

Dual-Ion NiNc Battery: A Sustainable Revolution for Sodium Organic Batteries

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Abstract: Dual-ion mobilities of Na organic batteries are investigated with *in-situ* XRD analysis and computational estimation considering molecular alignments in the solid state, signifying the interactive variations of ionic-pairs of an ionic liquid electrolyte and an antiaromatic molecule, nickel(II) norcorrole (NiNc). An appropriate cavity sphere in three-dimensional molecular alignments dispensed mobilities of dual-ion in an ionic liquid, resulting in high battery capacities, supplemented with the comparison of Mes-NiNc and Ph-NiNc molecular alignments. *In-situ* XRD experiment, computation, and simulation perspectives afforded prospective insertion and desertion behaviors of cations and anions.

Introduction

Sodium-ion batteries have been significantly attractive to scientists and engineers in energy-related science and engineering fields because of the sizeable natural abundance with low cost for sodium.^[1] Similar chemical properties of Na and Li have been facilitated to afford proficient battery electrode materials, whose achievements have been primarily suitable inorganic materials: Most cases have been derivative in the use of oxides and polyanionic compounds.^[2] However, a larger atomic mass and ionic radius of Na⁺ than that of Li⁺ has been the primary factor in having low energy density and charge/discharge performances. The recent desire to accomplish outstanding rechargeable batteries is probably obtained using organic compounds for electrode materials, manipulating sustainability and producibility of charge and discharge processes.^[3] Through the previous research, we have reported excellent Li⁺ and Na⁺ collaborative metal-organic batteries afforded with organic electrodes of an antiaromatic molecule, nickel(II) norcorrole (NiNc).^[4] We have comprehended that the critical factor awarding efficient battery performances is antiaromaticity. Nevertheless, exploring other prospective factors is necessary, kept track of, and the related investigation is reported somewhat herein.

The accomplishment of excellent organic batteries has been attempted in distinct approaches with the predictability of organic electrode dissolution.^[3-4] Metal-organic frameworks (MOFs), holding rigid and homogeneous porosity, super-ionic sieving

capabilities were adopted as a capable artificial separator to build healthier rechargeable organic batteries in K. Kang's research. The system has been introduced as perm-selective MOF gel membrane integrity.^[5]

In early reports, NiNc, described as a stable antiaromatic porphyrinoid, has been introduced to exhibit unique alignments of the molecules in both solid and solution states, substantially related to dynamics of magnetic properties.^[6] Molecular stackings of the antiaromatic compounds derived the enhancement of aromatic character, depended on the *meso*-substituents.^[6c] A uniquely staked, triple-decker structure of phenyl-substituted NiNc (Ph-NiNc) was elucidated in the crystallographic data. In contrast, the crystal structure of mesityl-substituted NiNc (Mes-NiNc) revealed the prohibition of molecular stackings in the crystalline. Such packing structures in crystalline states are noteworthy to afford the practical permeability of electrolytic ions to manipulate the post's high durability. The conducting factor of stable antiaromatic molecules towards the active battery-electrode materials is substantial for efficient charge-and-discharge performances.

McCullough et al. and Carlin et al. have first proposed the dual-ion battery with both cation and anion intercalating mobiles.^[7] A highly concentrated ionic liquid electrolyte (50 mol% Na[FSA]-[C₂C₁im][FSA] ([C₂C₁im]⁺: 1-ethyl-3-methylimidazolium and [FSA]⁻: bis(fluorosulfonyl)amide [Energy & Environmental Science 12 (11), 3247-3287] has been introduced in our rechargeable organic batteries, whose system occupied nickel norcorrole (NiNc) as the active electrode materials in sodium-organic batteries. Outcomes of the batteries were excellent, exhibiting inherent charge-discharge behaviors with high discharge capacity, high stability, and high Coulombic efficiency.^[5b] We demonstrated the excellent redox durability in the mechanism of a dual-ion battery of [FSA]⁻ and Na⁺, whose further investigation is necessary to verify the hypothesis.

