OL Organic Letters

pubs.acs.org/OrgLett

Letter

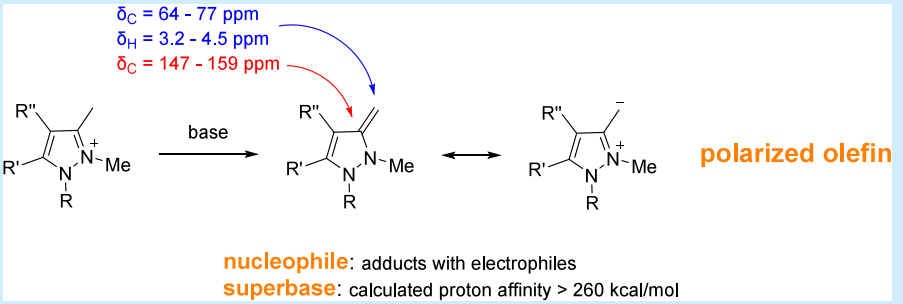
N-Heterocyclic Olefins of Pyrazole and Indazole

Bolin Zhu, Rouven Woyciechowski, Eike G. Hübner, Felix Lederle, and Andreas Schmidt*

Cite This: *Org. Lett.* 2025, 27, 5572–5577

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

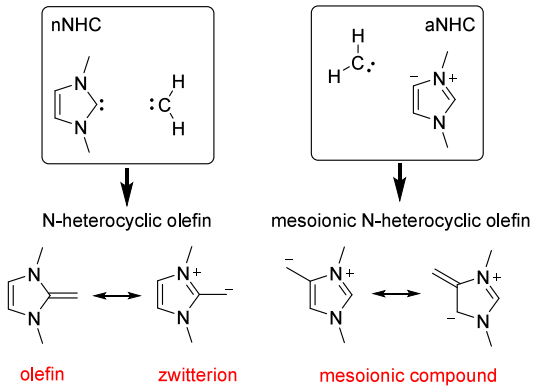


ABSTRACT: Deprotonation of 3-methylpyrazolium and 3-methylindazolium salts yielded *N*-heterocyclic olefins (NHOs) in excellent yields, which reacted with isocyanates, halogens, and carbon disulfide. Calculated proton affinities are 261 kcal/mol (indazole NHOs) and 272 kcal/mol (pyrazole NHOs). The calculated pK_a values are between 14.8 and 25.2, and bond lengths of the exocyclic double bond are slightly shorter than those of imidazole NHOs. As expected, the highest occupied molecular orbitals show significant atomic orbital coefficients at the exocyclic carbon atom.

In recent decades, the chemistry of *N*-heterocyclic carbenes (NHCs) has developed impressively,[1] and there has been a particular focus on their ligand properties for catalysis.[2] Today, a wide range of different structural types with customized properties are available. *N*-Heterocyclic olefins (NHOs) are formally the methylene adducts of NHCs (Scheme 1). The investigation of their properties and potential applications is currently the focus of interest.

The formal CH_2 adducts of the normal NHC (nNHC) imidazol-2-ylidene have an ene-1,1-diamine structural increment that can be described by a zwitterionic mesomeric structure, in which the exocyclic carbon atom carries a negative charge.[3] The formal adduct of methylene with the abnormal NHC (aNHC) imidazol-4-ylidene, imidazolium-4-methide, is a mesoionic compound[4] and, therefore, a member of a subclass of mesomeric betaines.[5] In the course of the development of NHOs, these hetarenium methides are now often referred to as mesoionic *N*-heterocyclic olefins (mNHOs).[6] The history of NHOs can be traced back several decades. The reaction of ene-1,1-diamine with Zeise's dimer to form a platinum complex was described in 1979.[7] The first reports of imidazole-based NHOs date from the 1990s.[8] NHOs of other ring systems were described (benzimidazoles,[9] 1,2,3-triazoles,[10] sydnones,[11] pyridines,[12,13] imidazol[1,5-*a*]pyridines[14]), and subsequently, adducts with Au(I),[12] Rh(I),[12] W,[15] Ir,[16] Pd,[17] Pb,[18] and others followed. Nucleophilicities,[19] Lewis basicities,[19] buried volumes,[19] proton affinities,[20] Brønsted basicities in DMSO,[10,21] and their donor strength[22] were examined. Catalytic reactions of NHOs described include sequestration of CO_2,[23] hydroborylation,[24] hydrosilylation,[25] transesterifications,[26] and polymerization of poly(propylene oxide),[27] MMA,[28] and DMMA.[28] Although the chemistry of NHCs of pyrazole[29] and indazole[30] has been investigated, NHOs based on these ring systems are unknown. They are, therefore, the subject of this work.

Scheme 1. Mesomeric Structures of the NHOs of Imidazole

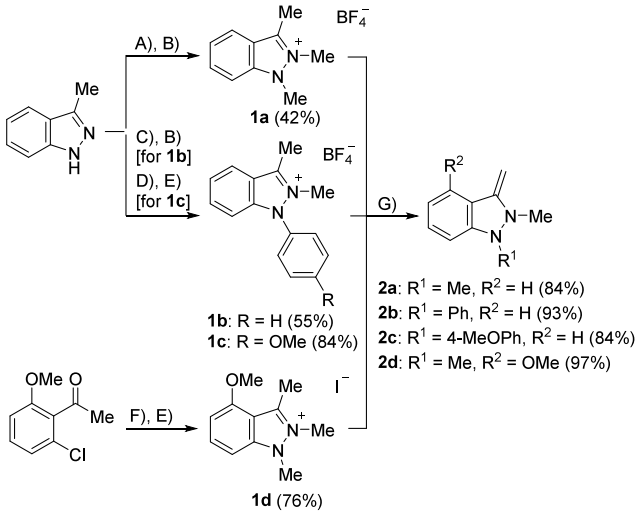


Received: February 24, 2025
Revised: May 9, 2025
Accepted: May 23, 2025
Published: May 28, 2025

