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N-Heterocycle-Fused Pentalenes by a Gold-Catalyzed Annulation of Diethynyl-Quinoxalines and -Phenazines

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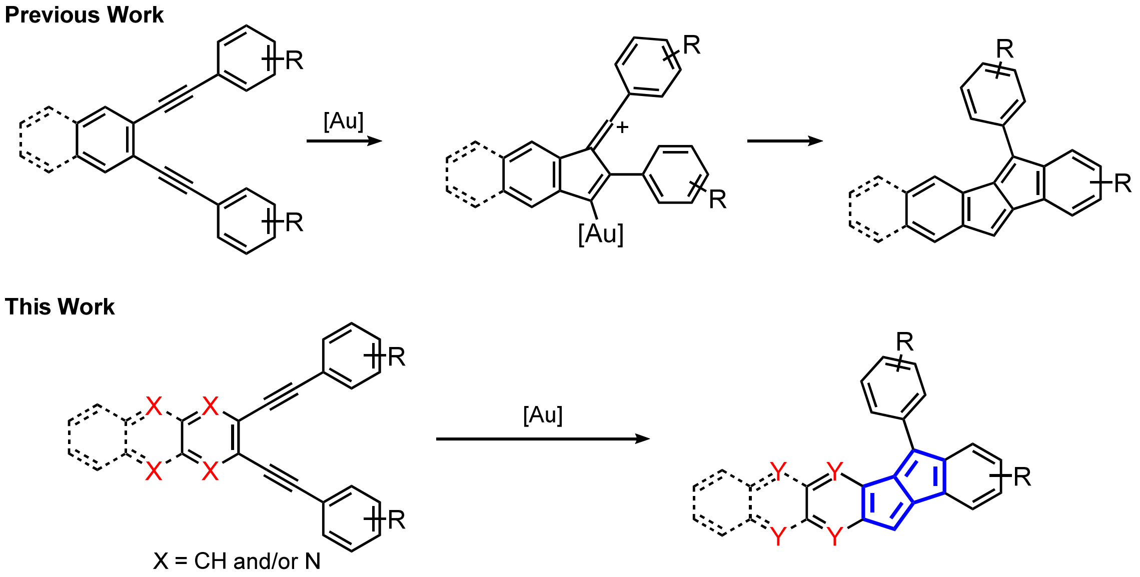
Abstract

The gold-catalyzed annulation of diethynyl N-heterocycles for the synthesis of quinoxaline-/phenazine-based pentalenes, and the study of their optoelectronic properties is described. The inhibition of the gold catalyst by the nitrogen centers in the substrate and the product could be overcome by increasing the reaction temperature to 130 °C, which in gold catalysis usually leads to catalyst decomposition. At 130 °C 6,7-di(arylethynyl)quinoxalines in chlorobenzene at afford the corresponding pentalenes. The annulation of 2,3-di(arylethynyl)quinoxalines requires an even higher temperature under microwave irradiation. The quinoxaline-based pentalenes showed lower LUMO levels compared to the corresponding naphthalene-based pentalenes.

Introduction

Homogeneous gold catalysis underwent a dramatic development during the last two decades.[1] Gold catalysts show a mild carbophilic π Lewis acidity and promote intra-/intermolecular nucleophilic addition reactions onto carbon-carbon multiple bonds. The alkyne itself can not only act as an electrophile but also as a nucleophile. For example gold acetylides can react as nucleophiles with π-activated alkynes, giving rise to vinylidene intermediates; non-terminal alkynes can be reacted with another π-activated alkyne to generate vinyl cation intermediates. Gold-catalyzed domino cyclizations of diynes provide an excellent entry towards polycyclic compounds including complicated and/or highly π-conjugated compounds.[2]

