covalently linked at the interior. The so obtained Pd$_{12}$L$_{24}$ nanospheres are shown to be suitable for coordinative post-modification after deprotonation. Selective formation of tetra-coordinated M$^8$ in Pd$_{12}$M$_n^8$L$_{24}$, tri-coordinated M$^8$ in Pd$_{12}$M$_n^8$L$_{24}$ nanospheres and two-coordinated M$^8$ in Pd$_{12}$M$_n^8$L$_{24}$ nanospheres is achieved as a result of different nitrogen donor ligands. A combination of pulsed EPR spectroscopy (DEER) to measure Cu–Cu distances in the different spheres, NMR studies and computational investigations, support the presence of the complexes at precise locations of the Pd$_{12}$M$_n^8$L$_{24}$ nanosphere. The general post-assembly modification methodology can be extended using other transition metal precursors or supramolecular systems and can guide precise formation and investigation of novel transition metal-complex containing nanospheres with well-defined composition.

Introduction

Inspired by the importance of self-assembly processes found in natural systems, supramolecular chemistry has evolved as a strategy to generate functional large molecular objects. In this context, a wide variety of polyhedral coordination cages and nanospheres with the general formula M$_n$L$_{2n}$ $n$ being 2, 3, 4, 6, 8, 9, 10, 12, 24 and 30 have been reported. Most of these symmetrical structures can be described as Platonic or Archimedean type solids which are formed from the square-planar complexation of metal ions with ditopic pyridine linkers, most often based on palladium. Next to the highly symmetrical nanospheres, lower symmetry analogues based on two different ditopic ligands can be formed, provided that the ligands are complementary in geometry. In the same manner, more complex structures have been reported such as stellated and “pregnant” cuboctahedra. Whereas most nanospheres reported are based on one type of metal center for the construction of the structure, supramolecular nanospheres bearing two different metals also emerged quite recently. Construction of bimetallic Archimedean solids has been mainly achieved by using non-symmetrical linkers, with preferred coordination to the corresponding two different metals used during the assembly process. In a typical procedure, the non-symmetrical building block is first coordinated to the first metal, obtaining a metal complex as the building block that is used in the next step for the formation of supramolecular nanospheres. If the coordination chemistry is sufficiently complementary, all three components can be mixed to yield the desired nanosphere in one step. Precisely formed nanospheres based on different metals can display stimuli responsive properties, for example by opening and closing mechanisms using a chemical signal, reminiscent of analogous metal triggered open-closing switches found in spherical capsids. Several [Pd$_x$M$_y$L$_z$] have been reported to have been prepared by a bottom-up approach, i.e., first preparation of ML$_z$ complex which is then used for sphere synthesis; however, there are only very few examples of a post-assembly modification approach. Compatibility issues between the first and the second coordination event complicate such strategies. Typically, the presence of ligands required for the formation of the coordination complex interferes with the sphere formation. Reported approaches can yield unique systems with interesting electrochemical, magnetic and sensing features. However, limitations are found when a certain number of metals need to be implemented inside of nanocages and not on the rim/frame making novel post-assembly modification techniques highly desirable.

In a post-assembly modification approach, polyhedral structures can be formed by classical design principles (Fig. 1). Furthermore, post-assembly modification...
approaches can be easily implemented into many known coordination-based systems, as the sphere-forming sides remain unchanged. Herein we describe a method for the selective formation of [Pd12M12L24], [Pd12M4L24] and [Pd12M4L24] nanospheres by post-modification of Pd12L24 nanospheres (Fig. 1). The reported procedure provides a new strategy for implementation of transition-metal complexes into supramolecular nanospheres. With our approach, we provide a general methodology for selective coordination post-modification of M12L24 nanospheres which potentially can be applied to other supramolecular systems or other ligand frameworks (e.g., phosphines and N-heterocyclic carbenes). The obtained nanospheres with specific amount of metals are anticipated to be useful for catalytic applications in which location and amount of M in a confined environment within nanospheres can be modified with unprecedented accuracy.

Results

With the goal to prepare nanospheres by self-assembly that can be used for coordinative post-modification, we started with design principles based on earlier reports. We envisioned a strategy of positioning protonated nitrogen donor ligands with dual functionality. The pKₐ values, that can be used for coordination chemistry after sphere formation. All building blocks were prepared according to standard organic procedures (as summarized in Section SI1).