https://doi.org/10.1021/acs.orglett.5c00775
Org. Lett. 2025, 27, 5572–5577

In this study, indazolium and pyrazolium salts were used as NHO precursors. The indazolium salt **1a** was prepared in good yields by two consecutive methylations with iodomethane[31] and Meerwein's reagent,[29] respectively (Scheme 3). The corresponding 1-phenylindazole derivatives **1b** and **1c** were easily obtained by copper-catalyzed N-phenylations[30,32] and subsequent methylations, with reaction with iodomethane instead of Meerwein's reagent yielding better yields in the case of compound **1c**, when nitrobenzene was added as a catalyst and higher temperatures (80 °C) were applied. The 4-methoxyindazole derivative **1d** was synthesized from 2-chloro-6-methoxyacetophenone with methylhydrazine under copper catalysis with subsequent methylation by iodomethane according to modified literature procedures.[33] All of the indazolium salts were obtained as colorless solids. The deprotonation of the precursor salts **1a**−**1d** in THF using strong bases yielded the desired NHOs **2a**−**2d** in very good yields as yellow−orange to yellow−brownish oils, with potassium hydride proving to be the ideal base for NHO synthesis in all cases, except for the deprotonation of compound **1b** (Scheme 2). The byproducts KI or KBF_4

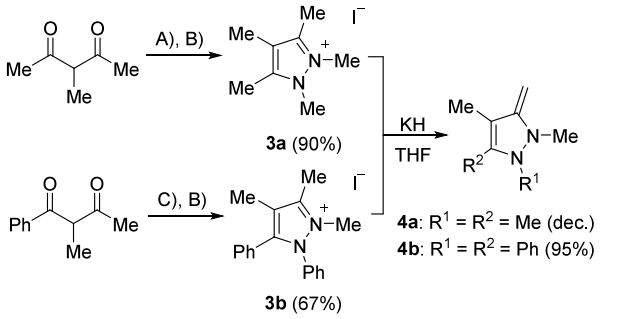
Scheme 2. Synthetic Routes of Precursor Indazolium Salts



could be easily filtered off. Compound **2b** could only be formed without decomposition when LiHMDS was used; however, the byproducts such as suspected $LiBF_4$ and hexamethyldisilane could not be completely separated, despite many attempts. The yield therefore refers to the crude product containing $LiBF_4$.

The yellow-colored pyrazolium salt **3a** was prepared starting from 3-methylpentane-2,4-dione and methylhydrazine under montmorillonite catalysis,[34] followed by methylation using iodomethane in the presence of catalytic amounts of nitrobenzene (Scheme 3). The reaction of 2-methyl-1-phenylbutane-1,3-dione with phenylhydrazine under copper catalysis[35] gave a pyrazole, which was subsequently methylated to give compound **3b** as an orange solid. Deprotonation with KH, respectively, gave pyrazole NHOs **4a** and **4b**. All indazole and pyrazole NHOs described here are yellow to orange oils or solids. With the exception of compound **4a**, which decomposed immediately during the drying process, the NHOs are stable in the absence of moisture and can be stored under an inert atmosphere at −20 °C for several days without significant changes in the NMR spectra. Whereas the

Scheme 3. Synthetic Routes of Precursor Pyrazolium Salts



indazole NHOs **2a**−**2d** are not soluble in nonpolar solvents, the pyrazole NHOs are highly soluble and could be easily extracted with pentane or toluene from the crude reaction mixture.

The polarization of the olefinic double bond is evident from the chemical shifts in the NMR spectra. The exocyclic carbons of the pyrazole and indazole NHOs appear between 64.1 and 76.2 ppm, and the corresponding ^{1}H NMR spectra shift between 3.2 and 4.0 ppm. Table 1 shows the comparison of chemical shifts between compounds **5**, **6**, **7**, and **8** (Figure 1) and the herein described pyrazole and indazole NHOs.

Table 1. Relevant Chemical Shifts of the Double Bonds of NHOs

NHO	solvent	^{1}H δ	^{13}C δ (C_{endo})	^{13}C δ (C_{exo})
5[8]	C_6D_6	2.77	153.6	40.2
6[9]	C_6D_6	3.12	152.7	47.0
7[12]	C_6D_6	3.34, 3.60		70.4
8[10]	tol-d_8	2.69, 3.47		49.7
2a	DMSO-d_6	3.78, 4.23	151.5	71.8
2b	DMSO-d_6	3.99, 4.42	150.9	73.2
2c	DMSO-d_6	3.92, 4.36	157.7	72.5
2d	DMSO-d_6	3.86, 4.51	155.6	76.2
4a	THF-d_8	3.19	158.8	64.1
4b	DMSO-d_6	3.49, 3.51	157.5	67.0
	C_6D_6	3.94, 3.85	158.6	67.5
	THF-d_8	3.52, 3.48	158.8	66.7
	tol-d_8	3.85, 3.76	158.5	67.5
11a	DMSO-d_6		147.8	73.5
11b	DMSO-d_6		147.1	73.4
11c	DMSO-d_6		148.0	73.5
11d	DMSO-d_6		148.1	73.5
11e	DMSO-d_6		151.1	72.5

The endo carbons of all listed NHOs are detectable in the ^{13}C NMR spectra between 150.9 and 158.8 ppm. When the chemical shifts of the terminal olefinic carbons are taken as a reference, a rough comparison of the degree of polarization between the different ring systems can be made, yielding the following ranking: imidazole > benzimidazole > triazole >

