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Formation of Benzimidazoisoquinolinium and Benzimidazoisoindolinum Cyclic Systems by the Reaction of 2-(2-Alkynylphenyl)benzimidazoles with Iodine and Iodine−Iodine Interaction Including Halogen Bonding in Their Crystal Structures

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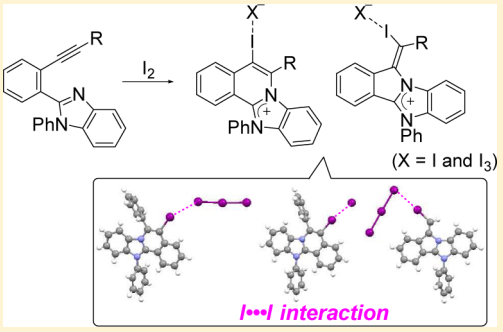
Supporting Information

ABSTRACT: The reaction of 2-(2-alkynylphenyl)benz[*d*]imidazoles with molecular iodine constructed 5- and 6-membered rings as novel organic salts in high yield. The constituted number of ring systems was influenced by the substituent at the triple bond: 6-membered rings were formed from compounds bearing aryl substituents, whereas 5-membered ones were obtained from compounds with hydrogen or alkyl substituents. The products were obtained with triiodide as a counteranion; however, compounds with iodide were also obtainable under certain conditions. We also revealed that they had an iodine−iodine interaction included in halogen bonding between an iodo moiety of the cation and a triiodide or iodide of the counteranion. The iodine−iodine interaction was formed with greater preference than the electrostatic interaction between the cationic atom and triiodide or iodide.



INTRODUCTION

Ring formation is one of the most important reactions to utilize the synthesis of various cyclic compounds including natural products, biologically active compounds, functional materials, and so on.[1−3] Intramolecular nucleophilic cyclization reaction yielded heterocyclic compounds when a heteroatom was used as a nucleophile. Iodine-induced cyclization reactions[4,5] were reported to form heterocycles such as (benzo)furans,[6] pyrroles,[7] indoles,[8] (benzo)thiophenes,[9] and (benzo)-selenophenes.[10] Those reactions yielded compounds in neutral form because the reaction was completed by the removal of a proton or alkyl substituent on a heteroatom. Recently, we reported that the ionic heterocycle, benzo[*c*]thiophen-1-aminium iodide, was obtained by the reaction of 2-alkynyl-benzothioamide with iodine (Scheme 1).[11] On the basis of our result, we suppose that cyclization reactions yield ionic heterocycles even if there is no leaving group on the heteroatom. However, there were few reports about salt formation by the reaction of halo-cyclization.[12] We herein report the reaction of 2-(2-alkynylphenyl)benz[*d*]imidazoles (**1**) with molecular iodine to give the corresponding ionic heterocycles, benz[4,5]imidazo[2,1-*a*]isoquinolin-7-ium (**2**$^+$) and benz[4,5]imidazo[2,1-*a*]isoindol-10-ium (**3**$^+$). Furthermore, we revealed an interaction including halogen bonding between iodine atoms on the cation and the counteranion (triiodide or iodide) by single-crystal X-ray analysis. The halogen bond[13,14] has the potential to be utilized in the construction of crystal structures,[15] application as an organic catalyst,[16] molecular recognition,[17] etc.[18]

RESULTS AND DISCUSSION

Ionic Heterocycle Formation with I_2. We tried to synthesize the reactants (**1a**−**e**) using the Sonogashira coupling reaction (Scheme 2). The compounds (**1a**, **1b**, and **1e**) were prepared by the condensation reaction of 2-aminodiphenylamine and 2-bromobenzaldehyde, followed by the Sonogashira coupling with ethynylene derivatives. The removal of a hydroxylisopropyl group of **1e** was utilized to obtain **1d**. It was possible to form **1c** by reaction with *p*-bromoanisole and **1d** prepared *in situ* from **1e** even in low yield, because **1c** was not obtained by the coupling reaction with *p*-methoxyphenylacetylene.

We first examined the reaction of **1a** (R = Ph) with 1 mol equiv of I_2 in $CHCl_3$ at ambient temperature. During the reaction progress, the precipitate was obtained. However, we found that **1a** remained even after a period of 67 h by TLC analysis. From ^{1}H NMR analysis of the precipitate, we observed two discrete peaks at 9.26 and 8.54 ppm with a ratio of 22:78, and no other byproduct was observed (see Figure S1). Such a downfield shift of the proton peak was also observed in the case of benzo[*c*]thiophen-1-aminium iodides (ca. 9.4 ppm), which have 5-membered cationic cyclic system.[11] Therefore, we

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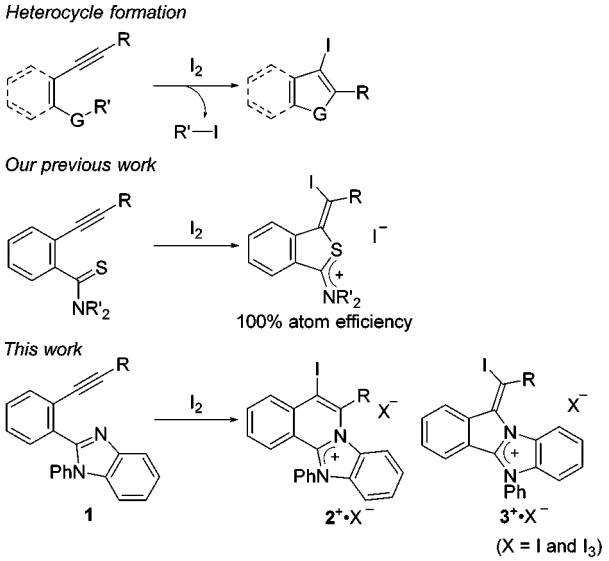
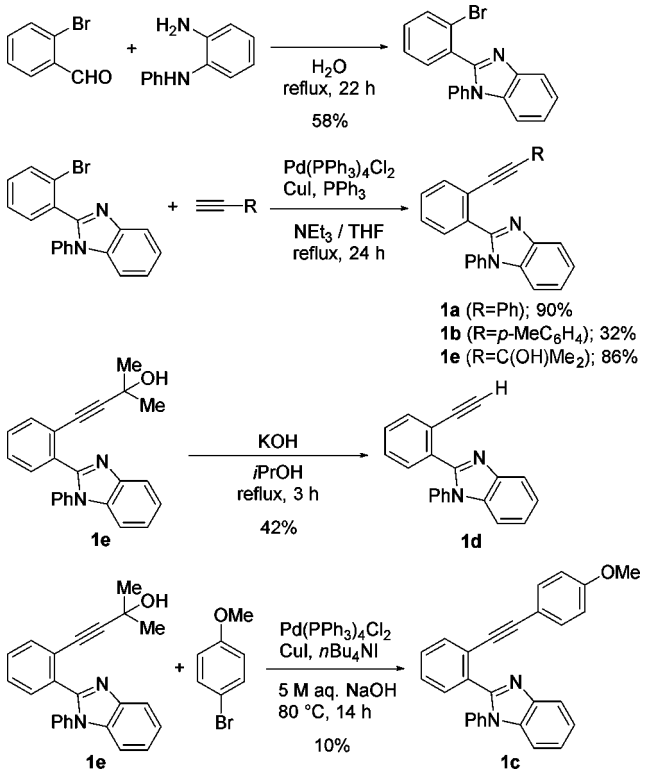
Scheme 1. Formation of Various Heterocyclic Systems by Iodocyclization Reaction