Pentalenes attract much interest due to their antiaromatic property. For the construction of dibenzo[a,e]pentalene structures, various synthetic routes were developed. For instance, a palladium-/rhodium-catalyzed intermolecular annulation of alkynes, a $B(C_6F_5)_3$-mediated cyclization of 1,2-diethynylbenzenes and anionic or radical anionic trans-annulations.[3] The development of synthetic methods towards dibenzo[a,e]pentalenes have been accompanied by studies focusing on their properties and potential application.[4] The optical and electrochemical properties of dibenzo[a,e]pentalenes are typically tuned by functional groups on the 5- and 10-position and on the benzene rings. In addition, heteroaromatic rings fused to the pentalene core have an effect on the properties. A thiophene moiety was shown to push up the HOMO level while an electron deficient pyridine moiety decreases the HOMO and LUMO levels.[5] Dibenzo[a,e]pentalenes show transistor properties especially π-extended derivatives were used as p-type semiconductors;[6] on the other hand, thiophene-substitued dibenzo[a,e]pentalenes, diacenopentalene dicarboximides and 5,10-bis(arylalkynyl)-substituted dibenzo[a,e]pentalenes exhibit lower-lying LUMO levels suitable for n-type semiconductor.[7] From the viewpoint of the lower LUMO energy, the introduction of quinoxaline/phenazine moieties is attractive because they typically push down the LUMO level. However, pyrazine dibenzo[a,e]pentalene derivatives are unknown, the development of a synthesis of the pentalene motif fused to quinoxaline/phenazine ring is highly desirable. Our group recently reported the $(IPr)Au(NCMe)SbF_6$-catalyzed annulation of 1,2-di(arylethynyl)benzenes to produce dibenzo[a,e]pentalene derivatives *via* a vinyl cation as key intermediate.[8] Based on that work, we envisioned a gold-catalyzed convenient synthetic route for quinoxaline-/phenazine-fused pentalenes from di(arylethynyl)quinoxlines and di(aryl)ethynylphenazines as easily available precursors. With regard to N-heterocycles such as pyridine and pyrazine in gold catalysis, the problem is that the coordination of N-heterocycles to the active cationic gold species typically deactivates the catalysts. Our studies on a gold-catalyzed annulation to afford quinoxaline-/phenazine-based pentalene derivatives in high yields are reported in this contribution, accompanied by optical and electronic property measurements of these new products.

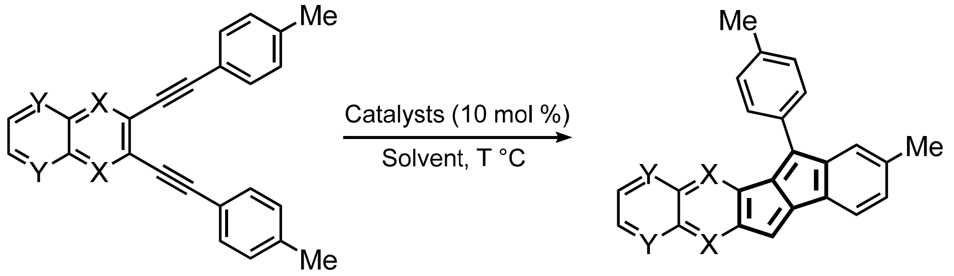


Scheme 1. Design of a synthesis of quinoxaline-/phenazine-based pentalenes.

2,3-Di(*p*-methylphenylethyny)quinoxaline **1aa**, which was synthesized from commercially available chemicals in two steps, was used as a model substrate (Table 1). First, we tested the previous reaction conditions,[8] but the reaction did not proceed at all with (IPr)AuCl/$AgSbF_6$ in benzene at room temperature (Entry 1). Considering a possible deactivation of the gold catalyst by the coordination of a pyrazine moiety, the reaction temperature was examined. At 110 °C in chlorobenzene, the desired pentalene **2aa** was produced in 50% yield while 29% of starting material **1aa** still remained (Entry 2). At 130 °C, diyne **1aa** was completely consumed within 16 h and pentalene **2aa** was obtained in 82% yield (Entry 3). The reaction was accelerated under microwave irradiation but the yield was not significantly improved (Entry 4). In contrast, neither (IPr)AuCl nor $AgSbF_6$ alone promoted the desired reaction, showing that a cationic gold species is necessary for the annulation (Entries 5 and 6).

Next, the synthesis of a pentalene directly fused to a pyrazine moiety was investigated. Under the optimized conditions for **1aa**, the 6,7-di(*p*-methylphenylethyny)quinoxaline **1ba** was completely consumed, but only a trace amount of the desired pentalene **2ba** was detected. Fortunately, pentalene **2ba** was produced in 47% yield at 130 °C for 1 h under microwave irradiation. The rapid and efficient heating by using microwave seems to assist the annulation of the vinyl cation and the aromatic ring. In the case of (IPr*)AuCl, the yield of the pentalene reached 89% (Entry 9).

