Simple phosphinate ligands access zinc clusters identified in the synthesis of zinc oxide nanoparticles

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The bottom-up synthesis of ligand-stabilized functional nanoparticles from molecular precursors is widely applied but is difficult to study mechanistically. Here we use 31P NMR spectroscopy to follow the trajectory of phosphinate ligands during the synthesis of a range of ligated zinc oxo clusters, containing 4, 6 and 11 zinc atoms. Using an organometallic route, the clusters interconvert rapidly and self-assemble in solution based on thermodynamic equilibria rather than nucleation kinetics. These clusters are also identified in situ during the synthesis of phosphinate-capped zinc oxide nanoparticles. Unexpectedly, the ligand is sequestered to a stable Zn11 cluster during the majority of the synthesis and only becomes coordinated to the nanoparticle surface, in the final step. In addition to a versatile and accessible route to (optionally doped) zinc clusters, the findings provide an understanding of the role of well-defined molecular precursors during the synthesis of small (2–4 nm) nanoparticles.

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Zinc oxide nanoparticles are used in a huge range of contexts, ranging from wide band gap semiconductors and photo-electronic materials\textsuperscript{1-3}, to catalysts and photoactive antimicrobial surfaces\textsuperscript{4-9}. Individualized nanoparticles are synthesized in solution via a similar broad range of techniques including sol-gel chemistry and hydrolysis/thermolysis routes\textsuperscript{10-13}. Regardless of the synthesis method, ZnO and indeed other nanoparticles are frequently capped by surfactants or organic ligands, commonly alkyl amines or carboxylic acids, to maximize solubility during growth and use. In these cases, as with many nanoparticle systems, a ligand is usually implicitly considered to control the synthesis, even if exchanged later\textsuperscript{14,15}. Despite the importance of such systems, the detailed mechanism by which discrete, often non-metallonic, molecular precursors and ligands are combined to form functionalized nanoparticles is not well understood\textsuperscript{16,17}. One very attractive approach to ZnO nanoparticle synthesis, pioneered by Chaudret and colleagues\textsuperscript{18}, hydrolyses organo-zinc reagents, at room temperature in organic solvents, to form crystalline Wurtzite products\textsuperscript{1,20}. This route provides small particles and is compatible with thermally-sensitive organic/polymer chemistry\textsuperscript{21}; it has enabled the preparation of high-performance composite photovoltaic (PV) cells\textsuperscript{22,23} colloidal catalysts\textsuperscript{20,24} and antimicrobial plastic\textsuperscript{25}. In the context of the mechanistic studies reported below, the route provides the opportunity for detailed control of precursor/ligand stoichiometry, as excess ligand can be avoided\textsuperscript{12}, and the extent of reaction is limited by water supply.

Metallic cluster complexes can grow to more than 1 nm in size and bridge between the domains of molecules and nanoparticulates\textsuperscript{25}; they frequently show unusual and impressive optical, electronic and magnetic properties\textsuperscript{26,27}. In contrast, the field of zinc-oxo cluster chemistry is relatively less developed, although it is known that alkyl zinc alkoxide/carboxylate clusters are useful precursors to form ZnO nanoparticles and thin films\textsuperscript{9,11-13,15,18,28}. Doped materials may also be prepared from heterobimetallic clusters, with improved properties attributed to intimate mixing of the two metals\textsuperscript{13,28}. Furthermore, tetrahedral zinc carboxylate clusters, [Zn$_4$O(CO$_2$R)$_6$], are ubiquitous vertices in metal organic frameworks (MOFs), showing outstanding gas sorption and separation characteristics, although they can be sensitive to attack from water or donor solvents\textsuperscript{29-33}. The metal-oxygen framework structures of reported precursors do not show general map directly onto the Wurtzite-ZnO structure\textsuperscript{0,12}; therefore, their transformations into nanoparticulate ZnO probably involves significant molecular rearrangement. In the case of [RZNOR]$_4$ complexes, alkoxide is lost before ZnO nucleation (to a Wurtzite structure) and the relationship of the ligands to the growing nanoparticle is not clear. Here we show that ligands may coordinate to cluster species, which act as spectators, while ZnO nucleation occurs and act as a ‘ligand reservoir’ that is only consumed at the end of the synthesis procedure.