Sphere synthesis

As such, the set includes a 4-dimethylaminopyridine (DMAP) (LDMAP), three pyrrolidine ligands (LPro, LProMe, L4ProMe), a dimethylamine (LDMNH₂) and an imidazole (LHIM) donor ligand (Fig. 2), next to the typical two pyridine functions needed for nanosphere formation. All four endo-functionalities represent well known nitrogen donor ligands with different pKₐ values, that can be used for coordination chemistry after sphere formation. For this purpose, all building blocks were protonated, using pyridinium tetrafluoroborate or pyridinium trifluoromethanesulfonate (Fig. 3A). After successful protonation, the resulting solutions were evaporated to dryness in vacuo to remove the formed pyridine. The resulting solids were dissolved in MeCN. Sphere formation was performed using the so obtained protonated ligands according to the following general procedure described explanatory for LDMAPH. To LDMAPH (10 µmol, 1 eq.) in MeCN-d₃ (1 mL), [Pd(MeCN)₄](BF₄)₂ (5.5 µmol, 0.55 eq.) is added and the solution is stirred for 24 h at room temperature. Analysis of the resulting solution shows a downfield shift of the pyridine...
In contrast to the above-mentioned building blocks, when LProMe was used under similar conditions, an ill-defined $^1$H-NMR spectrum was obtained, indicating that pure spheres were not formed. For this building block the difference in $pK_a$ between imidazole and pyridine is not sufficiently large for selective sphere formation. Alternatively, the sphere is formed which results in a $pK_a$ change similar to that observed for DMAP, leading to a more acidic imidazolium which is capable to protonate the pyridine sites of the building block, thereby decomposing the sphere.

### Coordinative post-modification

With five novel spheres in hand, the post modification procedure was explored by deprotonation of the encapsulated nitrogen donor ligands in the nanosphere and consecutive coordination to a metal ion/complex of choice. We decided to use cadmium and nickel as the metal for post-modification as analysis of the resulting structures with MS was expected to be straightforward. Keeping in mind the dynamicity of palladium-based nanospheres and the possible coordination of the inner ligands to palladium, all post modification experiments were performed at $-36 \, ^\circ\text{C}$ (as the nanosphere decomposes when the deprotonation is performed at room temperature, see Fig. S46 and S47†). At these low temperatures the exchange of the palladium–pyridine bond should be very slow. We first focused on post modification of $[\text{Pd}_{12}\text{LDMAPH}_{24}]$ as DMAP is known to be an excellent ligand for transition metals. First, 6 eq. of [Cd(OTf)$_2$(MeCN)$_4$] were added to a cooled solution of the $[\text{Pd}_{12}\text{LDMAPH}_{24}]$ nanosphere in MeCN, in line with an expected four to one coordination to Cd. Subsequently, 26 eq. of triethylamine were added to deprotonate the DMAP while keeping the solution at low temperature for 1 h. The solution was then
allowed to warm up to room temperature for 1 h and was analysed using various analytical techniques (Fig. 4A). The $^1$H-NMR spectrum suggests that the nanosphere remains intact as the position of the pyridine signals remain similar ($9 \text{ ppm}$) (Fig. 4B). Moreover, the simplicity of the $^1$H-NMR spectrum (with single position of the pyridine signals remains similar ($9 \text{ ppm}$) (Fig. 4B). DOSY NMR shows that the nanosphere has a similar diffusion coefficient as before the post modification, suggesting the structure did not change much in size (ca. $5.0 \text{ nm}$ before post-modification; ca. $4.6 \text{ nm}$ after post-modification with Cd; Fig. S49†). ESI-MS analysis displayed signals corresponding to different charged species of $[\text{Pd}_{12}\text{Cd}_{6}\text{DMAP}_{24}(\text{OTf})_{36}]^{n+}$ for $5 \leq n \leq 13$ (Fig. S50†). Importantly, the MS spectra did not contain any signals that could be attributed to nanosphere structures with a different palladium/cadmium stochiometry. The combination of all analytical techniques provides good support for the selective post modification of the DMAP containing palladium assembly to incorporate exactly 6 cadmium ions.