Table 1. Optimization of the reaction conditions.



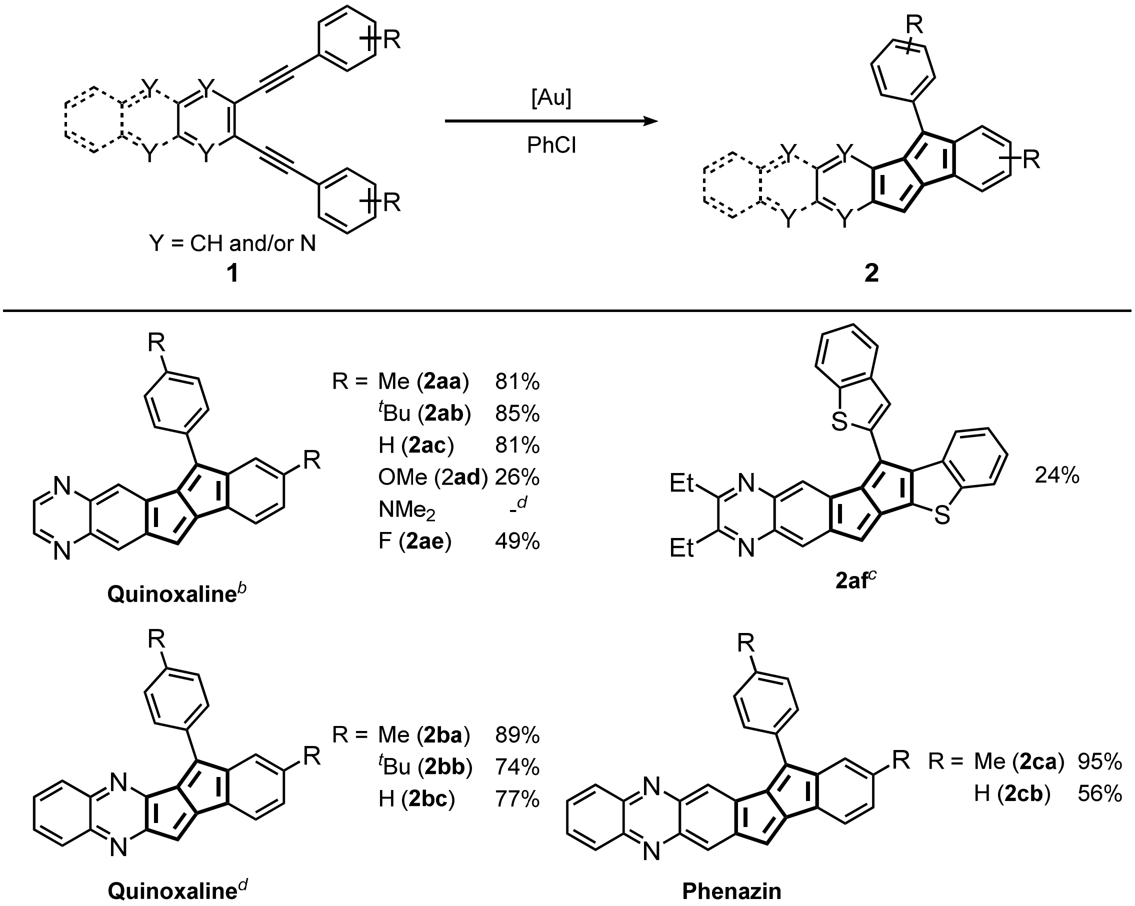
X = CH, Y = **N** (**1aa**)
X = **N**, Y = CH (**1ba**)

