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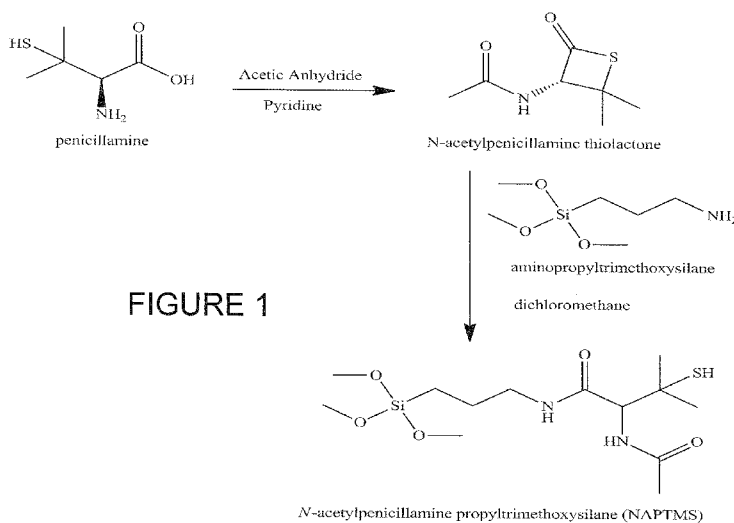
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(54) **Title:** NITRIC OXIDE-RELEASING S-NITROSOTHIOL-MODIFIED SILICA PARTICLES AND METHODS OF MAKING THE SAME

(57) **Abstract:** Provided according to some embodiments of the invention are methods of forming co-condensed silica particles. In some embodiments, the methods include reacting a thiol-containing silane and a backbone alkoxysilane in a reaction solution that comprises water to form thiol-functionalized co-condensed silica particles, wherein the thiol-functionalized co-condensed silica particles include a polysiloxane matrix and at least some of thiol groups are present within the polysiloxane matrix; and reacting the thiol-functionalized co-condensed silica particles with a nitrosating agent to provide the S-nitrosothiol-functionalized co-condensed silica particles. In some embodiments, provided are S-nitrosothiol-functionalized co-condensed silica particles.



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NITRIC OXIDE-RELEASING S-NITROSOTHIOL-MODIFIED SILICA PARTICLES AND METHODS OF MAKING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from U.S. Provisional Application Serial No. 61/447,368, filed February 28, 2011, and U.S. Provisional Application No. 61/565,694, filed December 1, 2011, the disclosure of each of which is hereby incorporated by reference herein in its entirety.

STATEMENT OF GOVERNMENT SUPPORT

The present invention was funded in part by government support under grant number 5-R01-EB000708 from the National Institutes of Health. The United States Government has certain rights in this invention.

FIELD OF THE INVENTION

The present invention relates to nitric oxide-releasing particles. More particularly, the present application relates to S-nitrosothiol-modified silica particles.

BACKGROUND OF THE INVENTION

Since the discovery of the physiological roles of nitric oxide (NO), much research has focused on the synthesis of NO-releasing materials/vehicles to elicit NO's characteristics as an antimicrobial agent, mediator of wound repair, or angiogenic cofactor. S-Nitrosothiols (RSNOs) are one class of endogenous NO donor believed to store/transport the majority of the body's natural reservoir of NO. As such, a large body of work has utilized low molecular weight RSNOs (e.g., S-nitroso-glutathione (GSNO), S-nitroso-N-acetylcysteine (SNAC), and S-nitroso-N-acetyl-penicillamine (SNAP)) as donors to spontaneously release NO. Although promising, the clinical application of low molecular weight NO donors has been slow due to both lack of tissue specific targeting and uncontrollable NO release kinetics. To address such shortcomings, NO donor precursors have been conjugated to larger scaffolds (e.g., proteins, dendrimers, and nanoparticles), thus enabling high NO storage per delivery vehicle and release profiles similar to their small molecule analogues.

Silica particles are among the most widely employed macromolecular scaffolds for biomedical applications due to facile synthetic strategies and minimal cytotoxicity. Previously, the surface of fumed silica particles (7–10 nm diameter) have been grafted with

SNAP, SNAC, and *S*-nitrosocysteine (CysNO) to create *S*-nitrosothiol-modified silica particles. However, the NO storage was limited to 0.021–0.138 $\mu\text{mol mg}^{-1}$ because the thiol functionalization was restricted to the exterior of the particle. Additionally, these systems are not able to tune particle size to fit a therapeutic system of interest. Alternatively, the hydrolysis and co-condensation of organosilane and tetraalkoxysilane precursors via sol-gel chemistry may represent a method for preparing a silica network with a higher concentration of organic functionalites. Indeed, the Stöber process (sol-gel chemistry with an alcohol solvent and an ammonia catalyst) has proven effective for synthesizing *N*-diazoniumdiolate-modified silica particles of diverse size and NO storage capacity. See, for example, U.S. Publication No. 2009/0214618 (Schoenfisch et al.), which is herein incorporated by reference in its entirety. The advantage of the Stöber method over surface grafting is that the co-condensation provides uniform incorporation of the organic (i.e., NO donor) functionality throughout the resulting silica network as opposed to restricted functionalization at the surface alone. As a result, such particles may exhibit significantly increased NO storage.

SUMMARY OF THE INVENTION

A first aspect of the present invention comprises a method of forming *S*-nitrosothiol-functionalized co-condensed silica particles comprising:

reacting a thiol-containing silane and a backbone alkoxysilane in a sol precursor solution that comprises water to form thiol-functionalized co-condensed silica particles, wherein the thiol-functionalized co-condensed silica particles comprise a polysiloxane matrix and at least some of thiol groups are present within the polysiloxane matrix; and

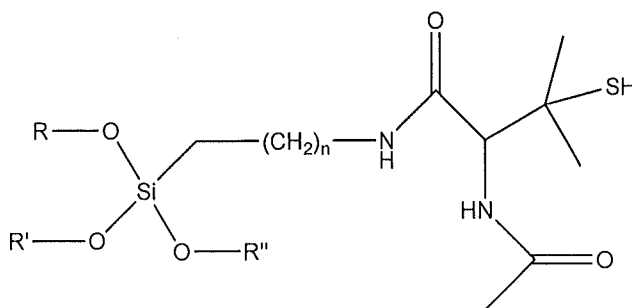
reacting the thiol-functionalized co-condensed silica particles with a nitrosating agent to provide the *S*-nitrosothiol-functionalized co-condensed silica particles.

A second aspect of the present invention comprises *S*-nitrosothiol-functionalized monodisperse co-condensed silica particles having an average particle diameter in a range of about 10 nm to about 100 μm .

A further aspect of the present invention comprises *S*-nitrosothiol-functionalized co-condensed silica particles having an NO storage in a range of about 0.01 μmol to about 10 μmol NO per mg particle.

Another aspect of the present invention comprises a *S*-nitrosothiol-functionalized co-condensed silica particle comprising tertiary nitrosothiol functional groups.

A further aspect of the present invention comprises a compound having the following structure:



wherein R, R' and R'' are each independently alkyl and n is 0 in a range of 0 to 10.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are included to provide a further understanding of the invention and are incorporated in and constitute a part of this application, illustrate certain embodiment(s) of the invention.

Figure 1 provides a scheme for the synthesis of N-acetylpenicillamine propyltrimethoxysilane (NAPTMS).

Figure 2 provides an ^1H NMR spectrum of the NAPTMS compound.

Figure 3 shows a solid-state cross polarization/magic angle spinning (CP/MAS) ^{29}Si NMR spectra of silica synthesized with (A) 0, (B) 25, (C) 40, (D) 60, (E) 75, and (F) 85 mol % MPTMS (balance TMOS). The Q and T bands have been designated.

Figure 4 shows the scanning electron micrographs of (A) 25, (B) 40, (C) 60, (D) 75 and (E) 85 mol% MPTMS (balance TMOS) and (F) 75 and (G) 85 mol % MPTMS (balance TEOS) particles synthesized with 16.0 M water, 5.5 M ammonia, and 0.1 M silane.

Figure 5 shows the scanning electron micrographs of (A) 25, (B) 40, (C) 60, (D) 75 and (E) 85 mol% MPTMS (balance TMOS) and (F) 75 and (G) 85 mol % MPTMS (balance TEOS) particles synthesized via a semi-batch process with a silane feed rate of 0.5 mL min^{-1} .

Figure 6 shows the scanning electron micrographs of 75 mol% MPTMS (balance TEOS) synthesized with (A) 47.0, (B) 42.0, (C) 40.6, (D) 36.5, (E) 32.5, and (F) 24.9 M water.

Figure 7 shows the scanning electron micrographs of (A-B) 25, (C-D) 40, (E-F) 60, (G-H) 75, and (I-J) 85 mol% MPTMS (balance TMOS) and (K-L) 85 mol % MPTMS (balance TEOS) particles synthesized with (A,C,E,F,G,I,K) 32.5 and (B, D, F, H, J, L) 24.9 M water.

Figure 8 shows a schematic for the S-nitrosothiol decomposition pathways.

Figure 9 shows the nitric oxide release from RSNO-modified 75 mol% MPTMS (balance TEOS) particles in the presence of (A) 0 (—), 60 (— —), 100 (···), and 200 (— ·) W

irradiation at 0 °C and (B) 0 (—), 10 (— —), and 25 (···) μM CuBr_2 /PBS solution at 0 °C. Note: 0 μM CuBr_2 is 500 μM DTPA (pH 7.4 PBS). The inset of A provides an enlarged view of NO release profile without irradiation.

Figure 10 shows SEM images of tertiary thiol-functionalized co-condensed silica particles according to some embodiments of the invention prior to sonication.

Figure 11 shows SEM images of tertiary thiol-functionalized co-condensed silica particles according to some embodiments of the invention after 30 minutes sonication followed by nitrosation.

Figure 12 shows SEM images of tertiary thiol-functionalized co-condensed silica particles according to some embodiments of the invention after 60 minutes sonication followed by nitrosation.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

The foregoing and other aspects of the present invention will now be described in more detail with respect to the description and methodologies provided herein. It should be appreciated that the invention can be embodied in different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

The terminology used in the description of the invention herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used in the description of the embodiments of the invention and the appended claims, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. Also, as used herein, "and/or" refers to and encompasses any and all possible combinations of one or more of the associated listed items. Furthermore, the term "about," as used herein when referring to a measurable value such as an amount of a compound, dose, time, temperature, and the like, is meant to encompass variations of 20%, 10%, 5%, 1%, 0.5%, or even 0.1% of the specified amount. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. Unless otherwise defined, all terms, including technical and scientific terms used in the description, have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs.

All patents, patent applications and publications referred to herein are incorporated by reference in their entirety. In the event of conflicting terminology, the present specification is controlling.

The embodiments described in one aspect of the present invention are not limited to the aspect described. The embodiments may also be applied to a different aspect of the invention as long as the embodiments do not prevent these aspects of the invention from operating for its intended purpose.

Chemical Definitions

As used herein the term "alkyl" refers to C₁₋₂₀ inclusive, linear (i.e., "straight-chain"), branched, or cyclic, saturated or at least partially and in some cases fully unsaturated (i.e., alkenyl and alkynyl) hydrocarbon chains, including for example, methyl, ethyl, propyl, isopropyl, butyl, isobutyl, *tert*-butyl, pentyl, hexyl, octyl, ethenyl, propenyl, butenyl, pentenyl, hexenyl, octenyl, butadienyl, propynyl, butynyl, pentynyl, hexynyl, heptynyl, and allenyl groups. "Branched" refers to an alkyl group in which a lower alkyl group, such as methyl, ethyl or propyl, is attached to a linear alkyl chain. Exemplary branched alkyl groups include, but are not limited to, isopropyl, isobutyl, *tert*-butyl. "Lower alkyl" refers to an alkyl group having 1 to about 8 carbon atoms (i.e., a C₁₋₈ alkyl), e.g., 1, 2, 3, 4, 5, 6, 7, or 8 carbon atoms. "Higher alkyl" refers to an alkyl group having about 10 to about 20 carbon atoms, e.g., 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, or 20 carbon atoms. In certain embodiments, "alkyl" refers, in particular, to C₁₋₅ straight-chain alkyls. In other embodiments, "alkyl" refers, in particular, to C₁₋₅ branched-chain alkyls.

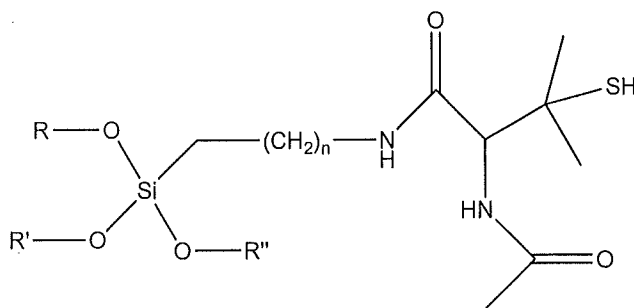
The term "mercapto" or "thio" refers to the -SH group.

Provided herein according to some embodiments of the invention are methods of forming co-condensed silica particles via the Stöber process. See, e.g., Stöber, W.; Fink, A.; Bohn, E. *J. Colloid Interface Sci.* **1968**, 26, 62 (incorporated by reference herein in its entirety). Particle formation under the Stöber process proceeds upon hydrolysis and condensation of silane precursors where the relative hydrolysis rates for the precursors dictate both the speed of particle growth and the likelihood of each silane's incorporation into the silica network. Excessive disparities between reaction rates of different silanes may lead to absence of particle formation upon attempted co-condensation.

