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(54) Title: STABLE CONCENTRATED METAL COLLOIDS AND METHODS OF MAKING SAME

(57) Abstract: A method for manufacturing stable concentrated colloids containing metal nanoparticles in which the colloid is stabilized by adding a base. This allows the metal particles to be formed in higher concentration without forming larger agglomerates and/or precipitating. The method of manufacturing the stable colloidal metal nanoparticles of the present invention generally includes (i) providing a solution comprising a plurality of metal atoms, (ii) providing a solution comprising a plurality of organic agent molecules, each organic agent molecule comprising at least one functional group capable of bonding to the metal atoms, (iii) reacting the metal atoms in solution with the organic agent molecules in solution to form a mixture comprising a plurality of complexed metal atoms, (iv) reducing the complexed metal atoms in the mixture using a reducing agent to form a plurality of nanoparticles, and (v) adding an amount of a base to the mixture, thereby improving the stability of the nanoparticles in the mixture. The base may be added before or after forming the nanoparticles.

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**STABLE CONCENTRATED METAL COLLOIDS
AND METHODS OF MAKING SAME
BACKGROUND OF THE INVENTION**

1. The Field of the Invention

5 The present invention relates to the manufacture of colloids containing metal nanoparticles. More particularly, the invention relates to concentrated metal nanoparticle colloids that are stabilized using a base.

2. Related Technology

10 Particulate catalysts are an important component of many industrial applications such as refining, organic synthesis, fine chemicals manufacturing, and many other industrial processes. Many of these catalyzed reactions require the use of precious metals such as platinum and palladium. Much effort has been made to make high performance catalysts that improve product yields for a given amount of precious metal used.

15 One technique for making high performance catalysts is to form particles in a solution using metal salts and an organic dispersing agent. The metal salts are dissolved in a solvent, reacted with the organic agent, and then reduced to cause formation of nanoparticles dispersed in the solvent. Because the particles are very small, *e.g.*, less than 1 micron, the dispersed particles
20 form a colloid. The colloidal particles are typically deposited on a catalyst support.

 One problem with making catalysts through a colloidal process is that the concentration of metal must be kept low to prevent precipitation and agglomeration of the metal. Using known manufacturing techniques, attempts
25 to make concentrated colloids have resulted in loss of the precious metal particles. Concentrating the colloid destabilizes the particles and causes the particles to agglomerate and/or precipitate. Particles that precipitate are not suitable for use as high performance catalysts and/or cannot be easily deposited on a support material.

30 Consequently, existing methods for manufacturing supported nanoparticles catalyst use metal colloids that have dilute concentrations of metal particles. The low concentration metal colloids are somewhat difficult

to use because of the relatively large solvent requirements. If the colloid is to be shipped, the excess weight and volume of the solvent significantly increases shipping costs. In addition, applying the particles to a support material is more difficult and expensive because the excess solvent must be removed.

BRIEF SUMMARY OF THE INVENTION

The present invention provides a method for manufacturing stable concentrated colloids containing metal nanoparticles. The colloid is stabilized by adding a base, which allows the metal particles to be formed in higher concentration without precipitating.

The method of manufacturing the nanoparticles of the present invention generally includes (i) providing a solution comprising a plurality of metal atoms, (ii) providing a solution comprising a plurality of organic agent molecules, each organic agent molecule comprising at least one anion, (iii) reacting the metal atoms in solution with the organic agent molecules in solution to form a mixture comprising a plurality of complexed metal atoms, (iv) reducing the complexed metal atoms in the mixture using a reducing agent to form a plurality of nanoparticles, and (v) adding an amount of a base to the mixture, thereby improving the stability of the nanoparticles in the mixture. The base can be added before or after particle formation.

The organic dispersing agent includes at least one functional group that can bond to the catalyst atoms. The organic dispersing agent can also include one or more functional groups for bonding with a support material. Examples of suitable functional groups for bonding with the catalyst atoms and/or the support material include one or more of a hydroxyl, a carboxyl, a carbonyl, an amine, an amide, a nitrile, a nitrogen with a free lone pair of electrons, an amino acid, a thiol, a sulfonic acid, a sulfonyl halide, and an acyl halide. In a preferred embodiment, the organic dispersing agent is a polyacrylic acid or polyacrylate salt.

It is believed that adding the base to the reaction mixture can stabilize the metal particles formed in the reaction by preventing acids from disrupting the bonds between the organic dispersing agent and the metal particles.