Comparison research to validate the interconnection and inter-relationship between the characteristic antiaromaticity and the permeability of 3D hierarchical packings in the electrode materials can signify the importance of scattering capability of ionic components in the battery electrolytes and high structural stability of the electrode materials during the charge/discharge processes. Herein, we report the investigations of battery

behaviors of Na-NiNc batteries in complementing them with two different active electrode materials, Ph-NiNc having *meso*-phenyl groups and Mes-NiNc having *meso*-mesityl groups. We attempted to comprehend how different three-dimensional alignments associate with the battery capacities upon the examination.

Results and Discussion

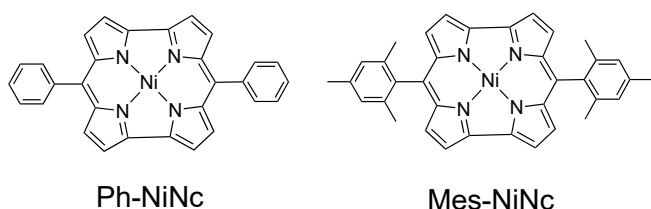


Figure 1. Molecular structures of Ph-NiNc and Mes-NiNc.

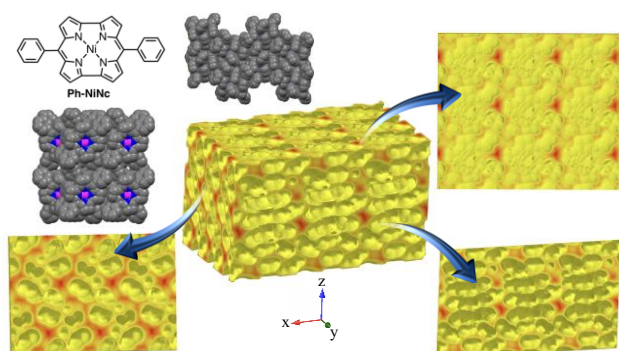


Figure 2. Molecular packing patterns of Ph-NiNc, represented with space filling model, and the display of the void spaces.

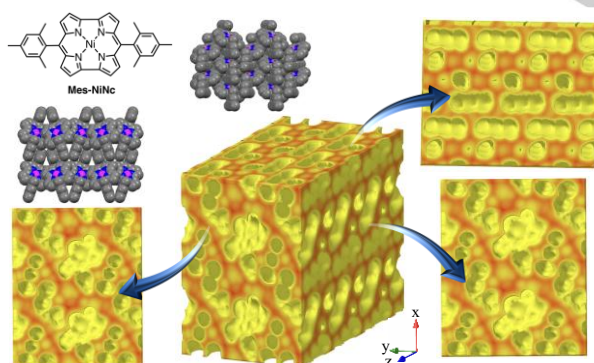


Figure 3. Molecular packing patterns of Mes-NiNc, represented with space filling model, and the display of the void spaces.

The synthetic procedure of Ph-NiNc and Mes-NiNc (Figure 1) have followed the literature methods as previously published.^[7] Their packing diagrams with space-filling models are based on single crystallographic data.^[6a] The packing structure of Ph-NiNc presented a significantly tightened alignment pattern (Figure 2),

while that of Mes-NiNc provided a loose packing pattern (Figure 3). Vacant spaces in the crystalline states were simulated for tracking the positions of dual-ion insertion/desertion during charge-discharge processes. The simulation came up with sponge-like displays for the occupancy and the vacancy in a complementary way: The hollowed space has been filled with the NiNc molecules. Accordingly, the occupied space with either yellow or red can be the actual vacancy that is probable for electrolyte ions.

The red-colored spots represent the high permeable positions of ions: The deeper red, the higher permeability. Mes-NiNc packing (Figure 3) provides a more significant permeation probability than Ph-NiNc molecular alignments (Figure 2). We predicted partial occupation with the ions in the Ph-NiNc electrode based on the simulations, where the occupation happened probably only on the surface area. On the other hand, Mes-NiNc packing showed larger permeable spaces for electrolyte ions, whose occupation would arise smoothly and full occupation completed.

