Radical Polymer Containing a Polytriphenylamine Backbone: Its Synthesis and Electrochemical Performance as the Cathode of Lithium-Ion Batteries

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A novel radical monomer containing triphenylamine and the 2,2,6,6-tetramethylpiperidinyl-*N*-oxy (TEMPO) radical has been synthesized. The corresponding linear homopolymer of 4-carboxy-*N*,*N*-diphenylaniline-2,2,6,6-tetramethylpiperidin-1-yloxy (PTPA-TEMPO) was then prepared by chemical oxidative polymerization. The chemical structure and electrochemical properties of the prepared polymers were characterized by Fourier transform infrared spectroscopy, ultraviolet–visible spectroscopy, scanning electron microscopy, cyclic voltammetry, and galvanostatic charge–discharge testing by the simulated lithiumion half-cell method. The results demonstrated that the as-syn-

thesized functional polymers exhibited an initial discharge capacity of up to 140 mAh g⁻¹ with two well-defined plateaus at the potential of 3.8 and 2.7 V versus Li/Li⁺. Furthermore, the PTPA-TEMPO electrode showed superior cycling and rate performances. The improved electrochemical performances were attributed to the construction of the novel linear radical molecular structure with PTPA as the conductive polymer backbone, which improved the long-range charge-carrier transportation and facilitated the Li⁺-ion insertion–extraction process in the aggregated polymer bulk during the charge–discharge process.

Since then, various studies have focused on the properties

of radical polymers themselves and conductive agents rather

Introduction

Studies on rechargeable secondary batteries composed of a radical polymer have become of great interest in recent years owing to their rapid electron transfer, high charge capacity, and an output voltage of 3.6 V against a lithium anode.^[1,2] The studied radical polymers generally have an oxygen-centered nitroxide radical, 2,2,6,6-tetramethylpiperidinyl-N-oxy (TEMPO), as the pendant group, which contains a resonance structure and usually displays two redox couples. During the charge-discharge process, TEMPO can be reversibly oxidized to the corresponding oxoammonium cation (p-type doping) and reduced to the corresponding aminoxy anion (ndoping).^[3] Poly(2,2,6,6-tetramethylpiperidinyloxy-4-yl type methacrylate) (PTMA) has been one of the nitroxide radical polymers most typically employed as the cathode-active material since first being proposed by Nakahara et al. in 2002.^[4] As reported,^[4] PTMA applied to the cathode in lithium-ion batteries exhibited an outstanding cathode performance: high capacity, high charging and discharging rate performance, long cycle life, and processing compatibility.

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independently, to increase the energy density of radical batteries and improve the battery performance.^[5,6] In most of those efforts, nitroxide radicals are attached generally to polymers with an aliphatic or nonconducting type of backbone, such as polymethacrylate,^[7] polynorbornene,^[8] cellulose,^[9] poly(*p-tert*butylaminoxy-styrene),^[10] and poly(vinyl ether).^[11] However, the above nitroxide radical polymers are derivatives of conventional plastics, which are insulators, thus resulting in electron transfer among the polymer molecules by means of hopping between the pendant redox sites (short-range conductivity), which are isolated in the polymer and the long-range conductivity is limited.^[1] As a result, a relatively high proportion of the conducting agent, even up to 60-80 wt%, is required in the fabrication of the composite electrode to improve the longrange conductivity and the utilization rate of nitroxide radical contained in the electroactive polymer. This leads the actual redox capacity of the composite electrodes to decrease seriously and extensive studies to use them as active materials for batteries to be impeded. The intrinsic conductivity of most radical polymers is rather low owing to the insulating backbone, so a combination of a stable radical with a conductive polymer is regarded as an effective way to produce a new radical polymer with an improvement of electron migration. A few TEMPO-containing polyacetylenes and polythiophenes have been synthesized and used as a cathode-active material in a rechargeable battery.^[3,12] Unfortunately, degradation of the unstable conducting polymer backbone enforced by the presence of the radical moiety is observed, which hinders the improvement of the electrochemical properties of the TEMPO-



based active polymer, as well the further exploration of the details of the charge–discharge process or of the influence of the conductive backbone on the electrochemical properties of TEMPO.