Although the alkyl zinc cluster chemistry using ligands such as alkoxide or carboxylate shows significant promise\textsuperscript{1,3,4-39}, utilization of alternative ligands is less well explored. Furthermore, attempts to analyse the speciation during carboxylate/alkoxide precursor transformations result in product mixtures and broadened, complex nuclear magnetic resonance (NMR) spectra. In contrast, ligands coordinated with a P-containing group provide a $^{31}$P NMR spectroscopic handle that allows for simple identification of individual cluster geometries even when a complicated mixture is present. Various discrete complexes of zinc phosphonate [RPO$_3$]$_2^-$ or dialkylphosphate [(RO$_2$)PO$_3$]$^-$_2$ are known as viable precursors to nanomaterials\textsuperscript{30-42}. One stand-out example is a well-defined Zn$_{12}$ cluster, which contains a Zn$_4$O core surrounded by Zn – Et fragments supported by eight phosphonate ligands\textsuperscript{41}. This cluster is proposed to be a viable precursor to porous zincophosphate materials. Phosphinate ([R$_2$PO$_3$]$^-$_2$) ligands are iso-electronic with carboxylates and could be attractive alternatives. The parent phosphinic acids are more acidic than carboxylic acids (for example, pK$_a$ diphosphonic phosphine acid (DPPA-H), 2.3; benzoic acid, 4.2) and thus, although the bonding to zinc is slightly weaker, they should be less susceptible to hydrolysis. Furthermore, having two R groups increases their steric protection and enhances hydrophobicity. Stability to hydrogenation and good solubilizing properties make diocetylphosphinate an interesting ligand for supporting nanoparticles used for quasi-homogeneous hydrogenation catalysis (for example, the hydrogenation of CO$_2$ to MeOH)\textsuperscript{43}. Despite their promise as ligands, well-defined zinc complexes and clusters coordinated by monoanionic phosphinate ligands are hardly studied\textsuperscript{43}.

Here, the reactions of simple, commercially-available diethyl zinc with various equivalents of phosphinic acids and water are used to reproducibly prepare a series of new clusters, which are all fully characterized, including by X-ray diffraction (XRD; Fig. 1). Alongside more typical alkyl-zinc-ligand and tetrahedral Zn$_4$O(ligand)$_4$ clusters, some very unusual larger structures are identified, including partially hydrolysed zinc clusters and those containing hydroxy or boroxine cores. Interestingly, these species all show equilibrium relationships with each other and other small molecules, suggesting the clusters may readily interconvert in solution. With the detailed understanding of these species, it is possible to directly identify them in situ during the synthesis of ZnO nanoparticles.

**Results**

**Synthesis of zinc phosphinate cluster complexes.** The first part of the study focused on understanding and characterizing the species present during simple reactions between diethyl zinc and DPPA-H (as a model ligand). Thus, the reaction between equimolar quantities of ZnEt$_2$ and DPPA-H forms a new tetra-zinc cluster, 1A. Its $^{31}$P($^1$H) NMR spectrum shows a sharp singlet (23.2 p.p.m.) and the $^1$H NMR spectrum shows a 1:1 ratio of ethyl:DPPA resonances (Supplementary Figs 1 and 2). Although the structures of alkyl zinc phosphate complexes are not yet reported, alkyl zinc carboxylates adopt a range of chemical structures\textsuperscript{44}, including hexa-\textsuperscript{35} or pentanuclear complexes\textsuperscript{37-39}. Crystals of 1A, analysed by XRD, show a distorted cubic structure [Zn$_4$Et$_2$(DPPA)$_4$] with a tetrahedral arrangement of zinc atoms (Fig. 2 and Supplementary Figs 3,4). Each zinc is singly coordinated to a P = O oxygen (P – O range, 1.492(2)–1.497(2) Å) and each P – O$^-$ oxygen atom (P – O range, 1.531(2)–1.534(2) Å) bridges between two zinc centres. The shape of 1A is most closely related to the ‘cubane’ structures of alkyl zinccoaloxides but with the phosphinate ligand adopting bidentate chelation\textsuperscript{13}.

Compound 1A is highly moisture sensitive and the addition of ~2 eq. of water (allowing full hydrolysis of all Zn – Et bonds) forms a new species, 2A, which also exhibits a single peak in the $^{31}$P($^1$H) NMR spectrum (32.9 p.p.m.; Supplementary Figs 5–8). Complex 2A is also a tetrazinc cluster of the form [Zn$_4$(μ$_3$O)(DPPA)$_4$]$_{m}$, featuring a central μ$_3$-oxo atom and six phosphinate ligands (Supplementary Fig. 9); the excess zinc/ethyl is likely to be hydrolysed to form NMR-silent insoluble ZnO particles. Compound 2A can also be directly prepared, in quantitative yield (NMR spectroscopy), by reaction of a 4:6:1 ratio of ZnEt$_2$:DPPA:H$_2$O, in toluene or CH$_2$Cl$_2$ (Fig. 3). The matrix-assisted laser desorption/ionization–time of flight (MALDI–ToF) mass spectrum shows a peak for [Zn$_4$O(DPPA)$_4$]$^+$ in keeping with the expected cluster formula (Supplementary Fig. 7). The $^1$H NMR spectrum shows a single environment for the
phenyl substituents in 2A (Supplementary Fig. 6). The crystal structures of 2A, grown either from toluene or CH$_2$Cl$_2$/hexane, show four independent molecules in the asymmetric unit. The phenyl groups could not be located to acceptable degrees of accuracy; however, [Zn$_6$(μ$_3$-O)(O$_2$P)$_6$]$_n$ units were observed (Supplementary Figs 9, 10). By using bis(4-methoxyphenyl) phosphinic acid, a fully resolvable crystal structure of 2B was obtained, a complex with an analogous structure to 2A (Fig. 3a). The structure of 2B shows a tetrahedral core of Zn$_4$O capped by six bidentate ligands, which show equal P–O bond lengths (within error), indicating a delocalized coordination mode (Supplementary Figs 11–15). Although such structures are not yet known for phosphinate ligands, they are commonly observed for other anionic ligands and the benzene dicarboxylate Zn$_6$O cluster is a common construct in MOFs.