When an identical procedure was performed using $[\text{Ni(BF}_4)_2(\text{MeCN})_4]$ as a precursor, ESI-MS analysis displayed signals only corresponding to different charged species of $[\text{Pd}_{12}\text{Ni}_{6}\text{DMAP}_{24}(\text{BF}_4)_3(\text{MeCN})_{18}]^{n+}$ for $8 \leq n \leq 19$ (Fig. 4C). Due to the paramagnetic character of nickel, all DMAP signals were no longer visible in the $^1$H-NMR spectrum as a result of coordination to paramagnetic Ni. The outer proton signals remain visible (although somewhat broader, Fig. 4B) and are located at similar shifts as found for the nanosphere structure before the post-modification. The presence of the sphere was further supported by DOSY NMR which displayed a similar diffusion coefficient as for the cadmium analogue ($\log D^\text{Ni} = -9.6$; $\log D^\text{Cd} = -9.54$), providing evidence that the developed technique is not only applicable for cadmium but also for nickel.

Next, we studied the post modification of $[\text{Pd}_{12}\text{LProH}_{24}]$ using the same methodology. A similar protocol for post modification was used, in which different equivalents of cadmium were added to a cold solution of $[\text{Pd}_{12}\text{LProH}_{24}]$ (Fig. S62 and S63†). $^1$H-NMR showed no changes of the sphere framework protons after the addition of cadmium, suggesting that the spherical structure remains intact (Fig. S62 and S63†). The DOSY spectrum shows that the species has a similar diffusion as before coordination to cadmium (before and after modification $d = 4.4 \text{ nm}$, Fig. S63†). MS analysis of the cadmium containing sphere and sphere precursor was not successful, which we attribute to difficulties in MS analysis already for the parent nanocage $[\text{Pd}_{12}\text{LProH}_{24}]$. As MS analysis is required for identification of metal–metal stochiometries, we focused on the alkylated variant of the nanocage $[\text{Pd}_{12}\text{LProMeH}_{24}]$ for post modification. After initial attempts using different amount ($6, 8, 12 \text{ eq.}$) of cadmium for the post modification of $[\text{Pd}_{12}\text{LProMeH}_{24}]$ in analogy to the DMAP containing nanocage (Fig. 5A), we observe from MS analysis that 8 cadmium complexes are in cooperated into the nanosphere. Therefore, we performed the post modification by addition of 8 eq. of $[\text{Cd(OTf)}_2(\text{MeCN})_4]$ to a cooled solution of $[\text{Pd}_{12}\text{LProMeH}_{24}]$, followed by addition of base. The so obtained mixture displays presence of the nanosphere (similar shifts of framework in $^1$H-NMR and DOSY, Fig. 5B). MS analysis of the solution provides evidence that only nanocage of the composition $[\text{Pd}_{12}\text{LProMe}_{24}\text{Cd}_8]$ is formed after applying our protocol (Fig. 5C). In analogy, also nickel can be in cooperated as supported by equivalent analysis techniques (although $^1$H-NMR and DOSY are broader due to the paramagnetic nature of Ni) (Fig. 5B, S67 and S68†).

Because the sphere containing $\text{LNMMeH}$ has a short length between sphere forming site and nitrogen donor after post-modification, we performed the post-modification of $[\text{Pd}_{12}\text{LNMMeH}_{24}]$ with 12 eq. of $[\text{Ni(BF}_4)_2(\text{MeCN})_4]$. $^1$H-NMR showed signals typical for the nanosphere indicating it again remains intact after the post modification (Fig. S74†). The DOSY spectrum supports that the sphere remains of the same size, displaying only one species in solution with a similar diffusion coefficient as the starting material ($d = 4.2 \text{ nm}$ before functionalization; paramagnetic DOSY after modification $d = 5.0 \text{ nm}$). MS analysis showed the sphere being intact (Fig. S76†).

Fig. 4 (A) Post-modification of $[\text{Pd}_{12}\text{LDMAP}_{24}]$ with Ni$^{2+}$ and Cd$^{2+}$. (B) $^1$H-NMR of the self-assembly before (middle) and after (top and bottom) post-modification; (C) measured ESI-MS spectra of $[\text{Pd}_{12}\text{Ni}_{6}\text{DMAP}_{24}]$ (inset: top, measured spectrum; bottom, simulated).
However, only signals of nanospheres with protonated and deprotonated ligands were observed, and nickel coordination could not be confirmed by MS analysis. We anticipate that the formed nickel complexes via the amine ligands are too labile.