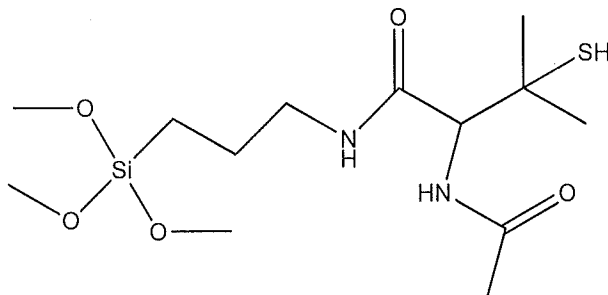
Provided according to some embodiments of the invention are methods of forming S-nitrosothiol-functionalized co-condensed silica particles that include reacting a thiol-

containing silane and a backbone alkoxy silane in a sol precursor solution that includes water to form thiol-functionalized co-condensed silica particles, wherein the thiol-functionalized co-condensed silica particles include a polysiloxane matrix and at least some of thiol groups are present within the polysiloxane matrix. In some embodiments of the invention, the methods further include reacting the thiol-functionalized co-condensed silica particles with a nitrosating agent to provide the S-nitrosothiol-functionalized co-condensed silica particles.

Any suitable thiol-containing silane may be used. In some embodiments, the thiol-containing silane includes a primary thiol, in some embodiments, a secondary thiol, and in some embodiments, a tertiary thiol. Combinations of different silanes may also be used. A suitable thiol-containing silane will be a silane that will allow for particle formation, and in some embodiments, monodisperse particle formation. Thus, some thiol-containing silanes may be suitable with some backbone alkoxy silanes and not suitable with others. In some embodiments, the primary thiol-containing silane is mercaptopropyltrimethoxysilane. In some embodiments, the tertiary thiol alkoxy silane has the following structure:
 $(OR)(OR')(OR'')Si(R^x)$, wherein R, R' and R'' are each independently H, alkyl or substituted alkyl and R^x is functional group that comprises a tertiary thiol group. In particular embodiments, the tertiary thiol alkoxy silane has the structure:



wherein R, R' and R'' are each independently H, alkyl or substituted alkyl and n is 0-10. In some embodiments, R, R' and R'' are each independently alkyl and n is 0-5. Furthermore, in particular embodiments of the invention, the tertiary thiol is a compound having the structure:



Any suitable backbone alkoxysilane may be used. As used herein, the term "backbone alkoxysilane" refers to an alkoxysilane that does not contain a thiol functional group. Examples include tetramethoxysilane, tetraethoxysilane, methyltrimethoxysilane, methyltriethoxysilane and butyltrimethoxysilane. A suitable backbone silane will be a silane that will allow for particle formation, and in some embodiments, monodisperse particle formation.

Any suitable concentration of water may be used. In some embodiments, the water concentration in the sol precursor solution is in a range of about 8 M to about 32.5 M.

In some embodiments, a catalyst, such as an ammonia catalyst, is included in the sol precursor solution. Any suitable concentration of catalyst may be used. However, in some embodiments, an ammonia catalyst is included in the sol precursor solution, in some embodiments, at a concentration in a range of about 1.9 M to about 5.5 M.

In particular embodiments of the invention, mercaptopropyltrimethoxysilane and tetramethoxysilane are reacted in the presence of water and an ammonia catalyst to form thiol-functionalized co-condensed silica particles. In some embodiments, the reaction occurs in a solution that includes mercaptopropyltrimethoxysilane and tetramethoxysilane at a total silane monomer concentration in a range of about 0.1 M to about 0.4 M, wherein the silane monomer includes about 25 to about 85 mol % mercaptopropyltrimethoxysilane. In some embodiments, water is present in the solution at a concentration in a range of about 8.0 to about 32.5 M and the ammonia catalyst is present at a concentration in a range of about 1.9 M to about 5.5 M.

In some embodiments of the invention, mercaptopropyltrimethoxysilane and tetraethoxysilane are reacted in the presence of water and an ammonia catalyst to form thiol-functionalized co-condensed silica particles. In some embodiments, the reaction occurs in a solution that includes mercaptopropyltrimethoxysilane and tetraethoxysilane at a total silane monomer concentration in a range of about 0.1 M to about 0.4 M, wherein the silane monomer includes about 75 to about 85 mol % mercaptopropyltrimethoxysilane. In some embodiments, water is present in the solution at a concentration in a range of about 8.0 to about 32.5 M and the ammonia catalyst is present at a concentration in a range of about 1.9 M to about 5.5M.

In some embodiments, methods of forming thiol-functionalized co-condensed silica particles include reacting a tertiary thiol-containing silane and a backbone alkoxysilane in the presences of water and an ammonia catalyst to form thiol-functionalized co-condensed silica particles. In some embodiments, the reaction occurs in a solution that includes tertiary thiol-

containing silane and alkoxy silane at a total silane monomer concentration in a range of about 0.1 M to about 0.4 M, wherein the silane monomer includes about 25 to about 85 mol % tertiary thiol-containing silane. In some embodiments, water is present in the solution at a concentration in a range of about 8.0 to about 32.5 M and the ammonia catalyst is present at a concentration in a range of about 1.9 to about 5.5 M.

The sol precursor solution may also be stirred/agitated as known to those of skill in the art, and other additives or silane monomers used in sol chemistry may be included in some embodiments of the invention.

In some embodiments of the invention, methods provided herein may be used to form nitrosothiol-functionalized co-condensed silica particles, which in some embodiments, are monodisperse. As used herein, the term "monodisperse" refers to particles having a uniform particle size, in some embodiments, having an average particle diameter ± 100 nm as measured from electron micrographs; a Z-average ± 60 nm as measured from dynamic light scattering; and/or having a polydispersity index ≤ 0.1 as measured via dynamic light scattering. In some embodiments, the methods described herein provide monodisperse particles having an average particle diameter of less than 100 microns, and in some embodiments, less than 1 micron. In particular embodiments, the methods used herein may provide monodisperse particles having an average particle diameter in a range of about 10 nm to about 100 μ m. In some embodiments, the particles have an average particle diameter in a range of about 200 to about 700 nm.

Any suitable method of nitrosating the thiol-functionalized co-condensed silica particles may be used. Further, any suitable nitrosating agent may be used. However, in some embodiments, the nitrosating agent includes acidified sodium nitrite, alkyl nitrites, including tertbutyl nitrite and isopentyl nitrite, and various nitrogen oxides including nitrous oxide, N_2O_3 , N_2O_4 and NO_2 . Examples of nitrosation may be found in Williams, D. L. H. *Acc. Chem. Res.* **1999**, *32*, 869, the contents of which are incorporated herein by reference in their entirety.

In some embodiments of the invention, the nitrosation chemistry conserves particle size integrity and yields monodisperse S-nitrosothiol-functionalized co-condensed silica particles. No changes in particle size have been observed following addition of the nitric oxide functionality to the macromolecular structure, a drawback that has been observed with other nitrosothiol-modified macromolecular donors. Furthermore, as shown below in the Examples, the thiol-functionalized co-condensed silica particles may be sonicated prior to nitrosation without deleteriously affecting the NO storage and/or morphology of the particles.

The co-condensed silica particles may include S-nitrosothiol groups throughout the particle, and as such, may provide enhanced NO storage properties. For example, in some embodiments of the invention, provided are S-nitrosothiol-functionalized co-condensed silicas particles that have an NO storage in a range of about 0.01 μmol to about 10 μmol NO per mg particle, and in some embodiments, 0.09 μmol to about 4.40 μmol NO per mg particle.

The incorporation of the S-nitrosothiol groups throughout the interior of the silica particle structure may also afford unexpected stability. Glutathione and other thiols are known to one skilled in the art to be a vial trigger for RSNO decomposition and release a variety of NO_x species. In some embodiments of the invention, the low porosity of the S-nitrosothiol-functionalized co-condensed silica particles protect the RSNO donors from premature decomposition by glutathione or other blood components, adding a level of nitric oxide stability when used in drug delivery applications.

EXAMPLES

Preparation of NAPTMS

Synthesis of N-Acetyl Penicillamine (NAP) Thiolactone. Acetic anhydride (96 mmol, 9.80 g) was added dropwise to a well stirred solution of D-(-) penicillamine (40 mmol, 5.97 g) in pyridine (50 mL) at 0 °C. After 30 min, the flask was removed from ice and allowed to stir at room temperature for 15 h. The resultant orange solution was partitioned between chloroform and dilute HCl and washed 4x with dilute HCl. After drying over MgSO₄, the organic phase was evaporated to yield an orange residue. The residue was first dissolved in absolute ethanol (20 mL), and then precipitated in pentane at -78 °C. The light yellow crystalline product was isolated by filtration (2.07 g, 30%). ¹H NMR (CDCl₃) δ 1.65 (s, CH₃), 1.86 (s, CH₃), 2.05 (s, NHCOCH₃), 5.68-5.70 (d, CH(CH₃)₂), 6.56 (NHCOCH₃). ¹³C NMR (CDCl₃) δ 22.52 (NHCOCH₃), 26.20 (CH(CH₃)₂), 30.22 (CH(CH₃)₂), 51.23 (CH), 169.37 (NHCOCH₃), 192.21 (SCO).

Synthesis of N-Acetyl Penicillamine Propyltrimethoxysilane (NAPTMS). APTMS (10 mmol, 1.78g) was added to a stirring solution of NAP thiolactone (10 mmol, 1.72 g) in methylene chloride (20 mL). The light yellow solution was stirred for 4 h at room temperature before distillation of the methylene chloride to yield NAPTMS as a viscous clear oil. ¹H NMR (CDCl₃) δ 0.54 (t, SiCH₂), 1.24 and 1.39 (s, CH(CH₃)₂SH), 1.54 (m,

SiCH₂CH₂), 1. 96 (s, NHCOCH₃), 2. 96 and 3. 21 (m, SiCH₂CH₂CH₂), 3. 44 (s, Si(OCH₃)₃), 4. 63 (d, CHC(CH₃)₂SH), 6. 99 (d, CHNHCOCH₃), 7. 70 (t, CH₂NHCOCH). ¹³C NMR (CDCl₃) δ □ 6. 59 (SiCH₂), 22. 42 and 22. 97 (CH(CH₃)₂SH), 28. 64 (NHCOCH₃), 30. 80 (SiCH₂CH₂), 41. 93 (CHC(CH₃)₂SH), 46. 23 (SiCH₂CH₂CH₂), 50. 35 (Si(OCH₃)₃), 60. 32 (CHC(CH₃)₂SH), 169. 64 (CHNHCOCH₃), 170. 17 (CHCONH).

The preparation of tertiary thiol-based precursors was investigated for the development of biomedical devices/therapeutics with continuous and photoactivatable NO release. A NAP thiolactone was thus synthesized to design such a precursor for the synthesis of NO-releasing xerogels. Penicillamine was reacted in the presence of acetic anhydride to generate the NAP thiolactone in situ. After characterization by ¹H and ¹³CNMR, the NAP thiolactone was directly coupled with APTMS to result in a tertiary thiol-bearing silane, referred to as NAPTMS (see **Figure 1**). Successful synthesis of this tertiary thiol-bearing silane was verified via ¹HNMR characterization (**Figure 2**).

Example 1: MPTMS

Ratios of mercaptosilane and alkoxysilane (25–85 mol% MPTMS, balance TMOS or TEOS) were added either as a bolus injection or dropwise via a Kent Scientific Genie Plus syringe pump at a flow rate of 0.25–3.0 mL/min through an 18.5 gauge needle to a solution of ethanol, water, and ammonium hydroxide. Solution was stirred for 2 h at room temperature, collected via centrifugation at 4500 rpm (10 mins), washed twice with 40 mL EtOH, recollected, and dried overnight at ambient conditions.

Our initial attempt to synthesize thiol-containing silica particles was based on a bolus injection of 3-mercaptopropyltrimethoxysilane (MPTMS) and alkoxysilane into EtOH/NH₄OH solution. The resulting concentrations of ammonia, water and total silane were 3.3, 8.0, and 0.2 M, respectively. Tetramethoxysilane (TMOS) proved to be a sufficient backbone silane for co-condensation with MPTMS as their combination (at various mole percentages) resulted in the formation of a white precipitate. (~300 mg yield).

As indicated by solution turbidity, a marked increase in reaction time was observed upon increasing the concentration of MPTMS up to 85 mol%. At this concentration, the time to form a visible product after combining the silanes was roughly 15 min. Product formation at MPTMS concentrations >85 mol% was not observed. The inability to form particles at greater MPTMS concentrations may be attributed to the disparate hydrolysis rates between

the silanes, suggesting that co-condensation requires a minimum concentration of the more readily hydrolyzable silane (i.e., TMOS) to initiate particle growth.

Materials synthesized via the co-condensation of MPTMS and tetraethoxysilane (TEOS) formed only in the concentration range of 75–85 mol% MPTMS. In contrast to the TMOS system, products with lower concentrations of MPTMS (e.g., 25 mol%) did not form using TEOS as a backbone, even at prolonged reaction times (up to 48 h).

Example 2: MPMDMS

Another thiol-functionalized monomer, 3-mercaptopropylmethyldimethoxysilane (MPMDMS), was also investigated. Unfortunately, the product yield (~5 mg) formed using MPMDMS with either TMOS or TEOS was significantly lower than MPTMS. The substitution of one of the hydrolyzable methoxy groups with a nonhydrolyzable methyl linkage in MPMDMS (vs. MPTMS) appears to decrease the resulting hydrolysis rate under basic conditions, possibly due to the inductive effect of electron density donation to the Si atom. As a result, the reaction with hydroxide anion to hydrolyze the silane may be inhibited. Particle formation may even be further limited as each MPMDMS molecule is capable of forming only two siloxane bridges. Consequently, particle formation using MPMDMS was unsuccessful.