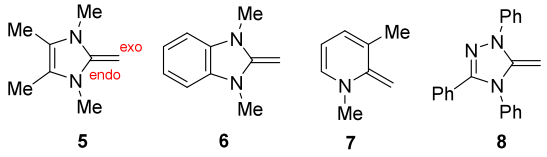


Figure 1. Reference NHOs from the literature.

https://doi.org/10.1021/acs.orglett.5c00775
Org. Lett. 2025, 27, 5572−5577

pyrazole > pyridine > indazole. A significant solvent dependence of the ^{1}H NMR resonance frequencies was demonstrated using NHO **4b** as an example. Replacing the solvent DMSO-d_6 with toluene-d_8, for example, resulted in a shift of the ^{1}H NMR resonance frequencies by up to $\Delta\delta$ = 0.45 ppm. It is also evident that, in both the pyrazole/indazole and imidazole/benzimidazole systems, phenyl substituents and fused benzene rings lead to a deshielding of the exocyclic CH_2 protons, while the carbon atoms are minimally shielded. The indazole NHOs react with elemental iodine or bromine analogous to imidazole NHOs[8] to give the corresponding iodo- and bromomethyl indazoles and pyrazoles, respectively (Scheme 4 and Table 2).

Scheme 4. Reaction of NHOs with Electrophiles

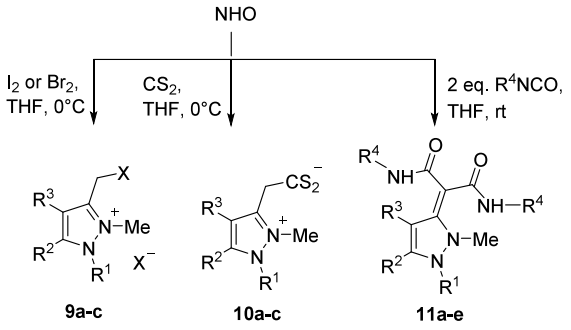


Table 2. Substitution Patterns and Yields of the Adducts

reaction	R^1	R^2	R^3	R^4	X	yield (%)
2a → 9a	Me	−CH=CH−CH=CH−			I	40
2b → 9b	Me	−CH=CH−CH=CH−			Br	70
4b → 9c	Ph	Ph	Me		Br	92
2a → 10a	Me	−CH=CH−CH=CH−				77
4a → 10b	Me	Me	Me			50
4b → 10c	Ph	Ph	Me			50
2a → 11a	Me	−CH=CH−CH=CH−		Ph		41
2a → 11b	Me	−CH=CH−CH=CH−		4-Cl-C_6H_4		46
2a → 11c	Me	−CH=CH−CH=CH−		2-MeO-C_6H_4		82
2a → 11d	Me	−CH=CH−CH=CH−		4-Me-C_6H_4		75
4a → 11e	Ph	Ph	Me	4-Cl-C_6H_4		48

Thus, methylated indazole NHO **2a** reacts with elemental iodine and bromine to give adducts **9a** and **9b** as pure and stable yellow solids. However, the decomposable phenyl derivative **9b** could not be separated from the reaction mixture as it already decomposed during filtration and formed a dark oil. The pyrazole NHOs **4a** and **4b** show different reactivities compared to the indazole NHOs. Only the bromination product **4b** was obtained, which yielded compound **9c** as a yellow solid. Carbon disulfide reacted with compounds **2a**, **4a**, and **4b** in THF to give red−orange adducts **10a−10c** that spontaneously precipitated from the reaction solution in sufficient yields. The phenyl derivative does not react under the same conditions.

The reaction of the indazole NHOs with various aryl isocyanates in THF gave the products **11a−11d** as yellow to orange precipitates in pentane. However, the adduct of compound **2b** with phenyl isocyanate could not be purified due to rapid decomposition. No product was obtained when alkyl isocyanates were employed. Pyrazol NHOs reacted with aryl isocyanates and yielded yellow adducts with poor stability. The only characterizable product proved to be compound **11e**, although the exocyclic double bond is part of the β-enaminocarbonyl chromophore, which is known to be a stabilizing push−pull group.[36] All of these products with isocyanates decompose at their melting point, indicating less stabilities than comparable adducts of other ring systems. The ^{13}C NMR signals of the double bonds, summarized in Table 1, appear at around 73 and 148 ppm, indicating highly polarized bonds. However, the adducts **11a−11e** apparently have a lower degree of polarization than the pyrazole, indazole, and imidazoline NHOs, whose ^{13}C NMR resonance frequencies appear between 71 and 166 ppm. Table 3 shows the

Table 3. Calculated Proton Affinities (PAs), pK_a Values, and Bond Lengths of the NHOs 2a, 2b, 4a, and 4b as Well as Reference NHOs

