A New Access to 4*H*-Quinolizines from 2-Vinylpyridine and Alkynes Promoted by Rhodium-N-Heterocyclic Carbene Catalysts

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N-bridgehead heterocycles are prevalent in many natural and synthetic biologically active alkaloids.^[1] The development of efficient synthetic methodologies for the preparation of these intricate structures has been the focus of intense research,^[2] among which transition metal catalysts have played a preeminent role.^[3] However, derivatives based on the quinolizine skeleton have received little attention, probably due to their instability, and are mainly limited to quinolizidine,^[4] quinolizinium salts^[5] or quinolizone^[6] compounds. Indeed, 4*H*-quinolizines are very scarce,^[7] particularly the 4-unsubstituted counterparts,^[8] and are usually involved in a tautomeric equilibrium with the corresponding butadienylpyridine derivatives (Scheme 1).^[9] Interestingly, we have now observed that the process can be shifted towards the quinolizine tautomer depending on the presence and position of certain substituents on the dienyl fragment. However, a straightforward and general method for the preparation of butadienylpyridines is still an important challenge for which organometallic catalysts emerge as a crucial node, as they can potentially achieve this task from 2-vinylpyridine and alkynes through sequential C-H activation and C-C coupling reactions.^[10] Particularly, we have been interested in the design of rhodium catalysts based on N-heterocyclic carbenes (NHCs)^[11] for new C-C and C-X bond forming reactions.^[12] Now, we have discovered that rhodium catalysts bearing NHC ligands give access to the elusive 4*H*-quinolizines with total atom economy under mild conditions.

Scheme 1. Tautomerization of 4*H*-quinolizines.

Our research group has recently reported that isolable mononuclear Rh-NHC species can be obtained by N-donor ligand promoted bridge cleavage reaction of the corresponding dimer.^[12c] Similarly, we have now observed that the treatment of [Rh(μ -Cl)(NHC)(η^2 -coe)]₂ (NHC = IPr (**1**), IMes (**2**); coe = cyclooctene; IPr = 1,3-bis-(2,6-diisopropylphenyl)imidazol-2-carbene; IMes = 1,3-bis-(2,4,6-trimethylphenyl)imidazol-2-carbene) with 2-vinylpyridine afforded RhCl(NHC)(κ -N, η^2 -CH₂=CHC₅H₄N) (NHC = IPr (**3**), IMes (**4**)) in good yields (see Supporting Information for synthetic details and NMR data). The chelating coordination of vinylpyridine is corroborated by an upfield shift for the olefinic protons (3.39-2.13 ppm) and the occurrence of *J*_{C-Rh} coupling for the carbon atoms of the alkenyl fragment (16-12 Hz) in the ¹H and ¹³C{¹H} NMR spectra, respectively.

It has been previously described that rhodium-phosphane catalysts promote efficiently the C-C coupling between alkenylpyridines and olefins,^[13] though the coupling with alkynes has not been reported up to date. Now, we have discovered that the introduction of an NHC ligand in complexes **3** and **4** allow for the straightforward preparation of butadienylpyridines from 2-vinylpyridine and alkynes (Scheme 2). Indeed, it is noticeable the ability of **3-4** to involve terminal alkynes in these type of transformation without the observation of competitive dimerization or polymerization processes.

Scheme 2. C-C coupling reactions mediated by Rh-NHC catalysts.

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Catalytic reactions were carried out in an NMR tube in C₆D₆ using a 1:1 pyridine:alkyne ratio. Preliminary tests with phenylacetylene under the optimized conditions, 40 °C at 5 mol % catalyst loading, showed that **4** was slightly more active than **3** (see table S1 in supporting information). Initially, it was observed the formation of (1*Z*,3*E*)-2-(4-phenylbuta-1,3-dien-1-yl)pyridine (Figure 1), however, unexpectedly it was accompanied with a new set of resonances that were unequivocally ascribed to 3-phenyl-4*H*-quinolizine (see below). The formation of this product may arise from a 6 π electrocyclization involving the two conjugated double bonds and one C=N of the pyridine moiety within an