During the manufacture of the nanoparticles, protons (*i.e.*, acid) can be formed when the metal ions are reduced. For example, if hydrogen is used as the reducing agent, protons are generated according to the following equation: $M^{2+} + H_2 \rightarrow M + 2H^+$, where M is a metal such as Pt or Pd. The increase in
5 protons lowers the pH of the reaction mixture.

The bond between the metal and the organic compound is maintained by the donation of an electron from the organic agent (*e.g.*, PAA⁻) to the metal (*e.g.*, the empty 5d orbital of Pd or Pt). However, protons released during the reduction of the metal ions can compete for the electrons of the organic agent
10 functional groups. This competitive bonding disrupts the bonding between the metal and the organic agent and can cause the free metal particles to agglomerate to form larger particles and/or precipitate.

The initial concentration of metal atoms affects the extent to which the reduction step changes the pH of the nanocatalyst composition. In a dilute
15 solution of metals, the solvent can more easily buffer the increase in proton concentration. However, as the metal concentration increases, the reduction step has an increased effect on the change in pH and a corresponding increase in the disruption of the interaction between the metal atoms and the organic agent molecules. By adding a base, the effects of the pH increase can be
20 offset via neutralization to maintain a more stable nanoparticle colloid.

These and other advantages and features of the present invention will become more fully apparent from the following description and appended claims as set forth hereinafter.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

I. INTRODUCTION

The present invention relates to metal colloids containing metal nanoparticles, methods of making the colloids, and supported nanocatalyst manufactured therefrom. The method for preparing the metal-containing
30 colloids generally includes reacting a plurality of metal ions and a plurality of organic agent molecules in solution to form metal complexes. The metal complexes are reduced to form nanoparticles dispersed in the reaction mixture.

A base is included in the reaction mixture to stabilize the nanoparticles and prevent agglomeration into larger particles and/or precipitation.

For purposes of the present invention, the term “particle size” refers to average particle size and “nanoparticle” refers to a particle having a particle
5 size between about 1 nm and about 1000 nm.

II. COMPONENTS USED TO MAKE METAL-CONTAINING COLLOIDS AND SUPPORTED CATALYSTS

A. Catalytic Metal Ions

Any metals or group of metals that can react to form a complex with
10 the organic agent molecules can be used to form colloids according to the present invention. The catalytic metals can exhibit primary catalytic activity or can be used as promoters or modifiers. Exemplary metals include noble metals, base transition metals, and rare earth metals.

Examples of base transition metals that may exhibit catalytic activity
15 include, but are not limited to, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, zirconium, molybdenum, tin, antimony, tungsten, and the like. These may be used alone, in various combinations with each other, or in combinations with other elements, such as noble metals, alkali metals, alkaline earth metals, rare earth metals, or non-metals.

Examples of noble metals, also referred to as platinum-group metals,
20 which exhibit catalytic activity, include platinum, palladium, iridium, gold, osmium, ruthenium, rhodium, rhenium, and the like. These may be used alone, in various combinations with each other, or in combinations with other elements, such as base transition metals, alkali metals, alkaline earth metals, rare earth metals, or non-metals.
25

Examples of rare earth metals that exhibit catalytic activity include, but
are not limited to, lanthanum and cerium. These may be used alone, in various
combinations with each other, or in combinations with other elements, such as
base transition metals, noble metals, alkali metals, alkaline earth metals, or
30 non-metals.

Optionally, non-transition metals can also be included, typically as
promoters or modifiers. Suitable non-transition metals include alkali metals

and alkaline earth metals, such as sodium, potassium, magnesium, calcium, etc., and non-metals such as phosphorus, sulfur, oxygen, and halides.

B. Organic Dispersing Agents And Organic Dispersing Agent Molecules

5 The organic dispersing agent, also referred to as a dispersing agent or an organic dispersing agent, is selected to promote the formation of nanocatalyst particles that have a desired size, stability, and/or uniformity. The dispersing agent molecules react with the metal ions to form ligands complexed with the metal ions.

10 Dispersing agents suitable for bonding metal ions include a variety of small organic molecules, polymers and oligomers. The dispersing agent interacts and bonds with metal ions dissolved or dispersed within an appropriate solvent or carrier. Bonding can occur through various suitable mechanisms, including ionic bonding, covalent bonding, Van der Waals
15 interaction/bonding, lone pair electron bonding, or hydrogen bonding.