Scheme 2. Preparation of 1



thought that two types of the cyclization product ($\mathbf{2a}^+$ and $\mathbf{3a}^+$) would be obtained, and the minor peak with 9.26 ppm would have a 5-membered cyclic cation ($\mathbf{3a}^+$). We could obtain a good crystal for measuring by single-crystal X-ray analysis (*vide infra*), and revealed that the major product was benz[4,5]-imidazo[2,1-*a*]isoquinolin-7-ium triiodide ($\mathbf{2a}^+ \cdot I_3^-$). Furthermore, from the elemental analysis of the precipitate, the wt % of C (obtained with C, 38.67%; H, 2.02%; N, 3.13%) were larger values compared to the product with triiodide (I_3^-) as a counteranion (calculated with C, 36.93%; H, 2.07%; N, 3.19%). Therefore, other compounds with iodide (I^-) as a counteranion would also exist. The yield of the cation part could be calculated from the integration of ^{1}H NMR with dibenzyl as an internal standard. Because there was no method to determine the ratio of I_3^- and I^- directly, we estimated it from the yield of the cation part and the weight of the product using simultaneous equations as follows

$$\text{From material balance: } W = (Y_{2^+} \times M_{2^+} + Y_{3^+} \times M_{3^+}) + (Y_{I_3^-} \times M_{I_3^-} + Y_{I^-} \times M_{I^-})$$

$$\text{From charge balance: } Y_{2^+} + Y_{3^+} = Y_{I_3^-} + Y_{I^-}$$

where W is the weight of the obtained precipitate; Y_{2^+}, Y_{3^+}, $Y_{I_3^-}$, and Y_{I^-} correspond to the number of moles (ions) of the obtained compounds; and M_{2^+}, M_{3^+}, $M_{I_3^-}$ (=380.7), and M_{I^-}(=126.9) are molecular (ion) weights. In the case of **1a**, both of M_{2^+} and M_{3^+} are 498.4. Y_{2^+} and Y_{3^+} were obtained from the ^{1}H NMR analysis using an internal standard (dibenzyl or terepthalaldehyde). Finally, we could determine the yield of each component both in cations and in anions within ±1% error (Table 1, entry 1). Although 1 mol equiv of I_2 was treated, I_3^- was a major component in the reaction in $CHCl_3$. The total yield of the cyclized product was 51%, and the recovery of **1a** was obtained in 49%. On the basis of the consumption of molecular iodine, this cyclization reaction proceeded efficiently.

To examine the influence of the solvent, the reaction was conducted in various solvents. In EtOAc and CH_3CN, the products with I_3^- were obtained as a major anion with the precipitate formation in medium yields (entries 2 and 3). When the reaction was treated in DMF, the ratio of I^- was increased (entry 4). By raising the reaction temperature, the reaction yielded no precipitate after the reaction, and the products bearing I^- were obtained in 74% yield, although the reaction period for 72 h was required to disappear **1a** on TLC (entry 5). When **1a** was treated with 2 mol equiv of I_2, which is an efficient amount to give the compound with I_3^- counteranion, the products with I_3^- were obtained in excellent yield within 1 h (entry 7). We also found that the complete conversion to the products with I_3^- based on molecular iodine was achieved within 1 h in the case of 1 mol equiv of I_2 in $CHCl_3$ when the reaction was stopped for 1 h even in remaining **1a** (entry 6). All of the reactions with **1a** gave the benz[4,5]imidazo[2,1-*a*]isoquinolin-7-ium structure ($\mathbf{2a}^+$) as major products. A sole countercation ($\mathbf{2a}^+$) was obtained from the reaction with a raised temperature (entry 5).

The reaction mechanism was proposed as follows (Scheme 3). The triple bond on **1a** was activated by coordination of I_2 to yield an iodonium cation (**A**). An intramolecular nucleophilic attack at the sp^2 nitrogen atom in intermediate **A** occurred, creating the cyclic structure ($\mathbf{2a}^+$ and $\mathbf{3a}^+$). The cyclized cation part will possess I^- as a counteranion at first, but equilibrium between I^- and I_3^- should exist at the beginning of the reaction because there is an excess amount of I_2. The triiodide compound is excluded as a precipitate from the reaction solution except for warming DMF solution. As a result, the cyclized product with I_3^- was obtained as a major product. Where there is no precipitate formation (entry 5), the equilibrium between I^- and I_3^- serves I_2 in the reaction conditions. Therefore, all of I_2 can react with the substrate to yield the cyclized product with I^- as a major product.

