Angewandte Essays

Attacking N_2

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New Approaches to Functionalizing Metal-Coordinated N_2**

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alkynes · click chemistry · high-energy molecules · nitrogen fixation · thermodynamics

Catalytic conversion of N_2 into value-added products is the challenge of attack on a refractory molecule. We develop herein ideas, using product thermodynamics, to gauge which derivatizing reagents hold special promise. Since N_2 is an especially stable molecule, it must be paired with an endothermic molecule to make the overall reaction exothermic. A number of unusual nitrogen heterocycle products are targeted in this way, based on derivatization with alkynes, with alkenes, or with allenes. Since the late transition elements (M) have M–heteroatom bonds which are readily subject to hydrogenolysis, aldehydes and ketones are also identified as potential traps. It is proposed that advantages arise from targeting organonitrogen products retaining an N–N bond, including double bonds. While fundamentally thermodynamic in character, such advantages may also translate into lowering of barriers in elementary processes, hence to improved rates. The ideas are general in nature, and thus invite testing among newly formed N_2 complexes of any metal.

A current goal of global importance is the conversion of diatomic nitrogen to value-added organonitrogen compounds. While improved,[1–13] less-energy intensive hydrogenation of coordinated N_2 ("nitrogen fixation", forming NH_3) is an attractive, if challenging goal owing to the importance of agricultural fertilizers, there are broader goals for organonitrogen compounds, including other fertilizers (e.g., urea), but also compounds useful in pharmaceutical and electronic materials applications.[14] The purpose of this Essay is to show that, in the absence of available experimental thermochemical data, it can be useful to go "prospecting", using density functional theory (DFT) calculations, for organic molecules with which to "derivatize" N_2. Our goal is to design new reactions for the conversion of N_2 into chemicals based on a thermodynamic concept: high energy reagents serve as fuel to convert the very stable, refractory molecule N_2.

The challenge of hydrogenation of coordinated, hopefully electron rich N_2 to N_xH_y compounds may be due in part to the fact that diatomic H_2 is not very electrophilic. Indeed, earliest efforts[2,15–20] in this quest have involved first protons (targeting NH_3) and carbon electrophile reagents (alkyl halides, etc.). A solution to this problem is proton-coupled electron transfer (PCET), which is the alternating delivery of electrons and protons, instead of H_2.[21–29] This approach however creates the challenge of preventing the protons from combining with the electrons to simply generate H_2 and Schrock and Yandulov have nicely solved this problem[29] by delivering the electrons with $[Cp^*_2Cr]$ ($Cp^* = \eta\text{-}C_5Me_5$) and using a weak and highly sterically hindered acid: an anilinium cation. From this success, H^+ clearly has a demonstrated ability to react with one metal nitride in the Schrock PCET reduction of N_2 to ammonia on molybdenum. However, this reaction is highly species-dependent, since another molybdenum-bound terminal nitride is found to be less Brønsted basic than even a neighboring coordinated tertiary phosphine.[22]

It is a truism of catalysis that one must only attempt reactions that are exergonic ($\Delta G° < 0$), hence thermodynamically favorable to permit high conversion into product. When chosen well, this thermodynamic preference is what makes it possible to convert alkynes into arenes … even with beach sand![30] The thermodynamics makes alkyne polymerizations sometimes dangerously explosive whereas olefin polymerizations are harder to accomplish, and less exergonic, since the entropy change is unfavorable. Likewise there are many cyclizations of diynes and enynes, but fewer with dienes. The Huisgen "click reaction" cyclizing alkyne and azide to a triazole is easily accomplished, since it is hugely exergonic. On the negative side, hydrogenation of N_2 to ammonia is not very exothermic, so, coupled with an unfavorable $\Delta S°$, this approach to ammonia production is thermodynamically challenging. The limited quantity of experimental organonitrogen thermodynamic data is a hindrance to establishing what reactions are exergonic; some body of data exists,[31] but less than desired. With the broadening availability of density functional methods, which give chemically useful accuracy even for larger molecules and those outside the experimental database, this situation is improved. We apply this approach herein to an important problem, that of choosing reagents

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which might convert N_2 into useful, value-added products beyond the production of NH_3. One benefit of this focus on rational choice of derivatizing reagents is that the conclusions are catalyst independent, hence broadly applicable. The second, and very challenging aspect of the problem is catalyst design, and we touch on only a few aspects of that herein, but success in N_2 conversion is critically dependent on choice of the partner reagent. A systematic approach to that search is the subject of this contribution.

