Conformationally Rigid Cyclic Tungsten Bis-Alkyne Complexes Derived from 1,1'-Dialkynylferrocenes

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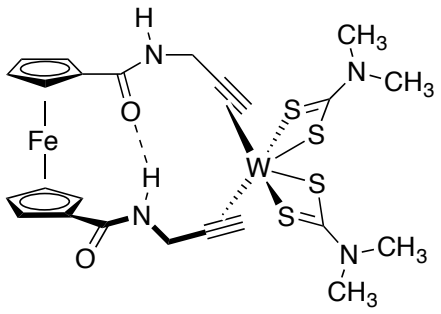
Graphical Abstract:



Abstract:

In exploring the conformational behavior of cyclic tungsten bis-alkyne complexes, two dialkynylamides (**14a** and **14c**) and two dialkynylesters (**14b** and **14d**) derived from 1,1'-ferrocenedicarboxylic acid were prepared. They were subsequently reacted with $W(CO)_3(dmtc)_2$ to yield the desired cyclic tungsten bis-alkyne complexes **8-11**. In the cyclization of **14a** to yield **8** a dimeric macrocyclic complex, **15**, featuring two tungsten bis-alkyne complexes in the ring, also was isolated. The conformational behavior of these complexes was assessed by analysis of the ^{1}H NMR resonances for the alkyne hydrogens, which appear around 11 ppm. The spectra for complexes **10**, **11** and **15** show multiple singlets of varying integrations for these protons, while the spectra for complexes **8** and **9** show only two resonances of equal integration for the alkyne hydrogens. The spectra for **8** and **9** changed very little when examined at higher temperatures, indicating that the solution conformation is robust. A ROESY spectrum was obtained for **8**. It did not show any crosspeaks between the two alkyne hydrogens. The NMR data shows that the alkyne ligands in **10**, **11** and **15** are able to rotate about the tungsten-alkyne bond; these complexes adopted several different solution conformations relating to syn and anti arrangements of the alkyne ligands. In contrast, complexes **8** and **9** adopt only one solution conformation, and the alkyne ligands in these species do not rotate about the tungsten-alkyne bond. The NMR spectra for **8** and **9** also show that these complexes are asymmetric. The ^{1}H NMR spectra for **8** and **9** show that each hydrogen atom has its own unique resonance in the ^{1}H NMR spectrum. There are 8 resonances for the 8 Cp protons, 4 resonances for the methylene protons, 2 resonances for the alkyne

protons, and in the case of **8**, 2 resonances for the NH protons. The two NH protons on complex **8** were found to have widely different chemical shifts. A DMSO titration was performed and it showed that one of the two NH protons in **8** is involved in an intramolecular hydrogen bond. Given that the diester **9** adopts a similar conformation as the diamide **8**, this intramolecular hydrogen bond appears to result from the conformation imposed by cyclization of the ring system. Overall, the data show that the ring system for **8** and **9** provides a unique, rigid, robust, and air stable cyclic molecule where the alkyne ligands are limited to one orientation, presumably the syn orientation. The lack of mobility for the alkyne ligands limits the cyclic molecule to only one solution conformation. Complexes **8** and **9** are the first reported examples of cyclic tungsten bis-alkyne complexes that only adopt a single, robust conformation in solution.

Keywords:

Tungsten, Bis-alkyne, Ferrocene, Constrained, Rigid

Highlights:

- Dialkynes derived from acylation of 1,1'-ferrocenedicarboxylic acid were prepared
- The dialkynes were coordinated to tungsten to generate cyclic bis-alkyne complexes
- Conformational mobility of the metallacycles was probed using NMR experiments

- The two smallest metallacycles adopted a single, rigid, asymmetric conformation
- The two largest metallacycles were conformationally flexible

1. Introduction

Both tungsten and molybdenum possess the ability to coordinate one or more alkyne ligands, and in some cases the resulting complexes are stable in the presence of oxygen. One type of complex that is air stable are the tungsten and molybdenum bis-alkyne dithiocarbamate octahedral complexes. They were investigated in the 1980s, most notably by Templeton and co-workers, who explored the nature of the bonding between the metal and the alkynes.[1] This work with bis-alkyne dithiocarbamate complexes showed that the alkyne ligands are three electron donors to the metal center, assume both syn or anti orientations relative to each other (Figure 1), and that the alkyne rotates freely about the tungsten-alkyne bond.[2]

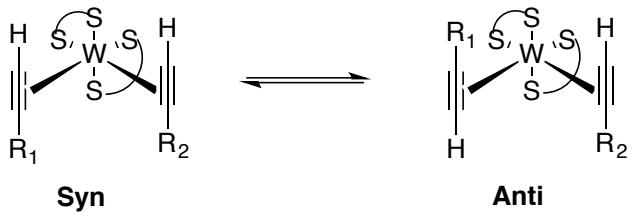
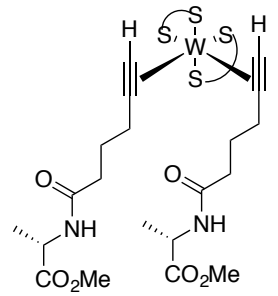


Figure 1. Syn and anti orientations of the alkyne ligands in tungsten bis-alkyne dithiocarbamate complexes. In most cases the alkynes can rotate about the metal-alkyne bond allowing the syn and anti conformers can equilibrate.

In more recent work the ability of tungsten bis-alkyne dithiocarbamate complexes to constrain or order the conformations of alkynylpeptides has been explored. In one set of studies two alkynylamino acids were coordinated to tungsten; for example, complex **1**. It was hypothesized that if intramolecular hydrogen bonds formed between the two alkynylamino acids in the bis-alkyne complex this would limit the alkyne ligands to only the syn orientation. However it was found that the two alkynylamino acids assume both syn and anti orientations, the alkynes freely rotate about their bond with tungsten, and that no hydrogen bonds are formed between the two coordinated amino acids.[3]



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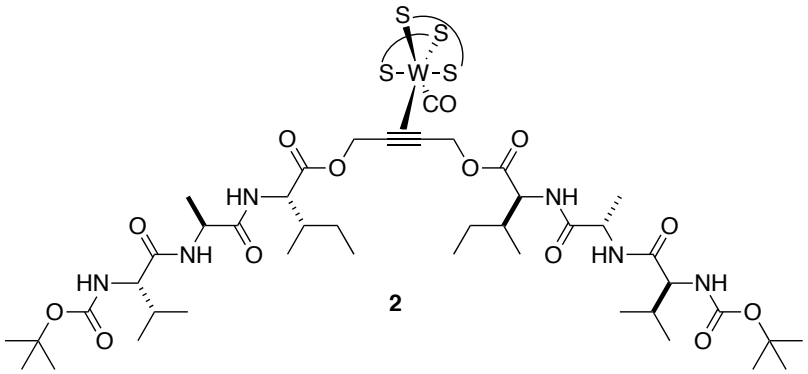

