

One-pot synthesis of monodispersed phosphazene-containing microspheres with active amino groups

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ABSTRACT: An amine-terminated nucleophile Hexakis (4-aminophenoxy) cyclotriphosphazene (HACP) was synthesized. Its chemical structure was identified by ¹H NMR and ³¹P NMR. Novel monodispersed phosphazene-containing microspheres with active amino groups on the surface have been successfully prepared through a one-pot precipitation polymerization of hexachlorocyclotriphosphazene with HACP. Just by single step, the microspheres were synthesized without stirring, surfactant and ultrasonic irradiation. The diameter of the obtained microspheres ranged from 0.1 to 0.5 μm with the rough surface. And, the onset of the thermal-degradation temperature was 460°C, which is attributed to the highly cross-linked structure and the introduced of the cyclotriphosphazene rings. Moreover, the products at variable stages of polymerization were measured by TEM. The formation mechanism was proposed which is corresponding with an oligomeric species absorbing mechanism. © 2015 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* **2016**, *133*, 43336.

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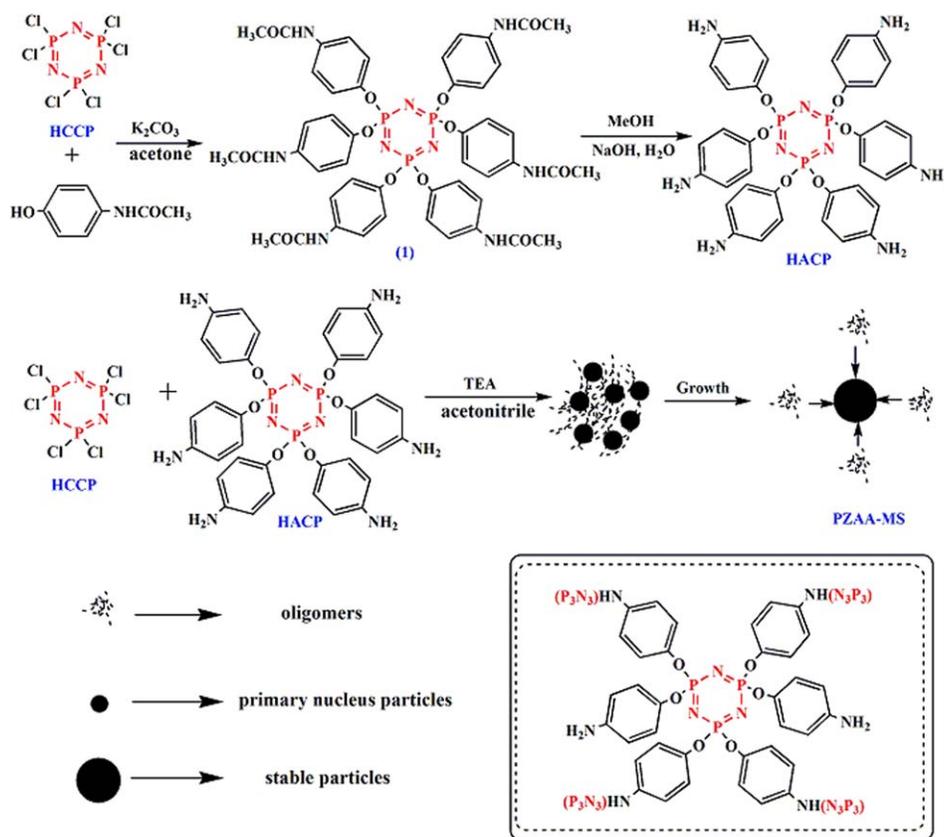
INTRODUCTION

Polymer microspheres as a very important branch of polymer material have attracted more and more attention due to their small size, large specific surface area, high mobility, easy recovery from the dispersion and reversible dispensability, etc. With the fast development of science and technology, the application of polymer microspheres has penetrated into every corner of our life, including commodities such as coatings¹ and cosmetics² or high value-added products such as immunoassay,³ DNA diagnosis,⁴ drug delivery system⁵ and biomimetic sensors⁶ and so on. In recent, polymer microspheres have been synthesized through many methods such as emulsion polymerization, soap-free emulsion polymerization, dispersion polymerization, precipitation polymerization, suspension polymerization, micro-emulsion polymerization, mini-emulsion polymerization, and seeded polymerization. Among them, precipitation polymerization has stood out as an attractive, simple, and seeming general method for producing high crosslinked products as spherical particles. Precipitation polymerization has a unique feature is the absence of any surfactant or stabilizer in the process of obtaining spherical particles.⁷ In general, some microspheres are used as they are, but others are modified before use. So, the