To provide the bonding between the dispersing agent molecules and the metal ions, the dispersing agent molecules include one or more appropriate functional groups. In one embodiment, the functional groups comprise a carbon atom bonded to at least one electron-rich atom that is more
20 electronegative than the carbon atom and that is able to donate one or more electrons so as to form a bond or attraction with a metal ion. Preferred dispersing agents include functional groups which have either a charge or one or more lone pairs of electrons that can be used to complex a metal ion. These functional groups allow the dispersing agent to have a strong binding
25 interaction with the metal ions.

In an exemplary embodiment, the functional groups of the dispersing agent comprise one or more members selected from the group of a hydroxyl, a carboxyl, a carbonyl, an amine, an amide, a nitrile, a nitrogen with a free lone pair of electrons, an amino acid, a thiol, a sulfonic acid, a sulfonyl halide, and
30 an acyl halide. The dispersing agent can be monofunctional, bifunctional, or polyfunctional.

Examples of suitable monofunctional dispersing agents include alcohols such as ethanol and propanol and carboxylic acids such as formic acid and acetic acid. Useful bifunctional dispersing agents include diacids such as oxalic acid, malic acid, malonic acid, maleic acid, succinic acid, and the like; dialcohols such as ethylene glycol, propylene glycol, 1,3-propanediol, and the like; hydroxy acids such as glycolic acid, lactic acid, and the like. Useful polyfunctional dispersing agents include sugars such as glucose, polyfunctional carboxylic acids such as citric acid, EDTA, pectins, cellulose, and the like. Other useful dispersing agents include ethanolamine, mercaptoethanol, 2-mercaptoacetate, amino acids, such as glycine, and sulfonic acids, such as sulfobenzyl alcohol, sulfobenzoic acid, sulfobenzyl thiol, and sulfobenzyl amine. The dispersing agent may even include an inorganic component (*e.g.*, silicon-based).

Suitable polymers and oligomers within the scope of the invention include, but are not limited to, polyacrylates, polyvinylbenzoates, polyvinyl sulfate, polyvinyl sulfonates including sulfonated styrene, polybisphenol carbonates, polybenzimidizoles, polypyridine, sulfonated polyethylene terephthalate. Other suitable polymers include polyvinyl alcohol, polyethylene glycol, polypropylene glycol, and the like.

In addition to the characteristics of the dispersing agent, it can also be advantageous to control the molar ratio of dispersing agent to the catalyst atoms in a catalyst suspension. A more useful measurement is the molar ratio between dispersing agent functional groups and catalyst atoms. For example, in the case of a divalent metal ion two molar equivalents of a monovalent functional group would be necessary to provide the theoretical stoichiometric ratio. Typically the molar ratio of dispersing agent functional groups to catalyst atoms is preferably in a range of about 0.001:1 to about 50:1. For hydrogen peroxide catalysts the ratio is advantageously in a range of about 0.5:1 to about 40:1, more preferably in a range from about 1:1 to about 35:1, and most preferably in a range of about 3:1 to about 30:1.

The use of the dispersing agent allows for the formation of very small and uniform nanoparticles. In general, the nanocatalyst particles formed in the

presence of the dispersing agent are preferably less than about 20 nm in size. In some cases, the nanocatalyst particles may be atomically dispersed. The nanocatalyst particles more preferably have an average particle size less than about 15 nm, and most preferably less than about 10 nm.

5 Finally, depending on the desired stability of the nanocatalyst particles on the support material, the dispersing agent can be selected to bond (*e.g.*, covalently bond) with the support material so as to anchor or tether the nanocatalyst particles and/or atoms to the support material. While the dispersing agent has the ability to inhibit agglomeration of the nanocatalyst
10 particles in the absence of anchoring, chemically bonding the nanocatalyst particles to the support material through a ligand is a particularly effective mechanism for preventing agglomeration.

Suitable functional groups for bonding with the support are the same types of functional groups as those suitable for bonding to the metal ions.
15 However, dispersing agent molecules can have different functional groups for bonding to the support and also for bonding to the metal ions.

C. Solvents

The metal ions are prepared in a solution that can be applied to a catalyst support material. The solution can contain various solvents, including
20 water and organic solvents. Solvents participate in catalyst formation by providing a solution for the interaction of metal ions and the dispersing agent molecules. Suitable solvents include water, methanol, ethanol, n-propanol, isopropyl alcohol, acetonitrile, acetone, tetrahydrofuran, ethylene glycol, dimethylformamide, dimethylsulfoxide, methylene chloride, and the like,
25 including mixtures thereof.