As supporting our expectation, excellent charge-discharge performances of sodium-organic batteries have been awarded by implementing Mes-NiNc active electrode in 50% Na[FSA]-[C₂C₁im][FSA] ionic liquid electrolyte. First, the durability of the organic electrode materials in sodium-organic batteries was enhanced significantly using the ionic liquid electrolyte, excluding the dissolution obstacle of electrode materials. Furthermore, the Na-NiNc cell with Mes-NiNc performed comparably larger charge/discharge capacities than the Na-NiNc cell with Ph-NiNc (Figure 4). The relatively small capacities outcoming with Ph-NiNc electrode sodium-organic battery was comprehended with the partial dual-ion insertion/desertion happening only on the surface area due to the knotted molecular alignment. Besides, the composition of the positive electrodes has been unified with 70, 25, and 5% for NiNc, CB, and PVDF.

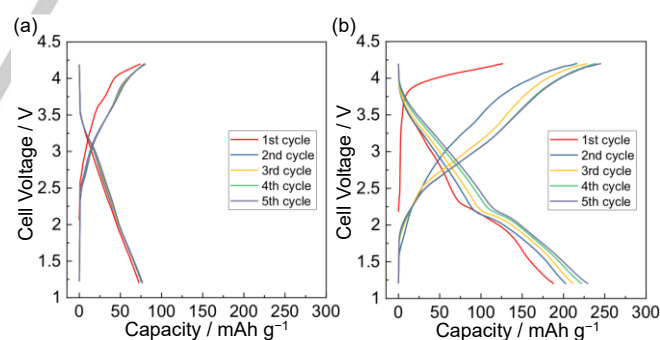


Figure 4. Charge/discharge performances of Na-NiNc cell in 50 mol% Na[FSA]-[C₂C₁im][FSA] electrolyte: (a) Ph-NiNc and (b) Mes-NiNc. The composition of the positive electrodes is NiNc:CB:PVDF = 70:25:5wt% and the cut-off voltage is 1.2–4.2 V with the current density of 200 mA g⁻¹.

X-ray diffraction patterns of the NiNc electrodes and NiNc powders were determined to verify the consistency between NiNc electrodes and NiNc powders (Figure S1). The diffractions afforded moderately reliable patterns, indicating the preparation of the electrode did not destroy the molecular packing patterns of NiNc.

