Supporting Information

Standardizing Size- and Shape-Controlled Synthesis of Monodisperse Magnetite (Fe₃O₄) Nanocrystals by Identifying and Exploiting Effects of Organic Impurities

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Figure S1. (A) Size distribution histograms and (B) characteristic lengths of monodisperse samples.

Figure S1 gives the size distribution histogram of the monodisperse samples cited in the paper. The characteristic length of each morphology is indicated by double arrow in (B).



Figure S2. Six batches of MNC prepared with the formula of Figure 1(D4). (a)-(f) 20 nm MNC cubes.

The formula with 1-octadecene (ODE) as solvent and benzaldehyde (BA) as additive is stable and efficient. Figure S6 shows 6 samples with the formula of Figure 1(D) (formula #28 in Table S1). The mean size (diagonal of the cube) is ~20 nm and size distribution is narrow enough to justify monodispersity.

Please see the attached AVI file.

Video S1. Animation of Shape Evolution Model of MNCs.

Please see the attached EXCEL file.

Table S1. Formulae List of All Cited Samples.

In Table S1, the mean reaction time is 90 min if not indicated otherwise. Set reaction temperature is 280 °C across all samples.

Peak #	Residence Time	Area %	ID	CAS #
1	5.65	1.92	Benzaldehyde	000100-52-7
2	10.26	91.71	Benzyl Ether	000103-50-4
3	10.73	1.75	Benzyl Benzoate	000120-51-4
4	11.49	0.97	Hexadecanoic Acid	000057-01-3

 Table S2. GC-MS Results of Naturally-oxidized benzyl ether.

Peak #	Residence Time	Area %	ID	CAS #
1	5.63	3.81	Benzaldehyde	000100-52-7
2	10.27	83	Benzyl Ether	000103-50-4
3	10.73	4.88	Benzyl Benzoate	000120-51-4
4	11.5	1.72	Hexadecanoic Acid	000057-01-3

 Table S3. GC-MS results of Artificially-oxidized benzyl ether.



Figure S3. TEM images of MNCs synthesized in BE and/or OBE. (a) Base case using fresh BE; (b) natural OBE; (c) 19 mL BE and 1 mL artificial OBE; (d) 17 mL BE and 3 mL artificial OBE; (e) 15 mL BE and 5 mL artificial OBE; (f) 20 mL artificial OBE; MNCs synthesized with ascending amount of TDD (g) 5.0 mmol; (h) 7.5 mmol, (i) 10.0 mmol. Scale bars equal 50 nm.

Benzyl Ether and Oxidized Benzyl Ether as Solvent. Figure S3 presents MNCs made in benzyl ether (BE) and oxidized benzyl ether (OBE). Blue labels, as shown in Figure S3, are employed throughout the manuscript for samples produced in fresh BE and/or natural/artificial OBE.

Fresh benzyl ether opened and stored in an argon-flushed glovebox yielded relatively polydisperse MNCs, Figure S3(a). However, when benzyl ether was naturally oxidized in the atmosphere, the resulting MNCs exhibited narrower size distribution and a mean diameter ~13.2 nm, Figure S3(b). Though the natural oxidation of BE during storage may

improve the monodispersity of the product MNCs, the level of reproducibility and control provided by natural aging of the solvent is limited. Thus, a simpler means of achieving the same results, while also providing a clearer understanding of the origin of this phenomenon, was needed.

To quantify and control the oxidation, fresh BE was bubbled with dry compressed air at \sim 50 °C to prepare artificially OBE. GC-MS results, Table S2 and Table S3, indicate that natural OBE and artificial OBE have similar composition with slight variations of major components. The artificial OBE was then tested as an additive to tune the synthesis of MNC. Representative results are presented in Figure S3(c), (d), (e), and (f), in which 5%, 15%, 25%, and 100% of the fresh BE was replaced with artificial OBE to tune the synthesis. Following the established approach in the literature,¹ these experiments all employed 1,2-hexadecanediol (HDD), oleylamine (OAm), and oleic acid (OA) (see Materials and Methods for details). With 1 mL OBE added to 19 mL fresh BE, the resulting MNCs, Figure S3(c), bear a high resemblance to the MNCs produced using fresh BE, Figure S3(a). When the added OBE was increased to 3 mL, the result, Figure S3(d) was similar to that produced using natural OBE, Figure S3(b). At this point, the natural OBE's influence on the resulting MNCs is properly simulated with artificial OBE. To further explore the potential of artificial OBE as an additive, we increased the OBE content to 5 mL. The resulting MNCs were extremely uniform in size and formed a hexagonal superlattice spontaneously, Figure S3(e). Using 20 mL of artificial OBE as the solvent (replacing 100% of the fresh BE) produced much larger faceted MNCs, Figure S3(f) and Figure S7.