We tried to examine the reaction of compounds with aromatic substituents with electron-donating groups and

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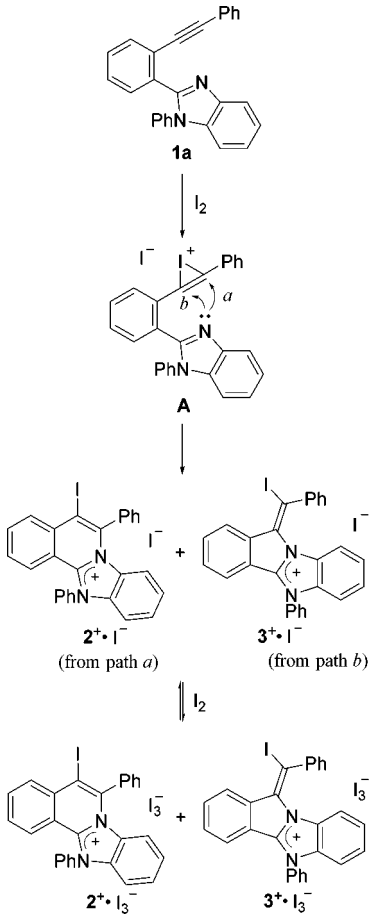
Table 1. Reaction of 1 with Iodine[a]

entry		R	solvent	mol equiv of I_2	time (h)	yield of cation (%)[b]		yield of anion (%)[c]		recovery of **1** (%)
						2^+	3^+	I_3^-	I^-	
1	**1a**	Ph	$CHCl_3$	1.0	67	40	11	45	6	49
2	**1a**	Ph	EtOAc	1.0	67	31	14	45	0	46
3	**1a**	Ph	CH_3CN	1.0	67	40	8	48	0	44
4	**1a**	Ph	DMF	1.0	67	44	13	27	30	43
5	**1a**	Ph	DMF[d]	1.0	72	84	0	10	74	0
6	**1a**	Ph	$CHCl_3$	1.0	1	38	12	50	0	50
7	**1a**	Ph	$CHCl_3$	2.0	1	75	18	93	0	0
8	**1b**	*p*-MeC_6H_4	DMF[d]	1.0	72	90	0	6	84	0
9	**1b**	*p*-MeC_6H_4	$CHCl_3$	2.0	1.5	83	9	71	21	0
10	**1c**	*p*-$MeOC_6H_4$	DMF[d]	1.0	72	92	0	7	85	0
11	**1c**	*p*-$MeOC_6H_4$	$CHCl_3$	2.0	1	100	0	100	0	0
12	**1d**	H	DMF[d]	1.0	72	[e]				0
13	**1d**	H	$CHCl_3$	2.0	1	0	92	92	0	0
14	**1e**	$C(CH_3)_2OH$	DMF[d]	1.0	72	[e]				29
15	**1e**	$C(CH_3)_2OH$	$CHCl_3$	1.0	72	0	51	49	2	39
16	**1e**	$C(CH_3)_2OH$	$CHCl_3$	2.0	24	0	100	100	0	0

[a]Reaction conditions: **1** (0.3 mmol), solvent (3 mL), room temperature. [b]Determined by the integration of ^1H NMR with an internal standard (dibenzyl or terephthalaldehyde). [c]Determined by the relation of material and charge balance. See the text. [d]Reacted at 100 °C. [e]A complex mixture.

Scheme 3. Plausible Mechanism of the Reaction and the Formation of the Products



aliphatic substituents at the triple bond because the electron-withdrawing substituent would decrease the reaction ratio to inhibit the coordination of I_2 at the triple bond. A *p*-tolyl substituted compound (**1b**) increased the ratio of 6-membered products ($\mathbf{2b}^+$) (entries 7 vs 9), and complete control of the 6-membered cyclization was achieved by the compound bearing a *p*-anisyl substituent (**1c**) (entry 11). The electron-donating substituent stabilizes the positive charge at the benzyl position. Thus, reaction path *a* in Scheme 3 was enhanced to yield the 6-membered cyclization product ($\mathbf{2c}^+$). When no substituted compound at the triple bond (**1d**) was treated with iodine in $CHCl_3$, 5-membered cyclization products ($\mathbf{3d}^+$) determined by single-crystal X-ray analysis (*vide infra*) were obtained as the sole cation part via path *b* (entry 13), although a complex mixture was obtained in DMF (entry 12). In the case of the reaction of **1e** bearing a bulkier substituent, $-C(CH_3)_2OH$, $\mathbf{3e}^+$ was also obtained as the sole cation part, although a prolonged reaction time was required (entries 15 and 16). Therefore, the preference of the cyclic system was determined by the stabilization of positive charge in intermediate **A**, especially when stabilized with a benzylic position.

In the case of the reactions of **1a**, **1b**, and **1c**, the ratio of counteranion could be switched to inhibit the precipitate formation by raising the reaction temperature (entries 5, 8, and 10). The reaction of **1d** and **1e** yielded a complex mixture under those conditions (entries 12 and 14). However, surprisingly, the reaction of **1e** in $CHCl_3$ yielded a product with I_3^- as a counteranion, even in the presence of 1.0 mol equiv of I_2 without the precipitate formation after the reaction (entry 15). There is no clear explanation for this result, but it suggested that the reaction was restricted toward the less reactive **1e** with I_2 by the equilibrium between I^- and I_3^- in $CHCl_3$ under ambient temperature.

Crystal Structure of Cyclic Compounds. We were interested in the crystal structure of products because the compounds may possess the possibility of a halogen bonding between the iodine atom on the cationic and anionic parts. Good crystals could be obtained to measure the single-crystal X-ray structure of $\mathbf{2a}^+\cdot I_3^-$, $\mathbf{2b}^+\cdot I_3^-$, $\mathbf{2c}^+\cdot I_3^-$, and $\mathbf{3d}^+\cdot I_3^-$ by recrystallization from $CHCl_3$ by diffusion of hexane vapor. The structures are summarized in Figure 1. All fused rings were aligned in the same plane, and phenyl rings on nitrogen were oriented perpendicularly. Distances and angles around imidazolium and iodovinyl moieties are listed in Table 2. Focusing on the benzimidazolium structure, little difference

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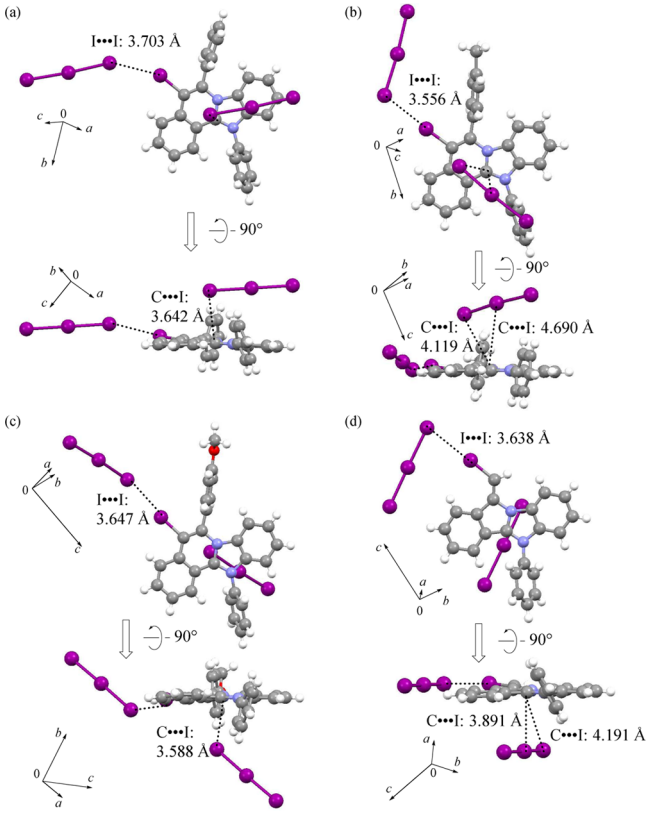