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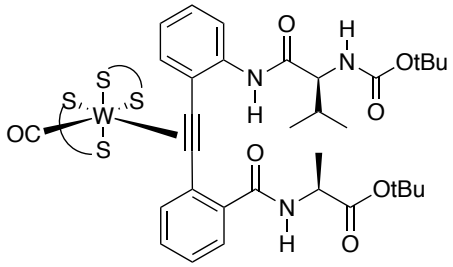

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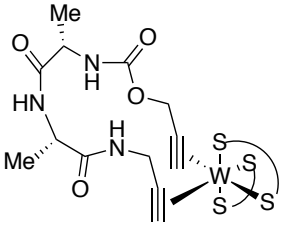

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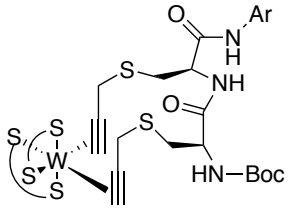

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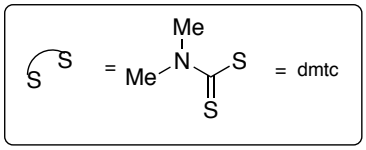


In a subsequent study symmetrical alkynylpeptides in which identical peptides were attached to each end of the alkyne were coordinated to tungsten; for example, the mono-alkyne complex **2**. It was hypothesized that the peptides at either end of the alkyne might hydrogen bond with each other. As with complexes like **1**, the symmetrical alkynylpeptides were observed to freely rotate about the tungsten-alkyne bond. However, no intramolecular hydrogen bonds were formed between the peptides at either end of the alkyne in these mono-alkyne complexes.[4]

In a further study, a peptide, **3**, constrained to a β-sheet conformation by a central diphenylacetylene subunit was coordinated to tungsten; in this case, the intramolecular hydrogen bond and the β-sheet conformation present prior to the addition of tungsten were retained upon coordination, even while the alkyne ligand was able to freely rotate about its bond with the tungsten.[5]

In all of the above cases, the peptide was linked to a single alkyne that was then coordinated to tungsten. In another set of studies, dialkynylpeptides were prepared, where the alkynes were located at both the N- and C-termini of the peptide. One example is complex **4**. These dialkynylpeptides were coordinated to tungsten to yield cyclic tungsten bis-alkyne complexes.[6-7] These were the first cyclic tungsten bis-alkyne complexes ever examined. Although it had been hoped that cyclization would limit these bis-alkyne complexes to the syn orientation, it was found that in all these complexes the alkyne ligands could adopt either syn or anti orientations with respect to the metal, and that in most cases the alkynes are able to equilibrate between the syn and anti orientations. In one case, a dialkyne derived from a single amino acid, the alkyne ligands adopted both syn and anti arrangements, but were unable to equilibrate, presumably due to constraints imposed by the relatively small ring system.[6]

In a follow-up study, dialkynylpeptides, where the two alkynes were located on the amino acid side chains, were coordinated to tungsten to yield a different set of cyclic tungsten bis-alkynylpeptide complexes.[8] One example is complex **5**. As in the previous studies of cyclic tungsten bis-alkynylpeptide complexes, the alkyne ligands adopted both syn and anti orientations with respect to the tungsten center,

and, except for the smallest ring system, showed the ability to equilibrate between the syn and anti orientations. With the smallest ring system examined in this study the alkynes appeared to adopt both syn and anti conformations, but were unable to equilibrate between the different conformations. Again, the likely reason for this behavior is the relatively small ring size, which locks the complex into the orientation resulting from coordination of the second alkyne ligand.

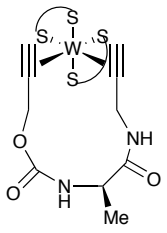
At the outset of the studies examining the cyclic tungsten bis-alkynylpeptide complexes, it had been presumed that cyclization would limit the alkyne ligands to only the syn orientation, but this has not been observed. This then posed a new question: could any cyclic tungsten bis-alkyne complex limit the alkyne ligands to either the syn or anti orientations? To answer this question research in our lab has focused on preparing and examining the conformational behavior of a variety (peptide and non-peptide) cyclic tungsten bis-alkyne complexes. Herein is reported the discovery of a rigid, conformationally constrained ring system that features, in the ring system, both a tungsten bis-alkyne complex and a 1, 1'-disubstituted ferrocene moiety.

2. Results

2.1 Design and Synthesis

Although tungsten bis-alkyne complexes have been known for some time,[1] cyclic tungsten bis-alkyne complexes, made by coordination of both alkynes in a dialkyne with tungsten, have only recently been examined. The first examples of

these species are cyclic tungsten bis-alkynylpeptides, where the two alkynes are appended to a peptide, either at the N- and C-termini, or on the amino acid side chains.[6-8] In most cases cyclization of a linear molecule will limit the conformational mobility of the cyclic species; however, the cyclic tungsten bis-alkynylpeptides studied to date have shown a remarkable degree of conformational flexibility, with the alkyne groups able to adopt both syn and anti arrangements about the tungsten center. In most of these cyclic species the alkynes can equilibrate between the syn and anti conformations. Only when the ring system formed by coordination to tungsten comprised 9-11 atoms is there any sign of conformational constraint. It was found the complexes **6** (a ring system of 11 atoms, where the tungsten-alkyne bond is counted as one bond between the tungsten and the interior alkyne carbon)[6] and **7** (a ring system of 9 atoms)[8] adopted only some of the possible conformations, and **6** and **7** were unable, even upon heating, to equilibrate between the different possible conformations.