preparation microspheres having functional groups on their surfaces with carbonyl, hydroxyl and amino groups can be modified with protein which has become a trend.⁸ Previously, many types of functionalized microspheres could be prepared by emulsion polymerization using, e.g., dienes and/or vinyl monomers. Different size and composition of functional microspheres have been obtained from addition polymerization, but relatively few condensation polymerizations have been reported. And, these reported methods for preparing monodisperse microspheres usually require multi-step, higher temperature, radiation, special apparatus and rigorous conditions. For example Naka *et al.*⁹ prepared monodisperse particles with broad size distributions under both the AIBN and the ⁶⁰Co γ-ray initiation in a variety of organic solvents. The mechanism of microspheres growth and colloidal stabilization are free of an added stabilizer were suggested the polymer particles grow by reacting with a portion of the oligomer formed in solution and with monomer. Yang *et al.*^{10,11} developed distillation-precipitation polymerization as a novel technique to synthesize polymer colloid. The essential of this method is to distill part of acetonitrile solvent in the process of reaction which makes the hydrophilic polymer to precipitate quickly from the reaction system. The mechanism of distillation-precipitation polymerization is also referred to

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Scheme 1. Synthesis of Hexakis (4-aminophenoxy) cyclotriphosphazene (HACP) and schematic illustration of the formation mechanism of the PZAA-MS. (P_3N_3) indicates other phosphazene cores. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

entropy precipitation.¹² The distillation–precipitation method brings not only the characteristics of precipitation polymerization such as no interfering reagent, high yield and environmental friendliness but also short reaction time (~ 1 – 2 h) and broader applicability, but which also has some inevitable questions involving complicated reactor and distillation process is difficult to control. And yet, the deadly threat is that the poor of colloid stability when the reaction mixtures are not stirred. Therefore, it is very important to develop a simple, low-energy and one-pot method under mild conditions.¹³

Hexachlorocyclotriphosphazene (HCCP) has been widely used in the synthesis of various advanced materials with different structures and morphologies, because of the excellent tailoring property of the skeletal nitrogen and phosphorus atoms and the unprecedented structural diversity.^{14,15} Tang *et al* have prepared a variety of morphologies cyclomatrix-type polyphosphazene with microspheres, nanotubes, nanowires, and networks using HCCP and 4,4'-sulfonyldiphenol (BPS),¹⁶ Benzidine,¹⁷ phloroglucinol,¹⁸ melamine (MA),¹⁹ resveratrol⁵ or (3,5-ditrifluoromethyl)phenylhydroquinone (6F-PH)²⁰ and so on. However, great efforts have been used in developing the functional surface of materials for their special applications. The materials described above need ultrasonic radiation to accelerate the process of reaction and promote colloidal dispersion in the process of polymerization. In the case of nanotubes, they could be obtained under ultrasonic radiation with 0–50 W.^{21,22} When the power of ultrasonic reached to 150 W, the microspheres were

obtained. Yet, ultrasonic has also increased the complexity and uncontrolled of the reaction, simultaneously it was harmful to human health when the power was too high. In this article, we chose cyclotriphosphazene derivative hexakis (4-aminophenoxy) cyclotriphosphazene (HACP) as reaction monomer here and obtained high cross-link microspheres with active amino groups, that is poly [cyclotriphosphazene-*co*-(hexakis (4-aminophenoxy))] microspheres (PZAA-MS), just by a simple and one-step precipitation polymerization. The PZAA-MS were prepared without stirring and ultrasonic radiation. This method provides a facile and new approach to obtain functional materials.

MATERIALS AND METHODS

Materials

Hexachlorocyclotriphosphazene (HCCP) (Aldrich) was recrystallized from dry hexane followed by two times sublimation ($60^\circ C$, 0.05 mmHg) before use (mp 112.5 – $113.0^\circ C$). 4-acetamidophenol, K_2CO_3 , acetone, methanol, NaOH, triethylamine (TEA) and acetonitrile were purchased from Shanghai Chemical Reagents (Shanghai, China). The K_2CO_3 was activated at $140^\circ C$ for 2 h prior to use. The acetone used as the solvent was redistilled from $KMnO_4$, and further distilled from anhydrous $CaSO_4$.