Samples of 2A exposed to moisture led to the formation of a new complex, 3A, which displays two $^{31}$P NMR signals in a 2:1 ratio (30.1 (1P), 24.2 (2P) p.p.m.; Supplementary Figs 16–20).

The addition of 5 eq. (versus 2A) of water to the solution results in a mixture comprising a relative molar ratio 2A:3A = 2:3. Solvated water is also observed in the NMR spectrum, suggesting equilibration between 2A, water and 3A (Fig. 3). It is important to emphasize that 3A reproducibly forms on addition of water to chloroform, toluene or tetrahydrofuran (THF) solutions of 2A.

The formula of 3A is [Zn$_6$(μ$_3$-OH)$_6$(DPPA)$_3$], established by XRD analysis of single crystals (Fig. 3b and Supplementary Fig. 18). Solid 3A can also be isolated in quantitative yield by direct reaction, in this case of a 1:1.5:0.75 ratio of ZnEt$_2$:DPPA-H$_2$O. The product has a pseudo trigonal prismatic shape, previously unknown for such zinc clusters. It also features three bridging zinc hydroxide ligands. The trigonal prismatic shape results from two planar triangular units of Zn$_6$(DPPA)$_3$, which are bridged by three further DPPA units and three hydroxides. In all cases, P–O bond lengths are similar, suggesting delocalized bonding.

The stability of the cluster may stem from the hydroxide groups being positioned just far enough from each other to hinder any further condensation reactions (Supplementary Fig. 21). Attenuated total reflection–infrared spectroscopy of a crystalline sample of 3A (dried under vacuum) shows a weak signal at 3,644 cm$^{-1}$ attributed to O–H stretches (not present for 2A), consistent with values reported for other bridging Zn$_6$(μ$_3$-OH) units: a second broad signal at 3,410 cm$^{-1}$ could be a different OH stretching mode or traces of adsorbed moisture (Supplementary Fig. 18).$^{46–49}$ The $^1$H NMR spectrum of 3A shows three sets of phenyl environments in a 1:1:1 ratio, which are assigned using correlation spectroscopy NMR (Supplementary Fig. 17). The solution structure is consistent with the solid-state structure, assuming that there is some flexibility enabling a D$_{3h}$ symmetry in solution. The six ‘planar’ DPPA units are assigned to two phenyl environments: one pointing approximately in the plane of the triangle and the other perpendicular. The third phenyl environment is attributed to the three ‘bridging’ DPPA units in which both phenyl groups occupy identical environments. The hydroxide protons are also observable as a sharp signal at 3.67 p.p.m., with a relative integral of 3H.

The formation of 3A is unexpected; the isolation and characterization of well-defined Zn-hydroxide complexes is usually challenging, often requiring the use of bulky, multi-dentate ligands.
for stabilization. Zinc-hydroxy species are of interest in a range of contexts, including as putative intermediates during ZnO nanoparticle synthesis and as models for a range of zinc-dependent metalloenzymes. Given interest in similar carboxylate-ligated Zn clusters, the different structures and reactivity observed here with phosphinate ligands is notable. The solid-state structure of 2B shows Zn−phosphinate bond lengths ranging from 1.917(2) to 1.960(2) Å, with an average (1.936(2) Å) slightly greater than that of the analogous Zn-benzoate structure Zn4O(O2CPh)6 (average = 1.926 Å), in line with slightly weaker bonding from the phosphinate. The Zn−O bonds in 2B are also lengthened (average 2B, 1.989(2) Å; Zn4O(O2CPh)6, 1.946 Å), presumably as a result of the larger size of the phosphinate chelate compared with a carboxylate (average P−O (2B), 1.512(2) Å; average C−O (Zn4O(O2CPh)6), 1.258 Å), which allows for an expansion of the Zn4O cluster. Compounds 2A/B react with water to form well-defined zinc hydroxide complexes, whereas the carboxylate analogue [Zn4O(CO2Ph)6] reacts as a Lewis acid towards water to form an aqua complex [Zn4(O3P3P6) (H2O) (THF)]31.