NHO	PA	PA[20]	pK_a	pK_a[21]	bond length (pm)	orbital contribution of C_{exo} to the HOMO (%)
2a	260.7		17.6		134.5	34
2b	262.1		14.8		134.4	31
4a	271.0		25.2		134.8	40
4b	273.4		21.8		134.9	41
5	273.2	273.9	25.7	24.5	135.7	42
6	260.6	262.4	17.2*	17.2	134.9	39

calculated[37] [6-311++G(2df,2p)/M06-2X//6-31G(d)/PBE0-D3] proton affinities of the pyrazole and indazole NHOs, which range from 260.7 kcal/mol (**2a**) to 273.4 kcal/mol (**4b**). For the sake of comparability, the values of imidazole NHO **5** and benzimidazole NHO **6** were also calculated. Their values are in the same range. Proton affinities of imidazole and triazole NHO superbases were also calculated earlier to range from 262 to 296 kcal/mol.[20] Table 3 also shows pK_a values calculated in DMSO via the indirect method [PCM/6-311++G(2df,2p)/M06-2X//6-31G(d)/PBE0-D3] and referenced to the value of 17.2 for compound **6**. The pK_a values are between 17.6 (**2a**) and 25.2 (**4a**), and for the compounds based on imidazole and benzimidazole, they are between 17.2 and 25.7. The literature values [SMD/6-311++G(2df,2p)/M06-2X//6-31+G(d)/B3LYP-D3] are also given for comparison. Calculated pK_a values of imidazole, triazole, and thiazole NHOs in DMSO are available in the literature.[21] Table 3 also presents calculated bond lengths *in vacuo* [6-31G(d)/PBE0-D3]. In line with the formulation of mesomeric structures, they are slightly longer than, for example, the $C_{sp^2}-C_{sp^2}$ bond length of ethene (132 pm), but they are far from reaching the values of a $C_{sp^2}-C_{sp^2}$ or $C_{sp^3}-C_{sp^2}$ single bond, like that in butadiene (148 pm) or toluene (151 pm). In comparison to the imidazole and benzimidazole NHOs, the indazole and pyrazole NHOs have slightly shorter calculated exocyclic C=C bond lengths, indicating less polarization than in the imidazole and benzimidazole NHOs. This is also reflected in the NMR values, as mentioned before. Notably, annulated phenyl rings attached to both the imidazole and pyrazole backbone reduce the polarization of the exocyclic double bond.

The highest occupied and lowest unoccupied molecular orbitals [6-31G(d)/PBE0-D3] of the NHOs **2a** and **4a** are

https://doi.org/10.1021/acs.orglett.5c00775
Org. Lett. 2025, 27, 5572−5577

shown in Figure 2, and those of the hypothetical examples **12a** and **12b** are presented in the Supporting Information.

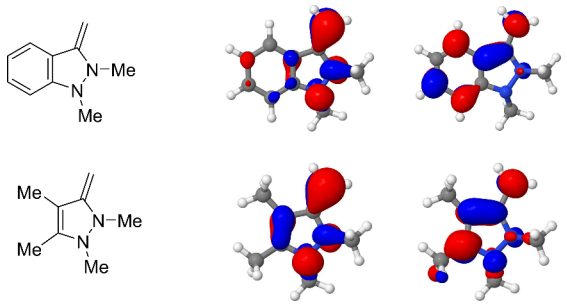


Figure 2. HOMO/LUMO profile of compounds **2a** (above) and **4a** (below).

Compounds **12a** and **12b** are the methylisocyanate adducts of the methyl-substituted pyrazole and indazole NHOs, respectively. The highest occupied molecular orbitals (HOMOs) of compounds **2a** and **4a** both show pronounced atomic orbital coefficients at the exocyclic olefinic carbon, around 10 percentage points higher for the pyrazole NHOs.

Their energies are summarized in Table S4 of the Supporting Information and shown graphically in Figure 3 as

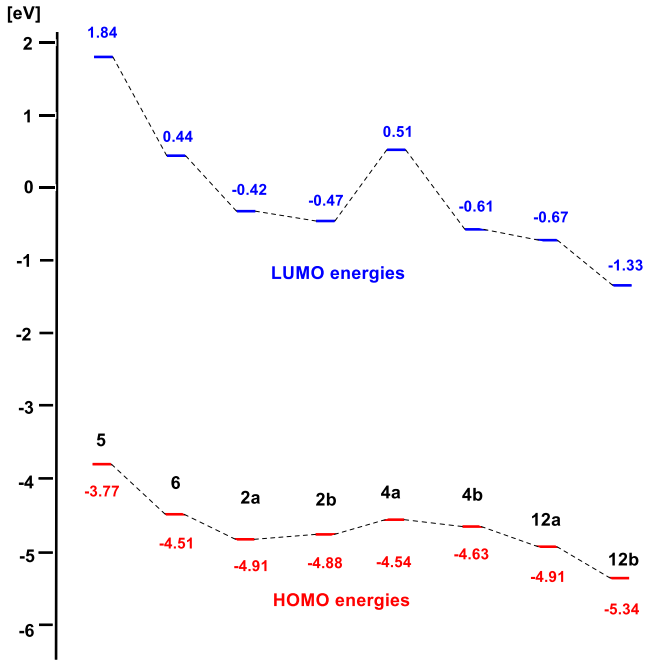


Figure 3. Comparison of frontier orbital energies.

a comparison with imidazole and benzimidiazole NHOs **5** and **6**. It is evident that indazole and pyrazole NHOs have lower HOMO energies and smaller HOMO/LUMO gaps than imidazole NHOs, indicating less nucleophilicity and reactivities that correspond to the experimental results. Among the calculated pyrazole and indazole NHOs, the pyrazole NHO **4a** has the highest HOMO/LUMO gap. The extended π systems of the hypothetical methylisocyanate adducts **12a** and **12b** cause a further reduction in the frontier orbital energies.

In summary, a total of six NHOs were synthesized, including four indazole NHOs and two pyrazole NHOs. These have an exocyclic double bond whose polarity is translated into nucleophilic properties against electrophiles, such as halogens, isocyanates, and carbon disulfide, as well as considerable calculated basicities, proton affinities, and characteristic NMR shifts. Among these NHOs and their reaction products with electrophiles, *N,N′*-dimethylindazole NHO **2a** and 2,4-dimethyl-1,5-diphenylpyrazole NHO **4b** exhibit optimal stability and reactivity. In comparison to the imidazole and benzimidazole NHOs **5** and **6**, the calculated bond lengths are slightly shorter and the frontier orbital energies, with the exception of pyrazole NHO **4a**, are on average smaller. Overall, the pyrazole and indazole NHOs and their properties are in line with those of the previously known NHOs of other ring systems but show characteristic differences to those, which encourage further work.