undetected (1*Z*,3*gem*)-butadienylpyridine species. Similar transformation has been previously observed for conjugated imines^[14] or oximes^[15] but dearomatization of a pyridine moiety is considerably more challenging.^[16] The similar initial rate for the formation of both organic products points out to a lack of regioisomeric preference in the C-C coupling process, but the (1*Z*,3*E*)-butadienylpyridine product smoothly isomerizes to produce the (1*E*,3*E*) derivative. A conversion of 97% was reached after 4 h with a TOF_{1/2} value of 35 h⁻¹ calculated at 50 % conversion of vinylpyridine. It is noticeable that the formation of 4-phenyl-4*H*-quinolizine was not detected. Both butadienylpyridine isomers were isolated by column chromatography methods but, unfortunately, the quinolizine derivative could not be recovered despite several attempts under different conditions.^[14c]

Figure 1. Monitoring of the reaction between 2-vinylpyridine and phenylacetylene catalyzed by **4** in C₆D₆ at 40 °C. C-C coupling reactions mediated by Rh-NHC catalysts.

The nature of the new organic product as 3-phenyl-4*H*-quinolizine was confirmed by multinuclear NMR experiments. A striking feature of the ¹H NMR spectrum is an unusual set of resonances at higher field (6.6-4.9 ppm) compared to that corresponding to aromatic protons, which is fully consistent with the presence of non-aromatic bicyclic system. The 4*H*-quinolizine structure was further confirmed by HSQC and HMBC ¹H-¹³C experiments. Remarkably, the methylene fragment at 4-position of the quinolizine skeleton was observed as a singlet at 4.38 ppm. Moreover, long range HSQC ¹H-¹⁵N correlation confirms the presence of a N-bridgehead heterocycle (Figure 2) with a δ(¹⁵N) of 117.5 ppm, which falls within the typical range for a trisubstituted amine. In sharp contrast, the (1*E*,3*E*)-butadienylpyridine compound was observed at 309.8 ppm.

Figure 2. ¹H-¹⁵N NMR correlation spectrum for a 4*H*-quinolizine.

Catalyst **4** is a versatile precursor for coupling reactions between 2-vinylpyridine and diverse terminal and internal alkynes (Table 1). Aromatic terminal alkynes reacted faster than aliphatic ones and with higher selectivity to 4*H*-quinolizine (entries 1-3 vs 4-6). Isomerization of the internal double bond from *Z* to *E* occurred also faster for aromatic than aliphatic substituted dienyl derivatives. The presence of an electron-withdrawing substituent on the phenyl ring increased the rate whereas selectivity to the N-bridgehead heterocycle decreased for both, electron-donating or -withdrawing groups (entries 1-3).

Table 1. Coupling reaction between 2-vinylpyridine and alkynes^a

Entry	substrate	t(h)	4 <i>H</i> -q ^b	<i>Z</i> - <i>E</i> ^c	<i>E</i> - <i>E</i> ^c	<i>Z</i> - <i>g</i> ^d	<i>E</i> - <i>g</i> ^d	vipy ^e	TOF _{1/2} (h ⁻¹)
1		4	48	3	46	-	-	3	35
2		1	43	2	48	-	-	7	51
3		6	36	16	31	8	-	8	29
4		5	7	37	-	45	10	1	26
5		9	9	39	-	38	11	3	23
6		20	7	74	2	14	-	2	4
7		14	16	47	-	-	-	37	3
8		14	51	36	12	-	-	1	15
9		12	23	69	6 ^f	-	-	2	3
10		3	45 ^g	25 ^h	23 ^h	-	-	6	18

^a0.5 mL of C₆D₆ with 5 mol % of catalyst at 40 °C; [subs] = 1M. ^b4*H*-quinolizine; ratio of ¹H NMR integration. ^c2-(buta-1,3-dien-1-yl)pyridine. ^d*gem*. ^eunreacted 2-vinylpyridine. ^f*E*-*Z* isomer. ^g4-methyl. ^h4-phenyl.