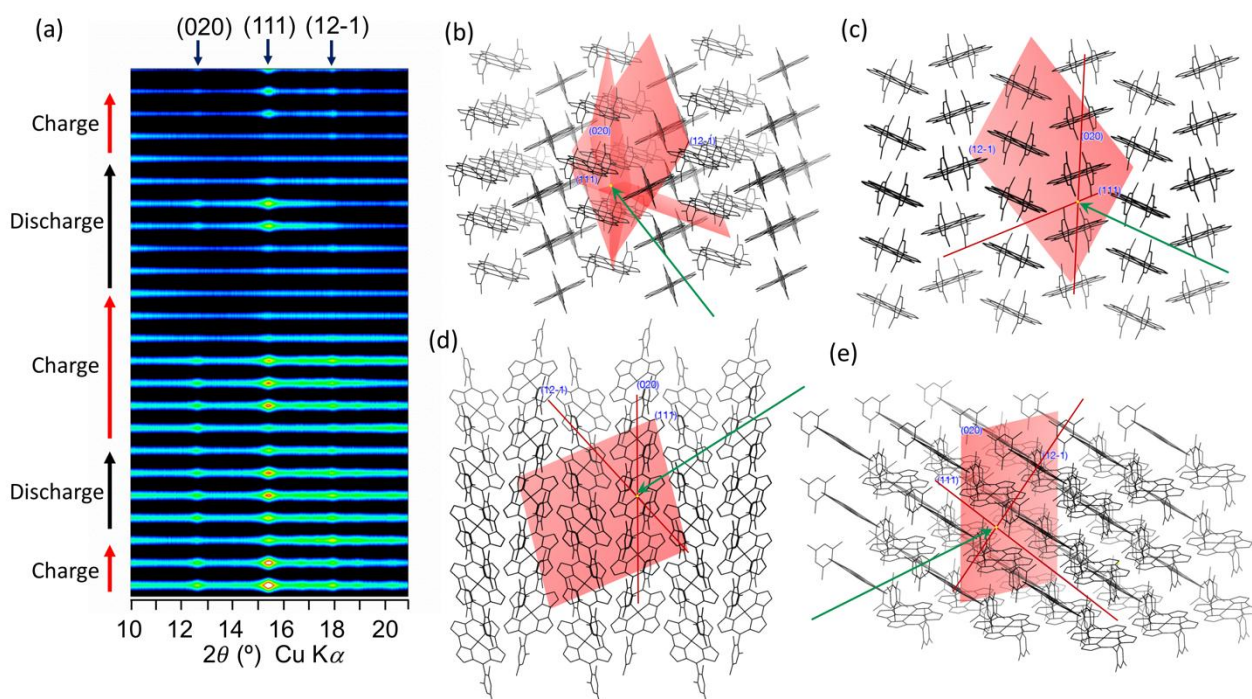


Figure 5. The selected 2D contour plot of *in-situ* XRD patterns and display of three *hkl* lines, 020, 111, and 12–1 in the crystalline packing of mes-NiNc: (a) The *in-situ* XRD patterns, (b) 3D view of the three *hkl* planes, and selected *hkl* plane objective views for (c) (12–1), (d) (111), and (e) (020).

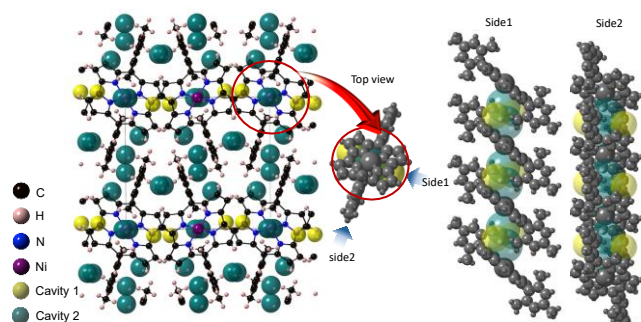


Figure 6. Display of cavities: radii of cavities are estimated with 1.81 Å for the cavity 1 and 2.08–2.24 Å for the cavity 2 of Mes-NiNc.^[8]

Once the consistency between the powder and electrode XRD patterns of Mes-NiNc was established, an *in-situ* XRD experiment was anticipated with a Na-NiNc battery prepared in the same procedure (Figures 5 and S2, in the Supporting Information). The diffraction lines at 12.6, 15.5, and 18.0° are indexed as 020, 111, and 12–1, respectively. As the patterns represent the highest and the lowest voltages (4.3 and 1.5 V) in a given potential window, those sequences disappeared in accord with anions and cations insertion. However, the middle of the window (2.5 V) showed those diffractions supporting the anions and cations desortions to the correlated positions, consistent with our previous electrochemical results using three-electrode cells.^[4c]

The triple point of the lattice planes was explored upon the crystal lattices based on the lattice planes that were deserved from the *in-situ* XRD experiment. Figure 5a presents the selected 2D contour plot of *in-situ* XRD patterns. Also, the three *hkl* planes, (020), (111), and (12–1) were projected with different orientation focusing in the crystalline packing of Mes-NiNc (Figures 5b-d).

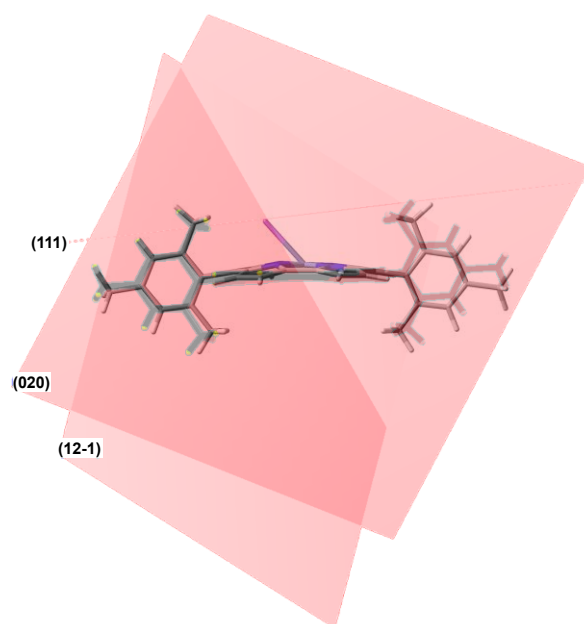


Figure 7. Comparison between a DFT calculated pair of $[\text{NiNc}]^{\cdot-}$ and Na^+ and the triple-point in packing diagram based of *in-situ* XRD results, an expected position of ion insertion to Mes-NiNc.