■ ASSOCIATED CONTENT

Data Availability Statement

The data underlying this study are available in the published article and its Supporting Information.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.orglett.5c00775.

Experimental procedures, characterization data, copies of ^{1}H and ^{13}C NMR spectra, HOMO−LUMO profiles, and details of calculations (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Andreas Schmidt − *Institute of Organic Chemistry, Clausthal University of Technology, D-38678 Clausthal-Zellerfeld, Germany*; orcid.org/0000-0002-6160-6108; Email: schmidt@ioc.tu-clausthal.de

Authors

Bolin Zhu − *Institute of Organic Chemistry, Clausthal University of Technology, D-38678 Clausthal-Zellerfeld, Germany*

Rouven Woyciechowski − *Institute of Organic Chemistry, Clausthal University of Technology, D-38678 Clausthal-Zellerfeld, Germany*

Eike G. Hübner − *Institute of Organic Chemistry, Clausthal University of Technology, D-38678 Clausthal-Zellerfeld, Germany; Fiber Optical Sensor Systems, Fraunhofer Heinrich Hertz Institute (HHI), D-38640 Goslar, Germany*

Felix Lederle − *Institute of Organic Chemistry, Clausthal University of Technology, D-38678 Clausthal-Zellerfeld, Germany; Fiber Optical Sensor Systems, Fraunhofer Heinrich Hertz Institute (HHI), D-38640 Goslar, Germany*; orcid.org/0000-0002-7369-7449

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.orglett.5c00775

Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) (a) Arduengo, A. J.; Harlow, R. L.; Kline, M. A Stable Crystalline Carbene. *J. Am. Chem. Soc.* **1991**, *113* (1), 361−363. (b) Doddi, A.; Peters, M.; Tamm, M. N-Heterocyclic Carbene Adducts of Main Group Elements and Their Use as Ligands in Transition Metal Chemistry. *Chem. Rev.* **2019**, *119*, 6994−7112. (c) Danopoulos, A. A.;

Simler, T.; Braunstein, P. N-Heterocyclic Carbene Complexes of Copper, Nickel, and Cobalt. *Chem. Rev.* **2019**, *119*, 3730−3961. (d) Schmidt, A.; Wiechmann, S.; Otto, C. F. N-Heterocyclic Carbenes. In *Heterocyclic Chemistry in the 21st Century—A Tribute to Alan Katritzky*; Scriven, E. F. V., Ramsden, C. A., Eds.; Elsevier: Amsterdam, Netherlands, 2016; Vol. *119*, Chapter 6, pp 143−172, DOI: 10.1016/bs.aihch.2016.02.002. (e) *N-Heterocyclic Carbenes*; Nolan, S. P., Ed.; John Wiley & Sons: Hoboken, NJ, 2014; DOI: 10.1002/9783527671229.

(2) (a) Biju, A. T. *N-Heterocyclic Carbenes in Organocatalysis*; Wiley/VCH: Weinheim, Germany, 2018; DOI: 10.1002/9783527809042. (b) Borguet, Y.; Zaragoza, G.; Demonceau, A.; Delaude, L. Assessing the Ligand Properties of 1,3-Dimesitylbenzimidazol-2-ylidene in Ruthenium-Catalyzed Olefin Metathesis. *Dalton Trans.* **2013**, *42*, 7287−7296. (c) Prades, A.; Viciano, M.; Sanaú, M.; Peris, E. Preparation of a Series of "Ru(P-Cymene)" Complexes with Different N-Heterocyclic Carbene Ligands for the Catalytic β-Alkylation of Secondary Alcohols and Dimerization of Phenylacetylene. *Organometallics* **2008**, *27* (16), 4254−4259.

(3) (a) Naumann, S. Synthesis, Properties and Applications of N-heterocyclic olefins in catalysis. *Chem. Commun.* **2019**, *55* (78), 11658−11670. (b) Roy, M. M. D.; Rivard, E. Pushing Chemical Boundaries with N-Heterocyclic Olefins (NHOs): From Catalysis to Main Group Element Chemistry. *Acc. Chem. Res.* **2017**, *50*, 2017−2025.

(4) (a) Ramsden, C. A.; Dumitrascu, F. Type A mesoionic compounds. In *Heterocyclic Mesomeric Betaines and Mesoionic Compounds*; Ramsden, C. A., Ed.; Elsevier: Amsterdam, Netherlands, 2022; Vol. *137*, Chapter 3, pp 71−189, DOI: 10.1016/bs.aihch.2021.09.003. (b) Newton, C. G.; Ramsden, C. A. Meso-ionic heterocycles. In *Heterocyclic Mesomeric Betaines and Mesoionic Compounds*; Ramsden, C. A., Ed.; Elsevier: Amsterdam, Netherlands, 2022; Vol. *137*, Chapter 6, pp 351−424, DOI: 10.1016/bs.aihch.2021.11.002. (c) Ollis, W. D.; Ramsden, C. A. Meso-ionic compounds. In *Heterocyclic Mesomeric Betaines and Mesoionic Compounds*; Ramsden, C. A., Ed.; Elsevier: Amsterdam, Netherlands, 2022; Vol. *137*, Chapter 5, pp 229−347, DOI: 10.1016/bs.aihch.2021.11.001. (d) Dumitrascu, F.; Ramsden, C. A. Type B mesoionic compounds. *Adv. Heterocycl. Chem.* **2022**, *137*, 191−225.