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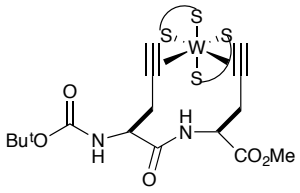

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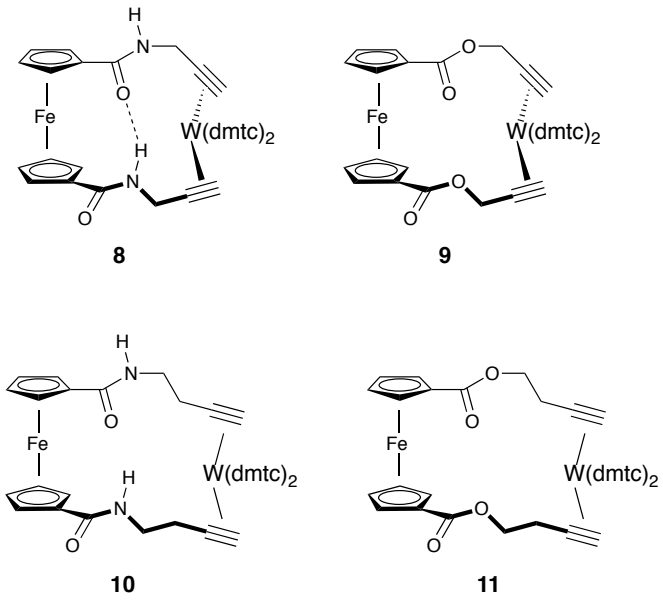
The limited conformational flexibility of **6** and **7** suggested that it might be possible for a cyclic tungsten bis-alkyne complex to be held to either the syn or anti alkyne orientation. As noted, cyclic tungsten bis-alkynes having 9-11 atoms in the ring have been observed, but ring systems having fewer atoms have yet to be seen. Attempts to make these smaller ring systems has only led to the formation of

oligomeric species, suggesting that a ring of only 9 atoms may be the lower limit for a cyclic tungsten bis-alkyne.

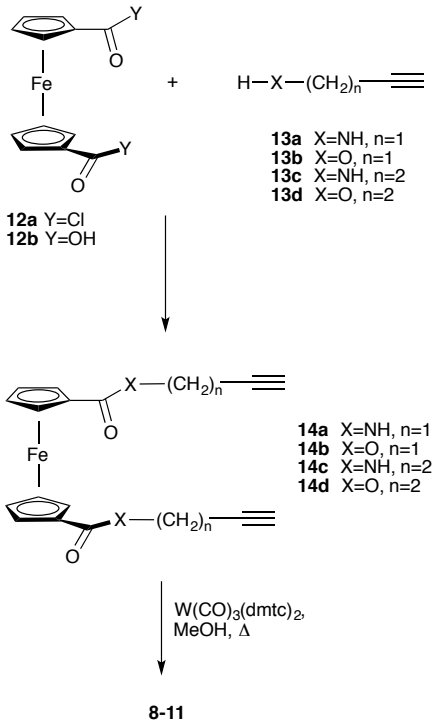
In searching for a constrained cyclic tungsten bis-alkyne complex, we have explored a number of dialkynes. For this study, four new cyclic tungsten bis-alkyne complexes, **8-11**, were prepared and examined. These novel dialkynes were derived from acyl derivatives of 1,1'-ferrocenedicarboxylic acid, **12b**. The cyclic species **8-11** are bimetallic, containing both iron and tungsten centers in the ring system.



The preparation of **8-11** was straightforward, as outlined in Scheme 1. Starting from either the commercially available 1,1'-ferrocenedicarboxylic acid (**12b**) or the readily prepared diacid chloride (**12a**),[10] acylation with the appropriate amine or alcohol (**13a-d**) provided the dialkynes **14a-d**. Subsequent reaction of **14a-d** with $W(CO)_3(dmtc)_2$[9] in dilute, refluxing methanol provided, after chromatographic purification, the desired cyclic tungsten bis-alkyne complexes **8-**

11. Complex **8** was obtained in an optimized yield of 87%. The yields for complexes **9-11** were not optimized and ranged from 22-61%. The purity of the products was established by HPLC. The identity of the products was established by ^{1}H and ^{13}C NMR spectroscopy coupled with mass spectrometry. Given that the target molecules contain both tungsten and iron, their molecular ion peaks in the mass spectrum have a distinctive isotope pattern; the appearance of this molecular ion pattern is strong confirmation for the identity of the complexes.[3] The products were all red-orange solids that, so far, have failed to produce crystals suitable for X-ray analysis.

Scheme 1



*2.2 Analysis of Complex **8***

The first complex examined (**8**) was the one derived from cyclization of dialkynyldiamide **14a**. The ^{1}H NMR spectrum of the dialkyne **14a** (Figure 2A) shows that the dialkynyldiamide is symmetrical, as there is only one resonance for the two amide NH protons, one resonance for the two methylene protons, one resonance for the two alkyne hydrogens, and two resonances for the two different Cp ring protons. The symmetrical nature of **14a** is also evident in the ^{13}C NMR spectrum, which shows only 7 carbon signals.

However, there is a remarkable change in the NMR spectrum after coordination of the tungsten. The ^{1}H NMR spectrum of **8** (Figure 2B) shows 2 separate resonances for the 2 alkyne hydrogens, 2 separate resonances for the 2 amide NH protons, 4 separate resonances for the 4 methylene protons, and 8 separate resonances for the 8 Cp ring protons. The alkyne hydrogens appear around 11 ppm, which has been observed in previously reported tungsten bis-alkyne complexes.[1] The ^{13}C NMR spectrum of **8** shows 24 peaks, one for each carbon in the molecule; here the chemical shifts of the alkyne carbons (around 180 ppm) are consistent with the chemical shift changes seen in previous tungsten bis-alkyne complexes.[1] Coordination of the tungsten and cyclization induce an asymmetry in the molecule, with each hydrogen and carbon in the molecule existing in its own unique environment.