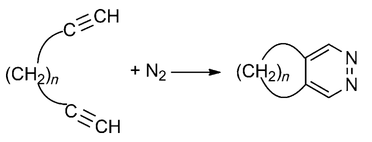
Pursuing this N_2 functionalizing goal beyond protons, the groups of both Fryzuk[32–34] and Chirik[35,36] have already observed that there are attractive products to be derived from molecular nitrogen, other than ammonia. This observation translates into making N_2 especially nucleophilic by coordination to highly reduced early transition elements (Zr, Ta …), then using electrophilic derivatizing reagents E to form N–E bonds. "Derivatizing reagents" are thus attractive if they have at least some trace of electrophilic character. Among Lewis acids, three coordinate B–H, Al–H, and unsaturated Zr–H reagents have shown some promise when the N_2 is strongly reduced by early-transition-metal centers, but the "azaphilic"[37] character of these electropositive metals makes such derivatizations stoichiometric, leaving reduced nitrogen products coordinated firmly to the metal center. Silanes, R_3Si–H have sufficient Lewis acidity that they also be successfully used as derivatizing reagents, and the resulting Si–N bond provides an additional thermodynamic boost to the reactions.[34,38,39] A significant advance was the observation that the carbon in CO_2 and related cumulenes is sufficiently electrophilic for N–C bond formation to occur, to make products containing both O–M and N–M bonds. Finally even CO[35] can "capture" nucleophilic N_2.

The present aim is directed towards broadening the range[40,41] of derivatizing reagents, to increase the chances of success, and the range of possible products, in N_2 utilization.

What Organic Reagents Lead to Thermodynamically Viable Products?

Our challenge herein is to envision some carbonaceous reagents that appear mechanistically viable to be attracted to nucleophilic N_2 nitrogen, and whose final organonitrogen product is thermodynamically downhill. We will be guided in this study by enthalpy changes. All condensation reactions envisioned herein suffer an entropy penalty of approximately 11 kcal mol^{-1} at 298 K (dominated by loss of translational entropy and hence species independent), so this is both intrinsic to the challenge and subject to minimization by elevated pressures and lower temperatures (catalysts must offer low barriers). Pressure also increases the N_2 solubility; low (ca. millimolar) solubility of most gases in most organic solvents slows rates of their reactions. A di-yne will diminish the entropy penalty [Eq. (a)] relative to two mole of alkyne.

Ken Caulton has been on the faculty of Indiana University since 1969, researching transition-metal complex reactivity, including complexes of hydrides and dihydrogen, as well as cleaving strong, refractory bonds with electron-rich or poor metal complexes. Establishing the characteristic reactivity of radical metal complexes led to his most recent activity: the concept to redox-active "non-innocent" ligands, intending these ligands to store either reducing or oxidizing equivalents for later delivery to substrate.

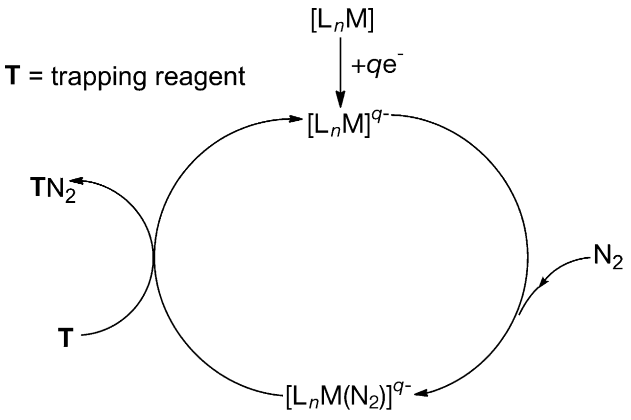


(a)

Alkyne cyclotrimerization,[42,43] and even coupling of four HC≡CH to give cyclooctatetraene,[44] as well as olefin polymerization suffer analogous entropy penalties, yet they are accomplished.