The cavities have been estimated from the Mes-NiNc packing diagram, varied as represented with yellow and green spheres in Figure 6. The highest population of the cavity spheres were allocated between two Mes-NiNc closest molecules, substantially matched with the triple point deduced with the three *hkl* planes exposing significant XRD appearance and disappearance.

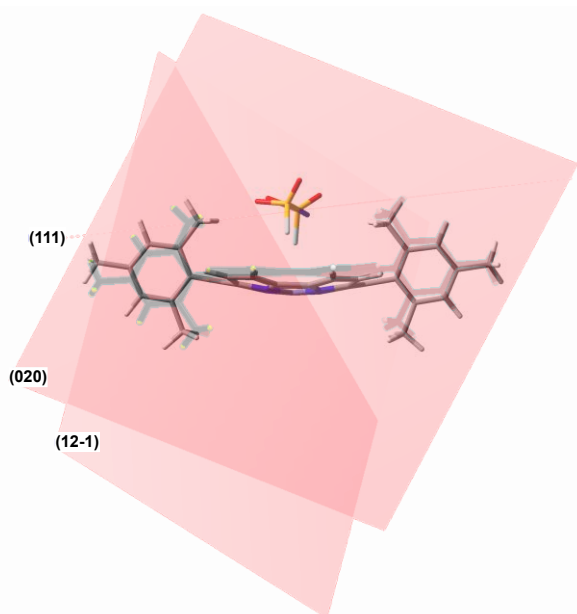


Figure 8. Comparison perspectives of an ionic pair, $[\text{NiNc}]^{\cdot+}$ and $[\text{FSA}]^{\cdot-}$: overlapped view of optimized outcome and the feasible triple-point in packing diagram of Mes-NiNc.

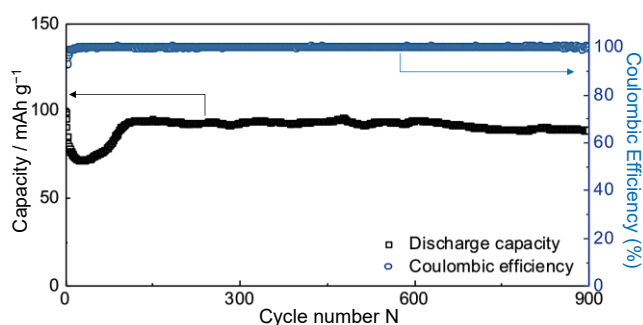


Figure 9. Discharge capacity and efficiency plots of 900 cyclic battery performances of a Na-Mes-NiNc battery: Composition of positive electrode = NiNc:CB:PVDF = 70:25:5wt%, Cut-off voltages = 1.2–4.2 V, and current density = 2 A g^{-1}

Computation outcomes substantially supported the insertion and desertion mobilities of dual-ion through Mes-NiNc molecular alignments. The respective ion pairs of $[\text{NiNc}]^{\cdot-}/\text{Na}^+$ (Figure 7) and $[\text{NiNc}]^{\cdot+}/[\text{FSA}]^{\cdot-}$ (Figure 8) occupied reasonably the prospective cavities obtained from Figure 5. The NiNc plane flat initially

suspended the attraction and repulsion behaviors of the distinct NiNc ion radical conformations with cation and anion in accord with the redox reactions. NiNc molecules were converted into $[\text{NiNc}]^{\cdot+}$ through the charging process, whose oxidation implemented insertion of anionic FSA. Antiaromatic nature destabilizes π -electron orbital energy configuration. The reduction of antiaromatic molecules probably destabilized the conformation. The deformation of the NiNc plane could be resulted from the attraction toward the electron-deficient cationic sodium to reduce the increased electron density by earning an electron. On the other hand, oxidation of antiaromatic molecules probably reduced the low stability by losing an electron. The deformation of the NiNc plane could result from the repulsion against the electron-dense anionic molecule.