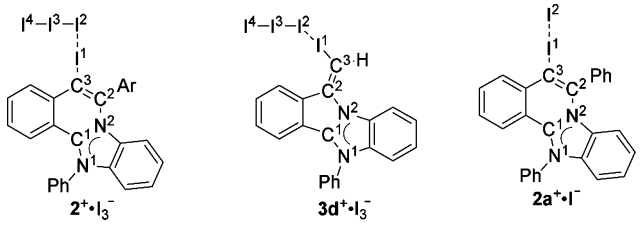
Figure 1. Molecular structures of (a) $\mathbf{2a}^{+}\cdot I_3^{-}$, (b) $\mathbf{2b}^{+}\cdot I_3^{-}$, (c) $\mathbf{2c}^{+}\cdot I_3^{-}$, and (d) $\mathbf{3d}^{+}\cdot I_3^{-}$ with the situation of I_3^{-} around the cation part obtained by single-crystal X-ray crystallographic analysis.

between two C−N bonds was observed within 0.03 Å. To the best of our knowledge, the smallest difference between C−N bond lengths of *N*-arylimidazole was 0.043 Å,[19] and the largest one of benzimidazolium was 0.028 Å.[20] Therefore, the imidazole moiety of the products possesses a resonance character such as imidazolium cation. On the contrary, the C−N bond formed by the cyclization reaction (N^2−C^2) was observed at around 1.40 Å. It is longer than the general C(sp^2)−N(planar) and C(aromatic)−N(planar) single bond lengths (1.36 and 1.37 Å, respectively).[21] The distance of the C^2−C^3 bond was shorter than that of the resonance C−C bond (1.38 Å). Thus, it was revealed that there was little resonance between imidazolium and C−C bonds derived from the triple bond in **1**.

As I_3^{-} possesses a negative charge, the interaction with the cationic imidazolium moiety should be attractive. However, the two crystal structures ($\mathbf{2b}^{+}\cdot I_3^{-}$ and $\mathbf{3d}^{+}\cdot I_3^{-}$) showed no interaction between I_3^{-} and the cationic carbon (C^1) on the imidazolium moiety with longer distances between C^1 and I_3^{-} (Figure 1b,c), whereas the distance between C^1 and iodine of I_3^{-} in $\mathbf{2a}^{+}\cdot I_3^{-}$ and $\mathbf{2c}^{+}\cdot I_3^{-}$ was observed within the sum of van der Waals radii [3.75 Å = 1.98 Å (I) + 1.77 Å (C)] (Figure 1a,c).

Focused on the halogen−halogen interaction, the edge of the iodine atom on I_3^{-} was situated in close contact with the iodine atom on the iodovinyl moiety of the cation structure. The distance between two iodine atoms was shortened about 10% compared to the sum of van der Waals radii of iodine [3.96 Å = 1.98 Å (I) + 1.98 Å (I)].[22] Bartashevich and co-workers report that the halogen bonding in the compounds of heterocyclic cations and I_3^{-} was mainly observed in the range of 3.7−3.8 Å.[23] Such a halogen bond was reported in terms of "charge-assisted halogen bond", which gave significant contraction of halogen−halogen distance.[17b,24] Mentioned above, there was little conjugation between iodovinyl and benzimidazolium moieties in $\mathbf{2a}$−$\mathbf{c}^{+}\cdot I_3^{-}$ and $\mathbf{3d}^{+}\cdot I_3^{-}$. Therefore, the driving force to make the interaction between two iodine atoms would be the inductive electron-withdrawing ability of the benzimidazolium cation. The three atoms (C^3, I^1, and I^2) were almost in linear alignment. It is reasonable for halogen bonding, although the C−I···I angle was slightly tilted from the ideal angle (180°).[13,25] On the basis of the difference in the two angles (C^3−I^1···I^2 and I^1···I^2−I^3) reported by Desiraju et al.,[15b] the compounds were categorized in $\mathbf{2a}^{+}\cdot I_3^{-}$ as type I contact and in $\mathbf{2b}^{+}\cdot I_3^{-}$, $\mathbf{2c}^{+}\cdot I_3^{-}$, and $\mathbf{3d}^{+}\cdot I_3^{-}$ as type II contact, which are actually halogen bondings.[26] Furthermore, it was found that I_3^{-} was located on various positions in crystalline structures in keeping with that interaction (Figure 1). These results suggested that the I···I interaction in those compounds has the ability to overwhelm both the electrostatic interaction between cationic and anionic atoms and the requirement of crystal packing.

Table 2. Selected Distances and Angles of Products in Single-Crystal X-ray Structure



compound	distance (Å)					angle (deg)	
	N^1−C^1	C^1−N^2	N^2−C^2	C^2−C^3	I^1···I^2[a]	C^3−I^1···I^2	I^1···I^2−I^3
$\mathbf{2a}^{+}\cdot I_3^{-}$	1.355	1.354	1.399	1.363	3.703 [93.5]	154.36	148.33
$\mathbf{2b}^{+}\cdot I_3^{-}$	1.344	1.372	1.403	1.342	3.647 [92.1]	170.75	106.73
$\mathbf{2c}^{+}\cdot I_3^{-}$	1.350	1.363	1.403	1.352	3.556 [89.8]	169.01	130.70
$\mathbf{3d}^{+}\cdot I_3^{-}$	1.337	1.353	1.433	1.332	3.638 [91.9]	174.16	79.05
$\mathbf{2a}^{+}\cdot I^{-}$	1.353	1.360	1.401	1.342	3.496 [88.3]	165.87	

[a]Value in parentheses was percentage of the contraction against the sum of van der Waals (vdW) radii (distance I^1···I^2/3.96 (sum of vdW of iodine) × 100).