New Trapping Approaches for Reduced Dinitrogen: Generalities

In this exercise in prospecting for reagents beyond H_2 that might turn atmospheric nitrogen into organonitrogen compounds, we seek reagents **T** to capture coordinatively activated dinitrogen (Scheme 1, which is generic with respect to $\mathbf{TN_2}$), either at the supplied metal center [L_nM], or following reduction of that metal center by qe^-, to move a precatalyst onto the catalytic cycle, for better N_2 binding and to alter the reactivity of N_2. The job of the (reduced) metal complex is to encourage attack on the coordinated N_2 by an unsaturated hydrocarbon, and thus facilitate C–N bond formation. The nucleophilic nitrogen atom has a reason to interact with an electrophilic carbon atom in an alkyne and, to a lesser extent, an alkene. The conversions we envision are generally π→σ electron rearrangements of unsaturated hydrocarbons, so we need electrons only to activate N_2 or other substrates, but with no net consumption of those



Scheme 1. Catalytic trapping of N_2.

electrons; note that, for some of these reactions, catalyst serves to polarize the substrate since the reactions are otherwise symmetry forbidden. In Scheme 1, variable "q" shows that the activation of substrate N_2 may potentially be accomplished by one or two electrons in this reaction which is catalytic in electrons. The characteristic of all of the cyclization reactions envisioned herein is that they involve no net consumption of electrons. Electrons may be needed to improve the coordination and polarization of N_2, but the cyclization reactions discussed below are catalytic in electrons; electrons play an activating role. This redox-neutral derivatization is possible since N_2 is the oxidant and the alkyne is the reducing agent. The reactions envisioned are conproportionation reactions.

What is the product **T**N_2 in Scheme 1? In some sense the hardest step in dinitrogen conversion is full separation of the two N atoms, which is why we focus herein on the trapping of reduced nitrogenous species by alkenes and alkynes, all featuring a surviving N−N connection. In fact, some interesting N_2 functionalizations already reported[25,38,45–48] stop at the hydrazine stage. Should products with single or double N−N bonds be targeted? Based on thermodynamic comparison to carbon analogues, carbon–carbon triple bonds generally have more negative heats of hydrogenation ($-41.7\,\text{kcal mol}^{-1}$ to form alkene)[31] than do C=C double bonds ($-32.5\,\text{kcal mol}^{-1}$),[31] which is taken as an indication of one alkyne π bond being more reactive than the alkene π bond. This is one reason for arguing that it would be better to target products where an N=N double bond is retained. Proceeding from N=N double to single bonds, a second factor intervenes: filled–filled repulsion between two vicinal lone pairs makes the single bond in hydrazines unusually weak. This is another reason why targeting N=N double bonds should be considered.

New Reactive Traps for N_2

The strategy described herein is to seek trapping reagents based on a general knowledge of "high-energy molecules."[49,50] The key is to find so-called high-energy molecules, and to use that characteristic to favor reaction enthalpies consuming such molecules; in this language, the high-energy molecule is seen as a "fuel" for derivatization, and is intended to offset the high thermodynamic stability of the nitrogen source, N_2. Hess' law says that the enthalpy of any reaction is the sum of the enthalpies of formation of products minus the sum of the enthalpies of formation of the reactants. For the enthalpy of reaction to be as negative as possible, it is necessary that reactants have enthalpies of formation that are only slightly negative or even positive.