The experiments described above employed 5 mmol of 1,2-hexadecanediol (HDD). In an effort to reduce the cost of each experiment and elucidate the effect of diol size, we replaced HDD with shorter and less expensive 1,2-tetradecanediol (TDD) for subsequent experiments. With a shorter hydrocarbon chain, the TDD is somewhat less effective in passivating the MNC surface, and thus we re-optimized the diol concentration. The volume of artificial OBE was set as 5 mL while the amount of TDD was varied to tune the morphology. With 5 mmol TDD, the MNCs, Figure S3(g), were larger in average size than those produced under the same conditions with HDD, Figure S3(d). They were also quasi-cubic, with large {100} planes and small {111} planes. Using 7.5 mmol TDD, Figure S3(h), produced MNCs with cubic morphology of ~20.0 nm. The size and monodispersity in this case were similar to the result obtained using HDD, Figure S3(e), but the morphology was different, with predominantly {100} planes, rather than {111} planes bounding the MNC surface. Further increase of the TDD to 10 mmol produced smaller and relatively polydisperse MNCs, Figure S3(i).



Figure S4. TEM images of MNCs synthesized in mixtures of BE, BA, and BB. Compared to the base case shown in panel (d), the variable(s) changed were (a) 7.5 mmol TDD; (b) 10.0 mmol TDD; (c) 15.0 mmol TDD; (d) base case; (e) degassing in air; (f) gentle heating rate; (g) solvent switched to ODE; (h) additive increased; (i) degassing in air with gentle heating rate. Scale bars equal 50 nm.

Benzyl Ether, Benzaldehyde, and Benzyl Benzoate as Solvent. Based on the clear effect of the artificial OBE as a useful additive in MNC synthesis and its composition, as revealed by GC-MS, we blended the major components, benzyl ether (BE), benzaldehyde (BA), and benzyl benzoate (BB) in various ratios to replicate the results obtained using OBE. For this, we used a hybrid solvent of 19.0 mL BE, 0.5 mL BA, and 0.5 mL BB. The samples presented in Figure S4 can be viewed as a set of univariate experiments each differing in one respect from the base case shown in Figure S4(d). Green labels, as shown in Figure S4, are employed throughout the manuscript for samples produced by adding both BA and BB to BE. We again varied the amount of TDD, to see its effect in the hybrid solvent (BE, BA, BB) environment, which can be compared to Figure S3(g, h, I). In the hybrid solvent experiments, the amount of TDD increased from the base case, panel (d), 5.0 mmol, to panels (a) 7.5 mmol, (b) 10 mmol, and (c) 15 mmol. Figure S4(d) shows highly uniform ~47.7 nm stars, i.e., cubes with extrusions at their vertices in the <111> directions. Such structures have been demonstrated as a high-performance T2 contrast agent for MRI.² Some MNCs in panel (a), prepared with 7.5 mmol TDD, still have extruded <111> vertices, but their average size decreased significantly compared to panel (d). Further increase of TDD to 10 mmol produced MNC cubes of smaller size with rounded vertices, as seen in panel (b). Increasing the amount of TDD to 15 mmol produced even smaller MNCs with poorer monodispersity and less defined shape, panel (c). The decrease in size and faceting with increased TDD is consistent with our observations using OBE as solvent and confirm the role of the diol in limiting the MNCs' growth.