(5) (a) Ollis, W.; Stanforth, S.; Ramsden, C. A. Heterocylic mesomeric betaines. *Tetrahedron* **1985**, *41*, 2239−2329. (b) Schmidt, A.; Wiechmann, S.; Freese, T. Recent advances in neutral and anionic N-heterocyclic carbene − betaine interconversions. Syntheses, characterizations and applications. *ARKIVOC* **2013**, *2013*, 424−469.

(6) (a) Hansmann, M. M.; Antoni, P. W.; Pesch, H. Stable Mesoionic N-Heterocyclic Olefins (mNHOs). *Angew. Chem.* **2020**, *132* (14), 5831−5836. (b) Liang, Q.; Song, D. Recent advances of mesoionic N-heterocyclic olefins. *Dalton Trans.* **2022**, *51* (24), 9191−9198.

(7) Ponti, P. P.; Baldwin, J. C.; Kaska, W. C. Interaction of Zeise's dimer, *trans*-μ-dichloro-bis(ethyleneplatinium chloride) with polar olefins. *Inorg. Chem.* **1979**, *18*, 873−875.

(8) (a) Kuhn, N.; Bohnen, H.; Kreutzberg, J.; Bläser, D.; Boese, R. 1,3,4,5-Tetramethyl-2-methyleneimidazoline—An ylidic olefin. *J. Chem. Soc., Chem. Commun.* **1993**, *14*, 1136−1137. (b) Kuhn, N.; Bohnen, H.; Henkel, G.; Kreutzberg, J. 1,3,4,5-Tetramethyl-2-methylenimidazolin - ein Olefin mit Ylid-artigen Eigenschaften. *Z. Naturforsch.* **1996**, *51*, 1267−1278.

(9) Reichardt, C.; Kaufmann, N. Eine verbesserte Methode zur Darstellung von 1,3-Dimethyl- und 1,3-Diethyl-2-methylenbenzimidazolin. *Chem. Ber.* **1985**, *118*, 3424−3427.

(10) Li, Z.; Ji, P.; Cheng, J. Brönsted Basicities and Nucleophilicities of N-Heterocyclic Olefins in Solution: N-Heterocyclic Carbene versus N-Heterocyclic Olefin. Which Is More Basic, and Which Is More Nucleophilic? *J. Org. Chem.* **2021**, *86* (3), 2974−2985.

(11) (a) Mummel, S.; Lederle, F.; Hübner, E. G.; Namyslo, J. C.; Nieger, M.; Schmidt, A. Sydnone Methides: Intermediates between Mesoionic Compounds and Mesoionic N-Heterocyclic Olefins. *Eur. J. Org. Chem.* **2023**, *26*, No. e202300216. (b) Mummel, S.; Lederle, F.; Hübner, E.; Namyslo, J. C.; Nieger, M.; Schmidt, A. Sydnone methides − a forgotten class of mesoionic compounds for the generation of anionic N-heterocyclic carbenes. *Angew. Chem., Int. Ed.* **2021**, *60*, 18882−18887.

(12) (a) Fürstner, A.; Alcarazo, M.; Goddard, R.; Lehmann, C. W. Coordination Chemistry of Ene-1,1-diamines and a Prototype "Carbodicarbene". *Angew. Chem. Int. Ed* **2008**, *47* (17), 3210−3214. (b) Kronig, S.; Jones, P. G.; Tamm, M. Preparation of 2-Alkylidene-Substituted 1,3,4,5-Tetramethylimidazolines and Their Reactivity Towards Rh^{I} Complexes and $B(C_6F_5)_3$. *Eur. J. Inorg. Chem.* **2013**, *2013*, 2301−2314.

(13) Sun, Q.; Eitzinger, A.; Esken, R.; Antoni, P. W.; Mayer, R. J.; Ofial, A. R.; Hansmann, M. M. Pyridinium-Derived Mesoionic N-Heterocyclic Olefins (py-mNHOs). *Angew. Chem., Int. Ed.* **2024**, *63*, No. e202318283.

(14) Esken, R.; Antoni, P. W.; Lorenz, Y.; Burdenski, C.; Kirchhoff, J.-L.; Strohmann, C.; Hansmann, M. M. Imidazo[1,5-a]pyridines − A Versatile Platform for Structurally Distinct N-Heterocyclic Olefins and π-Extended Heterocycles. *Angew. Chem., Int. Ed.* **2025**, No. e202506305.

(15) Imbrich, D. A.; Frey, W.; Naumann, S.; Buchmeiser, M. R. Application of imidazolinium salts and N-heterocyclic olefins for the synthesis of anionic and neutral tungsten imido alkylidene complexes. *Chem. Commun.* **2016**, *52*, 6099−6102.

(16) Iglesias, M.; Iturmendi, A.; Sanz Miguel, P. J.; Polo, V.; Pérez-Torrente, J. J.; Oro, L. A. Tuning PCP−Ir complexes: the impact of an N-heterocyclic olefin. *Chem. Commun.* **2015**, *51*, 12431−12434.

(17) Watson, I. C.; Schumann, A.; Yu, H.; Davy, E. C.; McDonald, R.; Ferguson, M. J.; Hering-Junghans, C.; Rivard, E. N-Heterocyclic Olefin-Ligated Palladium(II) Complexes as Pre-Catalysts for Buchwald−Hartwig Aminations. *Chem. - Eur. J.* **2019**, *25*, 9678−9690.