Equilibrium studies. To explore the factors controlling the equilibration of zinc-oxo and zinc-hydroxy clusters, variable-temperature NMR spectroscopy was applied, using a solution containing a 2:3 ratio of 2A:3A, over the temperature range 288–328 K (Supplementary Fig. 24). At each temperature, the equilibration was rapidly established, as confirmed by an identical second spectrum, obtained after ~15 min. The ratio of 2A:3A is easily determined from the 31P{1H} NMR spectra (see Supplementary Methods), with 2A being the major species at temperatures above 318 K. Under the experimental conditions, the concentration of water is low (0.059 M) but is all fully dissolved with no downfield signal, which would be expected from separated water droplets. Van’t Hoff analysis showed that ΔH̅ = −108 ± 3 kJ mol−1 and ΔS̅ = −238 ± 9 J K−1 mol−1 (Supplementary Fig. 25 and Supplementary Methods). Clearly, the hydroxo structure 3A is enthalpically favoured, but the entropic advantage results in 2A becoming dominant at higher temperatures. A similar equilibrium exists between zinc-oxo cluster 2B, water and 3B (Supplementary Figs 22 and 23). The equilibrium lies more towards the zinc oxo species, 2B, than in the 2A/3A system (2B/3B = 1:0.23 cf. 2A:2B = 1:0.9, 2.3 eq. water added). Van’t Hoff analysis revealed that ΔH̅ = −97 ± 3 kJ mol−1 and ΔS̅ = −234 ± 9 J K−1 mol−1 (Supplementary Fig. 26 and Supplementary Table 1). Compared with 2A/3A, the entropy of reaction is unchanged (within error), but the zinc hydroxyl cluster, 3B, is slightly less enthalpically favoured.

Figure 3 | Synthetic path and solid-state structures of 2B and 3A. Structures: (a) 2B and (b) 3A (H-atoms omitted for clarity). Views of the Zn cluster core structures, with aromatic groups omitted, are provided inside the coloured circle/box c) Synthesis and equilibrium of 2A/B and 3A/B. Reagents: (a) 1 eq. H2O, toluene or CH2Cl2; (b) 5 eq. H2O.

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(Supplementary Table 1). These results provide a thermodynamic rationale for the equilibration between the clusters and demonstrate the importance of the phosphinate ligand in controlling the relative stabilities of the clusters.

**Synthesis of a zinc-boroxine cluster.** The proximity of the three hydroxyl groups in 3A suggests the intriguing possibility of coordination of further atoms/molecules in the centre of the cluster (O–centroid distances 1.5–1.8 Å, Supplementary Fig. 21). In a different system and geometry, partially condensed trisilanol silsequioxanes have been widely used to bind heteroatoms for catalytic and other studies. The reactivity of trisilanol silsequioxanes has been widely used to bind heteroatoms for catalytic and other studies. In a different system and geometry, partially condensed cluster (O–centroid distances 1.5–1.8 Å, Supplementary Fig. 21). In a different system and geometry, partially condensed cluster (O–centroid distances 1.5–1.8 Å, Supplementary Fig. 21).

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especially given the presence of water in the solution equilibrium, resulting in preferential hydrolysis of the organometallic species, driving the equilibrium back towards 2A. An alternative approach is to use a different oxygen source to form the Zn–O–X moieties. In this regard, boric acid (B(OH)₃) is attractive for its aqueous stability and trigonal planar shape. Boric acid clearly reacts with a THF solution of 2A/3A, leading to the formation of a product 4A (Supplementary Figs 27–29). Compound 4A can also be prepared in quantitative yield (31P NMR) by the direct reaction of a 2:3:1 ratio of ZnEt₂, DPPA-H and boric acid, in THF (Fig. 4). Again, an equilibrium exists between 4A, 2A and 3A (Supplementary Fig. 33); when 17 eq. of water was added to a solution of pure 4A, a molar ratio of 89:7:4 for 4A:2A:3A formed, showing that 4A is favoured even under wet conditions. Crystals of 4A, grown from THF/hexane, show the structure as [Zn₆B₃O₃(DPPA)]₉ (Fig. 4b and Supplementary Figs 30 and 32). The planar cluster contains six zinc atoms surrounding a B₃O₃ core. Each zinc atom is tetrahedrally coordinated to three bridging phosphinate ligands and a μ₁-oxo ligand. The o xo ligands are each also coordinated to the boroxine core. Two phenyl substituents align above and below this boroxine core, suggesting some π–π stacking exists in the solid state, it is well known that boroxines exhibit partial aromaticity.

The structure of 4A is quite different to that of 2A or 3A and it is proposed that the spontaneous self-assembly is driven by the planar boroxine core. The Zn₆B₃O₃ cluster planarity may also be relevant for the construction of more complex two-dimensional materials, including MOFs. The structure of 4A is maintained in solution; two singlet signals in the 31P NMR spectrum are observed in a 2:1 ratio (22.7, 29.3 p.p.m.) as expected from the two environments (in and out of the plane) in the solid-state structure (Supplementary Fig. 27). The 1H NMR spectrum shows three sets of phenyl resonances in a 1:1:1 ratio (Supplementary Fig. 28).