To prepare the MNCs shown in Figure S4(e), the solution was degassed in air instead of argon. The MNCs had a bimodal distribution of size, i.e., the MNCs from a single batch have two peaks in the size distribution. The larger MNCs remained cubic, but the smaller MNCs' morphology was not well defined. Oxidation of the precursor solution in air during degassing definitely imposes an effect on the result, yet this effect is hard to pinpoint and quantify.

Temperature rate in this article is defined as the ratio of the difference of reaction temperature and degassing temperature over the corresponding period of time. With a gentler temperature rate (~2.7°C/min), the mean NC size decreased in Figure S4(f), compared to the MNCs prepared using a steeper temperature rate (~4.6 °C/min) in panel

(d). Slower heating provides a wider time window for nucleation, i.e., the solution remained longer in the temperature range at which nucleation occurs. This could generate a larger population of nuclei,³ and hence produce smaller NCs upon complete consumption of the monomers. When the solution was both degassed in air and heated with a gentle rate, the product MNCs were strikingly monodisperse with an average size \sim 6.8 nm, Figure S4(i). Combined with panel (e), we conclude that degassing in air decreases NC size.

Replacing BE with 1-octadecene, while still using 0.5 mL each of BA and BB, produced small cubes with rounded edges, as shown in Figure S4(g). Although BE and ODE are both considered as "non-coordinating" solvents, they still can loosely coordinate to the monomers.⁴ Thus, changing the primary solvent can affect the formation of MNCs by changing the activity coefficient of monomers.

As seen in Figure S4(h), increasing the amount of BA and BB produced cubes of smaller size (~39.9 nm) compared to the base case in panel (d), but with much sharper edges and vertices.



Figure S5. TEM images of MNCs synthesized in mixtures of BE and BA. Samples in panels (a) through (c) were prepared with TDD; those in panels (d) through (i) were prepared with HDD. Compared to the base case (a) with TDD, the variable(s) changed were (a) base case; (b) BA decreased to 2.0 mL; and (c) BA decreased to 0.5 mL. Compared to base case (d) with HDD, the variable(s) changed were (e) solvent switched to ODE; (f) HDD halved, and solvent switched to ODE; (g) HDD halved; (h) HDD halved and OAm decreased to 0.5 mL; (i) HDD halved and OAm increased to 2.0 mL. Scale bars equal 50 nm.

Benzyl Ether and Benzaldehyde as Solvent. To simplify the synthesis and pinpoint the most effective additive in controlling the MNCs' size and shape, the ternary solvent (BE+BA+BB) was replaced by a binary solvent (BE+BA). The samples presented in Figure S5 can be viewed as variations from base cases, which employed 15 mL BE and 5 mL BA with 10 mmol TDD (Figure S4(a)) or with 10 mmol HDD (Figure S4(d)). Yellow

labeling, as shown in Figure S5, is used throughout the manuscript for samples prepared by adding BA (without BB) to a non-coordinating solvent.

The average size of MNCs in Figure S5(a) is ~16.6 nm. Decrease of the additive, BA, to 2 mL produced the polydisperse MNCs in (b). Further decreasing BA to 0.5 mL resulted in MNCs of ca. 3.9 nm in Figure S5(c). The decrease in average size of the MNCs with decreasing BA was accompanied by a variation in shape from sharp cubes (a), to rounded cubes (b), and then to tetrahedra and dots (c), suggesting the correlation of the {111} planes' growth and the amount of BA. Switching the diol from TDD to HDD did not dramatically change the average MNC size, but the MNCs prepared with HDD showed rounded vertices and edges in Figure S5(d), implying a correlation between the vertices and edges' growth and the length of the diol, as discussed further in the main text. Note that the rounded cubes did not assemble into a cubic lattice. One reasonable speculation would be that the building block MNCs with zone axis [110] seem to align their easy axes of magnetization, i.e., [111], to stabilize the assembly, so the MNCs in panel (d) have elongated 2D projection.