D. Basic Compounds

A basic compound (*i.e.*, a base) is added to the reaction mixture to stabilize the nanoparticles formed in high concentrations. The basic compound can be a weak base or a strong base; however, weak bases are
30 preferred. Examples of suitable weak bases include sodium bicarbonate, sodium carbonate, ammonium carbonate, ammonium bicarbonate, ammonium acetate, sodium acetate, sodium phosphate, ammonium phosphate;

bicarbonates or carbonates of Li, Na, K, Rb, Cs, Be, Mg, Ca, Sr, Ba, ammonium and the like; organic bases such as aniline, pyridine, imidazoles, and amines (*e.g.*, trimethyl amine, methylamine, or dimethylamine). Other examples of suitable basic compounds include hydroxides of Li, Na, K, Rb, Cs, Be, Mg, Ca, Sr, Ba, ammonium, and the like.

It is also possible to add the base as a solid material. For example, ion exchange resins that have basic functional groups can be used. The solid material can be easily separated from the final colloid using simple techniques such as centrifugation and filtration.

10 **E. Reducing Agent**

A reducing agent is used to reduce the metal ions to a lower oxidation state. Any compound capable of reducing the metal ions can be used. In a preferred embodiment, the reducing agent is hydrogen. Other suitable reducing agents include small organic molecules such as formaldehyde, formic acid, methanol, ethylene, and hydrides such as lithium aluminum hydride and sodium borohydride.

15 **F. Support Materials**

The nanocatalyst particles are deposited and/or formed on a support material. The support may be organic or inorganic. It may be chemically inert, or it may serve a catalytic function complementary to the nanocatalyst. The support may be in a variety of physical forms. It may be porous or nonporous. It may be a three-dimensional structure, such as a powder, granule, tablet, or extrudate. The support may be a two-dimensional structure such as a film, membrane, or coating. It may be a one-dimensional structure such as a narrow fiber.

One class of support materials includes porous, inorganic materials, such as alumina, silica, titania, kieselguhr, diatomaceous earth, bentonite, clay, zirconia, magnesia, metal oxides, zeolites, and calcium carbonate. Another useful class of supports includes carbon-based materials, such as carbon black, activated carbon, graphite, fluoridated carbon, and the like. Other supports include polymers and other inorganic solids, metals, and metal alloys.

The nanocatalyst particles can be deposited within a wide range of loadings on the support material. The loading can range from about 0.01% to about 70 wt% of the supported nanocatalyst particles, more preferably in a range of about 0.1% to about 25%. In the case where the support material is porous, it is preferable for the surface area to be at least about 20 m²/g, more preferably at least about 50 m²/g.

III. METHODS OF MAKING COLLOIDS AND SUPPORTED NANOCATALYSTS

The process for manufacturing colloids according to the present invention can be broadly summarized as follows. First, one or more types of catalytic metal atoms (*e.g.*, in the form of a ground state metal or ionized metal salt) and one or more types of dispersing agent molecules (*e.g.*, in the form of a carboxylic acid salt) are selected. The metal atoms and the dispersing agent molecules are dissolved in a solvent and reacted to form a plurality of complexed metal atoms. The complexed metal atoms are reduced with a reducing agent to form a plurality of nanocatalyst particles dispersed in the solvent, thereby forming a colloid. A base is included in the mixture to improve the stability of the particles. The base allows the particles to be manufactured as a colloid in a more concentrated form and/or allows the colloid to be concentrated after particle formation without causing significant precipitation of the nanoparticles.

The base is preferably added in sufficient quantity to stabilize the colloidal particles. In an exemplary embodiment an amount of base is added to raise the pH by about 0.25, more preferably 0.5. The base should be added in sufficient quantity to yield a solution preferably having a pH of at least about 4.5, more preferably at least about 4.75, and most preferably at least about 5.0.

The concentration of the metal in the final colloid can be increased as compared to colloids that are not stabilized with a base. In an exemplary embodiment the concentration of the metal in the final colloid is preferably greater than about 150 ppm by weight, more preferably greater than about 200 ppm by weight, and most preferably greater than about 300 ppm by weight.

It has been found that adding a basic compound to the reaction mixture improves the stability of the nanoparticles and allows the nanoparticles to remain dispersed in the solvent in higher concentrations than colloids prepared without the base. This stabilization of the colloidal particles has been observed for mixtures with different initial pH. It is believed that the addition of base can have a stabilizing effect that is apart from and/or in addition to a mere adjustment in pH. However, the invention is not limited to this theory.

The concentration of the metal in the colloid is a consequence of the ratio of solvent to metal ions. Increasing the amount of solvent decreases the metal concentration, while decreasing the amount of solvent increases the metal concentration. In the method of the present invention, the metal concentration can be determined by selecting an initial ratio of metal to solvent that provides the desired concentration ratio or alternatively, the ratio of metal to solvent can be increased after the nanoparticles are formed by removing a portion of the solvent. A combination of both of these embodiments can also be performed.