Polytriphenylamine (PTPA), as well its derivatives, contains triphenylamine radical units and belongs to another family of radical polymers, which exhibited a reversible radical redox reaction during the charge and discharge processes.^[13,14] As a result, triphenylamine-based polymeric materials have been explored recently as the electrode material applied in the energy storage field, such as supercapacitors and lithium-ion batteries.^[14–16] As reported,^[14] the electrochemical and cell performance of PTPA as the cathode material was studied by a simulated three-electrode method. The results indicated that the PTPA-based electrode had not only superior high power capability but also high energy density at prolonged cycling and a well-defined voltage plateau of 3.8 V, which could contribute to the π -conjugated triphenylamine substructure and reversible redox radical nature of PTPA. As a solution, to design a novel molecular structure containing both PTPA and TEMPO moieties would be promising to produce a new functional material with improved cell performance.

Herein, a novel and linear radical polymer was constructed with PTPA as the conductive polymer backbone and TEMPO as the pendant groups. The structure and electrochemical properties of the prepared polymer were investigated systematically as cathode materials for Li-ion batteries. Furthermore, the possible relationships of the structure characteristics of PTPA-TEMPO and the improved electrochemical properties of the material are discussed in detail. Thanks to the construction of the novel linear radical molecular structure with PTPA as the conductive polymer backbone, we found that the PTPA-TEMPO-based electrode had remarkably improved charge-discharge performance compared with the as-prepared PTPAbased material and was promising as an advanced cathode material.

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Figure 1. FTIR spectra of samples of PTPA and PTPA-TEMPO.

amine and TEMPO moieties have been contained in the PTPA-TEMPO polymer, and have not been destroyed during the polymerization process.

The UV/Vis spectra (normalized absorbance) were further measured in *N*,*N*-dimethylformamide (DMF; 10^{-3} gL⁻¹) to explore the characteristics of PTMA, PTPA, and PTPA-TEMPO. As depicted in Figure 2 curve (b), the PTPA exhibits only one



Figure 2. UV/Vis spectra of a) PTMA, b) PTPA, and c) PTPA-TEMPO.

sharp absorption peak at 356 nm, which is attributed to the π - π^* electron transition of PTPA,^[18, 19] whereas curve (a) displays an absorption of 460 nm (n- π^*) resulting from the pendants of the nitroxide radical along the PTMA polymer chain.^[20] In contrast, two distinct absorption peaks are observed in the UV/Vis spectra of PTPA-TEMPO. The absorption peak at 375 nm is still ascribed to π - π * transition from the triphenylamine units, and another peak at 475 nm corresponds to the $n-\pi^*$ transition absorption of the pendants of the nitroxide radical along the polymer chain. In particular, the absorption peaks of nitroxide radical moieties in the PTPA-TEMPO redshift from the 465 nm of PTMA to 475 nm, thus implying that the site-to-site electron hopping process of the nitroxide radical by self-exchange reactions in PTPA-TEMPO becomes easier than that of PTMA. Furthermore, it can be observed that the π - π * electron transition of triphenylamine units for the PTPA-TEMPO also has a clear redshift relative to PTPA, which indicates the extended electron

Results and Discussion

Material characterization

Figure 1 shows the FTIR spectra of the as-prepared PTPA and PTPA-TEMPO. By comparison with the typical FTIR spectrum of PTPA,^[14] the main characteristic peaks of the PTPA can be found in both of the samples, and involve the fundamental vibrations of triphenylamine moieties for C=C ring stretching at 1594 cm⁻¹, C–C stretching at 1490 cm⁻¹, and C–H bending at 1328 cm⁻¹. The absorption peaks at 1276 and 820 cm⁻¹ correspond to the C-N stretching of the tertiary amine and a C-H out-of-plane vibration from 1,4-disubstituted benzene rings, respectively. Besides, a number of new bands can be clearly observed in the spectrum of PTPA-TEMPO, in which the absorption peak at 1708 cm^{-1} is ascribed to C=O (ester carbonyl) whereas the absorption peak at 1176 cm⁻¹ is the stretching of γ_{C-O-C} existing in the ester linkage. In particular, the absorption peak at 1365 cm⁻¹ is attributed to nitroxide radical groups in the polymers.^[17] These results indicate that both triphenyl-

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delocalization and the improved electron transportation in the polymers. This phenomenon can be explained as follows: the introduction of TEMPO units as the terminating group results in the molecular structure changing from a cross-linked structure to a linear structure, which relieves the steric torsion between triphenylamine units in PTPA and leads to improved π conjugation and electron transportation along the polymer chain. The improved electron transportation in the linear PTPA chain and a radical electron hopping process among the pendant nitroxide radical moieties will be of benefit to the charge-carrier transportation type changing from short-range conduction to long-range conduction, which is crucial for high-rate performance lithium batteries.