The Na-Mes-NiNc cell precisely performed the charge and discharge processes in a potential window of 1.2–4.2 V with high current densities. Figure 9 shows a set of plots of 900 cyclic charge and discharge performances with an average Coulombic efficiency of 99.8% for 900 cycles.

Conclusion

Antiaromatic conformations of NiNc molecules accompanied with Na-organic secondary batteries, whose charge and discharge performances were sizeable. Both Na-NiNc batteries prepared with Ph-NiNc and Mes-NiNc electrode materials produced a significant charge-discharge process. Furthermore, we obtained improved battery capacity with the Mes-NiNc electrode. Computational calculations revealed that the vacant space in the molecular packings of Ph-NiNc is lesser than that of Mes-NiNc. The appropriate hollow spheres in Mes-NiNc molecular alignments were deliberated to amplify the kinetic quantity of the dual-ion, where healthy redox processes with high discharge capacity and Coulombic efficiency were accomplished. Furthermore, the perspectives of ion pairs, Mes- $[\text{NiNc}]^{\cdot-}/\text{Na}^+$ and Mes- $[\text{NiNc}]^{\cdot+}/[\text{FSA}]^{\cdot-}$, distributed in charging and discharging, were suspected through optimization, whose orientations were in good agreement with the *in-situ* XRD projections.

Experimental Section

Preparation of Ph-NiNc and Mes-NiNc: Ph-NiNc [6c] and Mes-NiNc [6a] were prepared following the literature methods from *bis*(2,10-dibromodipyrin)-nickel complexes having meso-phenyl and meso-mesityl, respectively.

Electrochemical measurement: The electrochemical properties were measured in a 2032 type coin cell at 25 °C in the thermostatic chamber SU-242 (ESPEC) using an HJ1001SD8 charge-discharge test device (Hokuto Denko). A current density of 200 mA g^{-1} and 2 A g^{-1} were applied to the charge/discharge, and cycle tests, respectively, with the cut-off voltages of 1.2–4.2 V. Sodium metal (Sigma-Aldrich Chemistry, 99.95% purity) was cut into a disk and fixed on an Al plate current collector as the negative electrode. The positive electrode was prepared by mixing the active material, CB, and PVDF (70:25:5 wt%) and pasting it onto Al foil. A glass microfiber separator (Whatman GF/A) was impregnated in 50 mol% $\text{Na}[\text{FSA}][\text{-C}_{22}\text{im}][\text{FSA}]$ electrolyte.

***In-situ* XRD experiment:** The electrochemical cell for *in-situ* XRD measurement was prepared in a 2032 type coin cell with a hole on the top case. *In-situ* XRD measurements were performed using an air-tight cell

with a Kapton® window and a temperature controller (Rigaku). The diffraction patterns were recorded at a scan rate of 2° s^{-1} at 298 K under vacuum performed. The electrochemical measurements were controlled with an HZ7000 (Hokuto Denko). The cell was continuously charged and discharged at 50 mA g^{-1} during XRD measurements. Cutoff voltages were fixed at 1.5 V and 4.3 V as the lower and upper limits, respectively.

DFT Calculation of ionic pairs: All calculations were afforded with the Gaussian 09 program. The initial geometry of Mes-NiNc was transported from a crystallographic data^[6a, 6c] and optimized. The single reduction and oxidation states, $[\text{NiNc}]^{\cdot-}$ and $[\text{NiNc}]^{\cdot+}$, were then calculated with corresponding spin states in the basis set. Finally, counter sodium cation and FSA anion were applied into the redox states to optimize the position. The geometry optimizations were performed with Becke's three-parameter hydride exchange function and the Lee-Yang-Parr correlation functional (B3LYP/Gen).^[9]

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Keywords: durable organic electrode • dual-ion battery • sodium organic battery • permeability of organic electrode

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