2

Entry[a]		Catalysts (mol %)	Solvent	T/°C	Time/h	Yield **2**/%[b]
1	**1aa**	(IPr)AuCl/$AgSbF_6$	Benzene	rt	24	0
2	**1aa**	(IPr)AuCl/$AgSbF_6$	PhCl	110	24	50 (29)[c]
3	**1aa**	(IPr)AuCl/$AgSbF_6$	PhCl	130	16	81
4[d]	**1aa**	(IPr)AuCl/$AgSbF_6$	PhCl	130	1	82
5	**1aa**	(IPr)AuCl	PhCl	130	16	0
6	**1aa**	$AgSbF_6$	PhCl	130	16	trace
7	**1ba**	(IPr)AuCl/$AgSbF_6$	PhCl	130	18	trace (0)[c]
8[d]	**1ba**	(IPr)AuCl/$AgSbF_6$	PhCl	130	1	47 (0)[c]
9[d]	**1ba**	(IPr*)AuCl/$AgSbF_6$	PhCl	130	1	89 (0)[c]

a) **1** (0.05 mmol) in 1.5 mL of the solvent. b) Isolated yield.c) Recovery of **1**. d) Under microwave irradiation.

Next we explored the substrate scope (Scheme 2). The substituents at the aromatic moieties of the 2,3-di(arylethynyl)quinoxaline starting materials **1aa**-**1af** were examined first. The reactions of ^{t}Bu (**1ab**) and H (**1ac**) completed within 16 h at 130 °C giving rise to pentalenes **2ab** and **2ac** in 85% and 81% yields, respectively. A brownish single crystal of **2ac** was obtained and the connectivity was unambiguously confirmed by X-ray structural analysis (Figure 1). For electron donating groups, a MeO-substituted pentalene **2ad** produced in 26% yield, while a Me_2N-substituted diyne only gave a complex mixture. A fluoro-substituted substrate also transferred into the corresponding pentalene **2ae** in moderate yield. The introduction of a benzothiophen ring to the quinoxaline-fused pentalene is attractive because it is expected that the HOMO level of pentalene is pushed up and the HOMO-LUMO energy gap becomes smaller.[9] Therefore the reaction with 2-ethynylbenzothiophene-substituted quinoxaline **1af** was carried out and the corresponding donor-acceptor-substituted pentalene **2af** was successfully obtained in 24% yield. With regard to the 6,7-di(arylethynl)quinoxalines, the annulation of the diynes **1bb** and **1bc** also proceeded at 130 °C under microwave irradiation delivering pentalenes **2ba** and **2bc** directly fused to the pyrazine moiety in high yields. For π-extened pentalenes, the annulation of phenazine-substrates **1ca** and **1cb** were conducted and the corresponding pentalenes **2ca** and **2cb** were produced in 95% and 56% yields, respectively.



a) **1** (0.05 mmol) in 1.5 mL of PhCl. b) (IPr)AuCl/AgSbF$_6$ (10 mol %)) for 16 h at 130 °C. c) (IPr)AuCl/AgSbF$_6$ (10 mol %) for 1 h at 130 °C under microwave irradiation. d) (IPr*)AuCl/AgSbF$_6$ (10 mol %) for 1 h at 130 °C under microwave irradiation. d) A complex mixture.

Scheme 2. The gold-catalyzed annulation of di(arylethynl)quinoxalines and phenazines.