The morphologies of the PTPA and PTPA-TEMPO are shown in Figure 3. As can be seen, the PTPA has a dense aggregation structure with a size of several micrometers (Figure 3a). Com-



Figure 3. SEM images of powder samples: a) PTPA and b) PTPA-TEMPO.

paratively, when TEMPO as a functional terminating group is introduced into PTPA, the morphology of the obtained PTPA-TEMPO is different from that of PTPA under the same experimental conditions. As shown in Figure 3b, PTPA-TEMPO exhibits a loosely assembled spherical structure consisting of many small particles of size about 100 nm with good dispersion. This structural feature of PTPA-TEMPO may provide sufficient surface area and ionic channels for the contact of electrode-active material and electrolyte, and as a result, the much more electrode-active material is utilized effectively during the charge– discharge process and the electrochemical properties of PTPA-TEMPO are clearly improved. All of these factors are very important to prepare a good cathode material for Li-ion batteries.

Electrochemical performance

Figure 4 shows the cyclic voltammetry (CV) profiles of PTPA, PTMA, and PTPA-TEMPO measured in 0.1 M lithium perchlorate/acetonitrile solution. The PTPA electrode shows a couple of anodic and cathodic peaks at about 1.11 and 0.75 V with a potential separation of about 0.36 V, which corresponds to the charge–discharge reaction of the triphenylamine radical redox couple of PTPA. The approximately symmetrical peaks suggest a good insertion–extraction reversibility of the produced PTPA cathode-active material. PTMA displays a pair of redox potentials at 0.90 and 0.72 V versus Ag/AgCl, which are assigned to the oxidation of the nitroxide radicals to the corre-

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Figure 4. Cyclic voltammograms of a) PTPA-TEMPO, b) PTPA, and c) PTMA in 0.1 $\,\rm m$ LiClO₄/CH₃CN versus Ag/AgCl at a scan rate of 10 mV s^{-1}.

sponding oxoammonium cations or the p-type doping of the material.^[21] The corresponding difference in separation of the oxidation and reduction peak potentials is estimated as 0.18 V. Comparably, there are some differences for the CV curves of PTPA-TEMPO, in which one pair of reduction and oxidation peaks appearing at 1.03 and 0.91 V can be assigned to the redox reaction of triphenylamine units of PTPA-TEMPO and another pair of weak redox peaks at 0.83 and 0.76 V results from the p-type doping of nitroxide radical (from the nitroxide radicals to the oxoammonium cations). Furthermore, the corresponding peak-to-peak separations exhibited by the PTPA-TEMPO electrode are 0.12 and 0.07 V, respectively, which are relatively narrower than those of the PTPA and PTMA electrodes, thus implying the good oxidation/reduction reversibility of the produced active materials as cathode. Notably, a third couple of redox peaks with weak intensity appears near -0.2 V for PTPA-TEMPO (as shown in the inset of Figure 4a), which can be attributed to the redox couple of the n-type doping of nitroxide radical (from the aminoxy anion to the nitroxyl radicals) and does not occur in the CV curves of both PTMA and PTPA at the same position. It can be assumed that the introduction of stable conjugated PTPA as the main chain of TEMPO-containing polymer works as an electrocatalysis function, which promotes the redox reaction between the radical and aminoxy anion (n-type doping process), thereby leading to the appearance of a third pair of redox peaks. This electrocatalysis phenomenon is similar to that in previous reports,^[22,23] which indicated that the battery performance of the sulfurcontaining organic compound dimercaptan can be clearly improved by the introduction of polyaniline, owing to the electrocatalysis effect of polyaniline.

Charge-discharge performance

The charge-discharge behaviors of the as-prepared polymers as the cathode of lithium batteries have been investigated sys-



tematically by the simulated lithium-ion half-cell method to estimate the cell performance more realistically. The initial charge–discharge profiles of the polymer electrodes at 20 mAg^{-1} between 2.5 and 4.2 V are shown in Figure 5. The



Figure 5. Initial charge–discharge profiles of the polymeric electrode materials at a constant current of 20 mA g⁻¹ between 2.5 and 4.2 V in LiPF₆ in ethylene carbonate (EC)/dimethyl carbonate (DMC) (1:1, v/v) electrolyte versus Li/Li⁺.