(18) Guthardt, R.; Bruhn, C.; Siemeling, U. N-Heterocyclic olefins as dative carbon donor ligands for diaminoplumbylenes: Syntheses and crystal structures of adducts with 1,3,4,5-tetramethyl-2-methylene-imidazoline. *Polyhedron* **2021**, *194*, 114959.

(19) Eitzinger, A.; Reitz, J.; Antoni, P. W.; Mayr, H.; Ofial, A. R.; Hansmann, M. M. Pushing the Upper Limit of Nucleophilicity Scales by Mesoionic N-Heterocyclic Olefins. *Angew. Chem., Int. Ed.* **2023**, *62*, No. e202309790.

(20) Schuldt, R.; Kästner, J.; Naumann, S. Proton Affinities of N-Heterocyclic Olefins and Their Implications for Organocatalyst Design. *J. Org. Chem.* **2019**, *84*, 2209−2218.

(21) Wang, Z.; Niu, Q.; Xue, X.; Ji, P. The Brönsted Basicities of N-Heterocyclic Olefins in DMSO: An Effective Way to Evaluate the Stability of NHO−CO_2 Adducts. *J. Org. Chem.* **2020**, *85*, 13204−13210.

(22) Powers, K.; Hering-Junghans, C.; McDonald, R.; Ferguson, M. J.; Rivard, E. Improved synthesis of N-heterocyclic olefins and evaluation of their donor strengths. *Polyhedron* **2016**, *108*, 8−14.

(23) (a) Wang, Y.-B.; Sun, D.-S.; Zhou, H.; Zhang, W.-Z.; Lu, X.-B. CO_2, COS and CS_2 adducts of N-heterocyclic olefins and their application as organocatalysts for carbon dioxide fixation. *Green Chem.* **2015**, *17*, 4009−4015. (b) Saptal, V. B.; Bhanage, B. M. N-Heterocyclic Olefins as Robust Organocatalysts for the Chemical Conversion of Carbon Dioxide to Value-Added Chemicals. *ChemSusChem* **2016**, *9*, 1980−1985. (c) Wang, Y.-B.; Wang, Y.-M.; Zhang, W.-Z.; Lu, X.-B. Fast CO_2 Sequestration, Activation, and Catalytic Transformation Using *N*-Heterocyclic Olefins. *J. Am. Chem. Soc.* **2013**, *135*, 11996−12003.

(24) Hering-Junghans, C.; Watson, I. C.; Ferguson, M. J.; McDonald, R.; Rivard, E. Organocatalytic hydroborylation promoted by N-heterocyclic olefins. *Dalton Trans.* **2017**, *46*, 7150−7153.

(25) Kaya, U.; Tran, U. P. N.; Enders, D.; Ho, J.; Nguyen, T. V. N-Heterocyclic Olefin Catalyzed Silylation and Hydrosilylation Reactions of Hydroxyl and Carbonyl Compounds. *Org. Lett.* **2017**, *19*, 1398−1401.

(26) Blümel, M.; Noy, J. M.; Enders, D.; Stenzel, M. H.; Nguyen, T. V. Development and Applications of Transesterification Reactions Catalyzed by N-Heterocyclic Olefins. *Org. Lett.* **2016**, *18*, 2208−2211.