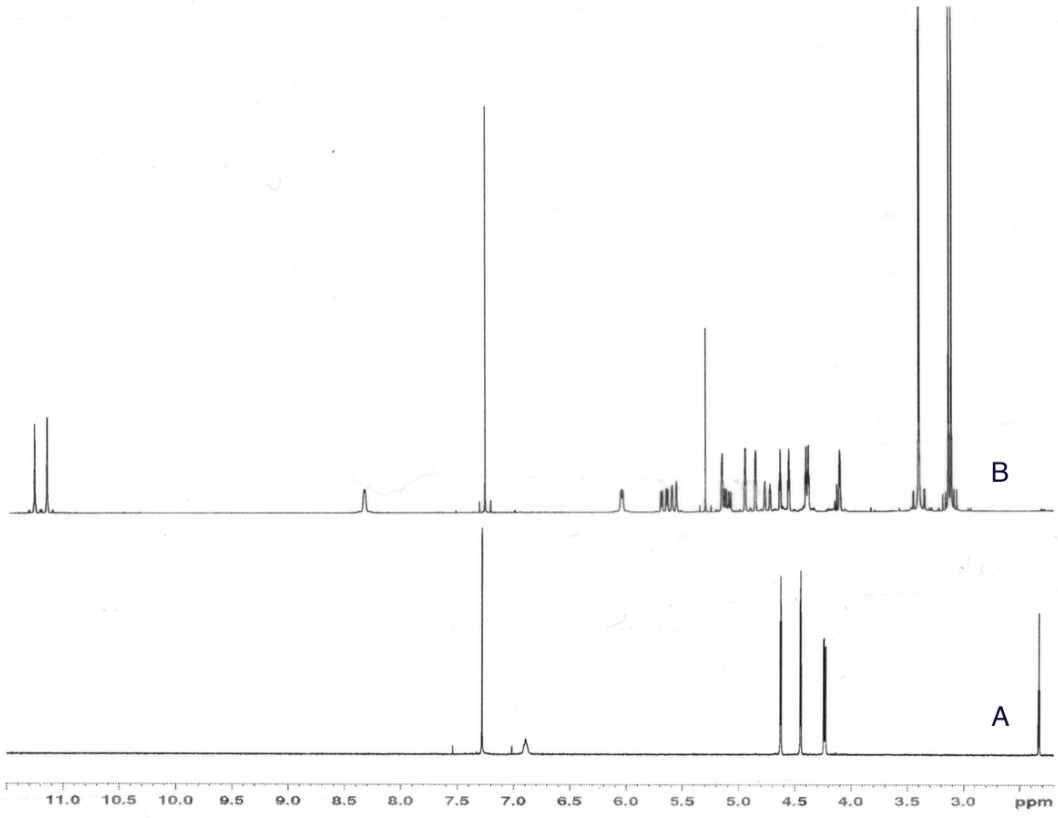


Figure 2. The ^{1}H NMR spectra of **14a** (A) and **8** (B). The spectrum of **14a** is consistent with a symmetrical structure. The spectrum of **8** is consistent an asymmetric structure where each proton is in a unique environment.

The most remarkable aspect of the ^{1}H NMR spectrum of **8** are the chemical shifts of the two amide NH protons, which appear at 8.3 ppm and 6.0 ppm, a difference of 2.3 ppm. This is an extremely large difference in chemical shift for two protons that, on paper, appear to be identical. Large differences in amide NH chemical shifts typically arise when one of the NH protons is involved in an intramolecular hydrogen bond, while the other is not.[11] To determine the hydrogen bonding environments of the two amide NH protons in **8**, this molecule was subjected to a DMSO titration.[13-18] This is an experiment in which the NMR

spectrum of the compound under study is recorded first in $CDCl_3$, a solvent that is not a strong hydrogen bond acceptor. Small amounts of d_6-DMSO, an aggressive hydrogen bond acceptor, are then added to the $CDCl_3$ solution and the NMR spectrum recorded with each new addition of d_6-DMSO. In this way the chemical shift of the NH protons can be followed as a function of the percent DMSO in solution. If an NH proton is exposed to the solvent, addition of the d_6-DMSO will induce a change in the chemical shift of this proton. On the other hand, if an NH proton is involved in an intramolecular hydrogen bond, its chemical shift will be unchanged by the addition of d_6-DMSO. A change in chemical shift indicates a proton exposed to the solvent, while little or no change in chemical shift indicates an NH involved in an intramolecular hydrogen bond.

The DMSO titration data for **8** is plotted in Figure 3. The NH proton located at 8.3 ppm in $CDCl_3$ undergoes very little change in chemical shift as the d_6-DMSO is added, indicating that this proton is involved in an intramolecular bond. Conversely, the NH proton located at 6.0 ppm in $CDCl_3$ undergoes a very large change in chemical shift as the d_6-DMSO is added, indicating that this proton is exposed to the solvent. The DMSO titration results point to one source of asymmetry in **8**, the vastly different hydrogen bonding environments of the two amide NH protons.

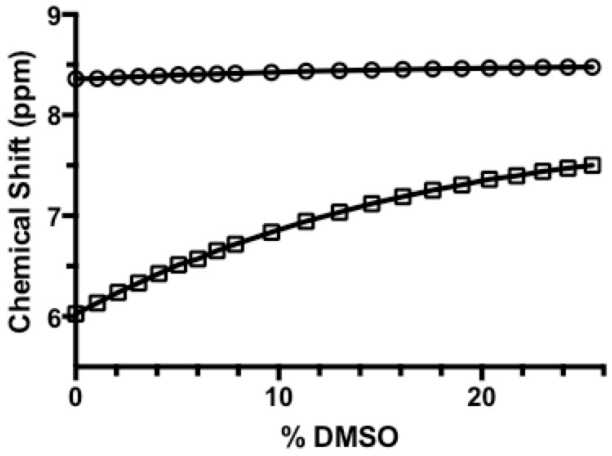


Figure 3. DMSO titration data for the two NH protons resonances in **8**. The NH proton located at 6.0 ppm in $CDCl_3$ shows a large change in chemical shift as the d_6-DMSO is added, indicating that this proton is exposed to the solvent. In contrast, the NH proton located at 8.3 ppm in $CDCl_3$ shows little to no change in chemical shift as the d_6-DMSO is added, indicating that this proton is involved in an intramolecular hydrogen bond.

For the NH proton in **8** that is involved in the intramolecular hydrogen bond, there is only one possible hydrogen bond acceptor, the amide carbonyl emanating from the opposite Cp ring. This intramolecular hydrogen bond is indicated in the structural drawing for **8**.

To further probe the conformational behavior of **8**, its ^1H NMR spectrum was also taken in d_6-DMSO at temperatures ranging from 295K to 325K. In Figure 4 is shown the alkyne hydrogen region (11.5-10.5 ppm) for **8** under these conditions. The two singlets start out relatively close together, and surprisingly, move further apart and broaden, rather than coalescing, as the temperature is increased. This behavior is consistent with **8** having a robust, rigid conformation that is not easily disrupted, even if the temperature is raised.

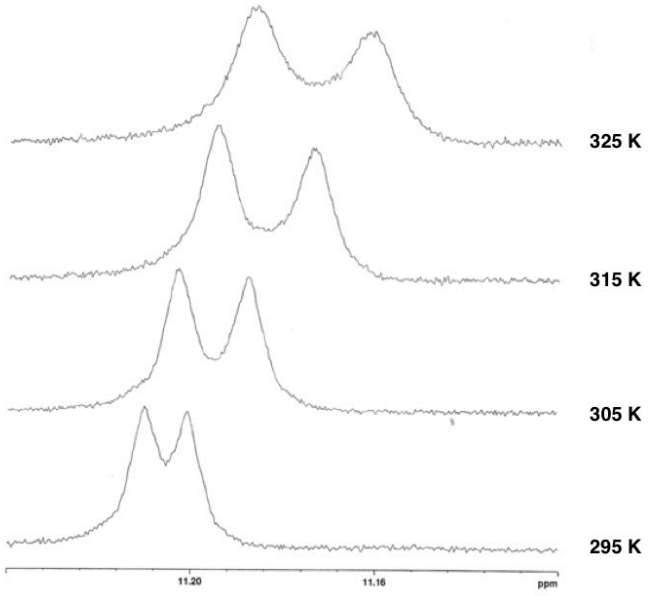


Figure 4. Variable temperature ^{1}H NMR spectra of the alkyne hydrogen region for **8** in d_6-DMSO at temperatures from 295K to 325K. The two singlets for the two alkyne hydrogens remain as two singlets, and their chemical shifts grow apart as the temperature is raised. This indicates that **8** adopts a single conformation, and that this conformation is not lost upon heating.