PTPA shows initial charge-discharge capacities of 104.3/ 97 mAh g⁻¹ with a typical discharge voltage plateau in the range of 3.5-4.1 V at the initial cycle, which is almost in accord with the reports.^[24] The coulombic efficiency from the above results is approximately 93%. For PTMA, the charge-discharge curves present one clear discharge voltage platform at about 3.6 V with an initial charge-discharge capacity of 86.8/ $84~\text{mAh}\,\text{g}^{-1}\text{,}$ which corresponds to $96.8\,\%$ of the coulombic efficiency. Comparatively, under the same conditions, the PTPA-TEMPO electrode exhibits an initial charge-discharge capacity of up to 146.6/140 mAh g^{-1} and 95.4% of the coulombic efficiency, with two clear discharge voltage platforms at about 3.8 and 2.7 V, respectively. The higher discharge voltage platform is attributed to the stacking up of the voltage platforms of both PTMA and PTPA. The lower plateau at 2.7 V corresponds to the n-type doping process with the redox couples changing from the nitroxide radical to the aminoxy anion. This characteristic has been presented in some reports,^[3,12] but the emerging reason for this voltage platform has not been mentioned. Therein, it is considered to be caused by the electrocatalytic function of the introduced PTPA to nitroxide radical pendants.

The improved specific capacity for PTPA-TEMPO can be attributed to the introduction of the conjugated conductive polymer backbone (PTPA), which is itself an electroactive material and can be partly responsible for the improvement of total capacity. Furthermore, the second voltage platform occurring at 2.7 V, as a result of the redox process of the second electron caused by the electrocatalysis function of the PTPA backbone to nitroxide radical pendants, is also ascribed to the increased discharge capacity. Notably, the voltage platform of the PTPA-TEMPO electrode at high voltage is clearly higher than that of either PTPA or PTMA, which can be ascribed to the electronwithdrawing effect of the C=O bond (ester carbonyl) existing in the ester linkage, which leads to the increase of the chargedischarge voltages of the PTPA part in PTPA-TEMPO.^[10] As a result of that, the redox couple of TEMPO is relatively weaker than that of PTPA in the CV curves of PTPA-TEMPO (as shown in Figure 4a). It can be considered that the capacity contribution from the TEMPO part in PTPA-TEMPO polymer (mainly obtained by the redox reaction process from the oxoammonium cations to the nitroxide radicals) is relatively less than that of the PTPA part, which results in the total higher voltage platform at about 3.8 V. This high voltage platform is favorable for producing a promising cathode material with high energy density.

We further investigated the cycling stability of the as-prepared polymers as cathode materials of Li-ion batteries, as shown in Figure 6. It was found that PTPA-TEMPO electrodes



Figure 6. Cycling stability of the polymeric electrode materials at a constant current of 20 mA g⁻¹ between 2.5 and 4.2 V in LiPF₆ in EC/DMC (1:1, v/v) electrolyte versus Li/Li⁺.

show a similar stable cycling performance to PTPA. After 50 cycles, the discharge capacity of PTPA decreases from its initial 97 mAh g⁻¹ to 84 mAh g⁻¹, with about 14% loss of capacity. The discharge capacity of PTPA-TEMPO drops from its initial 140 mAh g⁻¹ to 125 mAh g⁻¹, with only about 11% loss of capacity, which is even lower than the initial capacity of PTPA. As reported,^[25] the stability of the micromorphology and chemical structure of polymeric materials has a great influence on the charge–discharge cycling stability. The above results demonstrate that the structures of the PTPA-TEMPO electrodes are relatively stable, and during the electrochemical Li⁺-ion insertion–extraction process, the micromorphology and chemical structure of the polymeric materials are destroyed less, which makes the charge–discharge process quite reversible.