Synthesis of Hexakis (4-Aminophenoxy) Cyclotriphosphazene (HACP)

HACP was synthesized according to the reported previously including two steps, as follow.²³

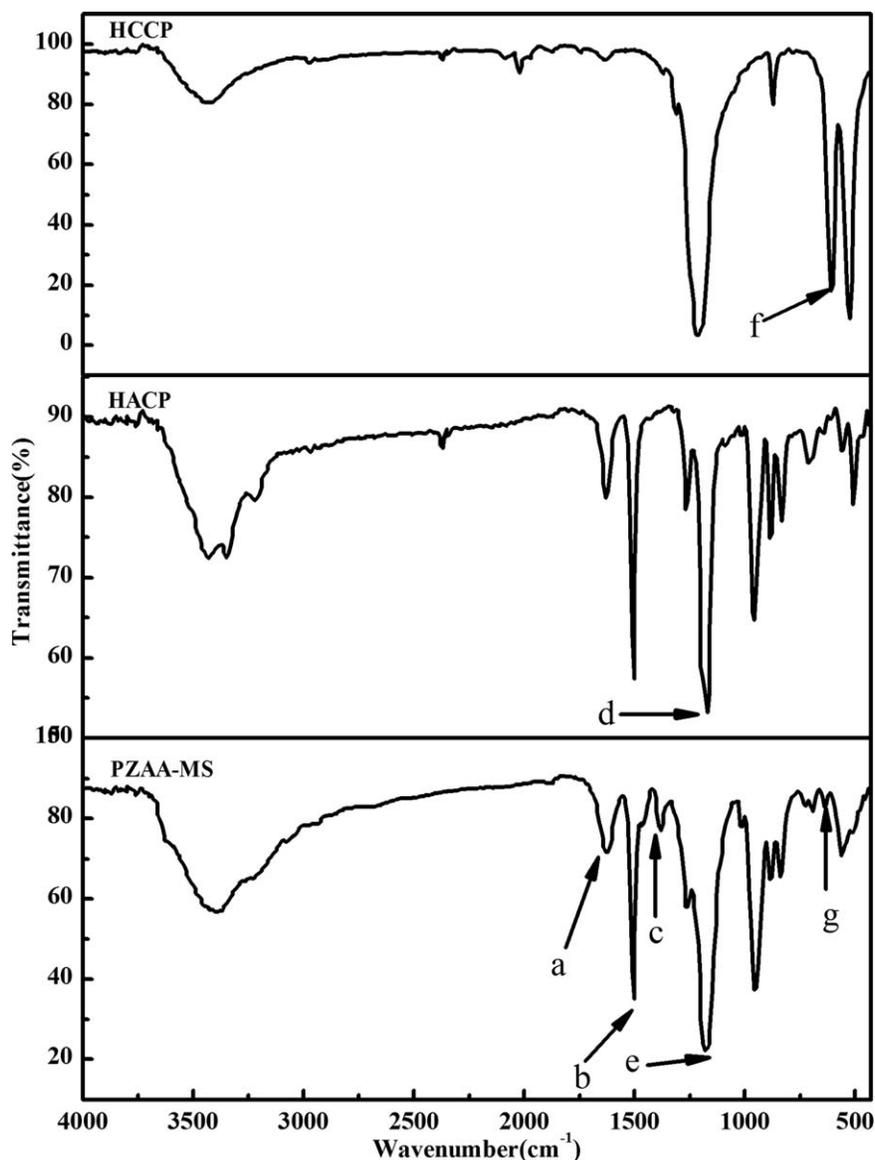


Figure 1. FT-IR spectra of HCCP, HACP and PZAA-MS.