**Synthesis of a partially hydrolysed Zn₁₁ cluster.** It is of interest to consider what role clusters such as 1–3 might take during the formation of phosphinate-coordinated zinc oxide nanoparticles by hydrolysis routes. We have previously reported the potential to introduce sub-stoichiometric quantities of...
carboxylic acid/phosphinic acid during ZnEt$_2$ hydrolysis, to deliver surface-ligated crystalline ZnO nanoparticles with well-defined sizes (2–4 nm). The capped nanoparticles show good solubility in organic solvents and have been used as quasi-homogeneous catalysts as well as in the preparation of high-loading fraction ZnO-polymer composites.$^{1,2}$ In general, there is significant interest in the preparation of ZnO nanoparticles by the controlled hydrolysis of organozinc reagents, including ZnEt$_2$, as it provides a room-temperature method to crystallize nanoparticle and a route to useful inorganic hybrid materials.$^{3,10,12,16,57}$ So far, however, the mechanism and intermediates implicated in the hydrolysis of well-defined organometallic reagents, with or without capping ligands, to nanoparticles is not at all well understood.$^{19}$ As a starting point to understanding how the particles form, we proposed that there may be some partly hydrolysed clusters present. The hydrolysis reaction occurs in solutions, often of inert organic solvents; thus, it is beneficial to apply solution-based spectroscopic techniques. A particular benefit of phosphate ligands, as noted above, is the facility to apply $^{31}$P{1H} NMR spectroscopy. Previous studies of ZnO nanoparticles have shown they approach surface saturation with ligand, when a mixture of 5 eq. of ZnEt$_2$ with one equivalent of ligand (typically diocetylphosphinic acid) is hydrolysed.$^{20}$ Introducing the water gradually allows the speciation during this process to be probed. Using DPPA as a model ligand and adding only one equivalent of water to this 5:1 mixture, a new phosphorus-containing cluster compound was identified by NMR spectroscopy (Supplementary Figs 34–36). By adjusting the ratios to favour this new species, we were able to form crystals from an 11:4:4 mixture of ZnEt$_2$, H$_2$O and DPPA-H. The isolated crystals revealed a cluster containing 11 zinc atoms, [Zn$_{11}$Et$_{10}$O$_4$(DPPA)$_4$]; elemental analysis was also and DPPA-H. The isolated crystals revealed a cluster containing 11 zinc atoms, [Zn$_{11}$Et$_{10}$O$_4$(DPPA)$_4$]; elemental analysis was also performed, showing a 5:1 ratio of new clusters (that is, the analogues 1A/B and 2A/B). 

### In situ identification of clusters in nanoparticle synthesis.

Having established the structures of clusters 1–5A and the generality to other related model ligands, their roles in ZnO nanoparticle synthesis was explored. In particular, the hydrolysis of ZnEt$_2$ was performed in the presence of the di-octylphosphinate (DOPA) ligands, which are representative of systems used to sterically stabilize nanoparticles. The long alkyl chains hinder crystalization, but the utility of the $^{31}$P NMR handle allows characterization. Using analogous procedures to the preparation of 1A/B and 2A/B, the clusters 1C (Zn$_6$Et$_{10}$O$_4$<sub>DOPA</sub>$_4$) and 2C (Zn$_6$O$_4$<sub>DOPA</sub>$_6$) were easily identified following the reactions of appropriate ratios of ZnEt$_2$ with DOPA-H (and water for 2C) (Supplementary Figs 44–48). Additions of an excess of water (≈ 6 eq.) to 2C leads to two $^{31}$P signals (which sum to 1% of the total integral considering residual 2C) indicative of the formation of 3C (Zn$_6$(OH)$_3$<sub>DOPA</sub>$_6$) (Supplementary Fig. 49). However, in this case, the equilibrium strongly favours 2C, likely to be due to the greater steric hindrance from the bulky ligand. Nevertheless, the speciation using the long-chain phosphate maps onto the model clusters already structurally characterized.