In the first embodiment, the colloid is prepared at full concentration (*i.e.*, the concentration of the metal is close to or the same as the final concentration). The metal atoms, organic dispersing agent, solvent, base, and other components are mixed together in an appropriate amount of solvent such that the colloid will have a desired final concentration of metal. (*e.g.*, 150 ppm by weight). In an alternative embodiment, the colloidal particles can be formed at a lower concentration and then a portion of the solvent can be removed to increase the metal concentration to a desired final concentration.

The base can be added to the reaction mixture at various points in the reaction sequence. In one embodiment, the base is added prior to or during formation of the colloidal nanoparticles. Protons created during the formation of the nanoparticles do not cause significant precipitation because of the added base. Preferably the base is added after the metal atoms are complexed with the organic dispersing agent such that the higher pH does not affect the formation of the organometallic complexes. Adding the base to the reaction mixture before particle formation can be advantageous because it allows the

nanoparticles to be formed in a more concentrated mixture, thus avoiding the difficulty and expense of concentrating the colloid after particle formation. Although the present invention includes stabilizing the particles before or during particle formation and thereafter increasing the concentration of the metal particles in the colloid.

In an alternative embodiment, the base is added to the reaction mixture after nanoparticles form. The base is added before significant precipitation occurs. The amount of time available to add the base after particle formation depends on the concentration of metal and the temperature, and the pH of the colloid. Depending on the instability of the particles, the base may need to be added within a few minutes or a few hours.

In the case where the final concentration of the colloidal nanoparticles is achieved by removing a portion of the solvent, the concentration of the metal atoms is kept low such that formation of the particles does not create enough protons to destabilize the colloid. In this case the base can be added before, during, or just after the colloidal solution is concentrated. As solvent is removed, the metal concentration increases. However, since the protons are neutralized with base, there is not a corresponding increase in protons (*i.e.*, drop in pH). In this manner, the concentration of the colloid can be increased without destabilizing the nanoparticles. Concentrating the colloid (*i.e.*, after particle formation) can be advantageous where adding base to the reaction mixture adversely affects particle formation and/or performance.

IV. EXAMPLES

The following examples provide formulas for making concentrated colloids containing metal nanoparticles. The formulas in the examples were prepared using a Pd²⁺ solution, a Pt⁴⁺ solution, and a polyacrylate solution.

The Pd²⁺ solution (0.0799 wt %) was prepared by dissolving 1.3339 g of PdCl₂ (Assay 59.57% Pd) in 4.76 g of HCl (12.1M) and diluting to 1000 ml with de-ionized water. The Pt⁴⁺ solution (0.010 wt. % Pt) was prepared by diluting 0.2614 g of H₂PtCl₆ (Mw: 517.92, 39.85% Pt by weight) to 1000 ml with de-ionized water. The polyacrylate solution was prepared by diluting 15

g of Poly(acrylic acid, sodium salt) solution (45 wt. % in water, MW 1200) to 100 g with de-ionized water.

Example 1: 611 ppm Metal Concentrated Colloid

Example 2 describes a method for making a colloid with a metal
5 concentration of 611 ppm by weight, according to the present invention. 75
ml of Pd²⁺ solution (0.0799 wt %), 12 ml of Pt⁴⁺ solution (0.010 wt %) and 10
ml polyacrylate solution (6.75 wt %) were mixed in a 250 ml flask. 0.125 g of
NaHCO₃ in 3 ml of de-ionized water was slowly added with stirring. The
solution was purged for 1.5 hr with nitrogen (100 ml/min), and then purge for
10 15 minutes with hydrogen (50 ml/min). The flask was then sealed and allowed
to stand overnight under stirring. After one week, this colloid still remained
stable (*i.e.*, no substantial precipitation was observed).

Example 2: 367 ppm Metal Concentrated Colloid

Example 2 describes a method for making a colloid with a metal
15 concentration of 367 ppm by weight, according to the present invention. 75
ml of Pd²⁺ solution (0.0799 wt %), 12 ml of Pt⁴⁺ solution (0.010 wt %) and 10
ml polyacrylate solution (6.75 wt %) were mixed and diluted to 163 ml with
de-ionized water in a 250 ml flask. 0.125 g of NaHCO₃ in 3 ml of H₂O was
slowly added with stirring. The solution was purged for 1.5 hr with nitrogen
20 (100 ml/min), and then purge for 15 minutes with hydrogen (50 ml/min). The
flask was then sealed and allowed to stand overnight with stirring. After one
week, the colloid still remained stable (*i.e.*, no substantial precipitation was
observed).