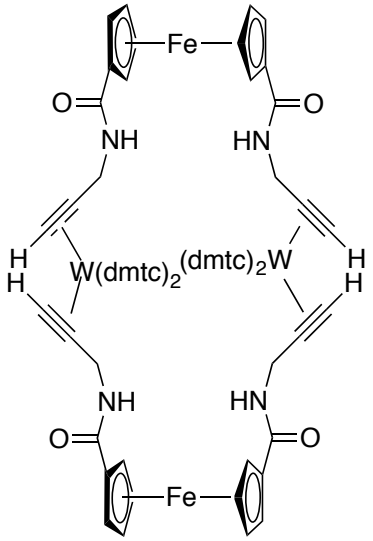
Overall, the data for **8** shows that it adopts a single conformation in solution, that this conformation is asymmetric, that the conformation generates an intramolecular hydrogen bond with only one of the amide NH protons, and that it is stable even at elevated temperatures. This is the first example of a cyclic tungsten bis-alkyne complex that adopts only one solution conformation. All other prior cyclic tungsten bis-alkyne complexes had adopted multiple solution conformations.[6-8]

In an effort to determine whether the two alkyne protons were in close proximity, the ROESY spectrum of **8** in $CDCl_3$ was obtained. The data did not

show a crosspeak between the two alkyne protons, which indicates that these protons are separated in space by at least 4Å. This suggests that the two alkynes are angled away from each other, as shown in the structural drawing for **8**.

*2.3 Analysis of Macrocycle **15***

In the course of purifying **8** a second complex was eluted from the flash chromatography column. Analysis of this complex by ESMS showed that it was **15**, a macrocyclic dimer of **8**. The ^{1}H NMR spectrum of **15** was consistent with this structure. The alkyne hydrogen region of **15** shows a large number of overlapping singlets, indicating that this macrocycle is conformationally flexible. The other resonances in the spectrum also display multiple peaks. The flexible nature of **15** is evidence that the fixed conformation of **8** is determined by its unique ring size.



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*2.4 Analysis of Complex **9***

One question about the rigid nature of **8** is the role of the intramolecular hydrogen bond. Does this hydrogen bond hold **8** to its single solution conformation? To answer this question the diester complex **9**, which does not have any NH protons that can form intramolecular hydrogen bonds, was prepared and examined.

The ^{1}H NMR spectrum of **9** showed that it, like **8**, adopts only one conformation in solution. This can be seen in the alkyne hydrogen region of **9** (Figure 5), near 11 ppm, where there are two singlets integrating to one proton each. Similarly, there are 8 separate resonances for the Cp protons, and 4 resonances for the methylene protons in **9**. That both **8** and **9** adopt only one solution conformation shows that the intramolecular hydrogen bond found in **8** does not dictate the solution conformation of this metallacycle. Rather, the intramolecular hydrogen bond in **8** is formed because the conformation of the ring imposed by cyclization forces the NH and C=O into close proximity.

The ^{1}H NMR spectrum of **9** was also examined in d_6-DMSO at temperatures varying from 295 K to 325 K. At 295 K there are two singlets integrating to one proton each. As the temperature is raised, the two singlets remain separate resonances. This behavior shows that **9**, like **8**, is limited to one solution conformation, and that conformation is stable even at elevated temperatures.

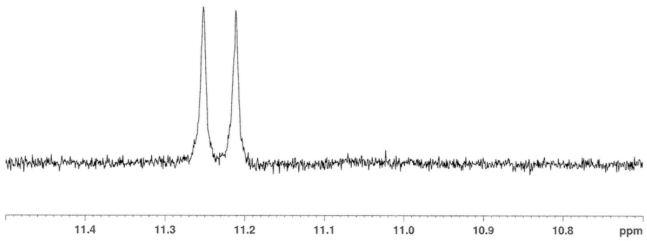

Figure 5. The alkyne hydrogen region for complex **9**. The two singlets each integrate to 1H. The presence of these two singlets indicates that **8** and **9** adopt similar conformations in solution.

*2.5 Analyses of Complexes **10** and **11***

To test the idea that the size of the ring in **8** and **9** is what limits these complexes to one solution conformation, a larger amide complex (**10**) and a larger ester complex (**11**) were examined. Both **10** and **11** possess rings that are two atoms larger than the rings found in **8** and **9**.

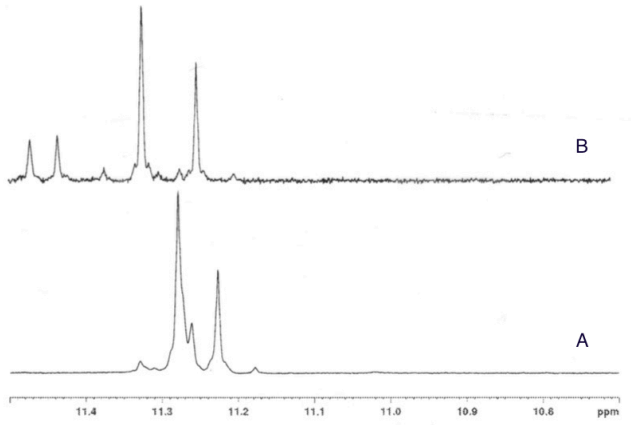

Figure 6. The alkyne hydrogen region of the ^{1}H NMR spectra of **10** (A) and **11** (B). Unlike **8** and **9**, **10** and **11** show multiple singlets having varying integral values in this region. The presence of multiple singlets indicates that **10** and **11** adopt multiple conformations in solution.