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After trying different recrystallization conditions, a single crystal included in pyridine was obtained by recrystallization of $\mathbf{2a}^{+}\cdot I^{-}$ from pyridine solution with diffusion of hexane vapor. An almost identical structure of the benzimidazolium part was present in $\mathbf{2a}^{+}\cdot I_3^{-}$ and $\mathbf{2a}^{+}\cdot I^{-}$ (Figure 2 and Figure S3). Contact between cationic carbon (C^1) and iodine atom was observed. An I···I halogen bond also existed with a 3.496 Å distance and with a nearly linear angle (165.87°). Therefore, the preference of I···I interaction would also be affected in the case of I^{-} as a counteranion.

CONCLUSION

The reaction of 2-(2-alkynylphenyl)benz[*d*]imidazoles (**1**) with I_2 gave novel 5- and 6-membered ring structures bearing iodine substituents as organic salts. The cyclization with activation of the triple bond by iodine occurred through a nucleophilic attack by a nitrogen atom at the benz[*d*]imidazolyl group toward the carbon atom in a benzylic position with the electron-donating substituents. The compounds with I_3^{-} were selectively obtained by the precipitate formation or by reaction with 2 mol equiv of I_2. Furthermore, by investigation of their crystal structures, it was revealed that the I···I interaction such as halogen bonding between iodine atoms in the iodovinyl moiety of the cation part and anion part was formed with greater preference than the electrostatic interaction between the cationic atom and triiodide or iodide.

EXPERIMENTAL SECTION

General Information. Melting points were uncorrected. NMR measurements were recorded with a 300 MHz spectrometer for ^{1}H NMR and with a 75 MHz spectrometer for ^{13}C NMR. Chemical shifts (δ) of ^{1}H NMR were expressed in parts per million downfield or upfield from tetramethylsilane in $CDCl_3$ (δ = 0) or DMSO-d_5 (δ = 2.49) as an internal standard. Multiplicities are indicated as s (singlet), d (doublet), t (triplet), m (multiplet), and bs (broadened singlet), and coupling constants (J) are reported in hertz units. Chemical shifts (δ) of ^{13}C NMR are expressed in parts per million downfield or upfield from $CDCl_3$ (δ = 77.0) or DMSO-d_6 (δ = 39.6) as an internal standard. Analytical thin-layer chromatography (TLC) was performed on glass plates that had been precoated with SiO_2 (0.25 mm layer thickness). Column chromatography was performed on 70−230 mesh SiO_2. Anhydrous $CHCl_3$ was distilled from $CaCl_2$ after washing with aq. NaOH and was stored with MS 4 Å. Anhydrous CH_3CN was distilled from sodium hydride and was stored with MS 3 Å. Anhydrous DMF was distilled from P_2O_5 under reduced pressure and was stored with MS 4 Å. All other materials were used without further purification. The reactions were performed under a nitrogen atmosphere.

Preparation of 1. *2-(2-Bromophenyl)-1-phenyl-1H-benz[d]-imidazole.*[27] To a solution of 2-aminodiphenylamine (0.923 g, 5.01 mmol) in H_2O (10 mL) was added 2-bromobenzaldehyde (1.85 g, 10.0 mmol). The mixture was stirred for 22 h under refluxing conditions. The reaction mixture was extracted with EtOAc (5 mL × 3), and the organic layer was dried with $MgSO_4$. After filtration and evaporation, the residue was subject to column chromatography on SiO_2 (hexane:EtOAc = 4:1) to give 2-(2-bromophenyl)-1-phenyl-1*H*-benz[*d*]imidazole (1.02 g, 2.92 mmol, 58%) as a colorless solid: mp = 158−159 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.22−7.39 (m, 10H), 7.46 (dd, J = 1.8 and 7.4 Hz, 1H), 7.54 (d, J = 7.9 Hz, 1H), 7.92 (diffused d, J = 7.5 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 110.6, 120.3, 122.9, 123.6, 123.7, 126.7, 127.0, 128.1, 129.3, 131.0, 132.3, 132.5, 132.8, 135.6, 135.9, 142.8, 151.5; IR (KBr disk) 3057, 1597, 1496, 1455, 1428, 1384, 1324, 1272, 1261, 1251, 1073, 1030, 1002, 772, 758, 742, 729, 709, 698 cm^{-1}. HRMS (ESI, orbitrap) m/z: [M + H]$^+$ Calcd for $C_{19}H_{14}N_2Br$ 349.0335; Found 349.0321.

*1-Phenyl-2-(2-(phenylethynyl)phenyl)-1H-benz[d]imidazole (**1a**).* To a solution of 2-(2-bromophenyl)-1-phenyl-1*H*-benz[*d*]imidazole (0.268 g, 0.767 mmol) in THF (0.8 mL) and NEt_3 (1.1 mL) were added ethynylbenzene (87.8 mg, 0.860 mmol), $Pd(PPh_3)_2Cl_2$ (12.6 mg, 0.018 mmol), CuI (6.3 mg, 0.033 mmol), and PPh_3 (9.3 mg, 0.035 mmol). The mixture was stirred for 24 h under refluxing conditions. After filtration with pads of Celite and Florizil and evaporation, the residue was subject to column chromatography on SiO_2 (hexane:EtOAc = 4:1) to give 1-phenyl-2-(2-(phenylethynyl)phenyl)-1*H*-benz[*d*]imidazole (**1a**) (0.256 g, 0.692 mmol, 90%) as a yellow oil: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.14−7.40 (m, 15H), 7.50 (diffused dd, J = 2.0 and 7.1 Hz, 1H), 7.55 (diffused dd, J = 2.5 and 6.5 Hz, 1H), 7.94 (diffused d, J = 8.6 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 87.7, 93.1, 110.3, 120.0, 122.8, 123.3, 123.9, 126.6, 127.7, 127.9, 128.1, 128.2, 129.0, 129.2 (broadened), 129.3, 130.8, 131.4, 132.2, 133.0, 125.8, 136.2, 143.0, 151.9; IR (NaCl plate) 3061, 2957, 2218, 1597, 1495, 1455, 1380, 1327, 1264, 1216, 1191, 1085, 1071, 1027, 1009, 979, 906, 825, 753, 691 cm^{-1}. HRMS (ESI, orbitrap) m/z: [M + H]$^+$ Calcd for $C_{27}H_{19}N_2$ 371.1543; Found 371.1525.