For the synthesis of functionalized nanoparticles, a Young’s tap NMR tube was loaded with a 5:1 ratio of ZnEt$_2$ and DOPA-H solvated in d$_8$-toluene, similar to conditions established previously.$^{20}$ Water was added in sequential 0.5 μl aliquots to the NMR tube (each aliquot making up 12.5% of the 4 μl required for total hydrolysis) under a flow of N$_2$. NMR spectra were recorded at each point along the hydrolysis pathway (after ~30 min reaction time at each point, Supplementary Figs 50–54). An internal standard (PP$_3$ in a capillary tube) was used to allow calculation of relative integrals from the $^{31}$P{1H} NMR spectra and to monitor the evolution of the cluster species during the reaction (Fig. 6b,c). It is worth noting that the reactions described above were performed at stoichiometries targeted to particular clusters, whereas the reactions on the path to nanoparticles occur in the presence of excess diethyl zinc. Initially, in the absence of water, 1C was observed alongside the excess ZnEt$_2$, as expected. Initial hydrolysis of the remaining Zn – Et bonds results in the loss of signal for 1C and the formation of a signal at 61.0 p.p.m., assigned to complex 5C (Zn$_{11}$Et$_{10}$O$_4$(DPPA)$_4$) (see Supplementary Note 1), accompanied by various low-intensity new signals. Compound 5C can be independently synthesized and also forms an equilibrium with 1C, 2C and ZnEt$_2$ as shown in Fig. 5 (Supplementary Figs 55–58). The other minor species (shown in Fig. 6c) are currently not assigned; the strongest signal is tracked in Fig. 6b and disappears after 38% total hydrolysis, leaving 5C as the dominant ligated species until hydrolysis nears completion (Fig. 6). In the accompanying series of $^1$H NMR spectra (Supplementary Fig. 51), the sharp ethyl signals for 5C also grow in and persist almost until hydrolysis is completed. The initially exchange-broadened signals for free ZnEt$_2$ sharpen as 1C and other clusters are consumed and then disappear as hydrolysis proceeds. Although the NMR spectra change little between 38 and 63% hydrolysis, a distinctive yellow colour emerges. It appears that the extra water reacts with ZnEt$_2$ to produce species that are silent in the $^1$H and $^{31}$P NMR spectra. This same yellow colour is observed during hydrolysis of ZnEt$_2$ in the absence of ligands and has been noted by other researchers preparing ZnO nanoparticles, although the speciation remains
Transmission electron microscopy (TEM) and powder XRD of this ‘yellow ZnO’ derived from a reaction of ZnEt₂ with 0.75 eq. of H₂O in toluene revealed a mainly amorphous polydispersed and agglomerated nanoparticulate material displaying a very broad, weak ZnO diffraction pattern (Fig. 6d and Supplementary Figs 59–61). Elemental analysis confirmed that some ethyl groups were also maintained, although no sharp signals attributable to ethyl moieties were observed in the ¹H NMR spectra. To monitor the formation of crystalline ZnO, the hydrolysis reaction, in the presence of DOPA ligands, was also followed by ultraviolet spectroscopy (290–400 nm; Supplementary Fig. 62). No optical absorption was observed in either the starting molecular precursors or 25% hydrolysed mixtures, confirming that the yellow colour is not associated with ligated species, 1C or 5C, but rather the product of partial ZnEt₂ hydrolysis, as noted above.

At 50% hydrolysis, a strong absorption is observed, which reduces smoothly, from 290–350 nm, but with no visible band edge typically associated with a crystalline ZnO species; this absorption is similar but stronger at 75% hydrolysis, as consumption of ZnEt₂ continues, and is attributed to highly defective/disordered amorphous ZnO nanoparticles, as discussed above. However, at 100% hydrolysis, the ultraviolet absorption drops significantly (consistent with the observed loss of yellow colour), giving a typical ZnO band edge signal, corresponding to nanoparticles with a diameter of ~3 nm (Supplementary Fig 63).

The final product of hydrolysis is colourless ZnO nanoparticles (2–3 nm) capped by di(ophosphinephosphate) ligands (ZnO@DOPA), extensively characterized previously (and here shown in Fig. 6e and Supplementary Figs 64–72), showing well-isolated crystalline ZnO cores in TEM (Supplementary Fig. 64), clear XRD features of Wurtzite ZnO (Supplementary Fig. 69), an identifiable organic content in elemental analysis, and maintaining a high solubility in toluene (unlike the hydrolysis product in the absence of phosphate). Both NMR and ultraviolet spectroscopy studies indicate that the ligand-capped ZnO@DOPA nanoparticles only form towards the end of the hydrolysis reaction (Fig. 6 and Supplementary Fig. 62). The nanoparticles are observed by ¹³¹P NMR spectroscopy as a broad signal after 75% hydrolysis (52 p.p.m. (full width at half maximum ~1,800 Hz)); the signal breadth is typical for ligands coordinated to nanoparticle surfaces (Supplementary Figs 66 and 67). After all the Zn – Et bonds are hydrolysed, a second new species (2C) is observed along with the nanoparticles in the ¹³¹P NMR spectra (Fig. 6b,c). Although the majority of phosphine is bound to nanoparticles, the zinc oxo cluster 2C forms as a significant byproduct (25% of total ligand). The presence of 2C, which has a high DOPA:Zn ratio, is consistent with the liberation of DOPA on the final hydrolysis of 5C and agglomeration of ZnO units (note: 3C was not observed here as it only forms as a very minor equilibrium partner with 2C in the presence of excess moisture). Compound 2C is soluble in acetone, unlike ZnO@DOPA nanoparticles, and thus can be easily removed, allowing the isolation of pure nanoparticles. It is notable also that Chaudret and colleagues and Mayer and colleagues have both reported that amine-ligated zinc oxide surfaces also exhibit exchange between coordinated and ‘free’ ligands; it is interesting to consider whether well-defined molecular zinc cluster complexes may also be present in these cases. However, low temperature and diffusion-ordered NMR spectroscopy studies (Supplementary Figs 66–68) showed no evidence of ligand exchange between the nanoparticles and 2C.