The rate performances of the polymer electrodes were further examined at different current rates of 50, 100, 300, and 500 mAg⁻¹. Compared with the parent PTPA, the PTPA-TEMPO electrode displays an improved rate capability with an enhanced current rate from 50 to 500 mAg⁻¹, as shown in Figure 7. The specific capacities for PTPA-TEMPO are 128.1, 122.0, 113.5, and 105.3 mAg⁻¹, with a 10 times increase in the current from 50 to 500 mAg⁻¹, which are still higher than that of PTPA at high current rate, although the decay rate of capaci-







Figure 7. Rate performances of the polymer electrodes in the voltage range from 2.5 to 4.2 V at various current rates of 50, 100, 300, and 500 mA g^{-1} .

ty is comparatively high. In addition, PTPA and PTPA-TEMPO present a quickly recovered ability of capacity, as the current rate gets back to 50 mAg⁻¹. The possible reasons for the improved high rate capability can be partly ascribed to the novel molecular structure design, in which introduction of the conjugated PTPA as the conductive molecular backbone improves the long-range charge transportation of the nitroxide free radical in the aggregated polymer (as indicated in the UV/Vis spectra), which leads to the rapid charge-transportation ability of PTPA-TEMPO and the higher rate performance. Furthermore, the introduction of the nitroxide radical as the terminating group into triphenylamine units leads to the molecular structure of PTPA changing from a cross-linked structure to a linear structure, which, as well as the tiny particle morphology of PTPA-TEMPO, will be convenient for Li⁺-ion insertion-extraction during the charge-discharge process, which is also responsible for the high rate capability. Thus, the novel PTPA-TEMPO polymer would be a good potential candidate for cathode materials of high-power lithium batteries.

Conclusion

A novel and linear 2,2,6,6-tetramethylpiperidinyl-N-oxy

(TEMPO)-based polytriphenylamine (PTPA) derivative, with PTPA as molecular backbone and TEMPO as pendant groups, has been synthesized successfully by chemical oxidation polymerization. Compared to PTPA, PTPA-TEMPO exhibited two clear voltage plateaus with a higher discharge capacity of 140 mAhg⁻¹ during the chargedischarge process, which was attributed to the electrocatalytic function of PTPA as a molecular backbone that promoted the ntype doping process with the redox couple changing from the nitroxide radical to the aminoxy anion. Also, the PTPA-TEMPO cathode presented good cycling stability with over 89% of the initial capacity after 50 cycles. Furthermore, the rate performance of the PTPA-TEMPO composite cathodes was improved, which was ascribed to both the introduction of the PTPA backbone in the TEMPO-based polymer and the construction of the linear molecular structure, which enhanced the long-range electron migration and Li⁺-ion insertion-extraction process in the aggregated polymer bulk during the charge-discharge process. All the results indicated that the designed PTPA-TEMPO as composite cathode is a promising candidate for potential applications in organic radical batteries.

Experimental Section

Materials

Diphenylamine (98%), 4-fluorobenzonitrile (99%), and 4-hydroxy-2,2,6,6-tetramethylpiperidine 1-oxyl free radical (99%) were purchased from Energy Chemical Reagent Co. Sodium hydride (60%), N-methylpyrrolidone (NMP, 99.9%, electronic grade), and N,N-dimethylformamide (DMF, 99.9%, HPLC grade) were purchased from Aladdin. All other reagents were received as analytical grade and used without further purification.

Syntheses

Synthesis of PTPA-TEMPO: The synthesis of the monomer (TPA-TEMPO) is shown in Scheme 1.

Synthesis of 4-cyano-N,N-diphenylaniline: Diphenylamine (5.1 g) and sodium hydride (1.5 g) were firstly dissolved in DMF (50 mL). Then 4-fluorobenzonitrile (4.5 g) was added to the above solution. The reaction was performed under a nitrogen atmosphere for 12 h at 110 °C. The resulting solution was extracted with dichloromethane and dried by anhydrous MgSO₄. The obtained 4-cyano-N,Ndiphenylaniline (1) was isolated by column chromatography as a yellow powder with 61.1% (4.98 g) yield.



Scheme 1. Synthesis route to PTPA-TEMPO.



¹H NMR (CDCl₃, 500 MHz): δ =6.94 (d, 2H), 7.20 (d, 4H), 7.25 (d, 2H), 7.39 (t, 4H), 8.05 ppm (d, 2H); MS (EI): *m/z* (%): 270.12.