*2-((2-(4-Methylphenyl)ethynyl)phenyl)-1-phenyl-1H-benz[d]-imidazole (**1b**).* This compound was prepared in 32% isolated yield (0.125 g, 0.325 mmol) for 1 day under refluxing conditions according to a procedure similar to that mentioned in **1a**: Colorless solid; mp = 53−54 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 2.26 (s, 3H), 6.99 (d, J = 8.2 Hz, 2H), 7.04 (d, J = 8.2 Hz, 2H), 7.18−7.23 (m, 2H), 7.27−7.38 (m, 8H), 7.45 (diffused dd, J = 2.6 and 6.3 Hz, 1H), 7.55 (diffused dd, J = 2.9 and 6.0 Hz, 1H), 7.94 (d, J = 8.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.4, 87.1, 93.4, 110.4, 119.8, 120.1, 122.8, 123.3, 124.1, 126.7, 127.7, 127.8, 128.9, 129.1, 129.4, 130.9, 131.4, 132.2, 132.9, 135.8, 136.3, 138.5, 143.1, 152.1; IR (KBr disk) 3059, 2922, 2216, 1597, 1499, 1452, 1380, 1326, 818, 752, 696 cm^{-1}. HRMS (ESI, orbitrap) m/z: [M + H]$^+$ Calcd for $C_{28}H_{21}N_2$ 385.1699; Found 385.1689.

*2-Methyl-4-(2-(1-phenyl-1H-benz[d]imidazol-2-yl)phenyl)but-3-yn-2-ol (**1e**).* This compound was prepared in 86% isolated yield (0.861 g, 2.44 mmol) for 1 day under refluxing conditions according to a procedure similar to that mentioned in **1a**: Colorless solid; mp = 143−144 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.31 (s, 6H), 3.15 (bs, 1H), 7.20−7.40 (m, 12H), 7.89 (dd, J = 1.4 and 6.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 31.0, 65.0, 80.2, 98.3, 110.4, 119.9, 122.9, 123.4, 123.8, 126.8, 127.7, 128.0, 129.3 (large intensity), 130.5, 132.3, 132.8, 135.6, 136.1, 142.6, 151.6; IR (KBr disk) 3232, 2976, 2224,1733, 1597, 1499, 1452, 1389, 1330, 1172, 1137, 968, 764, 750, 698 cm^{-1}. HRMS (ESI, orbitrap) m/z: [M + H]$^+$ Calcd for $C_{24}H_{21}N_2O$ 353.1648; Found 353.1640.

*2-((2-(4-Methoxylphenyl)ethynyl)phenyl)-1-phenyl-1H-benz[d]-imidazole (**1c**).* To a solution of **1e** (0.856 g, 2.43 mmol) in toluene (4 mL) were added 4-bromoanisole (0.466 g, 2.53 mmol), CuI (49.7 mg, 0.261 mmol), $Pd(PPh_3)_2Cl_2$ (0.172 g, 0.244 mmol), nBu$_4$NI (89.7 mg, 0.2463 mmol), and a 5 M aqueous solution of NaOH (1.6 mL, 8.0 mmol). The mixture was stirred at 80 °C for 14 h. After filtration with pads of Celite and Florisil and evaporation, the residue was subject to column chromatography on SiO_2 (hexane:EtOAc = 4:1) to give 2-((2-(4-methoxylphenyl)ethynyl)phenyl)-1-phenyl-1*H*-benz[*d*]imidazole (**1c**) (92.7 mg, 0.232 mmol, 10%) as a yellow solid; mp = 48−50 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 3.76 (s, 3H), 6.74 (d, J = 8.9 Hz, 2H),

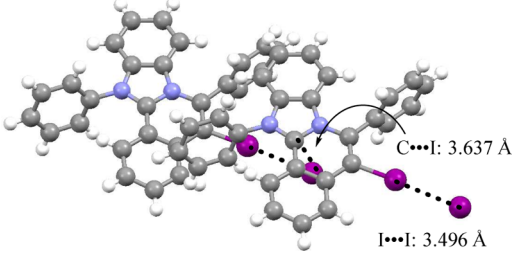

Figure 2. Interactions of $\mathbf{2a}^{+}\cdot I^{-}\cdot(\text{pyridine})_{0.75}$ obtained by single-crystal X-ray crystallographic analysis. Pyridines were omitted for clarity.

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7.09 (d, J = 8.9 Hz, 2H), 7.21 (d, J = 6.3 Hz, 1H), 7.22 (d, J = 7.6 Hz, 1H), 7.28−7.40 (m, 8H), 7.47 (diffused dd, J = 2.2 and 6.9 Hz, 1H), 7.55 (diffused dd, J = 1.9 and 7.1 Hz, 1H), 7.95 (d, J = 7.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 55.2, 86.5, 93.3, 110.4, 113.8, 115.0, 120.1, 122.8, 123.3, 124.3, 126.6, 127.6, 127.8, 129.1, 129.4, 130.8, 132.1, 132.7, 132.9, 135.8, 136.3, 143.1, 152.1, 159.6; IR (KBr disk) 3059, 2934, 2836, 2215, 1600, 1511, 1500, 1452, 1380, 1288, 1250, 1175, 1028, 833, 752, 696 cm^{-1}. HRMS (ESI, orbitrap) m/z: [M + H]$^+$ Calcd for $C_{28}H_{21}ON_2$ 401.1648; Found 401.1642.

*2-(2-Ethynylphenyl)-1-phenyl-1H-benz[d]imidazole (**1d**).* To a solution of **1e** (0.115 g, 0.326 mmol) in 2-propanol (1.5 mL) was added KOH (5.81 mg, 0.103 mmol). The mixture was stirred for 3 h under refluxing conditions. To the reaction mixture was added H_2O (20 mL), and was extracted with EtOAc (10 mL × 3). The organic layer was dried with $MgSO_4$. After filtration and evaporation, the residue was subject to column chromatography on SiO_2 (hexane:EtOAc = 2:1) to give 2-(2-ethynylphenyl)-1-phenyl-1*H*-benz[*d*]-imidazole (**1d**) (40.2 mg, 0.136 mmol, 42%) as a yellow solid; mp = 141−142 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 2.95 (s, 1H), 7.24−7.51 (m, 12H), 7.93 (d, J = 8.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 81.3, 81.5, 110.5, 120.3, 122.8, 122.9, 123.4, 126.9, 127.9, 128.5, 129.2, 129.3, 130.9, 133.1, 133.6, 135.9, 136.2, 143.0, 151.6; IR (KBr disk) 3288, 3066, 2107, 1597, 1495, 1472, 1456, 1432, 1386, 1323, 1254, 1087, 762, 753, 742, 700 cm^{-1}. HRMS (ESI, orbitrap) m/z: [M + H]$^+$ Calcd for $C_{21}H_{15}N_2$ 295.1230; Found 295.1216.