Example 3: Characterization of first generation mercaptosilane-based silica particles

Solid-state cross polarization/magic angle spinning (CP/MAS) ^{29}Si (71.548 MHz frequency) nuclear magnetic resonance (NMR) spectroscopy was performed on a Bruker 360 MHz DMX spectrometer (Billerica, MA). Particles were packed into 4 mm rotors and spun at 8.0 kHz. Spectra were collected at 5000 scans with the determination of chemical shifts in parts per million relative to an external TMS standard. Nitric oxide release was measured in real time (1 sec intervals) using a Sievers NOATM 280i Chemiluminescence Nitric Oxide Analyzer (NOA) (Boulder, CO). Calibration of the NOA was performed with both air passed through a Sievers NO zero filter and 26.39 ppm NO gas (balance N_2). Nitric oxide-releasing particles were immersed in 25 mL of deoxygenated solution and sparged with an 80 mL min⁻¹ N_2 stream. Additional N_2 was supplied to the reaction flask to match the collection rate of the NOA at 200 mL min⁻¹.

Temperature control was maintained using a water bath at 37 °C. Thermal and photo-initiated NO release were studied by conducting the experiments in 500 μ M DTPA (pH 7.4 PBS) to chelate trace copper and illuminating the sample flask with 60, 100, and 200 W incandescent bulbs, respectively. Copper-initiated NO release was studied by adding the particles to 25 mL of 10 or 25 μ M CuBr₂(aq). The NOA sample flask was shielded from light with aluminum foil for experiments where light was not the intended initiator of NO release. Particle size was determined using a Zetasizer Nano ZS Particle Size and Zeta Potential Dynamic Light Scattering (DLS) Instrument (Malvern, UK). Samples were suspended in PBS at a concentration of 1 mg mL⁻¹ and sonicated for 15 min prior to analysis. Scanning electron micrographs were recorded on a Hitachi S-4700 Scanning Electron Microscope (Pleasanton, CA).

To confirm the incorporation of mercaptosilane within the silica network and compare various compositions, solid-state ²⁹Si cross polarization/magic angle spinning nuclear magnetic resonance (CP/MAS NMR) was used to characterize the MPTMS/TMOS products as a function of MPTMS concentration. Silicon atoms of tetraalkoxysilanes appear in the NMR spectra as Qⁿ bands while those of organotrialkoxysilanes appear as Tⁿ bands. In both cases, n denotes the number of siloxane bonds attached to the Si atom. The greater number of siloxane bonds to the Si atom, the further the NMR band shifts upfield. **Figure 3** shows silica synthesized with (A) 0, (B) 25, (C) 40, (D) 60, (E) 75, and (F) 85 mol % MPTMS (balance TMOS). Particles synthesized entirely from TMOS exhibited only Q bands. With increasing MPTMS concentration in the solution used to prepare the particles, the T bands increased relative to the Q bands, confirming greater incorporation of MPTMS in the silica particle.

Sulfur weight percent of each composition was determined using elemental analysis and further corroborated the covalent incorporation of the mercaptosilane. The weight percent of sulfur in the silica was 4.92, 7.11, 11.67, 13.56 and 17.30 for the 25, 40, 60, 75 and 85 mol% MPTMS (balance TMOS) compositions, respectively. The TEOS-based particles were found to have sulfur weight percents of 16.15 and 19.34 for 75 and 85 mol% MPTMS, respectively. As expected, the weight percent of sulfur increased linearly with increasing MPTMS concentration in the initial solution.

Dynamic light scattering (DLS) measurements indicated that the sample was too polydisperse to accurately measure the particle size. Scanning electron micrographs (SEMs)

further indicated that the thiol-containing silica was polydisperse and exhibited nonspherical morphology more indicative of colloidal silica than individual particles. (data not shown).

Example 4: Variation of water, ammonia and silane concentrations and feed rate

We systematically varied synthetic parameters (i.e., water, ammonia, and silane concentrations) to tune the resulting particle morphology and achieve a more spherical shape. The composition of 25 mol % MPTMS (balance TMOS) was chosen as the model system for comparison due to minimal organic character.

For MPTMS particles, we found that increasing the water content from 8.0 to 16.2 M promoted the formation of spherical particles and prevented aggregation/fusion. Lower ammonia concentrations were shown to result in particles that lacked spherical shape and aggregated. Thus, we discovered that the ratio of water and ammonia to silane was a critical factor during particle synthesis. Upon considering all the data, we determined that the most spherical and monodisperse particles were the 25 mol% MPTMS (balance TMOS) particles were formed using 5.5 M ammonia, 0.1 M total silane, and 16.2 M water. Of note, the product yield (~70 mg) with this synthesis was lower than that obtained for the polydisperse colloidal silica. The decreased yield was due to the 4-fold decrease in the silane concentration used in the optimized synthesis.

Next, the concentration of MPTMS in the solution was increased to enhance the degree of thiol functionality and potential NO storage of the particles. **Figure 4** depicts the resulting particles as the concentration of MPTMS was increased from 25–85 mol% and backbone alkoxysilane varied between TMOS and TEOS. The particles were synthesized with 16.0 M water, 5.5 M ammonia, and 0.1 M silane.

As with the polydisperse colloidal silica system, the formation of particles was not observed for 25–60 mol% MPTMS (balance TEOS). Only 75 and 85 mol% MPTMS concentrations yielded particles with TEOS, illustrating how disparities in hydrolysis and condensation kinetics adversely affect and hinder particle formation. The 75 mol% MPTMS (balance TEOS) particles formed in a narrow size distribution and exhibited spherical morphologies (**Fig. 4F**). In contrast, 85 mol% MPTMS (balance TEOS) particles appeared aggregated (**Fig. 4G**). When using TMOS, 25 mol% MPTMS was the only concentration that yielded spherical, monodisperse particles (**Fig. 4A**). Particles with ≥ 40 mol% MPTMS

(balance TMOS) exhibited ideal morphologies, but with concomitant bimodal size distributions (**Fig. 4B-E**).

To remedy the bimodal size distribution that was observed for certain MPTMS compositions, we evaluated the effect of a silane feed rate of 0.5 mL min^{-1} on particle morphologies throughout the range of compositions (**Figure 5**). The slower feed rate improved the dispersity of the already narrow size distribution for 25 mol % MPTMS (**Fig 5A**). A pronounced improvement in the monodispersity was also noted for 40 mol % MPTMS (balance TMOS, **Fig. 5B**), with SEM indicating a particle diameter of $293 \pm 24 \text{ nm}$. Slower silane feed rates (e.g., 0.25 mL min^{-1}) resulted in slight monodispersity improvements (data not shown), but at lower yields (e.g., ~ 40 vs. 70 mg for 40 mol% MPTMS (balance TMOS) composition). Thus, 0.5 mL min^{-1} was determined to be the optimal feed rate as it allowed for a balance between sufficient particle yield and monodispersity. Similar to 25 mol% MPTMS (balance TMOS), the monodispersity of 75 mol% MPTMS (balance TEOS) improved, while the 85 mol% MPTMS (balance TEOS) system remained aggregated (**Fig 5F** and **5G**, respectively).

Additionally, the product yield increased to $\sim 170 \text{ mg}$ for these two compositions and can be attributed to the greater concentration of the larger MPTMS in the particles. Unfortunately, the semi-batch process proved problematic for 60, 75, and 85 mol% MPTMS (balance TMOS) particles. As shown in **Figure 5C-E**, the slowed silane addition resulted in both aggregation and the formation of a large silica network rather than monodisperse, spherical particles. To examine this phenomenon further, silane feed rates were varied ($0.25\text{--}3.0 \text{ mL min}^{-1}$) for 60 mol% MPTMS (balance TMOS). Feed rates $< 2.0 \text{ mL min}^{-1}$ resulted in polydisperse, aggregated silica, while faster feed rates ($2.0\text{--}3.0 \text{ mL min}^{-1}$) produced particles of a bimodal size (data not shown).

We then attempted to decrease the size of the particles to improve particle monodispersity. The 75 mol% MPTMS (balance TEOS) particles were chosen as a model system to examine the effect of the water concentration on particle size and morphology. As shown in **Figure 6**, 75 mol% MPTMS (balance TEOS) was synthesized with (A) 47.0, (B) 42.0, (C) 40.6, (D) 36.5, (E) 32.5, and (F) 24.9 M water. Water concentrations $\geq 40.6 \text{ M}$ favored rapid silane hydrolysis and condensation kinetics, leading to a highly condensed network rather than discrete, spherical particles. At a water concentration of 36.5 M, discrete particles were formed, but with morphologies featuring excessive aggregation. Monodisperse particles ($333 \pm 48 \text{ nm}$) were first observed at a slightly lower water concentration (32.5 M).

Particle size increased with decreasing water concentrations (456 ± 68 nm and 635 ± 63 nm for 24.9 and 16.2 M, respectively). Furthermore, the smaller particle sizes were accompanied with slightly lower yields for each composition. The yields for 75 mol% MPTMS (balance TEOS) particles were ~65, 150, and 170 mg for water concentrations of 32.5, 24.9, and 16.2 M, respectively. The differences in yield may be factors of the efficiency of particle collection (i.e., centrifugation rpm and duration) for the smaller particles rather than chemical differences.

The appropriate water concentrations (32.5 and 24.9 M) were next used to tune particle size and reduce the bimodal distribution characteristic of the 60, 75, and 85 mol% MPTMS (balance TMOS) particles. As shown in **Figure 7**, the intermediate water concentration (24.9 M) yielded particles with sizes of 179 ± 22 and 196 ± 25 nm for the 25 and 40 mol % MPTMS (balance TMOS) compositions, respectively. The greater water concentration (32.5 M) drastically increased the reaction kinetics for the mostly TMOS-based systems, resulting in highly-fused silica networks. Increasing the concentration of MPTMS (75 mol%) yielded monodisperse, spherical particles of 363 ± 51 and 279 ± 49 nm using 24.9 and 32.5 M water, respectively. Aggregated and fused particles were formed for the greatest MPTMS concentration (85 mol%) when using 24.9 M water. However, monodisperse particles (440 ± 84 nm) were formed when synthesized with 32.5 M water.

The TEOS-based counterpart to this system behaved similarly by yielding only discrete particles (506 ± 77 nm) when synthesized with the higher water concentration. At lower water amounts, the formation of aggregated particles was noted. The trend of decreasing particle yield with increasing water content that was observed for the 75 mol% MPTMS (balance TEOS) composition was mirrored for all other compositions evaluated. The yields for the 75 mol% (balance TMOS) particles decreased from ~120 to 60 mg upon increasing the water content from 24.9 to 32.5 M. Likewise, the 25 mol% MPTMS (balance TMOS) particle yield decreased from ~90 to 20 mg while the 40 mol% MPTMS system exhibited a decrease from ~50 to 9 mg upon increasing the water concentration from 16.2 to 24.9 M. The yields for both 85 mol% MPTMS compositions (i.e, TMOS and TEOS balance) at a water concentration of 32.5 M were ~160 mg. Perhaps of greatest significance, the elevated water concentrations used to synthesize the thiol-modified particles successfully resolved the bimodal nature of certain compositions not resolvable using a semi-batch process alone. Of note, 60 mol% MPTMS (balance TMOS) was the only composition that

consistently yielded particles of a bimodal nature. Increasing the water content regardless of addition method (bolus vs. semi-batch) resulted in a highly-fused silica network.

Particle sizes were also measured by DLS to corroborate particle monodispersity and size measured using SEM. As shown in **Table 1**, the DLS measurements were in agreement with the sizes calculated from the SEM images. The slightly increased average diameters observed with DLS may be attributed to particle hydration (DLS measurements conducted in solution). Like SEM, the DLS measurements indicated a narrow size distribution, as evidenced by low polydispersity indices for each composition.

TABLE 1

Particle composition (mol % MPTMS)	Water content (M)	Particle size ^a (nm)	Z-Average size ^b (nm)	Polydispersity index
75% (balance TEOS)	32.5	333 ± 48	416.2 ± 23.4	0.027
75% (balance TEOS)	24.9	456 ± 68	529.6 ± 23.7	0.018
75% (balance TEOS)	16.2	635 ± 63	718.0 ± 51.7	0.046
85% (balance TEOS)	32.5	506 ± 77	668.7 ± 46.0	0.040
25% (balance TMOS)	24.9	179 ± 22	258.4 ± 15.1 ^c	0.031
25% (balance TMOS)	16.2	252 ± 20	469.0 ± 24.8 ^c	0.025
40% (balance TMOS)	24.9	196 ± 25	240.7 ± 17.9 ^c	0.064
40% (balance TMOS)	16.2	293 ± 24	404.8 ± 28.2	0.045
75% (balance TMOS)	32.5	279 ± 49	431.2 ± 29.5	0.043
75% (balance TMOS)	24.9	363 ± 51	507.6 ± 30.8	0.032
85% (balance TMOS)	32.5	440 ± 84	696.2 ± 44.4	0.042

^aSize calculated from scanning electron micrographs of n = 120 particles

^bSizes acquired from dynamic light scattering measurements in pH 7.4 PBS for n = 3 syntheses

^cEthanol used as dispersant

Of note, PBS was used as a dispersant for compositions with a large concentration of MPTMS. However, smaller particles with a large degree of inorganic character (i.e., ≤40 mol% MPTMS) rapidly aggregated in this dispersant and caused erratic DLS measurements. This aggregation may be attributed to a large surface density of protonated silanol groups leading to unfavorable particle interaction. While basic conditions resulted in inconsistent DLS measurements due to particle dissolution, ethanol was a viable alternative dispersant as evidenced by the correlation between DLS and SEM measurements.

Elemental analysis was used to characterize the composition of the particles. As expected, the weight percentages of sulfur in the particles increased accordingly with the MPTMS mol% used to make the particles indicating incorporation of the thiol functionality (Table 2).