Step 1: Under a dry argon atmosphere, HCCP (5 g, 14.4 mmol) was added to a dried acetone solution (125 mL) containing 4-acetamidophenol (15.7 g, 103.9 mmol) and K_2CO_3 (21.5 g, 155.9 mmol). The mixture was slowly heated to $70^\circ C$ for 24 h under nitrogen atmosphere. After reaction, the solution was concentrated and the residue was dropped into hot water. The product was washed three times with acetone and hot deionized water, respectively. The resulting white solid $[N_3P_3(OC_6H_4\{NH-C(O)CH_3\}-4)_6]$ (1) was dried under reduced pressure in the presence of P_2O_5 . Yield: 13.2 g (89%). 1H NMR (DMSO- d_6): δ [ppm] 9.92(1H, $-NH$), 6.80–7.46(4H, dd, Ar-H), 2.05(3H, $-CH_3$). ^{31}P -NMR (DMSO- d_6): δ [ppm] 9.18.

Step 2: HACP $[N_3P_3(OC_6H_4\{NH_2\}-4)_6]$ was synthesized from (1). To a solution of (1) (5 g, 4.8 mmol) in methanol (150 mL), was added slowly a solution of NaOH (35 g) in water (25 mL), and the mixture was heated under reflux for 48 h. The off-white powder was collected by vacuum filtration. The solid was

then washed twice with water and ethanol respectively and dried *in vacuo* at $40^\circ C$ for 48 h. Yield: 2.8 g (75%). 1H NMR (DMSO- d_6): δ [ppm] 6.42–6.53(4H, dd, Ar-H), 4.91(2H, Ar- NH_2). ^{31}P -NMR (DMSO- d_6): δ [ppm] 10.03.

Synthesis of PZAA-MS

In a typical synthesis process (Scheme 1), HCCP (60 mg, 0.17 mmol) and HACP (135 mg, 0.17 mmol) were added to a three-neck flask containing 20 mL of acetonitrile. Then 145 μ L of TEA was added to the solution, and the mixtures were kept under room temperature ($25^\circ C$). Finally, white suspension was collected by centrifugation and washed several times with acetonitrile and water respectively, then dried in vacuum at $60^\circ C$ to yield white powder.

Microspheres Characterization

1H NMR and ^{31}P NMR spectra were measured on a Varian Mercury (Palo Alto, CA) VX-300 (300 MHz) spectrometer in