The presence of bulky substituents in aliphatic alkynes reduced the activity (entries 6-7). It is noticeable that the key (1*Z*,3*gem*)-butadienylpyridine isomers were detected for aliphatic alkynes, and consequently, the conversion to 3-*R*-4*H*-quinolizine is lower, which suggests that the tautomerization is disfavored in these cases.^[17] Monitoring of the reaction showed that the initially formed *Z*-*gem*-butadienylpyridine isomerizes to *E*-*gem* derivatives and tautomerizes to the 4*H*-quinolizine compounds (Figure 3). It is worthy of note that for aliphatic alkynes the isomerization of 1*Z*,3*E* to 1*E*,3*E* butadienylpyridines was not detected under catalytic conditions.^[18] Internal alkynes reacted

smoothly (entries 8-10). The configuration of the conjugated double bonds of the butadienyl products was confirmed by ^1H -NOE NMR experiments (see Supporting Information). In the case of 3-hexyne, the formation of the $1Z,3E$ derivative was initially observed with subsequent isomerization to $1E,3E$ and $4H$ -quinolizine compounds. However, diphenylacetylene behaved somewhat different. The initial rate for the $4H$ -quinolizine formation was higher but the N-heterocycle experienced a reopening to afford the $(1Z,3E)$ -2-(3,4-diphenylbuta-1,3-dien-1-yl)pyridine derivative with both phenyl groups disposed mutually *trans* (Figure 4). Dissymmetric 1-phenyl-1-propyne gave exclusively 4-methyl-3-phenyl- $4H$ -quinolizine and 2-(3-methyl-4-phenylbuta-1,3-dien-1-yl)pyridine.

Figure 3. Monitoring of the reaction between 2-vinylpyridine and 3-phenyl-1-propyne catalyzed by **4** in C_6D_6 at 40°C .

Figure 4. Monitoring of the reaction between 2-vinylpyridine and diphenylacetylene catalyzed by **4** in C_6D_6 at 40°C . DFT calculated ΔG (Kcal.mol^{-1}) for the tautomerization butadienylpyridine $\leftrightarrow$ $4H$ -quinolizine.

Scheme 3 shows a plausible mechanism for the formation of the 3-R- $4H$ -quinolizine compounds. Initially, the activation of a terminal C-H bond of the 2-vinylpyridine to generate rhodium-alkenyl-hydride species is proposed.^[19] The subsequent coordination of the alkyne, migratory insertion and reductive elimination should generate both $(1Z,3E)$ - or $(1Z,3gem)$ -butadienyl-pyridine products depending on the regioselectivity. In

both cases, the *Z* configuration of the internal double bond is kinetically favored if a concerted insertion mechanism is assumed. Then, formation of $4H$ -quinolizine skeletons can be rationalized via a metal-mediated or thermal electrocyclization. To shed light on this point, a solution of pure *Z-gem* isomer, (Z) -2-(3-benzylbuta-1,3-dien-1-yl)pyridine, in C_6D_6 was heated at 60°C . Monitoring of the reaction by NMR evidenced the smoothly formation of the $4H$ -quinolizine isomer, thus, pointing to a thermal activated cyclization process. In fact, an equilibrium mixture of 75/25, butadienylpyridine/heterocycle, was reached after 3 h, which was corroborated by the exchange peaks observed in the ^1H -NOE NMR spectrum at 80°C . It is noticeable that the formation of the *E-gem* regioisomer was not observed indicating that metal catalyst accounts for the *Z* to *E* isomerization of the internal double bond. A *cisoidal* configuration of the conjugated double bonds is essential for the electrocyclic reaction to take place, thus isomerization of the internal double bond a handicap to be overcome. A similar equilibrium mixture was observed after heating the $(1Z,3E)$ -butadienylpyridine obtained from 3-hexyne, but in this case the equilibrium is further shifted to the quinolizine compound in 60/40 molar ratio.

Insert Scheme 3

Scheme 3. Plausible mechanism for the formation of $4H$ -quinolizine derivatives mediated by **4**.

Theoretical calculations (DFT/m06-2x/ Kcal.mol^{-1}) for the thermodynamics of the tautomerization process were performed. In full agreement with experimental results, it was found that 3-phenyl- $4H$ -quinolizine is $1.83 \text{ Kcal.mol}^{-1}$ more stable than *Z-gem*-butadienylpyridine whereas the formation of 4-phenyl- $4H$ -quinolizine from the $(1E-3Z)$ -butadienylpyridine isomer is disfavored by $2.04 \text{ Kcal.mol}^{-1}$ (Figure 5). On the other hand, the calculated energies for diphenylacetylene were also in agreement with the experimental results. Although the $4H$ -quinolizine is $3.24 \text{ Kcal.mol}^{-1}$ more stable than the $(1Z,3Z)$ -butadienylpyridine isomer, not detected in the catalytic reaction, tautomerization to the $(1Z,3E)$ counterpart is also slightly favored ($-0.68 \text{ Kcal.mol}^{-1}$), thus explaining the smoothly tautomerization observed experimentally (Figure 4).