TABLE 2

Particle composition (mol % MPTMS)	Water content (M)	Sulfur content ^a (wt %)
75% (balance TEOS)	32.5	13.83 ± 3.01
75% (balance TEOS)	24.9	16.01 ± 1.71
75% (balance TEOS)	16.2	15.62 ± 1.90
85% (balance TEOS)	32.5	20.02 ± 3.88
25% (balance TMOS)	24.9	< 0.0 ^b
25% (balance TMOS)	16.2	0.51 ± 0.36
40% (balance TMOS)	24.9	1.09 ± 0.58
40% (balance TMOS)	16.2	3.08 ± 2.57
75% (balance TMOS)	32.5	18.29 ± 5.34
75% (balance TMOS)	24.9	15.30 ± 5.32
85% (balance TMOS)	32.5	20.55 ± 5.70

^aAverage weight percents are calculated from n = 3 syntheses

^bWeight percent was less than instrument limit of detection

Syntheses promoting the formation of discrete, spherical particles tended to be preferentially derived from one precursor as evidenced by a large gap in the transition from 40 to 75 mol% MPTMS (wt% 3.08 ± 2.57 and 15.62 ± 1.90, respectively). These values were in marked contrast to the sulfur wt% of the colloidal silica. Although the increased sulfur wt% were more linearly proportional for the colloidal silica, the lack of discrete, spherical particles was not ideal. The comparison of the two systems (colloidal vs. discrete particles) and syntheses reveals that a balance exists between silane incorporation and certain design criteria.

Example 5: Synthesis of Particles with NAPTMS

Procedure for 25% NAP-TMS balance TMOS/TEOS:

1. Dissolved 85.4 mg NAPTMS (tertiary precursor) in 3.95 mL of ethanol by vortexing
2. To the reaction mixture added 4.09 mL of water then added TMOS/ethanol mixture (71.9 μ L TMOS and 200 μ L ethanol) via syringe pump at a rate of 1.0 mL/min.
3. Added 6 mL of 5M HCL and let sonicate (120%) for 1 hour.
4. Added 4 mL of ammonium hydroxide and allowed to sonicate (120%) for 30 minutes.

Final Concentrations TMOS and TEOS Particles:

[Silane] = 0.0352 M

[Ethanol] = 3.85 M

$$[\text{Water}] = 42.8 \text{ M}$$
$$[\text{NH}_3] = 3.43 \text{ M}$$
$$[\text{HCl}] = 1.57 \text{ M}$$

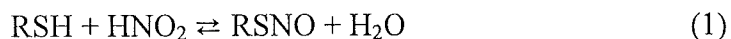
Size Characterization:

Particle Composition	Particle size (nm) SEM	Z-average size (nm) DLS	PDI
25% NAPTMS balance TMOS	802.8 ± 116	607.3 ± 28.9	0.17 ± 0.072
25% NAPTMS balance TEOS	820.2 ± 95	760.6 ± 27.3	0.16 ± 0.038

Example 6: Nitrosation of mercaptosilane-based silica particles

Thiols within the particles were nitrosated via reaction with nitrous acid.¹² Particles (~200 mg) were first added to 4 mL methanol (MeOH). While stirring, 2 mL of hydrochloric acid (5 M) was added to the suspension. A 2 mL aqueous solution containing sodium nitrite (2x molar excess to thiol) and DTPA (500 μ M) was then added to the particle suspension, and the mixture stirred for 2 h in the dark and on ice. Particles were collected by centrifugation at 4500 rpm (5 min), washed with 40 mL chilled 500 μ M DTPA(aq), recollected, washed with 40 mL chilled MeOH, recollected, and vacuum dried for 30 min while shielded from light. Particles were stored at -20°C in vacuo until further study.

The MPTMS-modified particles were nitrosated to enable NO storage and release. Briefly, the particles were treated with acidified sodium nitrite, generating nitrous acid, a nitrosating agent that reacts with thiols to form RSNOs (see Eq 1).



Since *S*-nitrosothiols prepared from primary thiols absorb light at 330–350 and 550–600 nm, successful RSNO formation was confirmed by the resulting red color of the particles after nitrosation. Furthermore, the intensity of the color increased with MPTMS mol% indicating greater RSNO formation.

As widely known, *S*-nitrosothiols decompose via a multitude of pathways (**Figure 8**). Both photo and thermal irradiation of RSNOs result in homolytic cleavage of the S-N bond, yielding NO and a thiyl radical. The thiyl radical may subsequently react with an RSNO to generate a disulfide and an additional equivalent of NO. Cu(I), resulting from the reduction of Cu(II) via trace thiolate ions, has been shown to be active in a catalytic RSNO decomposition mechanism. Transnitrosation between a thiol and an RSNO may also occur, resulting in the transfer of the nitroso functionality and formation of a new RSNO species that may decompose via the aforementioned pathways.

To assess the NO storage and release, RSNO-modified particles (~2 mg) were added to 500 μ M DTPA (pH 7.4 PBS) at a temperature of 0 °C, while measuring the ensuing NO release as a function of photolytic decomposition. As shown in **Figure 9A**, RSNO-modified silica particles exhibited photo-initiated NO release upon exposure to broadband, white light. Greater irradiation levels (i.e., power) resulted in elevated NO release from the particles. Of note, low levels of NO release (~15 ppb $\text{mg}^{-1} \text{s}^{-1}$) were observed at 0 °C and in the dark (**Figure 9A inset**). Others have shown that oxygen may react with NO to form dinitrogen trioxide (N_2O_3), an oxidant that also decomposes RSNOs. Elimination of oxygen from the storage environment of the RSNO-modified particles would thus be expected to increase the NO storage stability of the particles. Indeed, no significant loss in NO release capacity was measured upon storing the particles for 2 months at -20 °C in vacuo and in the dark.

Due to the rapid kinetics of the photo-initiated decomposition, total NO storage of the particles was assessed by exposing the particles to 200 W of broadband light. Indeed, >95 % of the NO stored was released after 5 h of irradiation at 200 W. As given in **Table 3**, the total NO released from the particles ranged from 0.09–4.39 $\mu\text{mol mg}^{-1}$. These levels of NO storage are an order of magnitude larger than previously reported RSNO-modified silica particles. Using the average sulfur weight percents in conjunction with the average NO storage values, the percent conversion of thiol to RSNO for the different particle compositions was calculated to be 58–78% for the 75 and 85 mol% MPTMS/TMOS and MPTMS/TEOS systems. The 25 and 40 mol% MPTMS particles were found to have lower thiol to RSNO conversions (54–63%).

TABLE 3

Particle composition (mol % MPTMS)	Water content (M)	Total NO released ^a ($\mu\text{mol mg}^{-1}$)
75% (balance TEOS)	32.5	3.24 ± 0.61
75% (balance TEOS)	24.9	3.58 ± 0.39
75% (balance TEOS)	16.2	3.15 ± 0.60
85% (balance TEOS)	32.5	3.95 ± 0.66
25% (balance TMOS)	24.9	0.09 ± 0.02
25% (balance TMOS)	16.2	0.10 ± 0.02
40% (balance TMOS)	24.9	0.34 ± 0.02
40% (balance TMOS)	16.2	0.52 ± 0.22
75% (balance TMOS)	32.5	3.31 ± 0.85
75% (balance TMOS)	24.9	3.73 ± 0.62
85% (balance TMOS)	32.5	4.39 ± 0.02

^aAverages are calculated from n = 3 syntheses and after 5 h of 200 W irradiation

The effect of copper on NO release was investigated as a function of copper concentration. These assays were performed using Cu(II) via CuBr_2 due to the insolubility of Cu(I) compounds in aqueous solutions. As expected, the NO release from the RSNO-modified particles correlated with the copper concentration (**Fig 9B**) with the greatest copper concentration examined (25 μM) generating the maximum NO release ($\sim 45 \text{ ppb mg}^{-1} \text{ s}^{-1}$).

The use of RSNO-modified particles for biomedical application likely necessitates an NO release trigger other than light or large concentrations of free copper ions. We thus evaluated NO release from the particles via thermal degradation at 37 °C using 75 mol% MPTMS (balance TEOS, $718.0 \pm 51.7 \text{ nm}$) as a model system. Particles were introduced into 500 μM DTPA (pH 7.4 PBS), maintained at 37 °C and shielded from external light while monitoring NO release over 48 h (**Table 4**). Under these conditions, the particles released a total of $1.17 \mu\text{mol NO mg}^{-1}$ with a corresponding half life of 2.95 h. When compared to the total amount released after 5 h using 200 W irradiation ($3.15 \mu\text{mol mg}^{-1}$, **Table 3**), the discrepancy may be attributed to inability to measure NO at low levels beyond 48 h and/or loss of NO through its reaction with oxygen present in the soak solutions. As evident by a pink hue, the particles still contained a portion of their NO payload even after 48 h of release.

TABLE 4

Time (h)	Instantaneous NO release (ppb mg ⁻¹ s ⁻¹) ^a
0	1205.7 ± 22.4
0.5	481.2 ± 7.7
1	355.7 ± 7.7
6	74.9 ± 0.7
12	33.2 ± 0.4
24	12.6 ± 0.2
48	2.50 ± 0.07

^aAverages are calculated from n = 3 syntheses

Example 7: Thermal Initiated NO Release Characterization of Primary and Tertiary RSNO Particles

For each particle composition, approximately 3 mg of particles were added to the collection flask containing PBS (500μM DTPA) and the NO release monitored over 75 min. The NO storage and release characteristics are shown in **Table 5**.

TABLE 5

Particle Composition	t[NO]total (μmol mg ⁻¹) at 75 minutes	[NO] _m max NO release (pmol mg ⁻¹)	time to get to max (min)
75% MPTMS balance TEOS (primary RSNO)	0.878	262	1.6
25% NAPTMS balance TMOS (tertiary RSNO)	1.70X10 ⁻³	0.913	32
25% NAPTMS balance TEOS (tertiary RSNO)	4.13X10 ⁻⁴	1.31	75

The NO storage and release characteristics of the 25% NAPTMS sample while under irradiation were also investigated. Using 200 W illumination, and 0.3 m distance, the results are shown in **Table 6**.

TABLE 6

Particle Composition	t[NO]total ($\mu\text{mol mg}^{-1}$) at 75 minutes	[NO] _m max NO release (pmol mg^{-1})	t to get to max (min)
25% NAPTMS balance TMOS (tertiary RSNO)	0.205	61.5	10.5

The results shown in Tables 5 and 6 shown that NO stability of the particles can be significantly increased by using a tertiary nitrosothiol-functionalized silica particles.

Example 8: Influence of particle sonication before/after nitrosation

Experiment 8A: Nitrosated particles no Sonication

1. Nitrosate 15 mg of particles in methanol, 5M HCl, and 2 mol X (vs. thiol) of NaNO₂/500 uM DTPA.
2. Collect and wash with cold dtpa and cold methanol. Dry under vacuum for 45 min in dark (covered with foil).
3. Add 1 mg of nitrosated particles to 5 mL PBS (DTPA)
4. Expose to 200 W illumination (30 cm from inside bottom of box)

Experiment 8B: Particle nitrosation then Sonication

1. Nitrosate 15 mg of particles in methanol, 5M HCl, and 2 mol X (vs. thiol) of NaNO₂/500 uM DTPA.
2. Collect and wash with cold dtpa and cold methanol. Dry under vacuum for 45 min in dark (covered with foil).
3. Add 1 mg of nitrosated particles to 5 mL of PBS (DTPA) and sonicate for 30 min on ice at amplitude = 50%.
4. Expose to 200 W illumination (30 cm from inside bottom of box)

Experiment 8C: Particle sonication (30 min at amplitude = 50%) then nitrosation

1. Sonicate 15 mg of non-nitrosated particles in 4 mL of Methanol on ice for 30 minutes on ice at amplitude = 50%.
2. Nitrosatesonicated particles in 4 mL of methanol, 5M HCl, and 2 mol X (vs. thiol) of NaNO₂/500uM DTPA.
3. Collect and wash with cold dtpa and cold methanol. Dry under vacuum for 45 min in dark (covered with foil).
4. Add 1 mg of nitrosated particles to 5 mL PBS (DTPA)
5. Expose to 200 W illumination (30 cm from inside bottom of box)

Experiment 8D: Particle sonication (60 min at amplitude = 50%) then nitrosation

1. Sonicate 15 mg of non-nitrosated particles in 4 mL of Methanol on ice for 60 minutes on ice at amplitude = 50%.
2. Nitrosatesonicated particles in 4 mL of methanol, 5M HCl, and 2 mol X (vs. thiol) of NaNO₂/500uM DTPA.
3. Collect and wash with cold dtpa and cold methanol. Dry under vacuum for 45 min in dark (covered with foil).
4. Add 1 mg of nitrosated particles to 5 mL PBS (DTPA)
5. Expose to 200 W illumination (30 cm from inside bottom of box)

The results of Experiments 8A-8D are shown in

Experiments (see above)	Total NO Concentration ($\mu\text{mol mg}^{-1}$)	Duration of NO Release (h)	No. of Experiments
7A	1.46 ± 0.16	24	N=3
7B	1.05 ± 0.13	24	N=3
7C	1.38 ± 0.37	24	N=3
7D	1.36 ± 0.23	24	N=3

SEM images of the particles formed in Example 7A are provided in **Figure 10**. SEM images of the particles formed in Example 7C are provided in **Figure 11**. SEM images of the particles formed in Example 7D are shown in **Figure 12**. These results show that particle morphology and nitric oxide storage is not significantly influenced by the sonication procedure. Thus, sonicating particles may be used to narrow size distribution and/or making smaller particles.

In the drawings and specification, there have been disclosed embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.