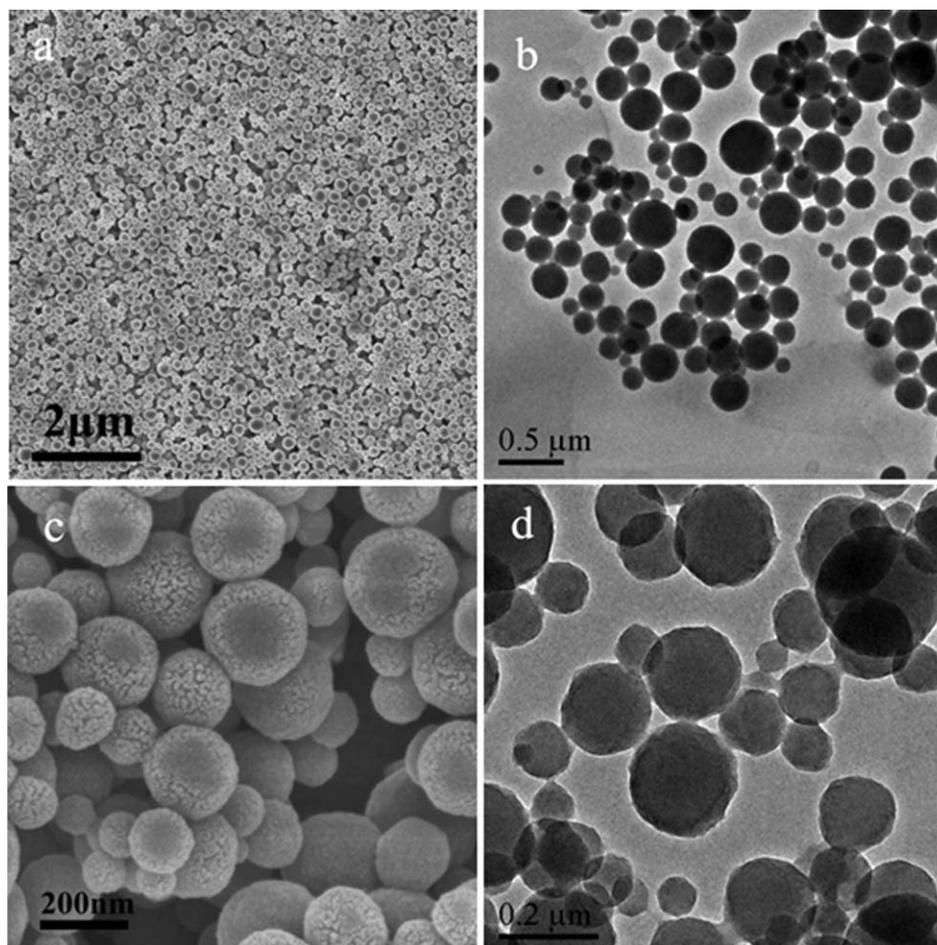


Figure 2. (a,c) SEM and (b,d) TEM images of the PZAA-MS.

dimethyl sulfoxide- d_6 with tetramethylsilane (TMS) as an internal standard. Infrared spectra (IR) were obtained with a Nexus470 FTIR Spectrometer using KBr discs or film samples. The size and morphology of obtained MS were determined at an acceleration voltage of 5.0 KV TEM (Tecnai G2 20S-Twin, FEI) and scanning electron microscopy (SEM) (SU8010, Hitachi, activation 10 kV, Japan). Thermogravimetric analysis data (TGA) were measured with a Seiko Instruments Exstar 6000 TG-DTA 6300 using a heating rate of $10^{\circ}\text{C min}^{-1}$ up to 800°C under N_2 .

RESULTS AND DISCUSSION

The main objective of this work was to introduce a simple method to synthesize PZAA-MS with amino group on their surface. Compared with the methods need ultrasonic radiation, this method not only saves energy, but also improves the controllability of the reaction. So, this interesting approach might open a novel, simple, economic route to preparing monodisperse phosphazene-containing microspheres.

The single-step synthesis route of PZAA-MS is illustrated in Scheme 1. And, the precipitation polymerization was conducted under the room temperature in the absence of ultrasound irradiation and stirring. Actually, the polymer PZAA-MS was obtained by nucleophilic replacement reaction between the ter-

минаl amino groups and P—Cl bonds. It obeyed an oligomeric species absorbing mechanism.²⁴ This strategy was inspired by the description of Ref. 20. The HACP was chose as nucleophile reagent instead of aromatic compounds such as benzidine, phloroglucinol or 4,4'-sulfonyldiphenol and the presence of large amounts of phosphazene units in the macromolecules could endow polymers with special functional properties to meet various needs. It could be found that the viscosity of

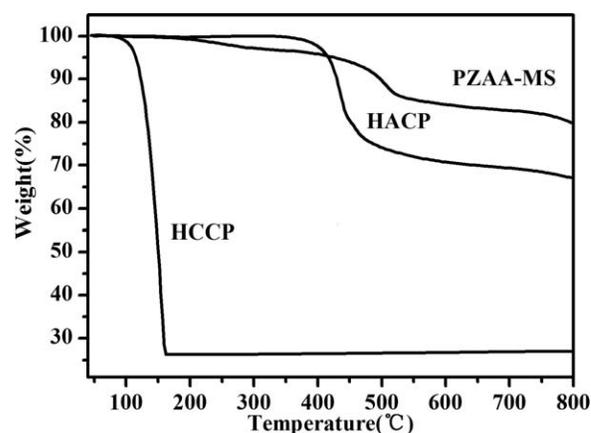


Figure 3. TGA curves of HCCP, HACP and PZAA-MS.