Switching the solvent from BE to ODE decreased the average MNC size (Figure S5(e)), which is similar to the decrease in size observed in Figure S4 (d) and (g). Together, these two pairs of experiments suggest that for fixed values of all other parameters, switching the solvent from BE to ODE reduces the average size of MNCs. Halving the amount of HDD, while keeping ODE as solvent, produced an increase in the average size of the MNCs in Figure S5(f), consistent with the known role of the diol in limiting NC growth. Figure S5(g) shows the MNCs synthesized in BE, but halving the amount of HDD relative to the base case in panel (d). As in the case of ODE as solvent, the size of the MNCs increased with reduced HDD content. However, in this case the NCs became relatively polydisperse, ranging from 16-50 nm, and were more nearly octahedral in shape, rather than cubic. Continuing from (g), halving the amount of OAm further increased the average size, Figure 3(h), while doubling the amount of OAm decreased the average size, Figure 3(i). Thus, OAm also serves to decrease the average MNC size in this synthesis.



Figure S6. TEM images of MNCs synthesized in ODE and BA. Compared to the base case in (a), the variable(s) changed were (a) base case; (b) reaction time extended to 110 min; (c) gentle heating rate; (d) OA decreased to 2.0 mL; (e) OA decreased to 2.0 mL and BA decreased to 1.0 mL; (f) OA decreased to 2.0 mL and TDD halved. Scale bars equal 50 nm.

1-Octadecene and Benzaldehyde as Solvent. The foregoing experiments adopted benzyl ether (BE) as solvent based on its use in many pioneering protocols for MNC synthesis.⁵⁻⁶ Clearly, monodisperse MNCs of various controlled sizes and shapes can be produced using BE with OBE/BA/BB as additive(s). However, given the better understanding of the susceptibility of BE to oxidation and the importance of the oxidation products in MNC synthesis, using a more stable solvent would be preferable. Replacing BE with a more stable solvent can be expected to improve the reproducibility of the synthesis. Thus, as already demonstrated in some cases above, we replaced the somewhat air-sensitive solvent, BE, with air-stable 1-octadecene (ODE) and added a controlled amount of the key BE oxidation product, BA. Samples shown in Figure S6 illustrate variations of the synthesis using ODE and BA, along with TDD, OAm, and OA. Each of these is a variation from the base case that produced the MNCs in Figure 4(a). Orange labeling, as shown Figure S6, is used throughout the manuscript for samples prepared by adding BA to ODE.

Extending the reaction time to 110 min had very little effect on the size or morphology of MNCs (Figure S6(b)), indicating that reaction is complete after 90 min, and any subsequent shape evolution is quite slow. The square lattice of self-assembled MNCs in Figure S6(b) is somewhat deformed, similar to Figure S5(d), and the MNC size remained approximately the same, and the morphology remained predominantly cubic. MNCs synthesized with a slower heating rate (Figure S6(c)), 2.7°C/min instead of 4.6°C/min, were similar to the base case in size, but showed extruded vertices rather than the perfectly cubic morphology.

Figure S6(d), (e) and (f) present MNCs synthesized with a reduced amount of OA (2 mL). Compared to those in panel (a), MNCs in (d) have smaller average size and more nearly octahedral shape that results into the hexagonal lattice, rather than the cubic lattice. Decreasing the amount of BA produced much less faceted particles in Figure 4(e). Halving the amount of TDD, in addition to decreasing the BA, increased the size dramatically, and increased the polydispersity in both size and shape, Figure S6(f).

These synthesis formulae using ODE as the primary solvent are better controlled and, in our hands, more reproducible than those using BE. Thus, they should be of broad interest to researchers needing monodisperse MNCs of specific size and shape.



Figure S7. SEM image of the sample in Figure S3(f).

Figure S7 shows the SEM image of the MNCs in Figure S3(f). It is clear that these MNCs are octahedra, not platelets.

Equation S1. Overall reaction for oxidation of benzyl ether to benzyl benzoate.

 $(C_6H_5CH_2)_2O + O_2 \rightarrow C_6H_5COOCH_2C_6H_5 + H_2O$

Equation S2. Overall reaction for oxidation of benzyl ether to benzaldehyde.

 $(C_6H_5CH_2)_2O + O_2 \rightarrow 2 C_6H_5CHO + H_2O$

References of Supporting Information

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