We Claim:

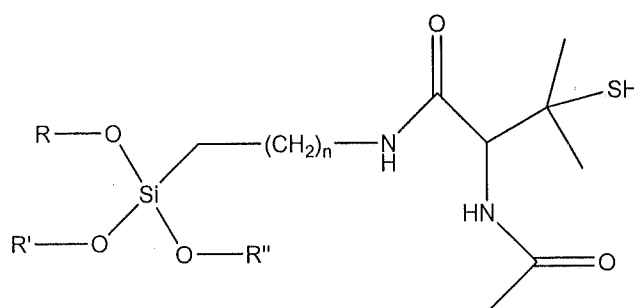
1. A method of forming S-nitrosothiol-functionalized co-condensed silica particles comprising:
reacting a thiol-containing silane and a backbone alkoxysilane in a sol precursor solution that comprises water to form thiol-functionalized co-condensed silica particles, wherein the thiol-functionalized co-condensed silica particles comprise a polysiloxane matrix and at least some of thiol groups are present within the polysiloxane matrix; and
reacting the thiol-functionalized co-condensed silica particles with a nitrosating agent to provide the S-nitrosothiol-functionalized co-condensed silica particles.
2. The method of claim 1, wherein the thiol-containing silane comprises a primary thiol-containing silane.
3. The method of claim 2, wherein the primary thiol-containing silane comprises mercaptopropyltrimethoxysilane and the backbone alkoxysilane comprises tetramethoxysilane.
4. The method of claim 3, wherein the sol precursor solution comprises an ammonia catalyst at a concentration in a range of about 1.9 to about 5.5 M;
wherein the total silane monomer concentration in the sol precursor solution is in a range of about 0.1 M to about 0.4 M;
wherein the total silane monomer concentration comprises about 25 to about 85 mol % mercaptopropyltrimethoxysilane; and
wherein the water is present in the sol precursor solution at a concentration in a range of about 8.0 to about 32.5 M.
5. The method of claim 2, wherein the primary thiol-containing silane is mercaptopropyltrimethoxysilane and the backbone alkoxysilane is tetraethoxysilane.
6. The method of claim 5, wherein the sol precursor solution comprises an ammonia catalyst at a concentration in a range of about 1.9 to about 5.5 M;
wherein the total silane monomer concentration in the sol precursor solution is in a range of about 0.1 M to about 0.4 M;

wherein the total silane monomer concentration comprises about 75 to about 85 mol % mercaptopropyltrimethoxysilane; and

wherein the water is present in the sol precursor solution a concentration in a range of about 8.0 to about 32.5 M.

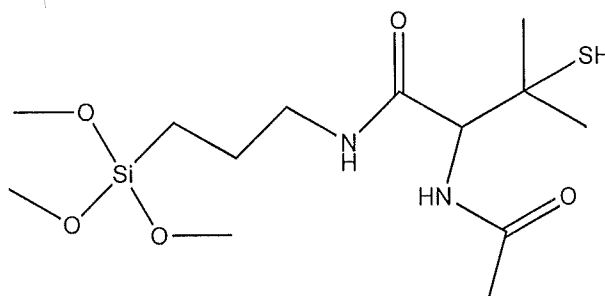
7. The method of claim 1, wherein the thiol-containing silane comprises a tertiary thiol-containing silane.

8. The method of claim 7, wherein the tertiary thiol-containing silane comprises a tertiary thiol having the following structure:



wherein R, R' and R'' are each independently alkyl and n is in a range of 0 to 10.

9. The method of claim 8, wherein the tertiary thiol-containing silane has the following structure:



10. The method of claim 8, wherein the backbone alkoxy silane comprises tetraethoxysilane.

11. The method of claim 10, wherein the sol precursor solution comprises an ammonia catalyst at a concentration in a range of about 1.9 to about 5.5 M;

wherein the total silane monomer concentration in the sol precursor solution is in a range of about 0.1 M to about 0.4 M;

wherein the total silane monomer concentration comprises about 25 to about 85 mol % tertiary thiol-containing silane; and

wherein the water is present in the sol precursor solution at a concentration in a range of about 8.0 to about 32.5 M.

12. The method of claim 1, wherein the thiol-functionalized co-condensed silica particles are sonicated prior to reacting the thiol-functionalized co-condensed silica particles with a nitrosating agent.

13. S-nitrosothiol-functionalized monodisperse co-condensed silica particles having an average particle diameter in a range of about 10 nm to about 100 μm .

14. The S-nitrosothiol-functionalized monodisperse co-condensed silica particles of claim 13, wherein the particles have an average particle diameter in a range of about 200 nm to about 700 nm.

15. The S-nitrosothiol-functionalized co-condensed silica particles of claim 13, wherein the particles have at least some nitrosothiol functional groups distributed within a polysiloxane matrix of the particles.

16. The S-nitrosothiol-functionalized co-condensed silica particles of claim 13, wherein the S-nitrosothiol functional groups comprise primary nitrosothiol functional groups.

17. The S-nitrosothiol-functionalized co-condensed silica particles of claim 13, wherein the S-nitrosothiol functional groups comprise tertiary nitrosothiol functional groups.

18. S-nitrosothiol-functionalized co-condensed silica particles having an NO storage in a range of about 0.01 μmol to about 10 μmol NO per mg particle.

19. The S-nitrosothiol-functionalized co-condensed silica particles of claim 18, wherein the particles have an NO storage in a range of about 0.09 μmol to about 4.40 μmol NO per mg particle.

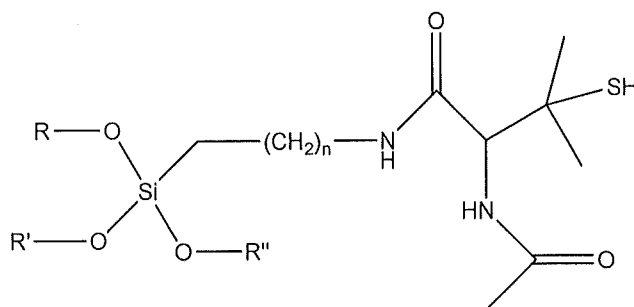
20. The S-nitrosothiol-functionalized co-condensed silica particles of claim 18, wherein the particles have at least some nitrosothiol functional groups distributed within a polysiloxane matrix of the particles.

21. The S-nitrosothiol-functionalized co-condensed silica particles of claim 18, wherein the S-nitrosothiol functional groups comprise primary nitrosothiol functional groups.

22. The S-nitrosothiol-functionalized co-condensed silica particles of claim 18, wherein the S-nitrosothiol functional groups comprise tertiary nitrosothiol functional groups.

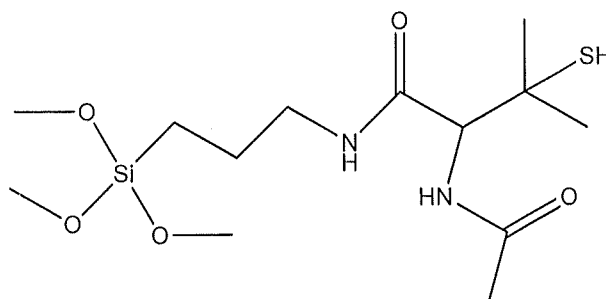
23. A S-nitrosothiol-functionalized co-condensed silica particle comprising tertiary nitrosothiol functional groups.

24. A compound having the following structure:



wherein R, R' and R'' are each independently alkyl and n is 0 in a range of 0 to 10.