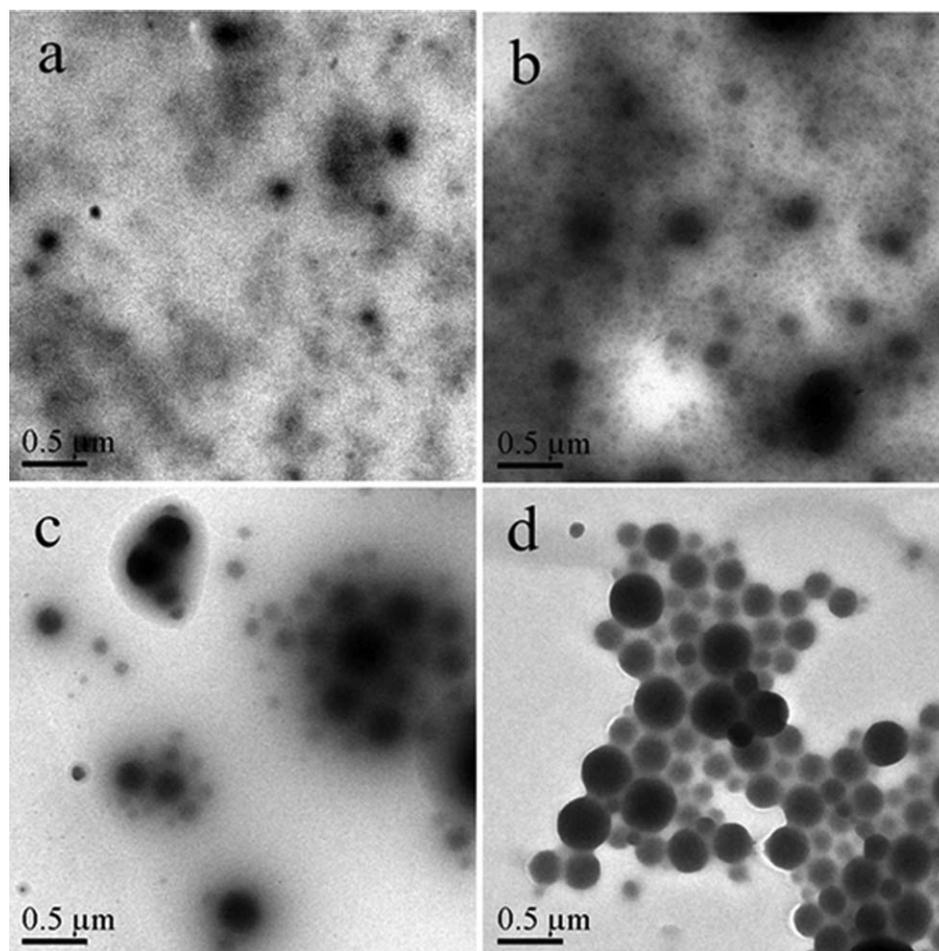


Figure 4. TEM images of the PZAA-MS at different formation stages.

reaction system was increased when the P—Cl bonds were substituted partly.²⁵ So, the advantage of HACP as reaction monomer is that it improves the heat-moisture resistance and flame retardancy of product, but has a certain contribution on the control of reaction rate. Based on the above saying, the oligomer is more likely to adsorb each other in the polycondensation reaction between HCCP and HACP. The polymerization was performed in a mixed solution of acetonitrile and TEA. Hydrogen chloride (HCl) was generated from the reaction and then absorbed by TEA to afford TEA·HCl. According to the description of Zhu *et al.*²¹ TEA·HCl plays an important role which could form nanofiber in tetrahydrofuran as the polymerization proceeded. The oligomers could adhere on the surface of TEA·HCl. Then the polymer nanotubes were obtained from the removal of TEA·HCl nanocrystals. In this article, the TEA·HCl could dissolve in acetonitrile simultaneously when it was generated. So, acetonitrile was critical for the formation of the microspheres, otherwise the oligomer will attach on the TEA·HCl nanocrystals to form nanotubes.

The chemical structure of the raw materials and as-prepared PZAA microspheres were characterized by FT-IR measurements. As shown in Figure 1, the characteristic peaks at 1630 cm^{-1} (a) and 1500 cm^{-1} (b) are attributed to the benzene ring absorption of the HACP units. The absorption peak at 1380 cm^{-1} (c) is assigned to

the inter ring C—C band of benzene. The P=N of cyclotriphosphazene in HCCP can be seen at 1200 cm^{-1} . By contrast, the characteristic peak of P=N band shows a different little shift to 1170 cm^{-1} (d) and 1180 cm^{-1} (e) in HACP and PZAA-MS, respectively, demonstrating the formation of new P—NH—(Ph) band. Furthermore, it can be seen that the strong adsorption peak of the P—Cl band of HCCP at 608 cm^{-1} (f) no longer exists in HACP, but it exists a little residual at 609 cm^{-1} in PZAA-MS, which is corresponding with the result of EDS (energy dispersive X-ray spectroscopy) as shown in Supporting Information Figure S1, that is, a small amount of chloride was detected except carbon, nitrogen, phosphorus, oxygen. Based on FT-IR and EDS analyses, the cross-linked phosphazene-containing structure with active amino groups was obtained, and the corresponding structure of PZAA-MS was proposed, as shown in Scheme 1.