Figure 5. Thermodynamic DFT-calculated free energies (ΔG , Kcal.mol^{-1}) for the tautomerization butadienylpyridine $\leftrightarrow$ quinolizine.

In conclusion, we have described the outstanding catalytic performance in C-C coupling reactions of new Rh-NHC catalyst leading to the formation of $4H$ -quinolizine derivatives under mild conditions with total atom economy. We have shown that the thermal 6π electrocyclization process leading to the formation of

N-bridgehead heterocycles is favored for internal- versus terminal-substituted butadienylpyridine derivatives. The design of improved catalysts for selective Z-gem-butadienylpyridine formation and reduced Z to E isomerization of the internal double bond is ongoing in our laboratories.

Experimental Section

Synthesis of catalysts. 3: A yellow solution of **1** (300 mg, 0.235 mmol) in 10 mL of toluene was treated with 2-vinylpyridine (50 μ L, 0.470 mmol) and was stirred at room temperature for 1 h. After filtration through Celite the solvent evaporated to dryness. Addition of hexane caused precipitation of a yellow solid, which was washed with hexane (3 x 4 mL) and dried in vacuo. Yield: 250 mg (84%). Anal. Calcd. for C₃₄H₄₃N₃ClRh: C, 64.61; H, 6.86; N, 6.65. Found: C, 64.92; H, 6.89; N, 6.62. **4:** The complex was prepared as described for **3** starting from **2** (300 mg, 0.271 mmol) and 2-vinylpyridine (58 μ L, 0.542 mmol). Yield: 260 mg (87%). Anal. Calcd for C₂₉H₃₅N₃ClRh: C, 61.38; H, 5.70; N, 7.67. Found: C, 61.05; H, 5.80; N, 7.26.

Standard procedure for the catalytic C-C coupling between 2-vinylpyridine and alkynes. A NMR tube containing a solution of 0.025 mmol of catalyst in 0.5 mL of C₆D₆ was treated with 0.5 mmol of 2-vinylpyridine and 0.5 mmol of the alkyne and heated at 40°C. The reaction course was monitored by NMR and the conversion determined by integration of the corresponding resonances in the ¹H NMR spectra of 2-vinylpyridine and the products.