Example 3: 367 ppm Metal Concentrated Colloid (Comparative)

Example 3 describes a method for forming a colloid using the same
25 formula as in Example 3 except that no base was added. Example 3 was
prepared for comparison with Example 2. 75 ml of the Pd²⁺ solution (0.0799
wt %), 12 ml of the Pt⁴⁺ solution (0.010 wt %) and 10 ml of the polyacrylate
30 solution (6.75 wt %) were mixed and diluted to 166 ml with de-ionized water.
The solution was purged for 1.5 hr with nitrogen (100 ml/min), and then purge
for 15 minutes with hydrogen (50 ml/min). The flask was then sealed and

allowed to stand overnight with stirring. On the following day, some precipitation of metal particles was observed on the bottom of the flask.

Example 4: 61 ppm Metal Colloid Preparation (Comparative)

Example 4 describes a Standard Preparation method of manufacturing
5 a colloid with a metal concentration of 61 ppm metal by weight (*i.e.*,
unconcentrated). 75 ml of the Pd²⁺ solution (0.0799 wt %), 12 ml of the Pt⁴⁺
solution (0.010 wt %) and 10 ml the polyacrylate solution (6.75 wt %) were
mixed and diluted to 1000 ml with de-ionized water in a flask. The solution
was purged for 1.5 hr with nitrogen (100 ml/min), and then for 0.5 hr with
10 hydrogen (100 ml/min). The flask was then sealed and allowed to stand
overnight with stirring. The colloid was stable for over a week.

Example 5: 122 ppm Metal Colloid Preparation (Comparative)

Example 5 describes a method of manufacturing a colloid with a metal
concentration of 122 ppm metal by weight. 75 ml of the Pd²⁺ solution (0.0799
15 wt %), 12 ml of the Pt⁴⁺ solution (0.010 wt %) and 10 ml of the polyacrylate
solution (6.75 wt %) were mixed and diluted to 500 ml with de-ionized water
in a flask. The solution was purged for 1.5 hr with nitrogen (100 ml/min), and
then for 0.5 hr with hydrogen (100 ml/min). The flask was then sealed and
allowed to stand overnight with stirring. The colloid was stable for over a
20 week.

Examples 2–5 show the effect of concentrating the colloid and adding
base or acid. The comparative concentrated colloid in Example 3 was not
stable whereas the standard (*i.e.*, unconcentrated) colloid of Example 4 was
stable. The only difference between Examples 3 and 4 was the amount of
25 solvent. Example 2, which had the same metal concentration as the unstable
comparative colloid in Example 4 was made stable with the addition of base.

Example 6: 367 ppm Metal Concentration Colloid (Comparative)

Example 6 describes a method for making a colloid with a metal
concentration of 367 ppm metal by weight using an acid. Example 6 was
30 prepared for comparison with Example 2, which was made using a base. 75
ml of Pd²⁺ solution (0.0799 wt %), 12 ml of Pt⁴⁺ solution (0.010 wt %), 10 ml
polyacrylate solution (6.75 wt %) and 0.1 ml of HCl (12.1M) were mixed and

diluted to 166 ml with de-ionized water in a 250 ml flask. The solution was purged for 1.5 hr with nitrogen (100 ml/min), and then switch to hydrogen flow (50 ml/min). After purging with H₂ for 7 minutes, black precipitate was observed on the bottom of the flask.

5 **Example 7: 367 ppm Metal Concentration Colloid (Comparative)**

Example 7 describes a method for making a colloid with a metal concentration of 367 ppm metal by weight using an acid. Example 7 was prepared for comparison with Example 2, which was made using a base. 75 ml of the Pd²⁺ solution (0.0799 wt %), 12 ml of Pt⁴⁺ solution (0.010 wt %), 10
10 ml polyacrylate solution (6.75 wt %) and 0.598 ml of HCl (12.1M) were mixed and diluted to 166 ml with de-ionized water in a 250 ml flask. The solution was purged for 1.5 hr with nitrogen (100 ml/min), and then with hydrogen (50 ml/min). After purging H₂ for only a few minutes, black precipitation was observed on the bottom of the flask. Examples 6 and 7 show
15 that addition of acid has an undesired effect on particle stability compared to the addition of base.