The morphology and microstructure of the as-obtained powder has been investigated by SEM and TEM measurements. Figure 2(a–d) show, with increasing magnification, the PZAA-MS is composed of monodisperse microspheres with average diameter about 200 nm and few impurities are observed. However, the PZAA-MS is not perfect spherical shape and uniform size. It can be seen from Figure 2(b) that the microspheres include the maximum size of $0.5\text{ }\mu\text{m}$ and the minimum size of $0.1\text{ }\mu\text{m}$. As shown in Figure 2(c), the microspheres have rather rougher

surface morphology because lots of nanoparticles are attached on their surface which is corresponding with the oligomeric species absorbing mechanism.

The thermal stability of the PZAA-MS was also investigated by thermogravimetric analysis (TGA), and the results are shown in Figure 3. It can be seen that there are two weight loss steps, the onset of the thermal degradation temperature (T_d) of the PZAA-MS occurred at round 200°C and the second one occurred at 460°C under nitrogen atmosphere. This result can be explained as follows: When the crossing degree of polymer is relatively low, its thermal decomposition temperature is also lower. So, the initial decomposition of the PZAA-MS is attributed to the part of polymer with relatively low cross-linking density, which constitutes less seven percent of the total. This observation of T_d is marked higher than that reported by Shim *et al.*²⁶ for T_d of the fully crosslinked poly (styrene-*co*-divinylbenzene) microspheres varied from 339.8 to 376.9°C. In addition, the weight loss is <20% when the temperature reaches 800°C. And, the decomposition temperature of HACP is reached to 380°C. PZAA-MS has much superior thermal stability compared with the two monomers, which may be owed to the existence of the inorganic–organic hybrid cyclotriphosphazene rings in the highly cross-linked hybrid structure.²⁷

To further investigate the formation mechanism of the PZAA-MS, the products at variable stages of polymerization were measured by TEM. During the initial stage of precipitation polymerization, the system was homogenous. That is, with the polymerization proceeding, the primary particles are precipitated from the solvent, which take a relatively extended period of time (12 h). The result is different from the description of Ref. 28, which showed that a milky white mixture was observed at once with the addition of TEA. At the initial stage, HCCP reacted with HACP to generate oligomers. Then, when the aggregation of oligomers reached one critical value, they would precipitate from the system as primary nucleus particles, as shown in Figure 4(a). Figure 4(b) shows the unstable nucleus particles adsorbed oligomers or the oligomers intertwined to form the secondary nuclei with diameters of 10–20 nm. These nuclei were unstable and aggregated with each other to form stable particles. Furthermore, the solubility test shows that the polymers of this phase are water solution. As can be seen in Figure 4(c), the secondary nuclei adsorbed oligomers to form stable seeds in size, instead of formation new nuclei. Owing to the stronger interaction with hydrogen bonds and the lower steric hindrance effect, the oligomers (gray) were around the stable seeds with diameters of about 50 nm. At the middle stage of the polymerization, the stable seeds continued to absorb the oligomers. In this stage, it can be seen that the quantity of oligomers decreased significantly in Figure 4(d). At last, the expected sizes of monodisperse microspheres were obtained. In the present case, the complete removal of TEACl and some oligomers could be a result of the high solubility of them in water and acetonitrile, which was could also explained why the PZAA-MS had rough surface.

CONCLUSIONS

In summary, a novel crosslinked cyclomatrix-type polyphosphazene material was prepared efficiently by facile precipita-

tion polymerization between hexachlorocyclotriphosphazene and HACP in acetonitrile without ultrasonic irradiation and stirring, which was, in essence, the nucleophilic replacement reaction between the terminal amino groups and P–Cl bonds. These microspheres performed high thermal decomposition temperature and high rate of residue, which suggested that the PZAA-MS can be used as raw material of carbon materials and flame-retardant materials. This approach could be extended to other similar polymerizations and used to obtain polymer microspheres with controlled dimensions and desired groups.

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