One definition of a high-energy molecule is based on its enthalpy of formation; if this is positive, it is termed a "high-energy" species. For example, this immediately identifies N_2O ($\Delta H_f^\circ = +19.6\,\text{kcal mol}^{-1}$)[31] as an appealing O-atom transfer reagent (but this is irrelevant for N_2 conversion); by this criterion, ozone ($\Delta H_f^\circ = +34\,\text{kcal mol}^{-1}$)[31] is also appealing. Ethylene, with a positive enthalpy of formation ($+12.5\,\text{kcal mol}^{-1}$)[31] also qualifies, but only weakly. We know that alkynes are also high energy among carbon compounds, which will favor reaction energies leading away from alkynes. Alkynes[51] are preeminent candidates because ΔH_f° for HC≡CH is $+54\,\text{kcal mol}^{-1}$.[31] Likewise both MeCN ($+18\,\text{kcal mol}^{-1}$)[31] and HCN ($+32\,\text{kcal mol}^{-1}$)[31] are "endothermic molecules;" triple bonds (other than in N_2) generally have that characteristic, so compounds containing them are attractive reagents. Moreover, allene, being a less-stable isomer of propyne, qualifies this class of hydrocarbons as attractive derivatization reagents; indeed isomerization energy is one parameter useful to quantify the term "high-energy molecule".