Example 8: Manufacture of Supported Catalyst

Example 8 describes a method for manufacturing a supported catalyst using the colloid prepared in Example 1, according to the present invention.
20 The supported catalyst with a loading of 0.1% Pd by weight was prepared as follows: sulfated silica beads (60 g) were placed in a 1 liter glass beaker. Sufficient amount of anhydrous methanol (99.5 %) was added to cover the support. The support was allowed to soak in methanol for 1 hr. After the excess methanol was drained, 100 ml of the colloid prepared in Example 2
25 was added. The resulting solution was heated with continuous rotation under an IR lamp at a temperature of 70–80 °C. This heating and drying step lasted for about 30 minutes until the drying process was complete. The resulting catalyst was then left in an oven (90 °C) overnight.

The catalyst was then reduced with hydrogen gas using the following
30 procedure: (i) purge at room temperature with nitrogen (100 ml/min) for 15 minutes; (ii) switch to hydrogen (100 ml/min); (iii) heat to 90 °C over 0.5 hour; (iv) hold for 2 hours at 90 °C; (v) ramp to 175 °C over 0.5 hour; (vi)

then hold for 17 hours at 175 °C. At the completion of the 17 hour hold, the catalyst was cooled to 150 °C and the reactor was purged with nitrogen (100 ml/min) at 150 °C for 4 hours. After final cooling the catalyst was ready for use.

5 **Example 9: Manufacture of Supported Catalyst (Comparative)**

Example 9 describes a method for manufacturing a supported catalyst using the comparative colloid prepared in Example 5. The supported catalyst with a loading of 0.1% Pd by weight was prepared as follows: sulfated silica beads (60 g) were placed in a 1 liter glass beaker. Sufficient amount of anhydrous methanol (99.5 %) was added to cover the support. The support was allowed to soak in methanol for 1 hr. After the excess methanol was drained, 100 ml of the colloid prepared in Example 2 was added. The resulting solution was heated with continuous rotation under an IR lamp at a temperature of 70–80 °C. This heating and drying step lasted for about 30 minutes until the drying process was complete. The resulting catalyst was then left in an oven (90 °C) overnight.

The catalyst was then reduced with hydrogen gas using the following procedure: (i) purge at room temperature with nitrogen (100 ml/min) for 15 minutes; (ii) switch to hydrogen (100 ml/min); (iii) heat to 90 °C over 0.5 hour; (iv) hold for 2 hours at 90 °C; (v) ramp to 175 °C over 0.5 hour; (vi) then hold for 17 hours at 175 °C. At the completion of the 17 hour hold, the catalyst was cooled to 150 °C and the reactor was purged with nitrogen (100 ml/min) at 150 °C for 4 hours. After final cooling the catalyst was ready for use.

25 **Example 10: Use of Supported Catalyst in H₂O₂ Process**

Example 10 describes a method for manufacturing H₂O₂ using the supported catalyst of Example 8. 6.15 g of the catalyst manufactured in Example 8 (containing 0.1% wt% Pd) was charged to a tubular fixed bed reactor with a nominal diameter of 0.5 inches. The tubular reactor was operated at a pressure of 750 psig, and maintained at an internal temperature of 35 °C. The tubular reactor was fed continuously with 2000 sccm (standard cubic centimeters per minute) of a gas feed containing 3 vol% hydrogen, 40

vol% oxygen, and the balance inert gas. The reactor was also fed continuously with 36 cc/hr of a liquid feed containing 4 wt% water, 400 ppmw H₂SO₄, and 15 ppmw NaBr and the balance methanol. Gaseous and liquid effluents from the tubular reactor were collected continuously and analyzed to obtain data on the amount of hydrogen converted and the amount of hydrogen peroxide generated. Based on these measurements, the hydrogen conversion was determined to be 60%, the selectivity to hydrogen peroxide (based on hydrogen converted) to be 71% and the productivity (g H₂O₂ produced per g Pd per hour) to be 390 g H₂O₂/g Pd/hr.

10 **Example 11: Use of Supported Catalyst in H₂O₂ Process (Comparative)**

Example 11 describes a method for manufacturing H₂O₂ using the supported catalyst of Example 9 (comparative). 6.15 g of the catalyst manufactured in Example 9 (containing 0.1% wt% Pd) was charged to the tubular reactor of Example 10. Reaction conditions, feed rates and compositions were the same as Example 10, with the exception that the feed rate was 2200 sccm. Based on effluent analysis, the hydrogen conversion was found to be 63%, the selectivity to hydrogen peroxide (based on hydrogen converted) to be 69%, and the productivity to be 450 g H₂O₂/g Pd/hr.