Procedure for the Cyclization of 1 with Molecular Iodine. To a solution of **1** (0.3 mmol) in solvent (3 mL) was added I_2 (1.0 or 2.0 mmol) at the appropriate temperature (see Table 1). After being stirred at that temperature, the precipitate was obtained. If no precipitate was obtained, *n*-hexane (30 mL) was added to give the precipitate. After collection of the solid and drying in vacuo, the corresponding cyclic compounds (**2** and/or **3**) were obtained. The yield of the cation part was estimated from the integration of ^{1}H NMR by dissolving the cyclic compound (5.0−10.0 mg) and terephthaldehyde or dibenzyl (ca. 10 wt % of the cyclic compound), as an internal standard, in DMSO-d_6. The method for the estimation of counteranion was described in the text.

*5-Iodo-6,12-diphenyl-12H-benz[4,5]imidazo[2,1-a]isoquinolin-7-ium Triiodide (**2a**$^+$·I_3^- (X = I_3)) and Iodide (**2a**$^+$·I^- (X = I)): Same NMR Spectra Were Obtained from **2a**$^+$·I_3^- and **2a**$^+$·I^-.* ^{1}H NMR (DMSO-d_6, 300 MHz) δ 5.87 (d, J = 8.7 Hz, 1H), 7.34 (d, J = 8.4 Hz, 1H), 7.40 (t, J = 7.6 Hz, 1H), 7.46 (d, J = 8.5 Hz, 1H), 7.65−7.74 (m, 3H), 7.77 (t, J = 7.4 Hz, 1H), 7.86−7.89 (m, 5H), 7.96 (m, 3H), 8.16 (t, J = 7.4 Hz, 1H), 8.54 (d, J = 8.3 Hz, 1H); ^{13}C NMR (DMSO-d_6, 75 MHz) δ 96.1, 113.0, 116.0, 116.2, 125.0, 125.8, 127.4, 127.9, 129.0, 130.1, 130.3, 130.4, 131.8, 132.0, 132.3, 134.1, 134.2, 134.6, 135.48, 135.54, 137.0, 139.3, 141.9. **2a**$^+$·I_3^-: 0.340 g of collected precipitate (entry 6 in Table 1); brown solid; mp = 244 °C (decomp.); IR (KBr disk) 3118, 3051, 2356, 2337, 1616, 1587, 1516, 1446, 756, 747, 715, 700 cm^{-1}. Anal. Calcd for $C_{27}H_{18}I_4N_2$: C, 36.93; H, 2.07; N, 3.19%. Found: C, 36.83; H, 1.97; N, 3.00%. **2a**$^+$·I^-: 0.165 g of collected precipitate (entry 5 in Table 1). Further purification was achieved by the recrystallization from $CHCl_3$ and hexane; yellow solid; mp = 329−330 °C; IR (KBr disk) 3120, 3051, 3026, 1617, 1518, 1482, 1466, 1448, 1325, 1025, 759, 716, 701 cm^{-1}. Anal. Calcd for $C_{27}H_{18}I_2N_2$: C, 51.95; H, 2.91; N, 4.49%. Found: C, 51.75; H, 2.97; N, 4.48%.

*5-Iodo-6-(4-methylphenyl)-12-diphenyl-12H-benz[4,5]imidazo-[2,1-a]isoquinolin-7-ium Triiodide (**2b**$^+$·I_3^- (X = I_3)) and Iodide (**2b**$^+$·I^- (X = I)).* Same NMR spectra were obtained from **2b**$^+$·I_3^- and **2b**$^+$·I^-: ^{1}H NMR (DMSO-d_6, 300 MHz) δ 2.59 (s, 3H), 5.98 (d, J = 8.6 Hz, 1H), 7.34 (d, J = 8.3 Hz, 1H), 7.42 (t, J = 8.1 Hz, 1H), 7.46 (d, J = 8.1 Hz, 1H), 7.56 (d, J = 8.0 Hz, 2H), 7.67 (m, 3H), 7.76 (t, J = 7.7 Hz, 1H), 7.88−7.97 (m, 5H), 8.15 (t, J = 7.9 Hz, 1H), 8.54 (d, J = 8.3 Hz, 1H); ^{13}C NMR (DMSO-d_6, 75 MHz) δ 21.5, 96.9, 112.9, 116.1, 116.2, 125.0, 125.8, 127.5, 128.0, 129.0, 130.0, 130.2, 130.8, 131.9, 132.3, 134.1, 134.2, 134.3, 134.6, 135.4, 135.6, 139.4, 141.5, 141.9. **2b**$^+$·I_3^-: 0.242 g of collected precipitate (entry 8 in Table 1). Further purification was achieved by the recrystallization from $CHCl_3$ and hexane; brown solid; mp = 267 °C (decomp.); IR (KBr disk) 3121, 3049, 1616, 1521, 1506, 1481, 1448, 1324, 824, 743, 698 cm^{-1}. Anal. Calcd for $C_{28}H_{20}I_4N_2$: C, 37.70; H, 2.26; N, 3.14%. Found: C, 37.53; H, 2.15; N, 2.96%. **2b**$^+$·I^-: 0.184 g of collected precipitate (entry 7 in Table 1); yellow solid; mp = 327−329 °C; IR (KBr disk) 3027, 1618, 1522, 1508, 1482, 1466, 1448, 1322, 1025, 823, 744, 702 cm^{-1}. Anal. Calcd for $(C_{28}H_{20}I_2N_2)_{0.93}(C_{28}H_{20}I_4N_2)_{0.07}$: C, 51.26; H, 3.07; N, 4.27%. Found: C, 51.00; H, 3.07; N, 4.14%.