25. The compound of claim 24, wherein the compound has the following structure:



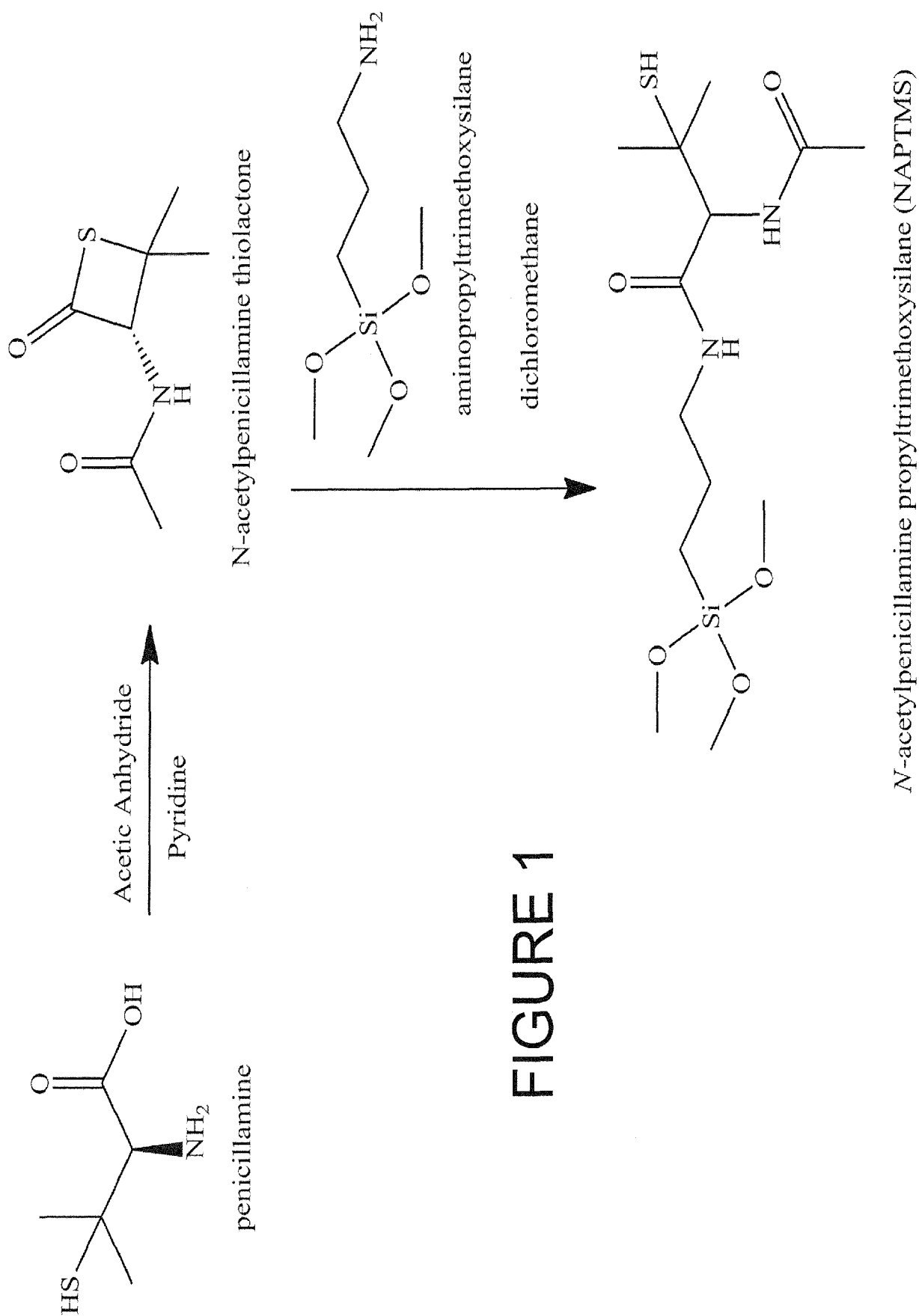


FIGURE 1

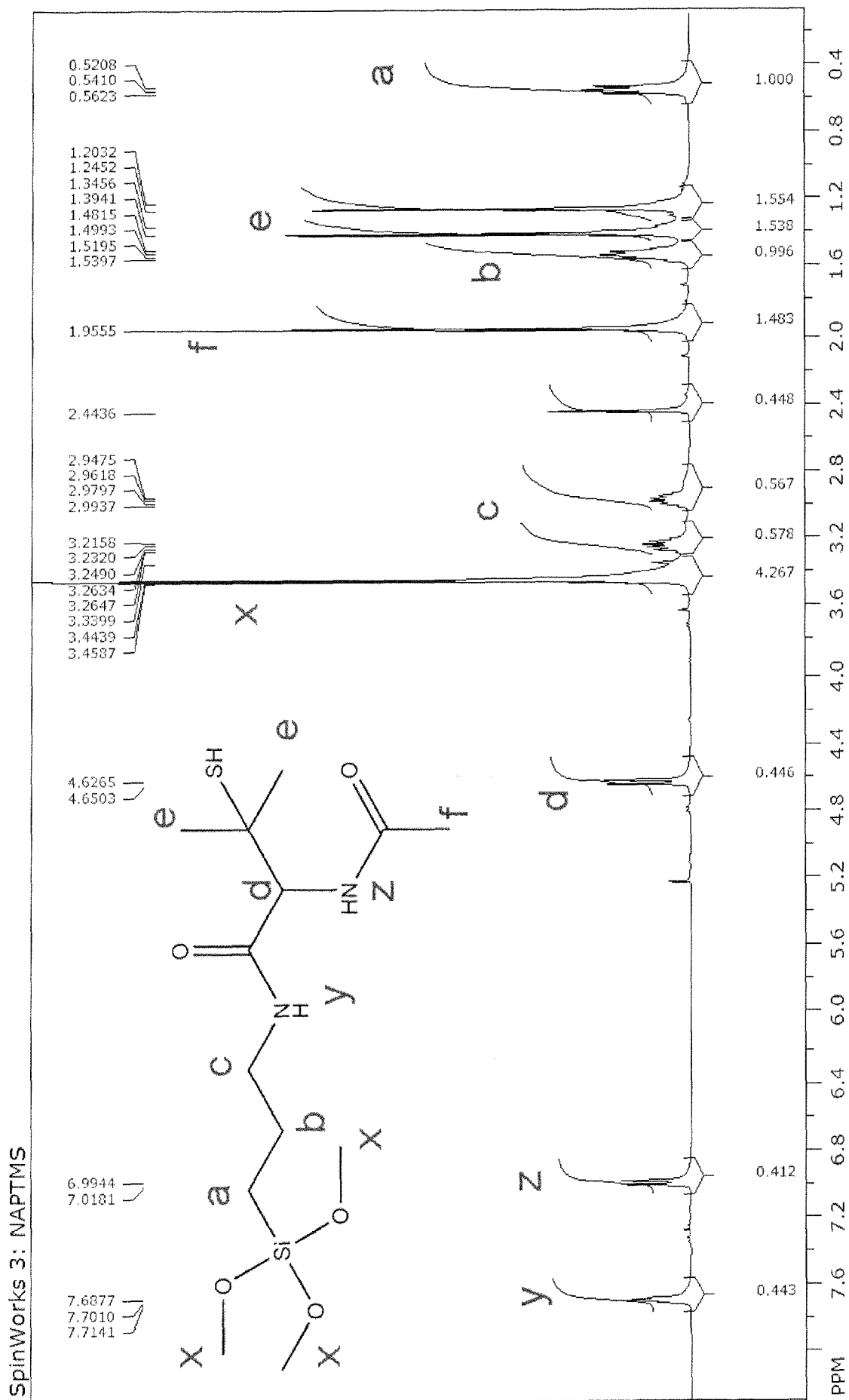


FIGURE 2

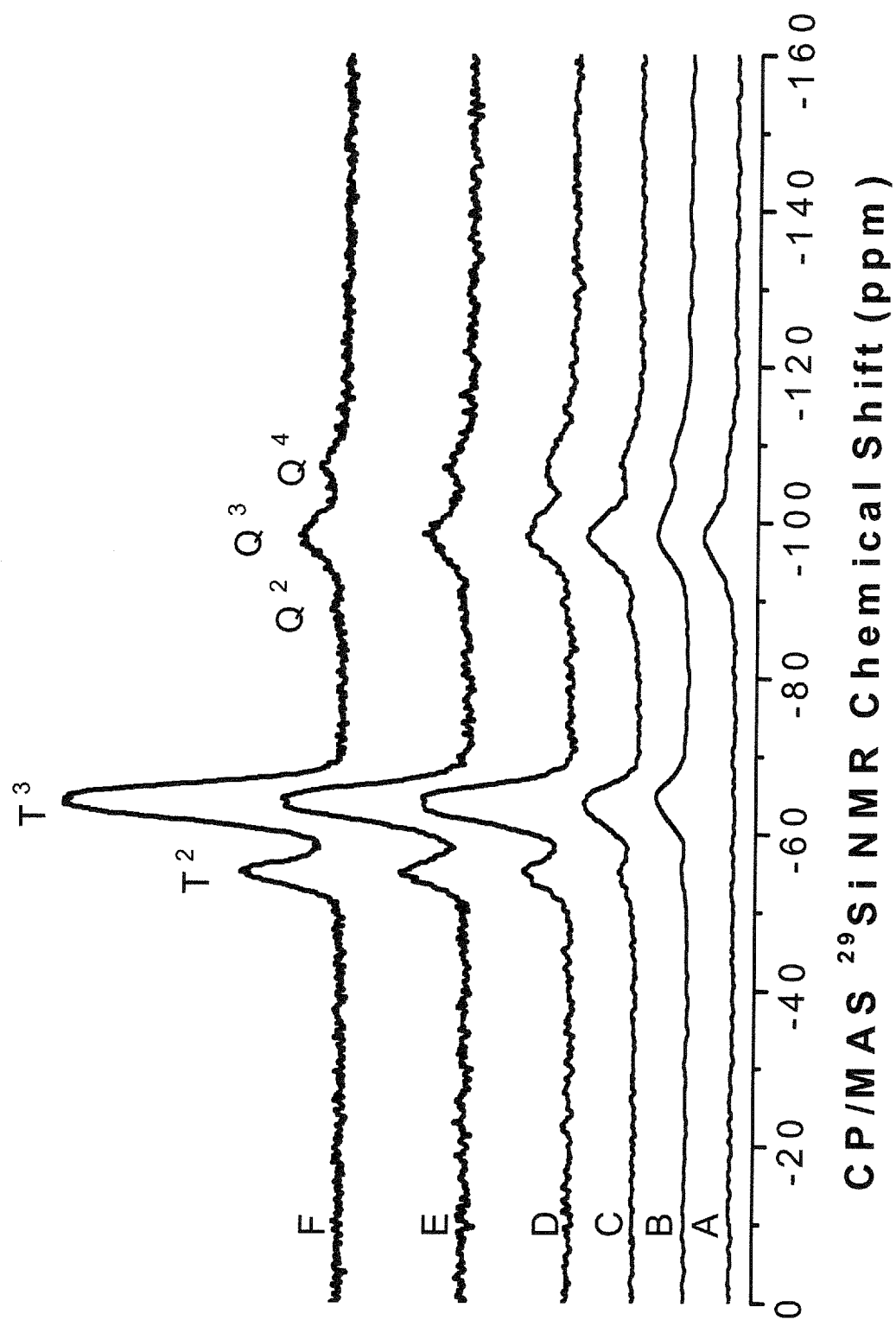


FIGURE 3

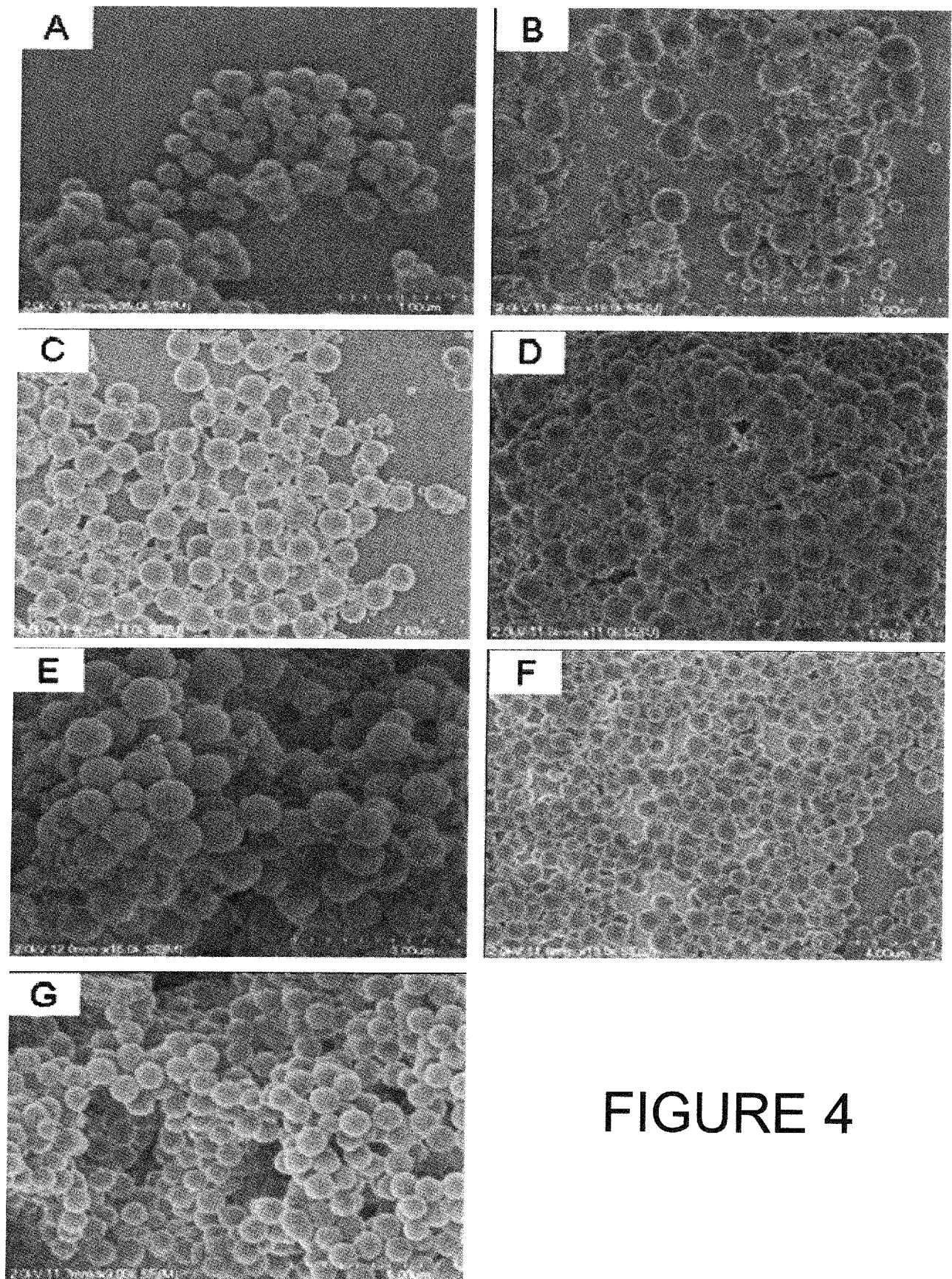


FIGURE 4

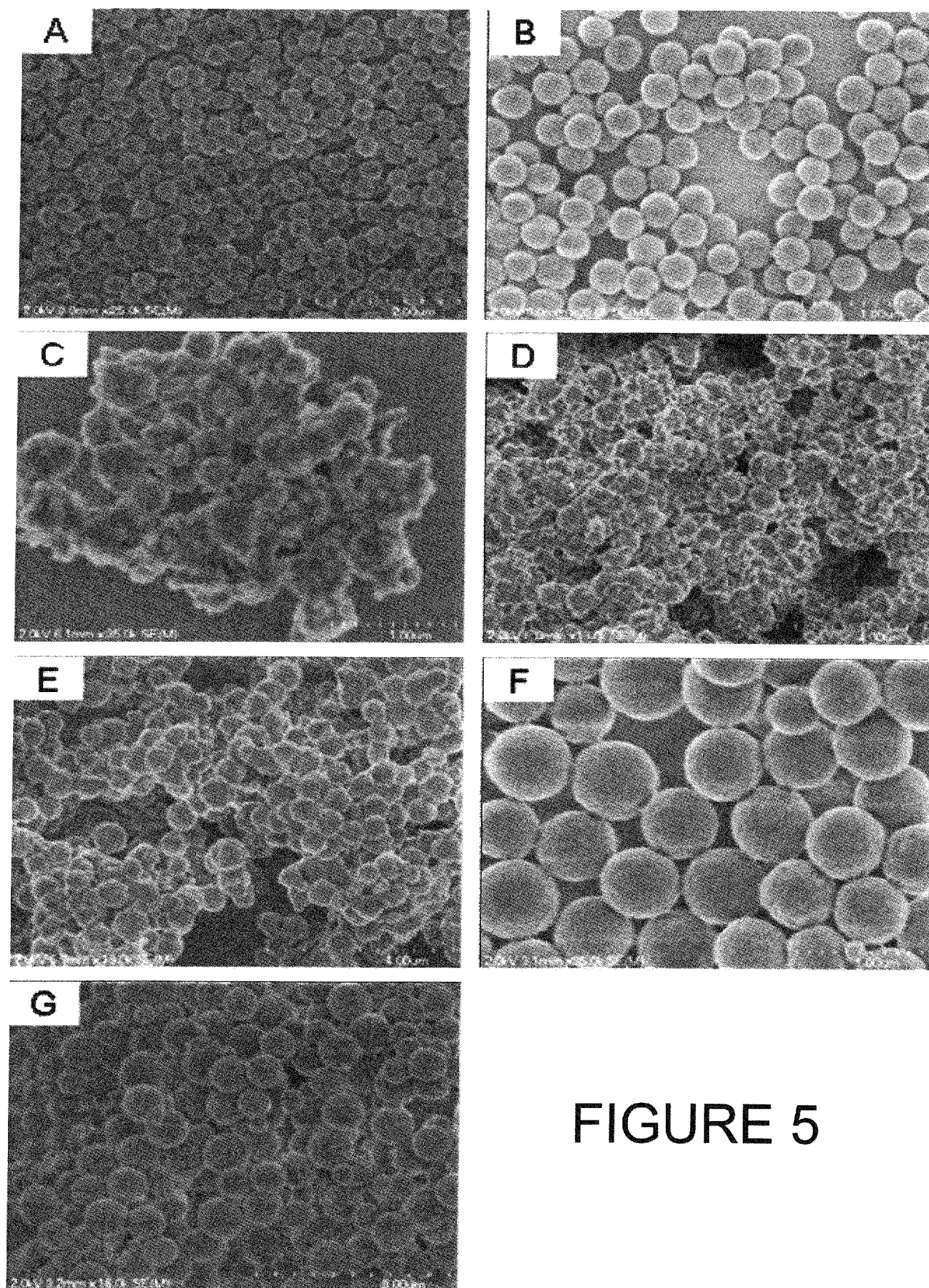