Figure 6 shows the alkyne hydrogen region for **10** and **11** in their ^{1}H NMR spectra. For both **10** and **11** there are multiple singlets in this region, and the singlets that can be distinguished vary in their integral values. That there are multiple peaks for the alkyne hydrogens in **10** and **11** indicates that these complexes, which have slightly larger rings than **8** and **9**, adopt several different solution conformations. Complex **11** was examined by variable temperature ^{1}H NMR in d_6-DMSO. The alkyne hydrogens coalesced to one peak at 325 K, indicating that the syn and anti isomers can equilibrate. Overall, the behaviour of **10** and **11** is similar to what has been seen with other cyclic tungsten bis-alkyne complexes, and is consistent with the conclusion that the rigid nature of **8** and **9** is derived from the unique size of their ring systems.

3. Discussion

The results show that complexes **8** and **9**, which have identical ring sizes, adopt a single, rigid conformation in solution, while complexes **10** and **11**, which possess slightly larger rings, are more flexible, with the alkyne ligands likely adopting syn and anti orientations. Complexes **8** and **9** are the first examples of cyclic tungsten bis-alkyne complexes in which the alkyne ligands are held to only one orientation, presumably the syn orientation. Given the nature of the complex, the two alkynes in **8** and **9** must be in relative close proximity.

Organic chemists have employed constrained ring systems to create molecules capable of molecular recognition.[19-21] Constrained ring systems made from organometallic moieties, like the ones described in this paper, offer the possibility of new molecular geometries that might be used for similar purposes. With **8** and **9** it is possible to imagine that groups capable of molecular recognition could be attached to the two terminal alkynes, which the ring system must hold in relative close proximity. Experiments to explore this possibility are underway.

4. Experimental

4.1 General procedures

Propargylamine hydrochloride, propargyl alcohol, 1-amino-3-butyne, 3-butyn-1-ol and anhydrous DMF were purchased from Aldrich Chemical. Diisopropylethylamine, triethylamine, and 1-ethyl-3-[3-dimethylaminopropyl]carbodiimide hydrochloride (EDC), were purchased from Acros Organics. 1, 1'-ferrocenedicarboyxylic acid was purchased from Strem Chemical. Methanol, hexanes, ethyl acetate, methylene chloride, toluene, ethyl ether, hydrochloric acid, sodium hydroxide, magnesium sulfate, and iodine were purchased from Fisher Scientific. Deuterated solvents were purchased from Cambridge Isotope Laboratories, Inc. 1-[Bis(dimethylamino)methylene]-1H-1,2,3-triazolo[4,5-b]pyridinium 3-oxid hexafluorophosphate (HATU) was purchased from Chem Impex International. $W(CO)_3(dmtc)_2$[9] and 1, 1'-ferrocencedicarboxylic acid chloride[10] were prepared as described. Silica gel for flash chromatography was purchased from Silicycle. NMR spectra were obtained on a Bruker Avance III 400 MHz instrument. Electrospray mass spectra were obtained on a LCQ APCI/Electrospray LC MS-MS. Samples for mass spectral analysis were dissolved in MeOH (approximately 1 mg/mL) in borosilicate glass test tubes. Theoretical mass spectral isotope patterns were calculated using the online isotope pattern calculator provided on the internet by the Swiss Federal Institute of Aquatic Science and Technology (Eawag).[11] HPLC analyses were performed on a Hitachi Elite LaChrom HPLC system equipped with L-2400 detector, an L-2200 autosampler and an L-2130 pump. Each run was monitored at 300 nm, which is the wavelength of maximum absorbance for the monoalkyne complexes. A Vydac Protein and Peptide C18 250 x 4.6 mm column was used as the stationary phase.

The mobile phase involved a linear gradient program using two solvents, 0.1% trifluoroacetic acid and acetonitrile. The gradient program started at a 20:80 mixture of acetonitrile and trifluoroacetic acid and changed to 100% acetonitrile over the course of 12 min. The solvent was then held at 100% acetonitrile for an additional 2 min.

*4.2 Preparation of Dialkyne **14a***

To a solution of 101 mg (0.325 mmol, 1.0 equiv.) of diacid **12b** in 50 mL CH_2Cl_2 was added 0.072 g (0.79 mmol, 2.5 equiv.) of propargylamine hydrochloride followed by 0.50 mL (3.6 mmol, 11 equiv.) of triethylamine. After stirring at 23^{o}C for 18 h the solvents were evaporated, the residue was redissolved in 50 mL EtOAc, and the organic layer was washed 3 x 25 mL 1M HCl, 3 x 25 mL 1M NaOH and 1 x 25 mL brine. The organic layer was dried ($MgSO_4$), filtered and evaporated to yield 96 mg (84%) of crude **14a**, which was purified by flash chromatography (1:1 EtOAc/hexanes) to provide 79 mg (70%) of pure **14a**: TLC (EtOAc), R_f 0.39; HPLC, R_t 6.00 min; ^{1}H NMR (400 MHz, $CDCl_3$): 6.89 (2H, t, J = 4.0 Hz), 4.61 (4H, t, J = 1.9 Hz), 4.43 (4H, t, J = 1.9 Hz), 4.21 (4H, dd, J = 5.7, 2.5 Hz), 2.31 (2H, t, J = 2.5 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): 170.3, 80.3, 77.2, 71.4, 71.3, 70.8, 38.6; ESMS, M + Na ion pattern calculated for $C_{18}H_{16}N_2O_2FeNa$: 369 (6.3), 370 (1.2), 371 (100), 372 (22.9), 373 (3.1); found 369 (7.1), 370 (1.5), 371 (100), 372 (21.5), 373 (1.8).