**Extension of the scope**

After the post-modification with nickel and cadmium, we wondered if our post-modification procedure is also applicable to other transition metals. In a small exemplary scope we post-modified [Pd_{12}L_{24}] nanospheres with two different first row transition metals such as Cu(BF$_4$)$_2$ and Co(BF$_4$)$_2$(H$_2$O)$_6$. The two investigated metals formed selectively the M$_6$Pd$_{12}$L$_{24}$ nanospheres when the same procedure was applied, as supported by MS analysis (Section SI3†). Relatively broad $^1$H-NMRs and inconclusive DOSY were obtained due to the paramagnetic character of the applied metals. Next to those bimetallic nanospheres, also one nanospheres containing three different metals [Pd$_{12}$L$_{24}$Cd$_6$Ni$_n$]$_2$ (for n = 0–4) was prepared using a mixture of [Cd(O Tf)$_2$(MeCN)$_4$] and Ni(O Tf)$_2$. In this experiment, a statistic distribution of the two metals is obtained with the total number of Cd and Ni being 6 (see ESI for details, Fig. S79–S82†).

Finally, also [Rh(COD)(MeCN)$_2$(BF$_4$)] was used for post-modification (Fig. 6A). The rhodium precursor requires only two extra ligands for formation of a tetracoordinated complex, as the COD occupies the other sites. As such, 12 of these transition metals can theoretically coordinate via post-modification of [Pd$_{12}$L$_{24}$] the [Pd$_{12}$Rh(COD)$_{12}$L$_{24}$] nanosphere was selectively formed as supported by $^1$H-NMR, DOSY and MS analysis (Fig. 6B and C).

**Kinetic properties of the post modified nanospheres**

After having established post-assembly modification techniques for the incorporation of a different number of transition-metal complexes into Pd$_{12}$L$_{24}$ nanospheres, we studied briefly the properties of the so formed complexes. In particular, we were wondering if the incorporated complexes behave differently from the molecular analogues. As we expected the rim of the nanocage to act as an extended linker between the inner nitrogen donors, we anticipated the inner nitrogen donors to act like multi-dentate ligands (opposed to monodentate, highly dynamic ligands without the nanosphere). To investigate our hypothesis, we followed the stability of [Pd$_{12}$Cd$_6$L$_{24}$] over the course of 24 h at 300 K using $^1$H-NMR with mesitylene as an internal standard (Fig. 7B). During the course of the experiment, all chemical shifts remained the same (quantity and position), indicating that the nanocage with internal Cd(DMAP)$_4$ complexes is stable. In contrast to that, when...
a molecular Cd(DMAP)₄ complex is added to a model nanosphere ([Pd₁₂L₂₄OBn]) (Fig. 7A), we observe quick decomposition of the nanosphere. Therefore, we conclude that whereas molecular Cd(DMAP)₄ complexes are highly dynamic in nature (leading to exchange with palladium corner stones), once implemented into the sphere through post-modification of [Pd₁₂LDMAP₂₄], the dynamics is significantly reduced (indicative of multidentate character of the inner nitrogen donors).

Localization of TMC within the nanospheres – metal ion-metal ion distance measurements