https://doi.org/10.1021/acs.orglett.5c00775
Org. Lett. 2025, 27, 5572−5577

(27) Naumann, S.; Thomas, A. W.; Dove, A. P. N-Heterocyclic Olefins as Organocatalysts for Polymerization: Preparation of Well-Defined Poly(propylene oxide). *Angew. Chem., Int. Ed.* **2015**, *54*, 9550−9554.
(28) Jia, Y. B.; Wang, Y. B.; Ren, W. M.; Xu, T.; Wang, J.; Lu, X. B. Mechanistic Aspects of Initiation and Deactivation in N-Heterocyclic Olefin Mediated Polymerization of Acrylates with Alane as Activator. *Macromolecules* **2014**, *47*, 1966−1972.
(29) (a) Hillrichs, K.; Namyslo, J. C.; Lederle, F.; Hübner, E. G.; Schmidt, A. Pyrazoles in the Intersection of Mesomeric Betaines and N-Heterocyclic Carbenes. Formation of NHC Selenium Adducts of Pyrazolium-4-aminides. *Synthesis* **2022**, *54*, 3351−3366. (b) Schmidt, A.; Guan, Z. Mesomeric Betaines and N-Heterocyclic Carbenes of Pyrazole and Indazole. *Synthesis* **2012**, *44*, 3251−3268.
(30) Guan, Z.; Wiechmann, S.; Drafz, M.; Hübner, E.; Schmidt, A. Pericyclic rearrangements of N-heterocyclic carbenes of indazole to substituted 9-aminoacridines. *Org. Biomol. Chem.* **2013**, *11*, 3558−3567.
(31) (a) Viña, D.; del Olmo, E.; López-Pérez, J. L.; San Feliciano, A. Regioselective Synthesis of 1-Alkyl- or 1-Aryl-1*H*-indazoles via Copper-Catalyzed Cyclizations of 2-Haloarylcarbonylic Compounds. *Org. Lett.* **2007**, *9* (3), 525−528. (b) Li, W.; Tang, J.; Li, S.; Zheng, X.; Yuan, M.; Xu, B.; Jiang, W.; Fu, H.; Li, R.; Chen, H. Stereodivergent Synthesis of Alkenylpyridines via Pd/Cu Catalyzed C-H Alkenylation of Pyridinium Salts with Alkynes. *Org. Lett.* **2020**, *22* (20), 7814−7819.
(32) Yong, F.-F.; Teo, Y.-C.; Tay, S.-H.; Tan, B. Y.-H.; Lim, K.-H. A ligand-free copper(I) oxide catalyzed stratgey for the N-arylation of azoles in water. *Tetrahedron Lett.* **2011**, *52* (11), 1161−1164.
(33) Counceller, C. M.; Eichman, C. C.; Wray, B. C.; Stambuli, J. P. A practical metal-free synthesis of 1H-indazoles. *Org. Lett.* **2008**, *10* (5), 1021−1023.
(34) Texier-Boullet, F.; Klein, B.; Hamelin, J. Pyrrole and pyrazole ring closure in heterogeneous media. *Synthesis* **1986**, *1986* (5), 409−411.
(35) Wang, H.; Sun, X.; Zhang, S.; Liu, G.; Wang, C.; Zhu, L.; Zhang, H. Efficient copper-catalyzed synthesis of substituted pyrazoles at room temperature. *Synlett* **2018**, *29* (20), 2689−2692.
(36) Wamhoff, H. Heterocylic *β*-enaminoesters, versatile synthons in heterocylic synthesis. *Adv. Heterocycl. Chem.* **1985**, *38*, 299−368.
(37) Density functional theory (DFT) calculations were carried out by using the multithreaded Firefly 8.2.0 QC package,[38] which is partially based on the GAMESS (U.S.)[39] source code, running on Windows 10 Pro (Version 10.0.17763.914, x86_64) on a 16 core AMD 2950X processor workstation. MM2-optimized structures were used as starting geometries. Complete geometry optimizations were carried out on the implemented 6-31G(d) basis set with the PDE0 density functional including dispersion correction D3. All calculated minima in the energy plot were proven to be true minima by the absence of imaginary frequencies. Solvent effects in DMSO were estimated by help of the polarizable continuum model implemented in Firefly. A second set of DFT calculations were carried out by using the multithreaded GAMESS 2022.R2 QC package,[39−41] running Windows 10 (10.0.19045.4046) on a 28 core Intel E5-2698 v3 processor workstation. The optimized structure from the first set was used as geometries, and single-point calculations were carried out on the implemented 6-311++G(2df,2p) basis set with the M06-2X density functional. Solvent effects in DMSO were estimated by help of the polarizable continuum model implemented in GAMESS. In the case of the calculations with a solvent model, residual low negative frequencies around 100 cm^{-1} were omitted for the calculation of thermochemistry in some cases. The protonation energy was calculated from the difference of the energies of the protonated and unprotonated species.[20] The pK_a values in DMSO were calculated via the indirect method referenced to structure **6**.[21,42] Molecular plots were obtained using Jmol 14.27.2.[43] Compositions of molecular orbitals were calculated using the AOMix program on basis of the calculations on the 6-31G(d)/PBE0-D3 level.[44,45]
(38) Granovsky, A. A. *Firefly, Version 8*; http://classic.chem.msu.su/gran/firefly/index.html.
(39) Schmidt, M. W.; Baldridge, K. K.; Boatz, J. A.; Elbert, S. T.; Gordon, M. S.; Jensen, J. H.; Koseki, S.; Matsunaga, N.; Nguyen, K. A.; Su, S.; Windus, T. L.; Dupuis, M.; Montgomery, J. A. General atomic and molecular electronic structure system. *J. Comput. Chem.* **1993**, *14*, 1347−1363.
(40) Gordon, M. S.; Schmidt, M. W. Advances in electronic structure theory: GAMESS a decade later. In *Theory and Applications of Computational Chemistry*; Dykstra, C. E., Frenking, G., Kim, K. S., Scuseria, G. E., Eds.; Elsevier: Amsterdam, Netherlands, 2005; Chapter 41, pp 1167−1189, DOI: 10.1016/B978-044451719-7/50084-6.
(41) Barca, G. M. J.; Bertoni, C.; Carrington, L.; Datta, D.; De Silva, N.; Deustua, J. E.; Fedorov, D. G.; Gour, J. R.; Gunina; Guidez, A. O. E.; Harville, T.; Irle, S.; Ivanic, J.; Kowalski, K.; Leang, S. S.; Li, H.; Li, W.; Lutz, J. J.; Magoulas, I.; Mato, J.; Mironov, V.; Nakata, H.; Pham, B. Q.; Piecuch, P.; Poole, D.; Pruitt, S. R.; Rendell, A. P.; Roskop, L. B.; Ruedenberg, K.; Sattasathuchana, T.; Schmidt, M. W.; Shen, J.; Slipchenko, L.; Sosonkina, M.; Sundriyal, V.; Tiwari, A.; Galvez Vallejo, J. L.; Westheimer, B.; Włoch, M.; Xu, P.; Zahariev, F.; Gordon, M. S. Recent developments in the general atomic and molecular electronic structure system. *J. Chem. Phys.* **2020**, *152* (15), 154102.
(42) Busch, M.; Ahlberg, E.; Ahlberg, E.; Laasonen, K. How to Predict the pKa of Any Compound in Any Solvent. *ACS Omega* **2022**, *7* (20), 17369−17383.
(43) *Jmol: An Open-Source Java Viewer for Chemical Structures in 3D*; http://jmol.sourceforge.net/ (accessed Nov 2019).
(44) Gorelsky, S. I. *AOMix: Program for Molecular Orbital Analysis, Version 6.94*, 2019; http://www.sg-chem.net/.
(45) Gorelsky, S. I.; Lever, A. B. P. Electronic structure and spectra of ruthenium diimine complexes by density functional theory and INDO/S. Comparison of the two methods. *J. Organomet. Chem.* **2001**, *635* (1−2), 187−196.

https://doi.org/10.1021/acs.orglett.5c00775
Org. Lett. 2025, 27, 5572−5577