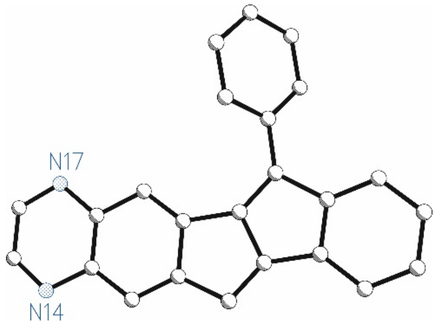
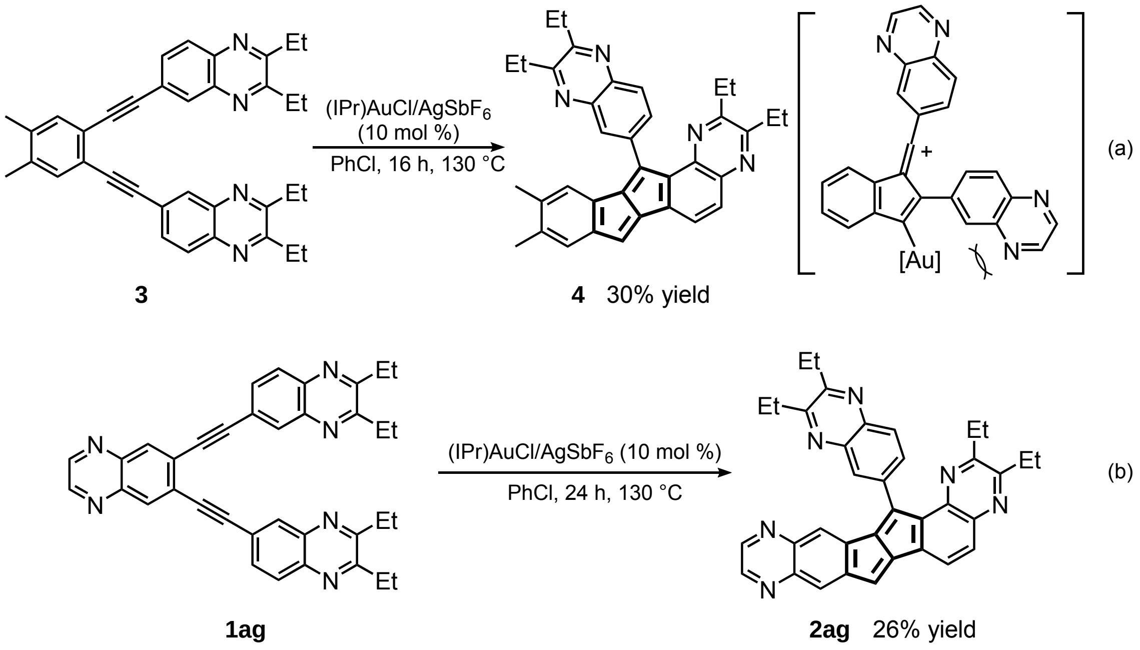


Figure 2. Solid state molecular structure of **2ac.** Hydrogen atoms are omitted for clarity.

We also attempted the reaction of 6-ethynylquinoxaline-substituted benzene **3a** (Scheme 3a). In this case besides the blocking of the catalyst, we wanted to know if the relatively electron-deficient quinoxaline was also able to insert into the intermediate vinyl cation. Indeed, under the optimized reaction conditions the annulation proceeded selectively at the 5-position of the quinoxaline to afford the corresponding pentalene **4a** in 30% yield. Based on the result with 2-ethynylnaphthalene-substituted benzene **3b** to selectively give the pentalene **4b** in high yield (Scheme S1), the selectivity is probably caused by the steric repulsion of the gold catalyst and the quinoxaline moiety. Inspired by the above result, we applied the optimized conditions to 6-ethynylquinoxaline-substituted quinoxaline **1ag** (Scheme 3b). The diquinoxaline-fused pentalene **2ag** was obtained in 26% yield.



Scheme 3. The reaction of 6-ethynylquinoxaline-substituted benzene **3** (a) and 6-

ethynylquinoxaline-substituted quinoxaline **1ag** (b).