This reaction trajectory is quite unexpected. The highly moisture sensitive alkyl–zinc complex 5C forms rapidly and is maintained throughout the majority of the hydrolysis reaction, sequestering essentially all the available ligand, whereas residual ZnEt₂ is consumed to form unligated ZnO nanoparticle precursors. A 50% hydrolysed mixture was monitored and found to be unchanged after 15 h, indicating that the system is in thermodynamic equilibrium, with 93% of the total phosphinate supply incorporated in the form of a stable cluster (minor unidentified species make up the balance to ~100% relative to the internal standard; Fig. 6c and Supplementary Figs 52 and 53). It is only near-full hydrolysis of all other Zn – Et species that 5C reacts with the ‘yellow’ ZnO precursors to form the phosphinate capped ZnO nanoparticles. Unlike previous reports in the literature, proposing cluster compounds as molecular building blocks that directly map onto the final nanoparticle (NP) crystal structure, here the cluster compounds do not obviously relate to Wurtzite and instead appear to act only as a reservoir of ligand. This fresh insight into ligand behaviour during nanoparticle synthesis has implications for the concepts of nanoparticle growth and stabilization.

The formation of ZnO nanoparticles by hydrolysis, under the same conditions, but in the absence of any ligand produces insoluble nanoparticles, with average particle sizes of ~3.5 nm (by XRD; Supplementary Fig. 73). The similarity in size range to the particles prepared using the DOPA ligands (2–3 nm by XRD) indicates that the ligand is not critical for particle size control, in keeping with the distribution of ligands only at the end of the reaction. Previous studies using carboxylate ligands and a similar synthetic protocol also found that ZnO particles were consistently formed within the 3–5 nm size range, regardless of the nature or loading of the ligand applied. Nonetheless, the ligands are important to produce well-dispersed and soluble nanoparticles, as they prevent aggregation observed in their absence. Furthermore, ligands are likely to have a significant impact on subsequent ripening and ageing of the nanoparticles.
Discussion

This study exploits an organometallic route to nanoparticles that delivers only the stoichiometric quantity of ligand. By avoiding the excess uncoordinated ligand used in many liquid-phase nanoparticle syntheses, the fate of the ligand at various stages of the reaction can be directly determined. Nanoparticle nucleation is often considered to be a non-equilibrium process, requiring high degrees of super-saturation and high concentrations of active surfactants to minimize the size of the critical nuclei, with particle size often controlled by kinetics, requiring hot injection, fast mixing and the like. Alternatively, sol-gel approaches often involve irreversible condensation reactions. The presence of ligands during nanoparticle synthesis is usually assumed to reduce the nucleation barrier and critical nucleus size, by reducing surface energy of the nascent nanoparticle. Smaller particles can therefore form, which are sterically stabilized against coalescence by the coordinated ligand. Here, this model is completely subverted as the ligands are observed to only interact at the end of the reaction. The behaviour found in this ZnO system may well be observed in other cases, where ligand supply can be varied.

The equilibrium is very unusual, yet provides a simple means to prepare zinc hydroxide clusters; such species are usually significantly more challenging to prepare, yet are important structures in bio-inorganic and other processes. A new planar Zn$_6$B$_3$ cluster, shown in Supplementary Fig. 50–53 for spectra and Supplementary Fig. 54 for Zn speciation plots). Area graph (c) shows that the sum of relative integrals remains close to 100% of the initial spectrum (100% total integral) was also observed between O-82% hydrolysis (shown in c and labelled by their $^{31}$P NMR signal (Supplementary Figs 50–53 for spectra and Supplementary Fig. 54 for Zn speciation plots)). Area graph (c) shows that the sum of relative integrals remains close to 100% of the initial spectrum (100% total integral) was also observed between O-82% hydrolysis (shown in c and labelled by their $^{31}$P NMR signal). Area graph (c) shows that the sum of relative integrals remains close to 100% of the initial spectrum (100% total integral) was also observed between O-82% hydrolysis (shown in c and labelled by their $^{31}$P NMR signal).

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In conclusion, the reactions between diethyl zinc, phosphinic acid and water lead to a rich variety of new clusters. Using bis(4-methoxyphenyl) phosphinic acid were used directly from suppliers and commercial reagents, relevant as single-source precursors to prepare (optionally doped) nanomaterials or as nodes in new families of metal-organic frameworks, this study highlights a number of useful principles. First, phosphinates are under-utilized ligands, which provide a diagnostic $^{31}$P NMR handle; a strong and distinct NMR signal from the binding group is extremely helpful for navigating complex mixtures to identify the correct stoichiometries for pure products. Second, the cluster species form through a series of reversible equilibria as hydrolysis proceeds, but specific products can be isolated directly once their composition is identified. These equilibrium processes should allow further investigation and interpretation of the nucleation and growth of nanoparticles.