*5-Iodo-6-(4-methoxylphenyl)-12-diphenyl-12H-benz[4,5]-imidazo[2,1-a]isoquinolin-7-ium Triiodide (**2c**$^+$·I_3^- (X = I_3)) and Iodide (**2c**$^+$·I^- (X = I)).* Same NMR spectra were obtained from **2c**$^+$·I_3^- and **2c**$^+$·I^-: ^{1}H NMR (DMSO-d_6, 300 MHz) δ 3.99, (s, 3H), 6.09 (d, J = 8.7 Hz, 1H), 7.35 (d, J = 8.3 Hz, 1H), 7.41 (d, J = 8.7 Hz, 2H), 7.45−7.48 (m, 2H), 7.58 (d, J = 8.7 Hz, 2H), 7.68 (t, J = 7.7 Hz, 1H), 7.75 (t, J = 7.4 Hz, 1H), 7.61−7.90 (m, 2H), 7.95−7.97 (m, 3H), 8.15 (t, J = 7.5 Hz, 1H), 8.53 (d, J = 8.2 Hz, 1H); ^{13}C NMR (DMSO-d_6, 75 MHz) δ 55.7, 96.9, 112.8, 115.6, 116.1, 116.2, 124.9, 125.9, 127.5, 127.9, 128.9, 129.2, 130.2, 131.6, 131.9, 132.3, 134.1, 134.2, 134.5, 135.4, 135.6, 139.3, 141.9, 161.3. **2c**$^+$·I_3^-: 0.156 g of collected precipitate (entry 10 in Table 1). Further purification was achieved by the recrystallization from $CHCl_3$ and hexane; brown solid; mp = 255 °C (decomp.); IR (KBr disk) 3118, 3052, 2927, 1616, 1507, 1481, 1448, 1294, 1255, 1175, 1025, 835, 744, 699 cm^{-1}. Anal. Calcd for $C_{28}H_{20}I_4N_2O$: C, 37.03; H, 2.22; N, 3.08%. Found: C, 37.24; H, 2.06; N, 2.97%. **2c**$^+$·I^-: 0.186 g of collected precipitate (entry 9 in Table 1); light brown solid; mp = 278−280 °C; IR (KBr disk) 3118, 3026, 2932, 2835, 1616, 1523, 1507, 1482, 1448, 1324, 1293, 1253, 1175, 1024, 835, 744, 701 cm^{-1}. Anal. Calcd for $(C_{28}H_{20}I_2N_2O)_{0.88}(C_{28}H_{20}I_4N_2O)_{0.12}$: C, 49.11; H, 2.94; N, 4.09%. Found: C, 48.94; H, 2.82; N, 4.05%.

*(E)-11-(Iodomethylene)-5-phenyl-5,11-dihydrobenz[4,5]imidazo-[2,1-a]isoindol-10-ium Triiodide (**3d**$^+$·I_3^-).* 0.185 g of collected precipitate (entry 12 in Table 1); brown solid; mp = 213-214 °C; ^{1}H NMR (DMSO-d_6, 300 MHz) δ 7.25 (d, J = 7.7 Hz, 1H), 7.60 (d, J = 8.0 Hz, 1H), 7.68 (t, J = 7.3 Hz, 1H), 7.73 (t, J = 7.5 Hz, 1H), 7.80 (t, J = 7.4 Hz, 1H), 7.85−7.94 (m, 5H), 7.98 (t, J = 8.0 Hz, 1H), 8.71 (d, J = 8.4 Hz, 1H), 8.95 (s, 1H), 8.98 (d, J = 8.1 Hz, 1H); ^{13}C NMR (DMSO-d_6, 75 MHz) δ 65.4, 82.3, 114.0, 122.8, 123.5, 125.4, 126.8, 126.9, 127.5, 127.9, 131.0, 131.3, 131.79, 131.83, 134.2, 135.3, 136.8, 138.1, 149.3; IR (KBr disk) 3067, 1559, 1497, 1478, 1458, 1439, 1143, 743, 711, 693 cm^{-1}. Anal. Calcd for $C_{21}H_{14}I_4N_2$: C, 31.45; H, 1.76; N, 3.49%. Found: C, 31.32; H, 1.69; N, 3.21%.

*(E)-11-(2-Hydroxy-1-iodo-2-methylpropylidene)-5-phenyl-5,11-dihydrobenz[4,5]imidazo[2,1-a]isoindol-10-ium Triiodide (**3e**$^+$·I_3^-).* 0.228 g of collected precipitate (entry 15 in Table 1); brown solid; mp = 74−76 °C; ^{1}H NMR (DMSO-d_6, 300 MHz) δ 1.92 (s, 6H), 5.90 (s, 1H), 7.07 (d, J = 7.8 Hz, 1H), 7.41 (d, J = 8.2 Hz, 1H), 7.57 (t, J = 7.3 Hz, 1H), 7.63 (t, J = 7.6 Hz, 1H), 7.67 (t, J = 7.4 Hz, 1H), 7.86−7.94 (m, 6H), 8.30 (d, J = 8.5 Hz, 1H), 9.29 (d, J = 8.4 Hz, 1H); ^{13}C NMR (DMSO-d_6, 75 MHz) δ 32.5, 79.6, 112.5, 119.9, 121.1, 122.8, 123.4, 125.8, 125.9, 126.7, 127.3, 130.6, 130.7, 131.1, 131.5, 131.9, 132.0, 133.7, 136.6, 143.3, 150.7; IR (KBr disk) 3420, 2993, 1622, 1569, 1498, 1478, 1456, 1331, 1172, 755, 696 cm^{-1}. Anal. Calcd for $C_{24}H_{20}I_4N_2O$: C, 33.52; H, 2.34; N, 3.26%. Found: C, 33.53; H, 2.34; N, 2.98%.

X-ray Crystallography. Data collections were carried out on a commercial X-ray diffractometer with Mo Kα or Cu Kα radiations. All structures were solved by a direct method using SHELXS-97,[28] and the non-hydrogen atoms were refined anisotropically against F^2, with full-matrix least-squares methods using SHELXL-97.[29] All hydrogen atoms were positioned geometrically and refined as riding.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00607.

^{1}H and ^{13}C NMR spectra of the products, list of X-ray crystallographic data, ^{1}H NMR spectrum of precipitate (Figure S1), ORTEP drawing of crystal structure (Figure S2), and single crystal structures of **3e**$^+$·I_3^- (Figure S3) and **2a**$^+$·I^-·(pyridine)$_{0.75}$ (Figure S4) (PDF)

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X-ray crystallographic data of $2a^+ \cdot I_3^-$ (CIF)
X-ray crystallographic data of $2b^+ \cdot I_3^-$ (CIF)
X-ray crystallographic data of $2c^+ \cdot I_3^-$ (CIF)
X-ray crystallographic data of $3d^+ \cdot I_3^-$ (CIF)
X-ray crystallographic data of $3e^+ \cdot I_3^-$ (CIF)
X-ray crystallographic data of $2a^+ \cdot I^- \cdot (\text{pyridine})_{0.75}$ (CIF)

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Notes

The authors declare no competing financial interest.

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