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- [1] a) J. P. Michael, *Nat. Prod. Rep.* **2008**, 25, 139; b) H. -F. Ji, L. Shen, *Molecules* **2011**, 16, 6732; c) R. A. Saporito, M. A. Donnelly, T. F. Spande, H. M. Garraffo, *Chemoecology* **2012**, 22, 159.
- [2] a) S. F. Martin, *Pure Appl. Chem.* **2009**, 81, 195; b) *Modern Heterocyclic Chemistry*, Vol. 4 (Eds: J. Alvarez-Builla, J. J. Vaquero, J. Barluenga), WILEY-VCH, Weinheim, **2011**; c) H. T. Pham, I. Chataigner, J.-L. Renaud, *Curr Org. Chem.* **2012**, 16, 1754.
- [3] a) J. A. Varela, C. Saa, *Chem. Rev.* **2003**, 103, 3787; b) I. Nakamura, Y. Yamamoto, *Chem. Rev.* **2004**, 104, 2127; c) D. M. D'Souza, T. J. J. Müller, *Chem. Soc. Rev.* **2007**, 36, 1095; d) S. Perreault, T. Rovis, *Chem. Soc. Rev.* **2009**, 38, 3149.
- [4] a) W. E. Doering, R. A. N. Weil, *J. Am. Chem. Soc.* **1947**, 69, 2461; b) K. A. Tehrani, M. D'hooghe, N. De Kimpe *Tetrahedron* **2003**, 59, 3099; c) C. Tsukano, A. Oimura, I. Enkhtaiyan, Y. Takemoto, *Org. Lett.* **2012**, 14, 1902; d) L. Liu, L. Zhang, *Angew. Chem. Int. Ed.* **2012**, 51, 7301.
- [5] a) B. S. Thyagarajan, *Adv. Heterocycl. Chem.* **1965**, 5, 291; b) C. Sotiriou-Leventis, A. -M. M. Rawashdeh, W. S. Oh, N. Leventis, *Org. Lett.* **2002**, 4, 4113; c) A. Nuñez, B. Abarca, A. M. Cuadro, J. Alvarez-Builla, J. J. Vaquero, *J. Org. Chem.* **2009**, 74, 4166; d) M. Tian, H. Ihmels, S. Ye, *Org. Biomol. Chem.* **2012**, 10, 3010.
- [6] a) V. Boekelheide, C. -T. Liu, *J. Am. Chem. Soc.* **1952**, 74, 4920; b) A. Schwartz, Z. Pál, L. Szabo, K. Simon, I. Hermecz, Z. Mészáros, *J. Heterocycl. Chem.* **1987**, 24, 645; c) M. Hagimori, S. Matsui, N. Mizuyama, K. Yokota, J. Nagaoka, Y. Tominaga, *Eur. J. Org. Chem.* **2009**, 5847; d) S. Mochida, N. Umeda, K. Hirano, T. Satoh, M. Miura, *Chem. Lett.* **2011**, 39, 744.
- [7] a) O. Diels, K. Alder, *Liebigs Ann. Chem.* **1932**, 498, 16; b) R. M. Acheson, G. A. Taylor, *J. Chem. Soc.* **1960**, 1691; c) W. K. Gibson, D. Leaver, *J. Chem. Soc.* **1966**, 324; d) T. N. Grant, C. L. Benson, F. G. West, *Org. Lett.* **2008**, 10, 3985.
- [8] R. M. Acheson, S. J. Hodgson, R. G. M. Wright, *J. Chem. Soc., Perkin Trans. I* **1976**, 1911.
- [9] a) V. Boekelheide, W. G. Gall, *J. Am. Chem. Soc.* **1954**, 76, 1832; T. Miyadera, E. Ohki, I. Iwai, *Chem. Pharm. Bull.* **1964**, 12, 1344; c) T. Miyadera, Y. Kishida, *Tet. Lett.* **1969**, 25, 397; d) G. G. Abbot, D. Leaver, K. C. Mathur, *J. Chem. Res.* **1978**, 224.
- [10] a) F. Kakiuchi, S. Murai, *Acc. Chem. Res.* **2002**, 35, 826; b) V. Ritleng, C. Sirling, M. Pfeffer, *Chem. Rev.* **2002**, 102, 1731; c) Y. J. Park, J. -W. Park, C. -H. Jun, *Acc. Chem. Res.* **2008**, 41, 222; d) D. A. Colby, R. G. Bergman, J. A. Ellman, *Chem. Rev.* **2010**, 110, 624; e) T. W. Lyons, M. S. Sanford, *Chem. Rev.* **2010**, 110, 1147; f) P. B. Arockiam, C. Bruneau, P. H. Dixneuf, *Chem. Rev.* **2012**, 112, 5879.
- [11] a) W. Hermann, *Angew. Chem. Int. Ed.* **2002**, 41, 1290; b) S. Würtz, F. Glorius, *Acc. Chem. Res.* **2008**, 41, 1523; c) J. M. Praetorius, C. M. Crudden, *Dalton Trans.* **2008**, 4079; d) S. Díez-González, N. Marion, S. P. Nolan, *Chem. Rev.* **2009**, 109, 3612.