After establishing the precise formation of heterometallic nanospheres and supported a unique coordination environment around the internally formed complexes for [Pd₁₂LDMAPH₂₄Cd₈] and [Pd₁₂LProMe₂₄Cd₈], we wanted to identify the location of the interior complexes. Because growing crystals of the large self-assembled M₁₂L₂₄ spheres is challenging, we were not able to obtain suitable crystals for X-ray analysis. We therefore further studied the location of the transition-metal ions in the [Pd₁₂M₄L₂₄] and [Pd₁₂M₄L₂₄] nanospheres via their characteristic distances. Our post-modified nanospheres represent structures related to mathematical stellated cuboctahedra (e.g., Fig. 8A). Therefore [Pd₁₂M₄L₂₄], have defined distances between the inner metal-nodes M (1 or 2, Fig. 8A). In structure 1, all complexes are located in the six square windows of the nanosphere. In contrast, in structure 2, four complexes are located below a palladium center and two in the square windows (Fig. 8A). In order to support the location of the transition metal complexes M, we measured the Cu(n)–Cu(n) distances within the [Pd₁₂Cu₄LDMAP₂₄] nanosphere using EPR spectroscopy. First, regular EPR was recorded of [Pd₁₂Cu₄LDMAP₂₄] and [Pd₁₂Cu₄LPro₂₄] (Fig. S83 and S84†). Fitting of the obtained EPR spectra reveals as expected Cu(n) species with 4 surrounding nitrogen ligands (in the case of LPro, the 4th vacant site is occupied by acetonitrile). Furthermore, tetrahedral ligand orientation is observed, building the fundament for computational investigation (vide infra). Next, we used DEER (double electron electron resonance), a pulsed EPR method that is specific to the dipolar interaction of paramagnetic centers and thereby their distance.⁵⁹-⁶³ Although DEER is established and perhaps most well-known in the biochemistry field for nitroxide spin labels⁶⁴ it is used since 2003 to determine Cu(n)–Cu(n) distances in the nanometer range.⁶⁵-⁶⁷ For detailed information on the method, the setup and the analysis involved to obtain the distances, see Section SI5.† The DEER data show that [Pd₁₂Cu₄LDMAP₂₄] has two Cu–Cu distances (Fig. 8 B, red trace). A shorter distance, r₁, at 1.9 nm and a longer one, r₂, at 2.7 nm (Table 1). The intensity of the peak at r₂ is smaller than that of r₁. Validation with DEER analysis⁶⁸ shows that both peaks are essential to describe the data. The observed distances are compared to those based on the PM3 modeled (Table 1) structures 1 and 2 of [Pd₁₂Cu₄LDMAP₂₄] (Fig. 8 A). For Pd₁₂Cu₄LDMAP₂₄, the observed distances match the ones from PM3 model of both model 1 or 2 (with slight better fit for the longer distance of 1), supporting incorporation of six copper complexes inside the sphere. From soley distance measurements, a clear differentiation of the two possible structures 1 or 2 (Fig. 8A) is not possible. However, as we have shown, dynamic exchange of the coordinated DMAP is very slow inside the nanocage. The simple ¹H-NMR of the Cd containing nanocage suggest therefore, with is single set of DMAP signals, that all complexes experience the same chemical
environment. As depicted (Fig. 8A), only structure 1 provides the same chemical environment for the TSM located inside the nanosphere (i.e., all complexes are located in the square windows). Therefore, our analytical methods suggest the location of the TSM a post-assembly modification in the square windows (structure 1, Fig. 8A). To further support this, both potential structures 1 and 2 (Fig. 8A) were optimized in silico. To estimate the binding free energy of the copper ion (Cu\(^{2+}\)) we constructed a series of models representing association at the cross (Fig. 9A) Cu\(_1\)Pd\(_6\)(LDMAP\(_4\))(py)\(_{12}\) or square face (Fig. 9B) Cu\(_1\)Pd\(_4\)(LDMAP\(_4\))(py)\(_8\). The two model structures were first

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Table 1 Experimental and PM3 model-derived distance parameters obtained for Pd\(_{12}\)Cu\(_6\)(LDMAP\(_8\)) and Pd\(_{12}\)Cu\(_6\)(LPro\(_8\)). The DEER data were analyzed by means of Tikhonov regularization. \(\langle r \rangle\) is the center of the distribution distance in nm, \(S(r)\) the width, for details, see SI5 in ESI.
optimized with a GFN2-xTB Hamiltonian and analytical line-
arized Poisson–Boltzmann (ALPB) implicit solvation parame-
terized for acetonitrile. Afterwards, these optimized models
were used for molecular dynamics calculations with harmonic
restraints between the outermost Pd$^{2+}$ centers to preserve the
overall structure of the cage. In the specific cases of the in-
tersection binding site (Fig. 9A), Cu$_1$Pd$_5$(L$^{DMAP}$)$_4$(py)$_{12}$ and Pd$_5$(-
L$^{DMAP}$)$_4$(py)$_{12}$, the Pd$^{2+}$ center was not restrained. A total of 64
frames were extracted from the 1 ns molecular dynamics
trajectory for which the single-trajectory binding free energies
were computed from the single point energy difference for each
frame with and without Cu$^{2+}$ at a GFN2-xTB level of theory with
ALPB implicit acetonitrile solvation. We observe that the
binding of the copper ion in either of the two positions has non-
significant (ns*) difference in energy (Fig. 9B). However, the
structural changes at the ligand framework have significant
energetic penalty for the nanosphere (Fig. 9C). Whereas the
deformation of the nanocage remains relatively small when the
copper is located in the square windows (Fig. 8A, 1), a signifi-
cantly higher deformation penalty is observed when the copper
is located below the palladium (Fig. 8A, 2). Therefore, all
analytical methods (DEER, H-NMR) and theoretical calculations
support location of all transition metal complexes at the square
windows of Pd$_{12}$L$^{DMAP}$$_{24}$, suggesting that structure 1 (Fig. 8A)
is the most likely one.