Methods

Experimental details. All manipulations were undertaken using a nitrogen filled glovebox or using a Schlenk line, unless otherwise stated. DPPA and DOPA-H mixture (*the signal for the ZnO@DOPA nanoparticles is broad, leading to less accurate integration). Alongside the unknown cluster displayed in level of magnification (scale bar, 10 nm; note, Zn-containing phase appears pale on a dark background).
Syntheses and characterization of 1A. \( \text{ZnEt}_2(\text{DPPA}) \): \( \text{DPPA-H (88.3 mg, 0.405 mmol) was placed in a Young’s tap flask and dissolved in CH}_2\text{Cl}_2 (3.5 mmol). To this, } \text{ZnEt}_2 (50 mg, 0.405 mmol) was added and the evolution of ethane gas was observed. Hexane was layered on the solution, allowing the growth of white crystalline 1A over several days (isolated yield: 35 mg, 23%). Alternatively, the mixture was stirred for 30 min before addition of a solution of water (4 μl, 0.22 mmol) in dry acetone (0.1 ml). The volume of solvent was reduced to ~7 ml, by vacuum, before layering the solution with hexane (~40 ml) to allow the formation of crystals, which were dried by layering over sodium (benzophenone, for hexane) and then done so by layering over potassium hydroxide and then finally dried by layering over sodium (benzophenone, for hexane) and then done so by layering over potassium hydroxide and then finally dried.

Syntheses and characterization of 2A. \( \text{Zn}_4\text{Et}_4(\text{DOPA})_4 \): \( \text{DOPA-H (88.3 mg, 0.405 mmol) was placed in a Schlenk flask with a stirrer bar and dissolved in CH}_2\text{Cl}_2 (20 ml). To this, } \text{ZnEt}_2 (100 mg, 0.81 mmol) was added and the evolution of ethane gas was observed. The solution was stirred for 30 min, before addition of a solution of water (4 μl, 0.22 mmol) in dry acetone (0.1 ml). The volume of solvent was reduced to ~7 ml, by vacuum, before layering the solution with hexane (~40 ml) to allow the formation of crystals, which were dried by layering over sodium (benzophenone, for hexane) and then done so by layering over potassium hydroxide and then finally dried by layering over sodium (benzophenone, for hexane) and then done so by layering over potassium hydroxide and then finally dried.

Syntheses and characterization of 3A. \( \text{Zn}_4\text{Et}_4(\text{DPPA})_4 \): \( \text{DPPA-H (88.3 mg, 0.405 mmol) was placed in a Schlenk flask with a stirrer bar and dissolved in CH}_2\text{Cl}_2 (20 ml). To this, } \text{ZnEt}_2 (100 mg, 0.81 mmol) was added and the evolution of ethane gas was observed. The solution was stirred for 30 min before addition of a solution of water (4 μl, 0.22 mmol) in dry acetone (0.1 ml). The volume of solvent was reduced to ~7 ml, by vacuum, before layering the solution with hexane (~40 ml) to allow the formation of crystals, which were dried by layering over sodium (benzophenone, for hexane) and then done so by layering over potassium hydroxide and then finally dried by layering over sodium (benzophenone, for hexane) and then done so by layering over potassium hydroxide and then finally dried.

Syntheses and characterization of 4A. \( \text{Zn}_4\text{Et}_4(\text{DOPA})_4 \): \( \text{DOPA-H (25 mg, 0.405 mmol) were placed in a Young’s tap flask and stirred with a stirrer bar. To this, } \text{THF (10 ml) was added and } \text{ZnEt}_2 (100 mg, 0.81 mmol) was added and the evolution of ethane gas was observed. The solution was stirred for 30 min before addition of a solution of water (4 μl, 0.22 mmol) in dry acetone (0.1 ml). The volume of solvent was reduced to ~7 ml, by vacuum, before layering the solution with hexane (~40 ml) to allow the formation of crystals, which were dried by layering over sodium (benzophenone, for hexane) and then done so by layering over potassium hydroxide and then finally dried by layering over sodium (benzophenone, for hexane) and then done so by layering over potassium hydroxide and then finally dried.
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Acknowledgements
The EPSRC are acknowledged for funding (EP/K035274/1, EP/M013839/1 and EP/H046380/1).

Author contributions
S.D.P. conducted all experimental work. E.R.W. conducted all TEM characterization and additional information.

How to cite this article: Pike, S. D. et al. Simple phosphinate ligands access zinc clusters identified in the synthesis of zinc oxide nanoparticles. Nat. Commun. 7, 13008 doi: 10.1038/ncomms13008 (2016).

Additional information
Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing financial interests: The authors declare no competing financial interests.

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How to cite this article: Pike, S. D. et al. Simple phosphinate ligands access zinc clusters identified in the synthesis of zinc oxide nanoparticles. Nat. Commun. 7, 13008 doi: 10.1038/ncomms13008 (2016).

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