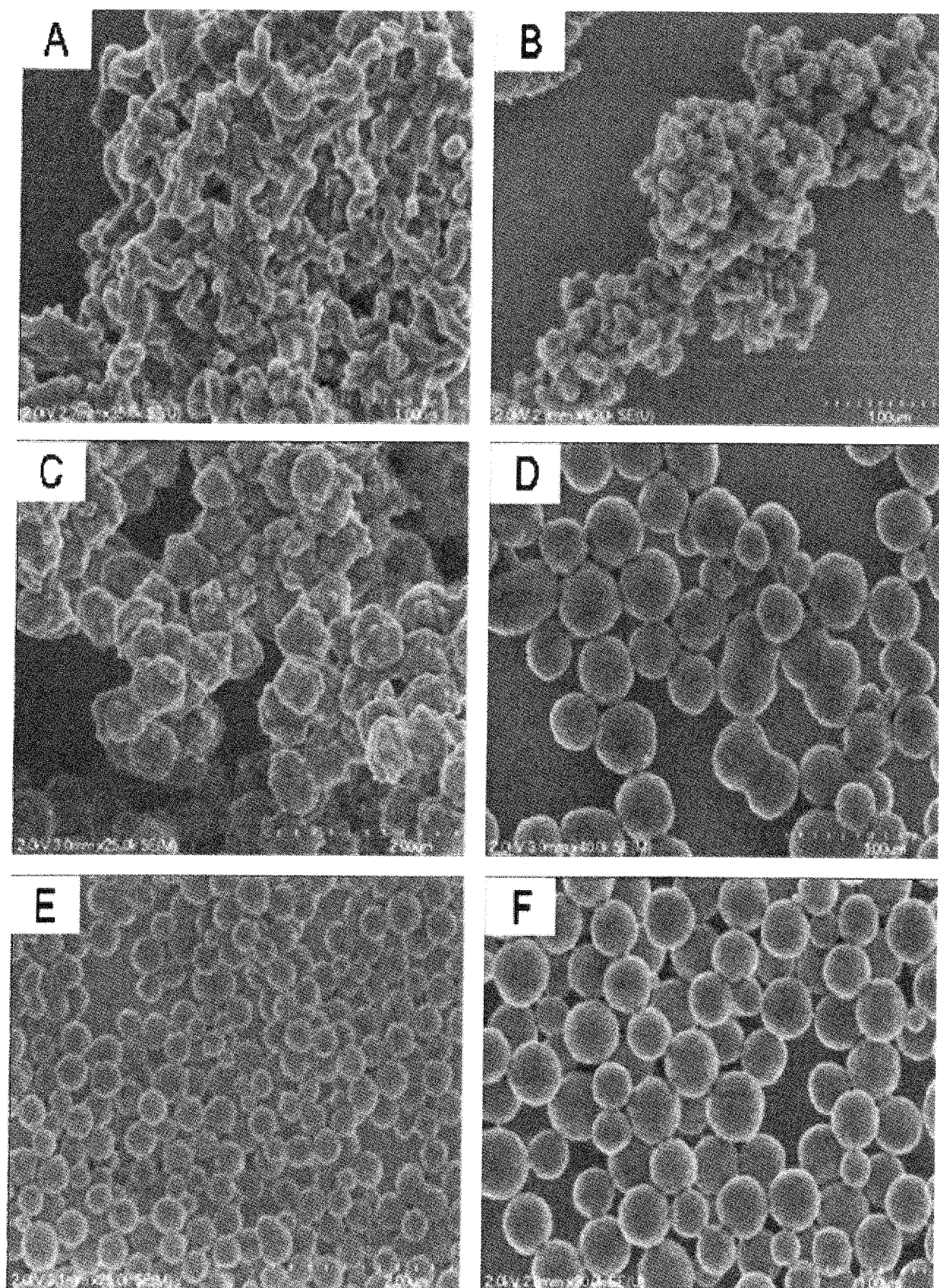
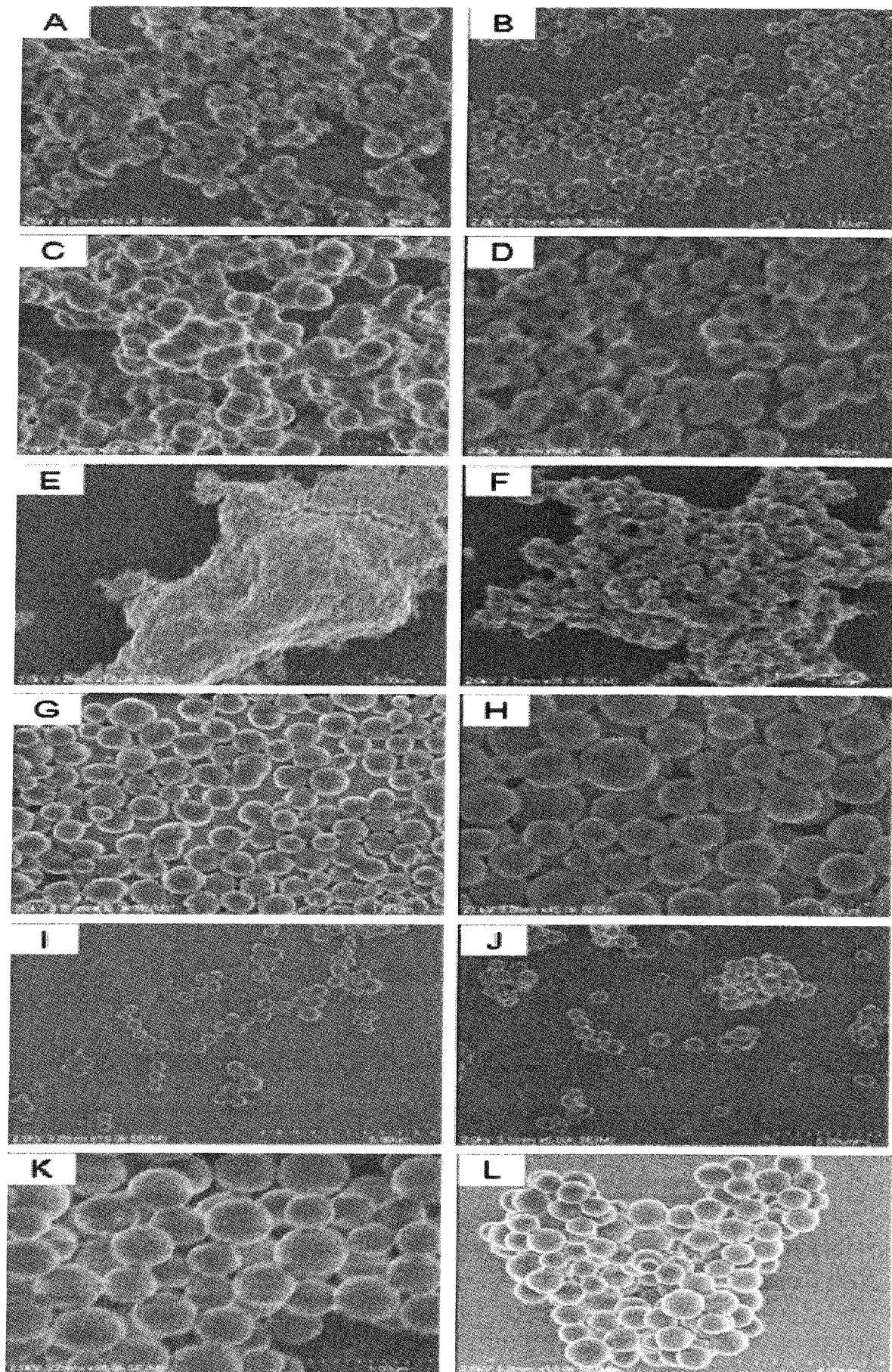


FIGURE 5

**FIGURE 6**

**FIGURE 7**

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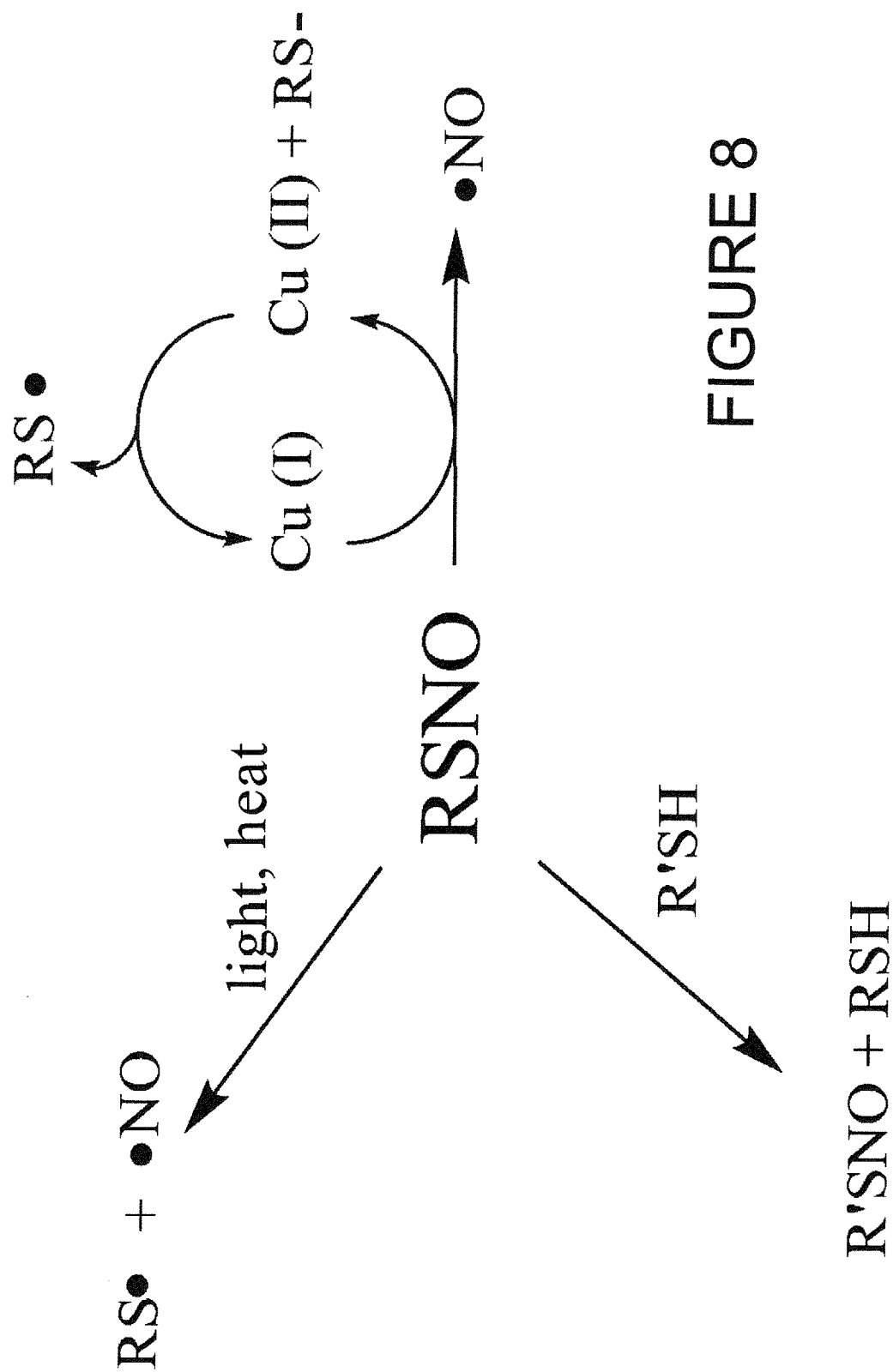
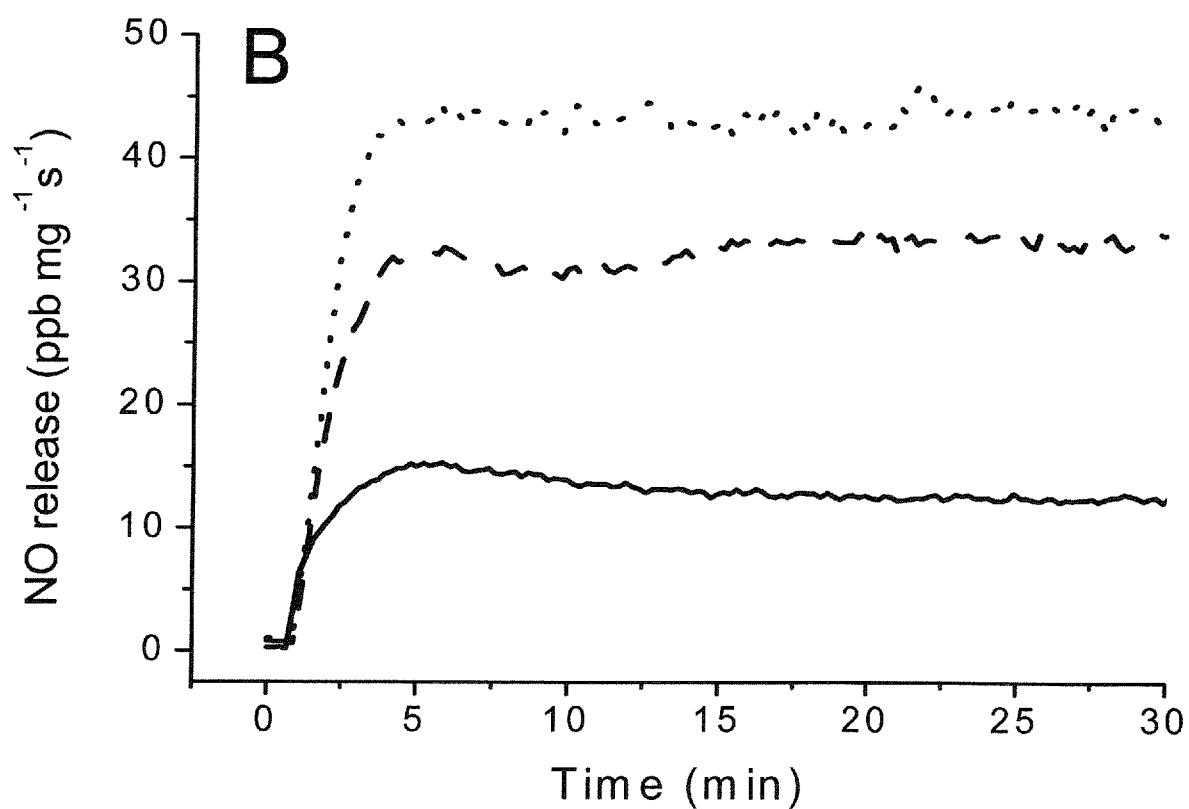
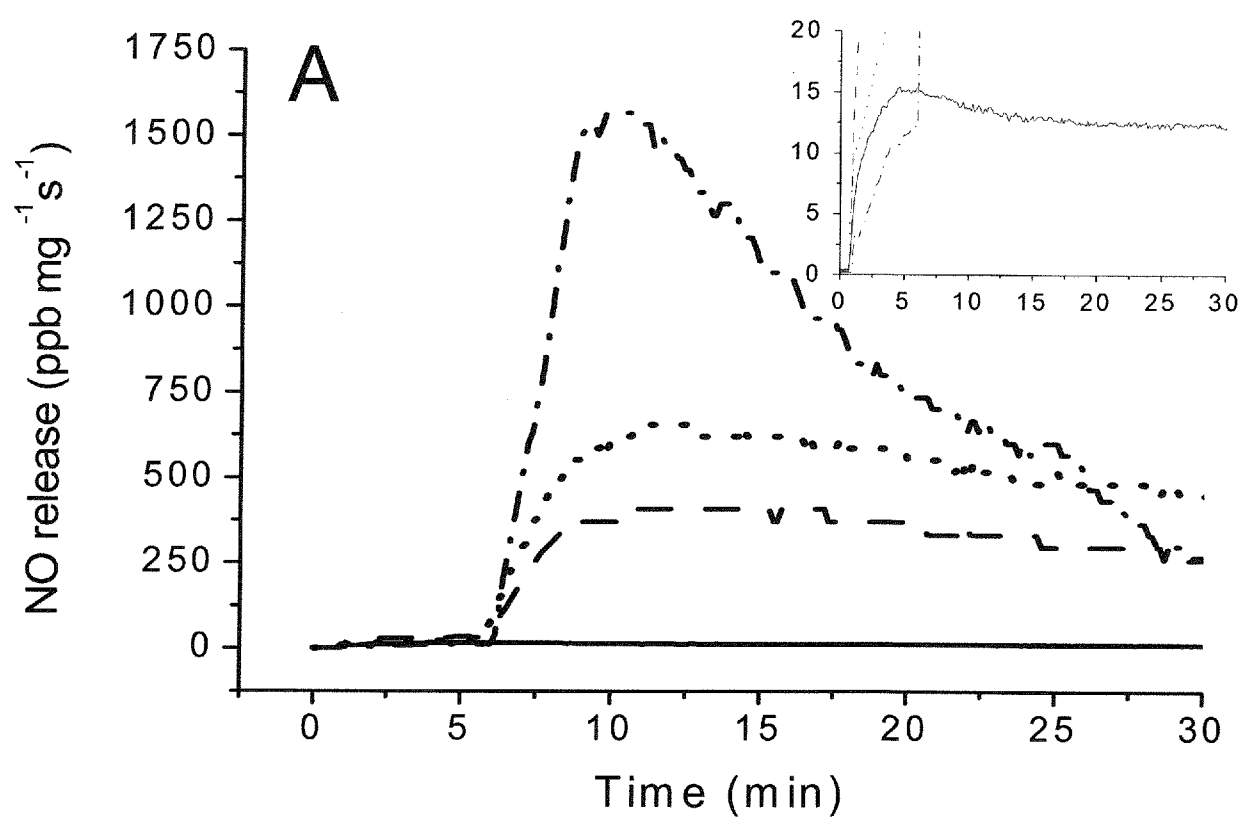
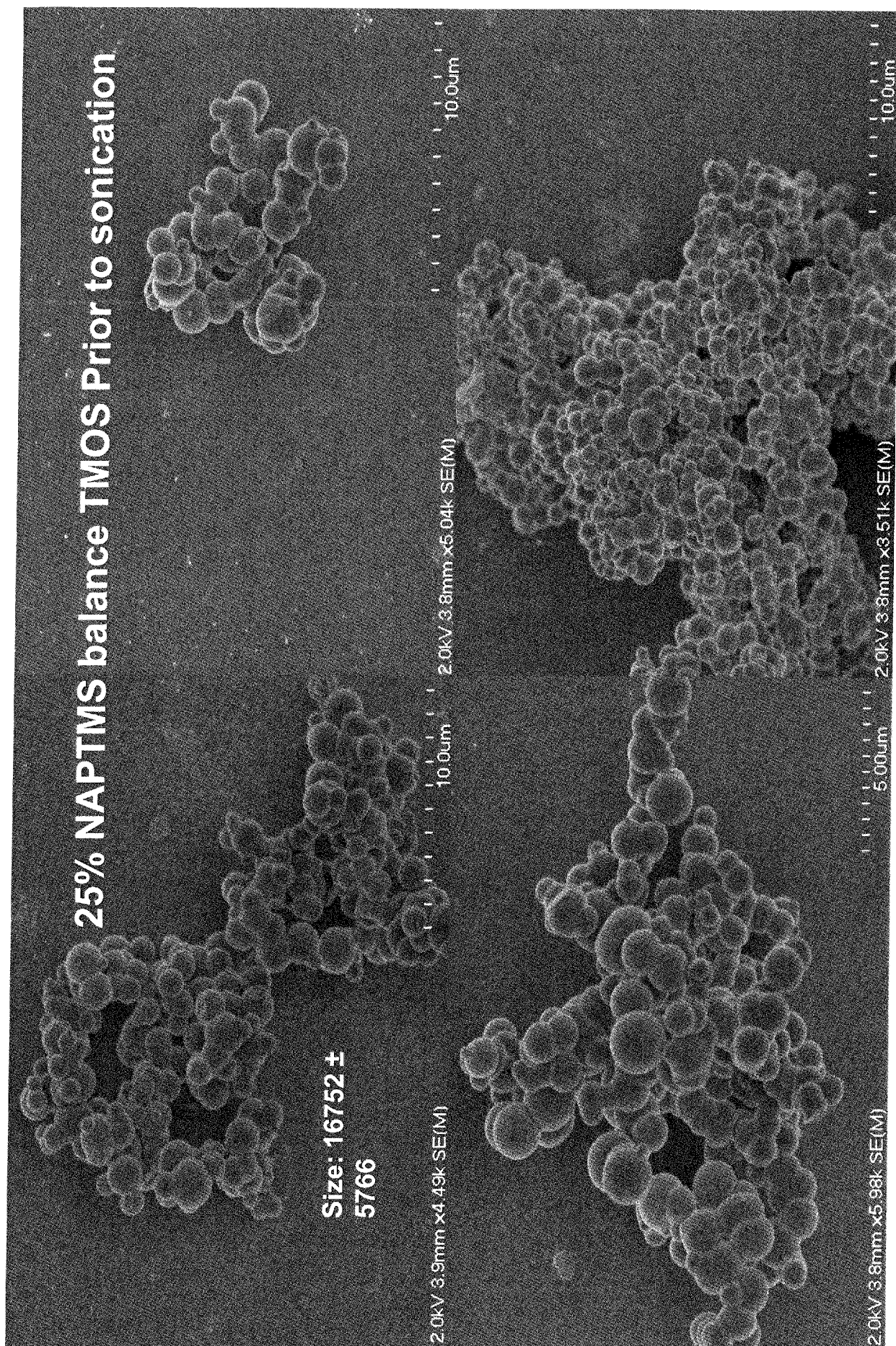