- [12] a) M. V. Jiménez, J. J. Pérez-Torrente, V. I. Bartolomé, V. Gierz, F. J. Lahoz, L. A. Oro, *Organometallics* **2008**, 27, 224; b) A. Di Giuseppe, R. Castarlenas, J. J. Pérez-Torrente, F. J. Lahoz, V. Polo, L. A. Oro, *Angew. Chem. Int. Ed.* **2011**, 50, 3938; c) L. Palacios, X. Miao, A. Di Giuseppe, S. Pascal, C. Cunchillos, R. Castarlenas, J. J. Pérez-Torrente, F. J. Lahoz, P. H. Dixneuf, L. A. Oro, *Organometallics* **2011**, 30, 5208; d) A. Di Giuseppe, R. Castarlenas, J. J. Pérez-Torrente, M. Crucianelli, V. Polo, R. Sancho, F. J. Lahoz, L. A. Oro, *J. Am. Chem. Soc.* **2012**, 134, 8171; e) G. Lázaro, M. Iglesias, F. J. Fernández-Alvarez, P. J. Sanz-Miguel, J. J. Pérez-Torrente, L. A. Oro, *ChemCatChem*, In press DOI:10.1002/cctc.201200309.
- [13] a) N. Fujii, F. Kakiuchi, N. Chatani, S. Murai, *Chem. Lett.* **1996**, 25, 939; b) Y. -G. Lin, J. -B. Kang, Y. H. Kim, *Chem. Commun.* **1996**, 585; c) N. Fujii, F. Kakiuchi, A. Yamada, N. Chatani, S. Murai, *Chem. Lett.* **1997**, 26, 425; d) Y. -G. Lin, J.-B. Kang, K. Lee, Y. H. Kim, *Heteroatom Chem.* **2002**, 13, 346; e) P. Buskens, D. Giunta, W. Leitner, *Inorg. Chim. Acta* **2004**, 357, 1969.
- [14] a) I. Hasan, F. W. Fowler, *J. Am. Chem. Soc.* **1978**, 100, 6696; b) C. Cao, Y. Li, Y. shi, A. L. Odom, *Chem. Commun.* **2004**, 2002; c) D. A. Colby, R. G. Bergman, J. A. Ellman, *J. Am. Chem. Soc.* **2008**, 130, 3645; d) T. Kobayashi, K. Takeuchi, J. Miwa, H. Tsuchikawa, S. Katsumura, *Chem. Commun.* **2009**, 3363; e) H. Wei, Y. Wang, B. Yue, P. -F. Xu, *Adv. Synth. Catal.* **2010**, 352, 2450; f) K. Tanaka, K. Fukase, S. Katsumura *Synlett* **2011**, 2115; g) S. Duttwyler, C. Lu, A. L. Rheingold, R. G. Bergman, J. A. Ellman, *J. Am. Chem. Soc.* **2012**, 134, 4064.
- [15] a) M. L. Meketa, S. M. Weinreb, Y. Nakao, N. Fusetani, *J. Org. Chem.* **2007**, 72, 4892; b) K. Parthasarathy, M. Jeganmohan, C. -H. Cheng, *Org. Lett.* **2008**, 10, 325; c) K. Kohno, S. Azuma, T. Choshi, J. Nobuhiro, S. Hibino, *Tet. Lett.* **2009**, 50, 590; d) R. M. Martin, R. G. Bergman, J. A. Ellman, *J. Org. Chem.* **2012**, 77, 2501.
- [16] a) H. Wang, Y. Wang, C. Peng, J. Zhang, Q. Zhu, *J. Am. Chem. Soc.* **2010**, 132, 13217; b) S. P. Roche, J. A. Porco Jr., *Angew. Chem. Int. Ed.* **2011**, 50, 4068.
- [17] Although other metal catalysts promote the formation of Z-Z butadienylpyridines, the presence of quinolizine tautomers has not been detected: a) Y. Nakao, K. S. Kanyiva, T. Hiya, *J. Am. Chem. Soc.* **2008**, 130, 2448; b) Y. Kuninobu, Y. Fujii, T. Matsuki, Y. Nishina, K. Takai, *Org. Lett.* **2009**, 11, 2711.
- [18] A pure sample of 2-((1Z,3E)-5-phenylpenta-1,3-dien-1-yl)pyridine in the presence of 5 mol% of **4** gave 33 mol% of the (E,E) isomer after 16 h at 80 °C.
- [19] a) G. Jia, D. W. Meek, G. C. Galluci, *Organometallics* **1990**, 9, 2549; b) R. Castro-Rodrigo, M. A. Esteruelas, S. Fuentes, A. M. López, S. Mozo, E. Oñate, *Organometallics* **2009**, 28, 5941.