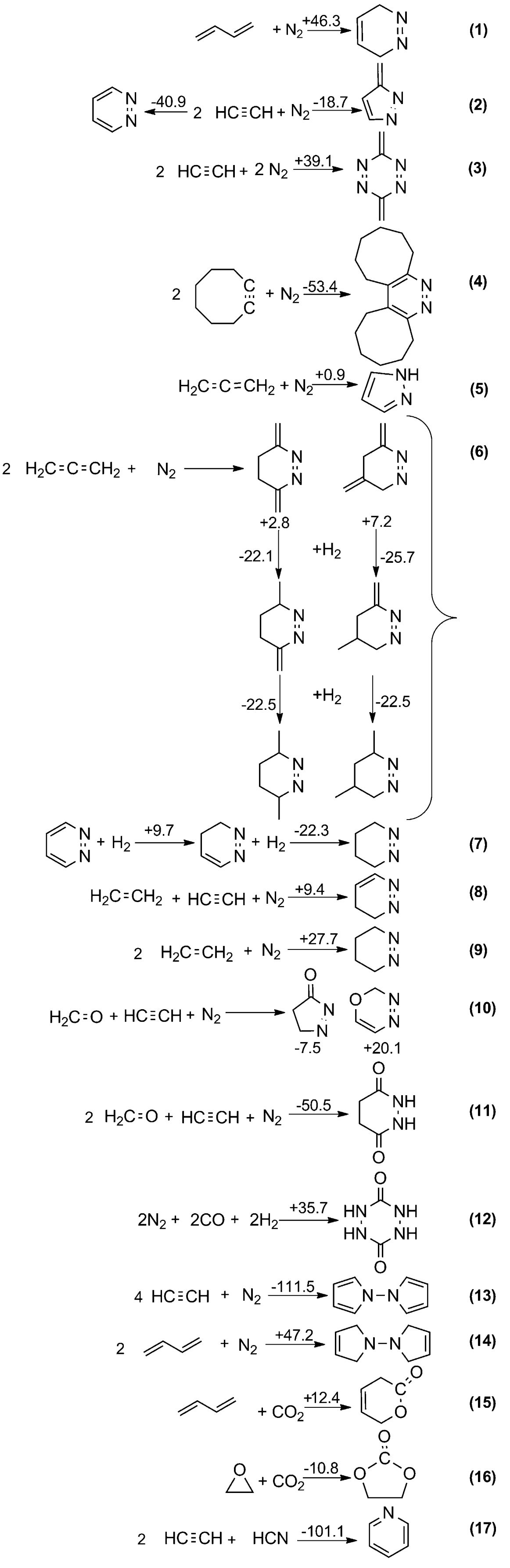
High-Energy Molecule Precedents

The utility of basing our reasoning on the concept of high-energy molecules in selecting our traps is exemplified by the currently seemingly ubiquitous Huisgen alkyne/azide cyclization ("click" reaction).[52] Viewed from the standpoint of both alkyne and azide being highly oxidized species, hence both "oxidants", they should not react. Viewed from the point of view that the reaction requires a transition state where the reagent linear N=N=N unit must bend, it might be anticipated to have a high barrier to cyclization. However, both of these predictions are incorrect, as judged by the ease of reaction observed in the many reported examples. Success in this case can be attributed to the high energy of both reagents; since each occupies a high-energy region of their energy surface, formation of any alternative products is thus exothermic. The validity of the "high-energy molecule" principle is evident, since reaction of HC≡CH with HN_3 to form the triazole is exothermic by $54.9\,\text{kcal mol}^{-1}$! Phenyl azide, like many nitrogen-rich compounds, is an endothermic molecule, with a $\Delta H_f^\circ > +80\,\text{kcal mol}^{-1}$.[31]

Reliability Testing

There is a limited amount of experimental thermodynamic data on organonitrogen compounds, so we have complemented those with data calculated by DFT methods for other organonitrogen compounds; DFT has been benchmarked[53–55] to be accurate for molecules of the type we consider, so can be relied on for our survey of dinitrogen reactions, particularly for molecules containing only C, H, and N; for example, comparison of the examples in Table 1 to available experimental data[31] shows an average error of only $3\,\text{kcal mol}^{-1}$. Additionally, comparison[56] of most of the DFT results in Table 1 to (higher level) calculations at the CCSD(T) level shows the largest difference is $11\,\text{kcal mol}^{-1}$, which does not alter any conclusion in what follows. For further testing the validity of this idea of "reactive capture" applied to another very stable molecule, some examples of trapping of CO_2 are also provided in Table 1, Equations (15) and (16). Ring strain assists Equation (16), while lack of ring strain, and conjugation in butadiene, make Equation (15) unfavorable.

Table 1: Calculated (DFT) ΔH (0 K) [$\mathrm{kcal\,mol^{-1}}$] of N_2 Functionalization.



Derivatization Thermodynamics: Generalities

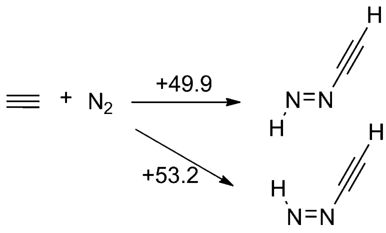
Comparisons within Table 1 are useful for drawing simple and broadly applicable generalizations as to what enhances reaction exothermicity. These are merely simple deductions from the energy balance implicit in Hess' law. Results in Table 1 confirm that alkynes are most promising as trapping reagents [Eq. (1) vs. (2)]. A successful prior example of this general strategy is Bönnemann's cyclotrimerization[57,58] of two alkynes with one nitrile, to give a pyridine (highly thermodynamically favorable, at $-107\,\mathrm{kcal\,mol^{-1}}$,[31] because alkynes and nitriles are both endothermic molecules). Allene is also attractive, to give a pyrazole [Eq. (5), in which near-thermoneurality indicates that even catalytic ring opening of pyrazoles has potential]. For reactions that are only unfavorable by approximately $10\,\mathrm{kcal\,mol^{-1}}$, their prospects could be improved by introducing compensating steric factors that have such magnitude.[59] For example, *trans*-cyclooctene has a strain energy of approximately $7\,\mathrm{kcal\,mol^{-1}}$, as does norbornadiene.