*4.3 Preparation of Complexes **8** and **15***

To a refluxing solution of 40 mg (0.11 mmol, 1.0 equiv.) of **14a** in 115 mL of degassed MeOH under N_2 was added dropwise over 5 min via an addition funnel, a solution of 59 mg (0.12 mmol, 1.1 equiv) of $W(CO)_3(dmtc)_2$ in 5 mL of degassed CH_2Cl_2. After 5 min the solution turned dark green and after another 2.5 h the solution was lemon yellow. The solution was cooled to 23°C and the solvents were evaporated to yield a crude orange solid. Flash chromatography (EtOAc) provided 74 mg (87%) of pure **8** as an orange solid: TLC (EtOAc), R_f 0.39; HPLC, R_t 8.97 min; ^{1}H NMR (400 MHz, $CDCl_3$): 11.28 (1H, s), 11.17 (1H, s), 8.35 (1H, d, J = 4.7 Hz), 6.01 (1H, d, J = 6.2 Hz), 5.68 (1H, ddd, J = 18.0, 5.8, 1.2 Hz), 5.59 (1H, ddd, J = 15.9, 2.5, 0.7 Hz), 5.16 (1H, td, J = 2.6, 1.2 Hz), 5.11 (1H, ddd, J = 15.9, 6.8, 1.3 Hz), 4.95 (1H, td, J = 2.6, 1.4 Hz), 4.86 (1H, dt, J = 2.6, 1.4 Hz), 4.75 (1H, ddd, J = 18.5, 2.7, 1.4 Hz), 4.64 ((1H, ddd, J = 2.8, 2.6, 1.4 Hz), 4.56 (1H, ddd, J = 2.8, 2.6, 1.4 Hz), 4.41 (1H, ddd, J = 2.8, 2.6, 1.2 Hz), 4.39 (1H, ddd, J = 2.8, 2.6, 1.2 Hz), 4.09 (1H, td, J = 2.6, 1.2 Hz), 3.40 (3H, s), 3.39 (3H, s), 3.13 (3H, s), 3.11 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): 208.3, 207.4, 186.8, 183.1, 181.3, 179.0, 170.4, 170.0, 76.8, 76.2, 72.1, 72.0, 71.8, 71.4, 71.1, 70.9, 70.6, 70.5, 70.2, 48.6, 44.3, 39.9, 39.5, 39.4, 38.8; ESMS, M + Na ion pattern calculated for $C_{24}H_{28}N_4O_2S_4FeWNa$: 791 (4.1), 792 (3.3), 793 (66.0), 794 (54.4), 795 (100), 796 (36.3), 797 (85.8), 798 (27.5), 799 (17.6), 800 (4.8); found 791 (6.8), 792 (7.0),

793 (67.5), 794 (55.5), 795 (100), 796 (38.0), 797 (90.5), 798 (25.0), 799 (14.8), 800 (3.0).

The solvent in the column was changed to 9:1 EtOAc/MeOH, and 6 mg (7%) of an additional product, the dimer **15**, was also obtained: TLC (9:1 EtOAc/MeOH), R_f 0.18; ^{1}H NMR (400 MHz, $CDCl_3$): 11.3-10.9 (4H, ms), 8.2-6.5 (4H, m), 5.5-4.0 (24H, m), 3.5-3.0 (32H, ms); ESMS, M + Na ion pattern calculated for $C_{48}H_{56}N_8O_4S_8Fe_2W_2Na$: 1561 (2.3), 1562 (3.6), 1563 (23.0), 1564 (33.9), 1565 (70.7), 1566 (68.1), 1567 (100), 1568 (77.5), 1569 (86.2), 1570 (50.7), 1571 (44.7), 1572 (22.6), 1573 (13.4), 1574 (5.5), 1575 (2.2); found 1561 (3.0), 1562 (5.1), 1563 (22.8), 1564 (34.8), 1565 (78.1), 1566 (69.0), 1567 (100), 1568 (84.9), 1569 (83.7), 1570 (56.7), 1571 (51.1), 1572 (24.3), 1573 (15.9), 1574 (6.1), 1575 (4.1).

*4.4 Preparation of Dialkyne **14b***

To a solution of 200 mg (0.730 mmol, 1.0 equiv.) of diacid chloride **12a** in 2.0 mL DMF was added 1.17 g (3.07 mmol, 4.2 equiv.) of HATU and another 1.0 mL DMF. The resulting solution stirred for 10 min. Next, 425 mL (7.37 mmol, 10 equiv.) of propargylalcohol followed by 1.0 mL diisopropylethylamine (5.7 mmol, 8.0 equiv.) and 1.0 mL DMF were added. After stirring for 18 h the reaction mixture was poured into 50 mL ethyl acetate and washed 3 x 25 mL 1M HCl, 3 x

25 mL 1M NaOH and 1 x 25 mL brine. The organic layer was dried ($MgSO_4$), filtered and evaporated to yield crude **14b**, which was purified by flash chromatography (1:3 EtOAc/hexanes) to provide 143 mg (56 %) of pure **14b**: TLC (1:3 EtOAc/hexanes), R_f 0.33; HPLC, R_t 10.3 min; ^{1}H NMR (400 MHz, $CDCl_3$): 4.91 (4H, dd, J=2.4, 1.9 Hz), 4.85 (4H, d, J=1.9 Hz), 4.50 (4H, dd, J=2.4, 1.9 Hz), 2.53 (2H, t, J = 2.4 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): 169.8, 78.3, 74.8, 73.3, 71.9, 71.6, 51.9; ESMS, M + Na ion pattern calculated for $C_{18}H_{14}O_4FeNa$: 371 (6.3), 372 (1.2), 373 (100), 374 (22.2), 375 (3.4); found 371 (5.5), 372 (1.0), 373 (100), 374 (19.5), 375 (2.1). HRMS, M + H calculated for $C_{18}H_{15}O_4Fe$: 351.0320. Found: 351.0323.

*4.5 Preparation of Complex **9***

To a refluxing solution of 40 mg (0.114 mmol, 1.0 equiv.) of **14b** in 114 mL degassed MeOH under N_2 was added, dropwise over 20 min via an addition funnel, a solution of 57.8 mg (0.114 mmol) of $W(CO)_3(dmtc)_2$ in 30 mL degassed CH_2Cl_2. After heating at reflux for 2.5 h the solution had turned a bright, golden yellow. The solution was cooled to 23^{o}C and the solvents evaporated to yield 143 mg of crude product. Flash chromatography (1:1 hexane:EtOAc, followed by EtOAc) was used to obtain 26 mg (33 %) of pure **9** as an orange solid: TLC (1:3 EtOAc/hexanes), R_f 0.47; HPLC, R_t 12.2 min; ^{1}H NMR (400 MHz, $CDCl_3$): 11.23 (1H, s), 11.19 (1H, s), 5.97 (1H, dd, J =16.6, 1.2 Hz), 5.95 (1H, dd, J = 13.7, 0.9 Hz), 5.86 (1H, dd, J = 13.7, 1.2 Hz), 5.82 (1H, dd, J =16.6, 1.3 Hz), 5.82 (1H, td,

J=2.6, 1.2 Hz), 5.00 (1H, td, J=2.5, 1.2 Hz), 4.85 (1H, td, J=2.6, 1.3 Hz), 4.63 (1H, dt, J=2.6, 1.3 Hz), 4.57 (1H, dt, J=2.6, 1.3 Hz), 4.47-4.41 (3H, m), 3.42 (3H, s), 3.40 (3H, s), 3.15 (3H, s), 3.11 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): 209.2, 209.1, 187.2, 183.8, 183.3, 176.0, 171.6, 171.4, 73.8, 73.5, 73.2, 72.7, 72.1 (2 overlapping peaks), 72.0 (2 overlapping peaks), 71.8, 71.2, 71.1, 65.1, 39.6, 39.4, 39.0, 38.8; ESMS, M + Na ion pattern calculated for $C_{24}H_{26}N_2O_4S_4FeWNa$: 793 (4.1), 794 (3.3), 795 (66.2), 796 (54.5), 797 (100), 798 (35.9), 799 (74.9), 800 (23.3), 801 (14.6), 802 (3.7), 803 (1.2); found 793 (7.7), 794 (7.0), 795 (69.8), 796 (55.7), 797 (100), 798 (35.1), 799 (83.1), 800 (30.2), 801 (18.1), 802 (5.4), 803 (4.0).