For the [Pd$_{12}$M$_8$L$^{Pro}$$_{24}$], identification of the exact location
of M was found to be more complicated. The distance distribu-
tion of [Pd$_{12}$Cu$_4$L$^{Pro}$$_{24}$] has one broad peak centered at
1.8 nm, with a tail in the distribution that extends to approxi-
mately 3 nm (Fig. 10B, blue trace, Table 1). Because of short
evolution times (see S15†), for distances above 2.8 nm, the shape
of features in the distance distribution is not reliable. There-
fore, in [Pd$_{12}$Cu$_4$L$^{Pro}$$_{24}$], validation shows that the part of the
distance distribution from 2.2 nm to longer distances is not relia-
bility, i.e. the confidence interval (green shaded area) extends
as far as the baseline, showing that this part of the distance
distinction is not essential to fit the data. Also, for the [Pd$_{12}$-
Cu$_4$L$^{Pro}$$_{24}$] nanosphere the observed distance of 1.8 nm matches
rather well that of the PM3 calculated structure 2.0 nm (ex-
pected in both potential models of the nanosphere, 1 and 2,
Fig. 10A and Table 1). Next to this, also two longer distances at
2.8 and 3.4 nm are expected based on the calculated structure
for 1. Although the distribution (Fig. 10B) shows some intensity
in this distance region, such distances cannot be reliably
determined given the short evolution time of the DEER traces
(see S8†). Structure 2 (Fig. 10A) should also display a distance
of 2.4 nm in similar intensity as 2.1 nm. The missing of a feature
for 2.4 nm in the measurement, hints towards a higher proba-
bility of 1 over 2 for proline functionalized nanospheres. Due to
the broadness of the $^1$H-NMR, a certain determination of TSM
location was not possible without X-ray structure analysis.
However, missing features of 2 in the DEER measurement
provide support for structure 1 (Fig. 10A).

Conclusion
In summary, we described a new procedure for the selective
post-assembly modification of Pd$_{12}$L$_{24}$ nanospheres by metal
coordination. Pd$_{12}$L$_{24}$ nanospheres with different types of
protonated nitrogen-donor ligands within the interior can be
prepared, provided that a sufficient $pK_a$ difference exist between the
endo-functionality and the pyridines of the sphere forming
building block. The selective protonation protects the inner
nitrogen-donor ligands for coordination to palladium during
sphere formation. Novel spheres can be obtained bearing
exactly 6, 8 or 12 transition metal complexes after addition of
a second metal of choice and deprotection by deprotonation.
The post-assembly modification strategy used here on Pd$_{12}$L$_{24}$
assemblies establishes guidelines for post-modification of other
supramolecular systems, leading to new opportunities to make
materials with unique coordination motifs, compositions and
geometrical features. Given the specific number of metals
present in catalytic centers of enzymes, such as four copper
atoms in laccase, this methodology may enable to make more
precise models for such enzymes by selective formation of
nanostructures with a different number of metal centers at
a well-defined location. As such, these nanospheres provide an
exciting opportunity for further investigations.
Data availability

Data that support the findings of this study are present in the article and its ESI.† The corresponding author will provide additional data not available in these documents upon reasonable request.

Author contributions

Conceptualization: EOB, JNHR; formal analysis: EOB, LP, FZ, DAP; funding acquisition: JNHR, BdB, MH; investigation: EOB, LP, FZ, DAP, SM; supervision: JNHR; validation: EOB, LP, FZ, DAP, SM, MH, BdB, JNHR; visualization: EOB; writing – original draft: EOB; writing – review & editing: EOB, LP, FZ, DAP, SM, MH, BdB, JNHR.

Conflicts of interest

There are no conflicts to declare.

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