Condensation of two alkynes with one N_2 is exothermic to form both five and six membered rings [Eq. (2)]. An approach to products whose thermodynamic stability is unfavorable [Eq. (3)] is to simultaneously (i.e., while still catalyst bound) hydrogenate their C=C bond, since this gives an additional enthalpy yield of over $20\,\mathrm{kcal\,mol^{-1}}$ per C=C bond. This is evident from Table 1 Equations (6) and (7), which shows a constancy of the heat of hydrogenation which is predictably diminished only when aromaticity is interrupted [Eq. (7)]. In another approach to improving reaction enthalpy, we have estimated the enthalpy yield of strain release by comparing the cyclization of N_2 with two HCCH versus that with two cyclooctynes. This shows an energy benefit [Eq. (4) vs. Eq. (2)] from releasing the two 159° C–C≡C bond angles in cyclooctyne.[59–61] Cyclooctyne, while atypical, might serve as a useful candidate for screening for catalytic N_2 derivatization leads.

Terminal Alkyne C–H Bonds

Alkynes have already been used to functionalize coordinated N_2, but only terminal alkynes were reported,[36,62] and they first manifested their reactivity as Brønsted acids, hence they protonated anionic N atoms, with the resulting acetylide carbanion then binding to the metal center. One exception[46] nicely showed the formation of a vinyl group (i.e., H addition to alkyne), but also the desired C–N bond. We suggest that this observed C–N bond formation originates in part from the thermodynamic principles we discuss.

On the other hand, some terminal-alkyne hydrogen-transfer products are precluded because they are endothermic, that is, they are excluded for thermodynamic, not kinetic reasons. For example, the reaction of N_2 with acetylene by C–H addition across the N–N bond [Eqs. (18), (19)], energies in $\mathrm{kcal\,mol^{-1}}$ are both highly endothermic compared to the cyclization reactions that we target. This situation is understandable in that they fail to convert the C–C triple bond, and thus lack that advantage of high-energy molecule utilization. Catalysis cannot lead to C—H addition across N≡N.



(18)

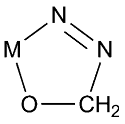
(19)

Derivatization with Polar Multiple Bonds

Another possible product-stabilizing approach to maintaining N—N bonds is to introduce polarity into product, as shown in Table 1, Equation (12); this heterocycle derives an incremental energy yield from oxidized carbon, but also hydrogenates N—N multiple bonds; we find this reaction is so enthalpically unfavorable in the gas phase that hydrogen bonding in condensed media will improve this only modestly. While formation of urea itself is also exothermic (−29.9 kcal mol^{-1} [31]) relative to $N_2 + CO + 2H_2$, it lacks the mechanistic simplicity/advantage of retaining some N—N bonds.[63] Using thermodynamics to anticipate any polar product is important, because product detection will require chemical derivatization prior to GC analysis; if such a polar product were not anticipated, it would probably be overlooked by the commonly used analytical methods.

Regarding facile release of product, early transition metals are oxophilic, and more generally "heterophilic", and an M—E bond ($E = OR, NR_2$), once formed, is too stable to remove with reagents such as H_2 or additional substrate (to close a catalytic cycle). This problem disappears for the later transition metals, where it is established[64–67] that late transition-metal alkoxide or amide complexes react readily with H_2 (1 atm, room temperature) to form metal hydride and H—E, so H_2 is a very attractive reagent for product release.

Therefore, when the catalyst involves such a later transition element, oxygen-containing traps can be explored. A mechanistic advantage is that carbon attached to oxygen is electrophilic, hence related to the Chirik and Fryzuk electrophiles as derivatizers. Formaldehyde is only 3 kcal mol^{-1} more stable than $H_2 + CO$,[31] so deserves consideration as a derivatizing reagent, owing to its electrophilic carbon. We can envision it binding to nucleophilic nitrogen (**I**) and leading to products in Equations (10) and (11) in Table 1. Although H_2CO is not an endothermic molecule ($\Delta H_f° = -27.7$ kcal mol^{-1}),[31] comparing reaction enthalpies where H_2CO replaces one HCCH is impressive (cf. Equation (2) in Table 1); this strategy for thermodynamically driving the conversion [Eq. (10)] leads to two isomeric products, only one of which is exothermic. Doubling the amount of formaldehyde "fuel" is even more favorable [Eq. (11) versus (10)].