Synthesis of 4-carboxy-*N*,*N***-diphenylaniline**: Potassium hydroxide (2.1 g) and 4-cyano-*N*,*N*-diphenylaniline (1.0 g) were firstly dissolved in a mixture of deionized water (30 mL) and glacial acetic acid (20 mL) in a predried three-necked flask and heated at reflux (85 °C) for 48 h. The reaction mixture was then cooled and hydrochloric acid (1 m) was added dropwise to the reaction solution until the pH value of the reaction solution was adjusted to about 1. The white precipitate was then isolated by fitration and washed with a large amount of water. The obtained white powder of 4-carboxy-*N*,*N*-diphenylaniline (**2**) was dried in vacuum at 60 °C for 24 h to give an 82% (0.82 g) yield.

¹H NMR (CDCl₃, 500 MHz): δ =7.00 (t, 2H), 7.17 (m, 6H), 7.34 (t, 4H), 7.92 (d, 2H), 10.43 ppm (s, 1H; sharp COOH); MS (EI): *m/z* (%): 288.

Synthesis of 4-carboxy-*N*,*N*-**diphenylaniline-2,2,6,6-tetramethylpiperidin-1-yloxy (TPA-TEMPO)**: 4-Hydroxy-2,2,6,6-tetramethylpiperidine-1-oxyl free radial (1.6 g) and 4-carboxy-*N*,*N*-diphenylaniline (2.0 g) were dissolved in dichloromethane (50 mL) in a predried three-necked flask, then 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (0.4 g) as dehydrating agent and 4-dimethylaminopyridine (1.6 g) as acylating catalyst were added, with stirring for 24 h at room temperature. The reaction mixture was then separated by vacuum filtration. The filtrate was washed with saturated brine three times and the organic phase was dried over sodium sulfate. The ester was purified by column chromatography using silica gel and petroleum ether/ethyl acetate to afford the title compound as a pink powder with 61.8% (1.9 g) yield.

Chemical polymerization of TPA-TEMPO: The polymers of 4-carboxy-*N*,*N*-diphenylaniline-2,2,6,6-tetramethylpiperidin-1-yloxy

(PTPA-TEMPO) and triphenylamine (PTPA) were prepared by chemical oxidative polymerization of TPA-TEMPO and TPA in chloroform (20 mL) by using ferric chloride as oxidant. The solution was stirred 24 h at room temperature under N₂. After completion of the solution polymerization reaction, the mixture was poured into methanol to deposit the polymer product, which was then isolated by filtration and washed with methanol several times. Finally, the polymer product was isolated by filtration and dried in vacuum at 60 °C for 12 h. The colors of the PTPA-TEMPO and PTPA were light gray and yellow, respectively.

Characterization and electrochemical measurements

FTIR spectra were obtained on a Nicolet 6700 spectrometer (Thermo Fisher Nicolet, USA) with KBr pellets. UV/Vis spectra were recorded on a Varian Cary 100 UV/Vis spectrophotometer (Varian, USA). Scanning electron microscopy (SEM) measurements were taken using a Hitachi S-4800 scanning electron microscope (Hitachi, Japan). Cyclic voltammetry (CV) tests were performed with a CHI 660C electrochemical workstation, in $0.1 \,\text{m}$ LiClO₄/CH₃CN versus Ag/AgCl at a scan rate of 10 mV s⁻¹.

For cathode characterization, a CR2032 coin-type cell was used and assembled in an argon-filled glove box. The cathodes were prepared by coating a mixture containing 50% of prepared polymers, 40% acetylene black, and 10% poly(vinylidene fluoride) binder on circular Al current-collector foils, followed by drying at 60 °C for 24 h. After that, the cells were assembled with lithium foil as the anode, the prepared electrodes as cathode, and 1 \mbox{M} LiPF₆ dissolved in ethylene carbonate (EC) and dimethyl carbonate (DMC) (EC/DMC = 1:1, v/v) as the electrolyte. Charge-discharge measurements were performed on a LAND CT2001 apparatus using a constant current density at room temperature.

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Energy saving: A linear radical polymer with polytriphenylamine (PTPA) as the conductive polymer backbone and 2,2,6,6-tetramethylpiperidinyl-*N*-oxy (TEMPO) as pendant groups has been synthesized as an energy storage material. PTPA-TEMPO exhibited superior electrochemical performance as the cathode of lithium batteries (see figure) and was promising as an advanced cathode material.



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Radical Polymer Containing a Polytriphenylamine Backbone: Its Synthesis and Electrochemical Performance as the Cathode of Lithium-Ion Batteries