*4.6 Preparation of Dialkyne **14c***

To a solution of 500 mg (1.82 mmol, 1.0 equiv.) of the diacid **12b** in 3 mL DMF was added 0.374 mL (4.56 mmol, 2.5 equiv.) of 1-amino-3-butyne, followed by 665 mg (3.46 mmol, 1.9 equiv.) of EDC. The resulting solution stirred at 23^{o}C for 18 h, after which it was diluted with 40 mL CH_2Cl_2. The organic layer was washed 3 x 25 mL 1M HCl, 3 x 25 mL 1M NaOH and 1 x 25 mL brine. The organic layer was dried ($MgSO_4$), filtered and evaporated to yield 397 mg (58 %) of pure **14c**: TLC (2:1 EtOAc/hexanes), R_f 0.38; HPLC, R_t 6.97 min; ^{1}H NMR (400 MHz, $CDCl_3$): 6.92 (2H, t, J=5.4 Hz), 4.56 (4H, dd, J=2.1, 1.9 Hz), 4.40 (4H, dd, J=2.1, 1.9 Hz), 3.57 (4H, q, J=6.4 Hz), 2.58 (4H, dt, J=6.4, 2.6 Hz), 2.06 (2H, t, J=2.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) 170.5, 81.9, 78.2, 71.2, 70.9, 70.0, 38.4,

19.5; ESMS, M + Na ion pattern calculated for $C_{20}H_{20}N_2O_2FeNa$: 397 (6.3), 398 (1.2), 399 (100), 400 (22.9), 401 (3.1); found 397 (7.6), 398 (5.2), 399 (100), 400 (21.3), 401 (2.3).

*4.7 Preparation of Complex **10***

To a refluxing solution of 40 mg (0.106 mmol, 1.0 equiv.) of **14c** in 110 mL of degassed methanol under N_2 was added dropwise over five minutes via an addition funnel, a solution of 54 mg (0.106 mmol, 1.0 equiv) of $W(CO)_3(dmtc)_2$ in 5 mL of degassed CH_2Cl_2. After five minutes the solution turned dark green and after another 2 h the solution was lemon yellow. The heat was removed to let solution cool to 23^oC and the solvents were evaporated. Flash chromatography (EtOAc) was used to obtain 52 mg (61%) of pure **10** as an orange solid: TLC (EtOAc), R_f 0.38; HPLC, R_t 9.34 min; ^1H NMR (400 MHz, $CDCl_3$): 11.6-11.1 (2H, ms), 5.1-3.8 (14H, m), 3.7-3.0 (16H, m); ESMS, M + Na ion pattern calculated for $C_{26}H_{32}N_4O_2S_4FeWNa$: 819 (4.1), 820 (3.4), 821 (65.4), 822 (55.7), 823 (100), 824 (38.1), 825 (74.7), 826 (25.0), 827 (14.8), 828 (4.0); found 819 (8.7), 820 (10.7), 821 (61.4), 822 (64.9), 823 (100), 824 (49.0), 825 (64.4), 826 (22.9), 827 (13.8), 828 (4.6)

*4.8 Preparation of Dialkyne **14d***

To a solution of 240 mg (0.772 mmol, 1.0 equiv.) of diacid chloride **12a** in 5 mL CH_2Cl_2 was added 350 mL (4.62 mmol, 6.0 equiv.) of 3-butyn-1-ol followed by 1.2 mL (8.6 mmol, 11 equiv.) of triethylamine. After stirring at 23°C for 18 h the solvents were evaporated, the residue was redissolved in 30 mL EtOAc, and the organic layer was washed 3 x 20 mL 1M HCl, 3 x 20 mL saturated $NaHCO_3$ and 1 x 25 mL brine. The organic layer was dried ($MgSO_4$), filtered and evaporated to yield 150 mg of crude **14d**, which was purified by flash chromatography (15:85 EtOAc/hexanes) to provide 93 mg (32 %) of pure **14d**: TLC (1:3 EtOAc/hexanes), R_f 0.47; HPLC, R_t 10.82 min; ^{1}H NMR (400 MHz, $CDCl_3$): 4.87 (4H, dd, J = 2.1, 1.9 Hz), 4.45 (4H, dd, J = 2.1, 1.9 Hz), 4.34 (4H, t, J = 6.7 Hz), 2.66 (4H, dt, J = 6.7, 2.6 Hz), 2.06 (2H, t, J = 2.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) 170.2, 80.4, 73.1, 72.4, 71.7, 69.9, 62.2, 19.2; ESMS, M + Na ion pattern calculated for $C_{20}H_{18}O_4FeNa$: 399 (6.3), 400 (1.4), 401 (100), 402 (24.4), 403 (3.9); found 399 (8.4), 400 (5.3), 401 (100), 402 (33.7), 403 (8.7).

*4.9 Preparation of Complex **11***

To a refluxing solution of 34 mg (0.090 mmol, 1.0 equiv) of **14d** in 90 mL degassed MeOH under N_2 was added dropwise over 20 min via an addition funnel a solution of 46 mg (0.090 mmol, 1.0 equiv) of $W(CO)_3(dmtc)_2$ dissolved in 5 mL

degassed CH_2Cl_2. After 16 h the solvents were evaporated to yield a brown solid. Flash chromatography (2:1 hexanes:EtOAc) was used to obtain 16 mg (22 %) of pure **11**: TLC (1:1 EtOAc/hexanes), R_f 0.50; HPLC, R_t 12.7 min; ^{1}H NMR (400 MHz, $CDCl_3$): 11.4-11.1 (2H, ms), 5.0-3.5 (16H, m), 3.5-3.0 (16H, ms); ESMS, M + Na ion pattern calculated for $C_{26}H_{30}N_2O_4S_4FeWNa$: 821 (4.1), 822 (3.3), 823 (65.5), 824 (55.3), 825 (100), 826 (37.7), 827 (74.8), 828 (24.6), 829 (14.9), 830 (4.0); found 821 (5.6), 822 (7.4), 823 (69.0), 824 (55.7), 825 (100), 826 (36.1), 827 (78.5), 828 (22.2), 829 (14.2), 830 (4.0).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at ……

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