The results from Examples 10 and 11 demonstrate that a catalyst made with the high concentration colloid of the present invention gives performance that is essentially equivalent to a comparative catalyst made using a low concentration colloid. In particular, the selectivity towards hydrogen peroxide production for the catalyst of the present invention is equal to or higher than that of the comparative catalyst.

25 The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

CLAIMS

What is claimed is:

1. A method for making a concentrated metal colloid, comprising:
 - (i) mixing together a solvent, a plurality of metal atoms, and a plurality of organic agent molecules, each organic agent molecule comprising at least one functional group capable of bonding with the metal atoms;
 - (ii) reacting the metal atoms with the organic agent molecules to form a mixture comprising a plurality of complexed metal atoms;
 - (iii) reducing the complexed metal atoms in the mixture using a reducing agent to form a plurality of nanoparticles; and
 - (iv) adding an amount of a base to the mixture, thereby improving the stability of the nanoparticles in the mixture,wherein the final concentration of the metal in the mixture is at least about 150 ppm by weight.
2. A method as in claim 1, wherein the base is a weak base.
3. A method as in claim 2, wherein the weak base comprises a base selected from the group consisting of ammonium acetate, sodium acetate, sodium phosphate, ammonium phosphate, organic bases, aniline, pyridine, imidazoles, trimethyl amine, methylamine, dimethylamine, and carbonates or bicarbonates of Na, Li, K, Rb, Cs, Be, Mg, Ca, Sr, Ba, or ammonium.
4. A method as in claim 1, wherein the final concentration is at least about 200 ppm by weight.
5. A method as in claim 1, wherein the final concentration is at least about 300 ppm by weight.
6. A method as in claim 1, wherein the reducing agent is hydrogen gas.
7. A method as in claim 1, wherein the base is added before the nanoparticles are formed.
8. A method as in claim 1, wherein the base is added after the nanoparticles are formed.

9. A method as in claim 1, wherein the amount of base added raises the pH of the mixture by at least about 0.25.

10. A method as in claim 1, wherein the amount of base added raised the pH of the mixture by at least about 0.5.

5 11. A method as in claim 1, wherein the base is added so that the mixture has a pH of at least about 5.0.

12. A method as in claim 1, further comprising removing a portion of the solvent to achieve the final concentration.

10 13. A method of manufacturing a supported catalyst comprising depositing the nanoparticles of claim 1 on a catalyst support material.

14. A colloidal suspension of nanoparticles manufactured according to the method of claim 1.

15. A method for making a supported catalyst, comprising:

15 (i) mixing together a solvent, a plurality of metal atoms, and a plurality of organic agent molecules, each organic agent molecule comprising at least one anion;

(ii) reacting the metal atoms with the organic agent molecules in a solvent to form a mixture comprising a plurality of complexed metal atoms, wherein the concentration of metal atoms is greater than
20 about 150 ppm by weight;

(iii) reducing the complexed metal atoms in the mixture using a reducing agent to form a plurality of nanoparticles, the nanoparticles forming a colloid;

(iv) adding an amount of a base to the mixture to raise the pH
25 by at least about 0.25, thereby improving the stability of the nanoparticles in the mixture; and

(v) contacting the colloid with a catalyst support material and removing the liquid portion of the colloid to yield a supported catalyst.

30 16. A method as in claim 15, wherein the concentration of metal atoms is greater than about 200 ppm by weight.

17. A method as in claim 15, wherein the concentration of metal atoms is greater than about 300 ppm by weight.

18. A method as in claim 15, wherein the amount of base added raised the pH of the mixture by at least about 0.5.

5 19. A method of manufacturing hydrogen peroxide comprising reacting hydrogen and oxygen in the presence of the catalyst formed according to the method of claim 15.

20. A concentrated colloidal metal composition, comprising:
a solvent;

10 a plurality of nanoparticles suspended in the solvent thereby forming a colloidal composition, each nanoparticle comprising a plurality of metal atoms and having a plurality of organic dispersing agent molecules bonded to at least a portion of the metal atoms, wherein the metal atoms have a concentration greater than about 150
15 ppm by weight and wherein the colloidal composition has a pH such that the colloidal nanoparticles are substantially stable in the solvent.

21. A concentrated colloidal metal composition as in claim 18, wherein the concentration of metal atoms is greater than about 200 ppm.

22. A concentrated colloidal metal composition as in claim 18,
20 wherein the concentration of metal atoms is greater than about 300 ppm.

23. A concentrated colloidal metal composition as in claim 18, wherein the colloidal composition has a pH of at least about 5.0.