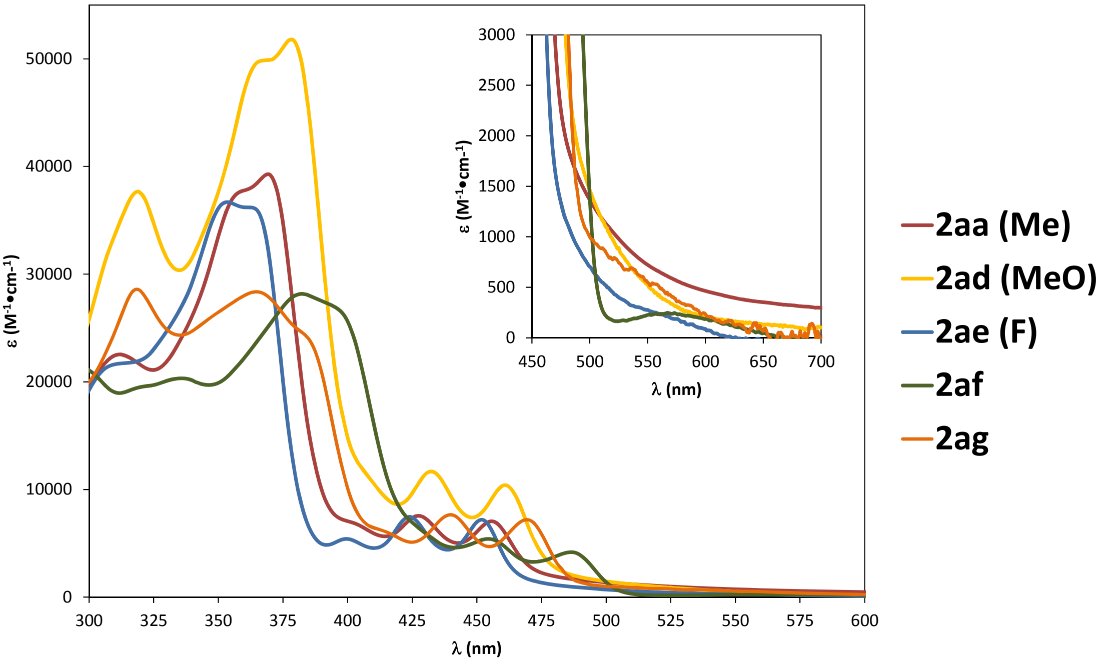


Figure 2. UV absorption of **2aa**, **2ba**, **2ad**, **2ae**, **2af** and **2ag**.

The optical properties of the pentalenes **2aa**, **2ba**, **2ca**, **2ad, 2ae**, **2af**, **2ag**, **4** were measured by UV/Vis absorption spectroscopy (Figure 2 and S1). The absorptions at 428 nm and 456 nm of **2aa** can mainly be attributed to the symmetry-allowed HOMO → LUMO+1 and HOMO-1 → LUMO transitions (Table S2) based on TD-DFT calculations in CH$_2$Cl$_2$. The pentalene **2ba** exhibits the corresponding two peaks at similar wavelengths (λ = 424 and 450 nm) than **2aa**. In contrast, the benzothiophene-fused pentalene **2af** and diquinoxaline-fused pentalene **2ag** shows a significant bathochromic shift of the wavelengths (**2af**; λ = 455 and 487 nm, **2ag**; λ = 440 and 469 nm). Moreover, in the case of pentalen **2af**, the absorption of the symmetry-forbidden HOMO → LUMO transitions is observed at around 567 nm, which is also suggested by TD-DFT calculations. The HOMO and LUMO levels of **2aa**, **2ba**, **2ca**, **2af**, **2ag**, **4** were estimated by cyclic voltammetry in CH$_2$Cl$_2$ and TD-DFT calculations in the gas phase (Table S1). According to cyclic voltammetry, LUMO levels (**2aa**; -3.19 eV, **2ba**; -3.33 eV, **2ca**; -3.26 eV, **2af**; -3.33 eV, **2ag**; -3.26 eV, **4**; -3.15 eV) are lower than in the corresponding 12-phenylbenzo[4,5]pentaleno[1,2-b]naphthalene **2d** (LUMO = -3.01 eV) (Supporting Information),[10] as expected due to the introduction of a pyrazine moiety. The benzothiophene moiety contributed strongly to a smaller

HOMO-LUMO energy gap (E_g) of the pentalene **2af** (**2aa**; E_g = 2.61 eV, **2ba**; E_g = 2.51 eV, **2ca**; E_g = 2.61 eV, **2af**; E_g = 2.21 eV, **2ag**; 2.64 eV, **4**; E_g = 2.41 eV).

In conclusion, we developed the synthesis of quinoxaline-/phenazine-based dibenzo[a,e]pentalenes from the corresponding diynes by gold catalysts. The reactivity of 6,7-di(arylethynyl)quinoxalines and 2,3-di(arylethynyl)quinoxalines are significantly different; the annulation of 6,7-di(arylethynyl)quinoxalines proceeded at high temperature to afford the corresponding pentalenes in good to high yields, but the reaction of 2,3-di(arylethynyl)quinoxalines requires high temperature under microwave irradiation. The quinoxaline-based pentalenes showed lower LUMO levels compared to the corresponding naphthalene-based pentalene. As the poisoning of gold catalysts by such N-heterocyclic substrates is a general problem in gold catalysis, the protocol developed here, which is based on the increased thermal stability of the gold catalysts in the presence of these catalyst poisons, will certainly be very useful for many researchers in the field beyond the synthesis of π-extended N-heterocycle-fused pentalenes for material science reported here.

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