FIGURE 8

**FIGURE 9**

**FIGURE 10**

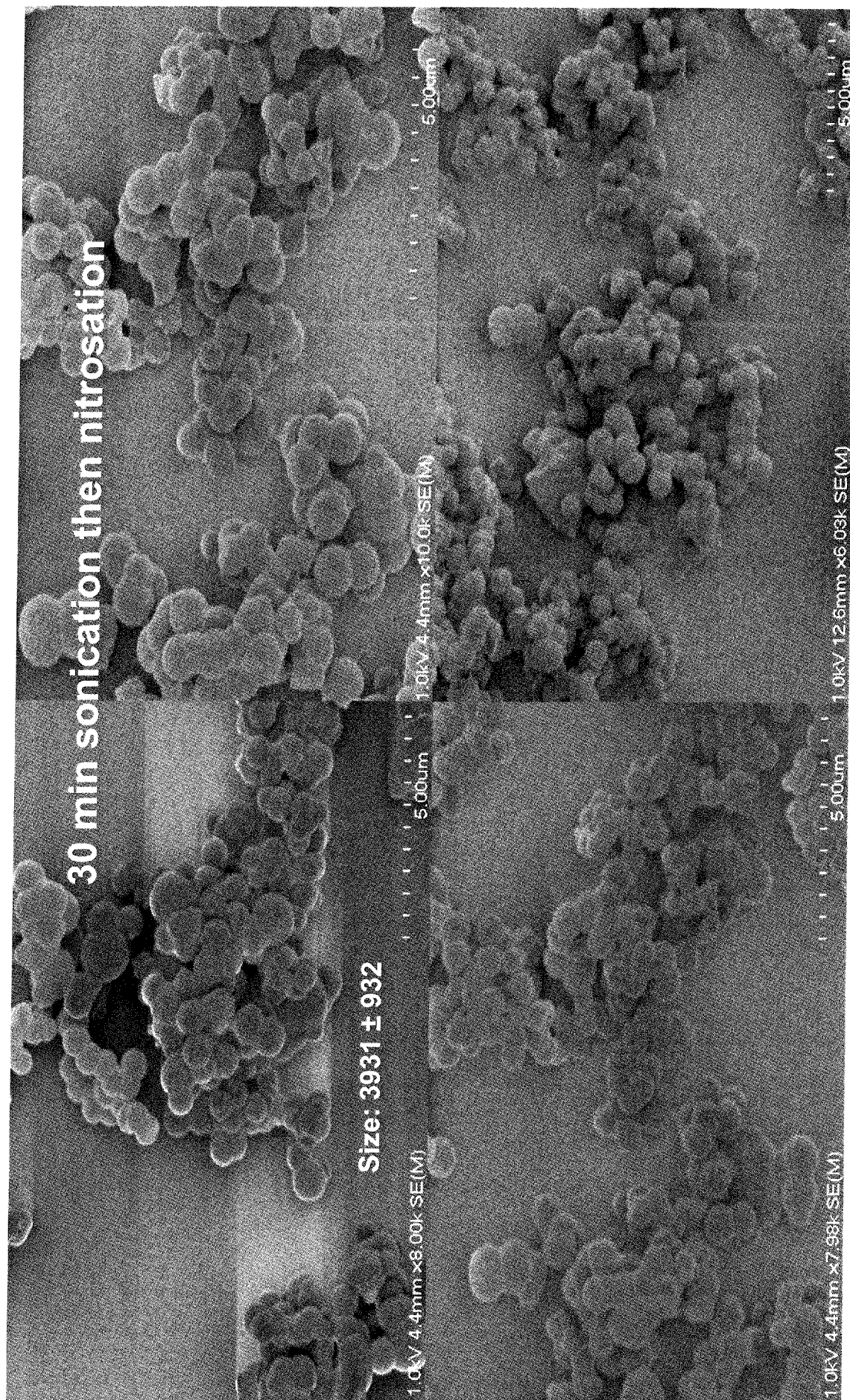


FIGURE 11

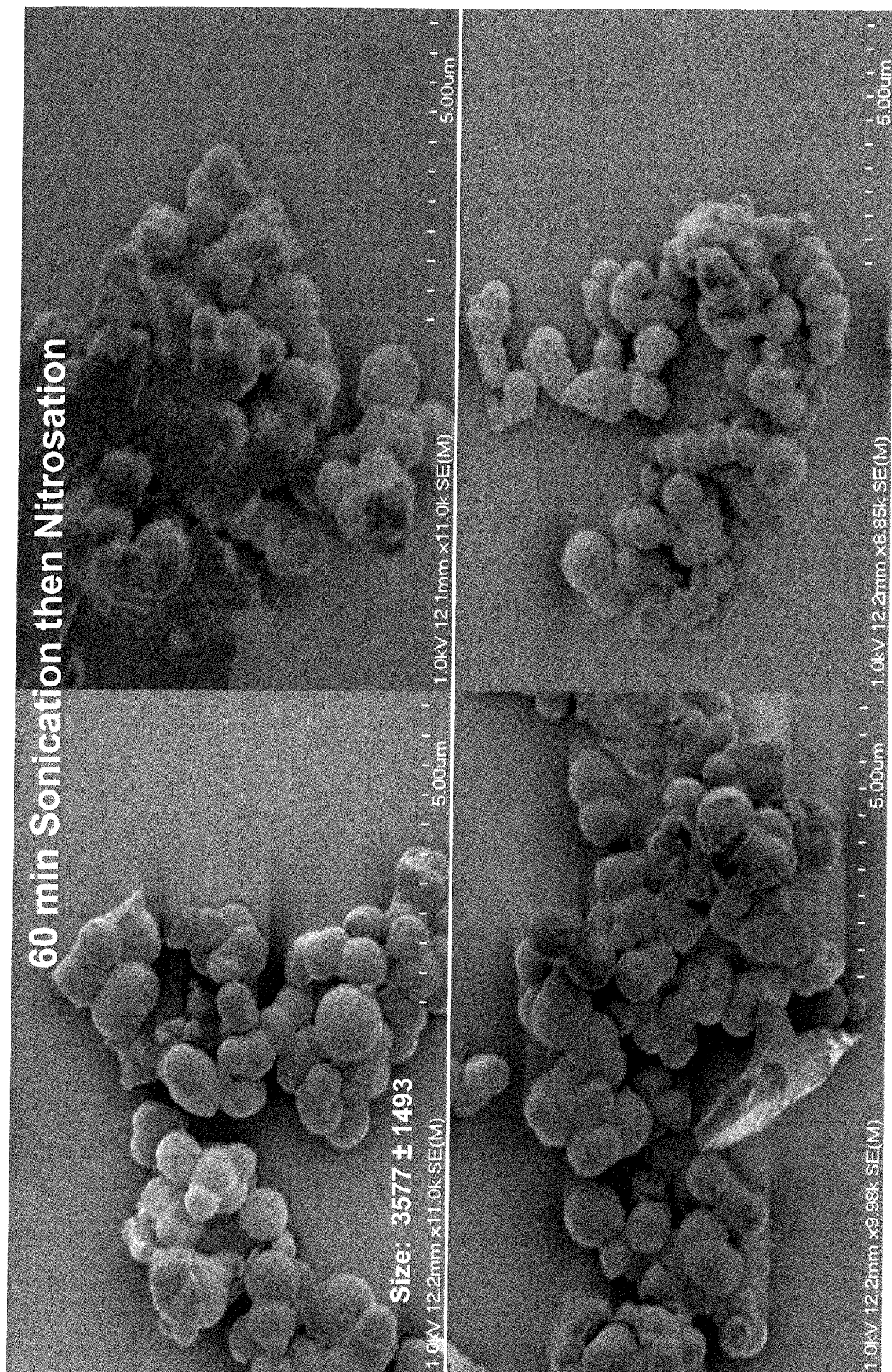


FIGURE 12