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Other Relevant Generalizations

The lesson from comparing Equations (2) and (3) in Table 1 is that it is daunting to try to consume two N_2 molecules. A similar conclusion comes from comparing Equation (11), in which alkyne serves as fuel, and Equation (12), which consumes two N_2 molecules.

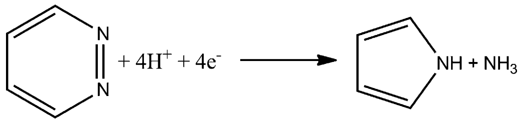
This raises a point about catalyst design and its impact on the structure of the coordinated N_2. For derivatization by electrophiles, end-on binding of N_2 polarizes the two nitrogen atoms differently (i.e., breaks the nitrogen symmetry equivalence found in η^2 and bridging structures) and we believe this is advantageous in maximizing the nucleophilicity of η^1-bound N_2. One way to argue this point is that the twofold symmetry of bridging N_2 equally divides whatever anionic character is transferred to coordinated N atoms. Linear M-N-N coordination, in contrast, should put unequal amounts of charge on the N atoms, with the terminal being the more nucleophilic; this should provide a kinetic advantage.[37]

Another approach to N—N bond retention, in seeking acceptable thermodynamics, is condensation of alkynes with N_2 to make the hydrazine, which in our case is actually two N-coupled pyrroles [Eq. (13)]. For comparison, analogous coupling with butadiene, which is 7.9 kcal mol^{-1} more stable than 2-butyne,[31] would deliver a hydrazine with some residual, but isolated, ring unsaturation [Eq. (14)]. As is evident from Table 1, the bipyrrole product is hugely favorable enthalpically (4:1 alkyne:N_2 ratio), while the absence of aromaticity leaves the butadiene trapping reaction endothermic, just as it did in Equations (1) and (15).

Comparison of Equation (2), giving a six-membered ring product, and Equation (8) reveals the unfavorable thermodynamic impact (loss of 50.3 kcal mol^{-1}) of replacing one alkyne reagent by an alkene. For comparison, if the alkyne is replaced instead by formaldehyde [Eq. (2) vs. (10)], then the energy "loss" is only 33.4 kcal mol^{-1}. If two formaldehydes are condensed with one alkyne and one N_2, to form the cyclic diamide in Equation (11), that loss is totally removed.

It was noted above that the adjacent (vicinal) nitrogen atoms experience lone pair/lone pair (filled/filled) repulsions, which makes the N—N bond in hydrazines weak. This situation also suggests that low-energy mechanisms exist for N—N cleavage, either using H_2 or reducing equivalents ($2e^-$), to cleave the species shown in Equation (12) of Table 1 into urea; this could be a way to reverse the otherwise endothermic N_2 functionalization in Equation (12). Similarly, if NH_3 is desired, it and pyrrole are to be formed from pyridazine by PCET (Scheme 2).[68]

The key to any successful "cross-coupling" reaction is to avoid homocoupling, in this case, of two alkynes or two allenes. This suggests avoiding terminal alkynes, for which side reactions can be accelerated by H migration. Delivering the more reactive reagent, alkyne, by syringe-pump also

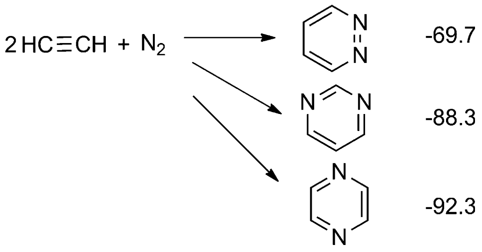


Scheme 2. Proton-coupled electron transfer of pyridazine.

minimizes homocoupling; this chemical-engineering solution was used very successfully in homogeneous nickel-catalyzed cyclotrimerization [Eq. (17)] of two alkynes with one RC≡N to make pyridines.[57,58]

N–N Bond Retention: Asset or Liability?

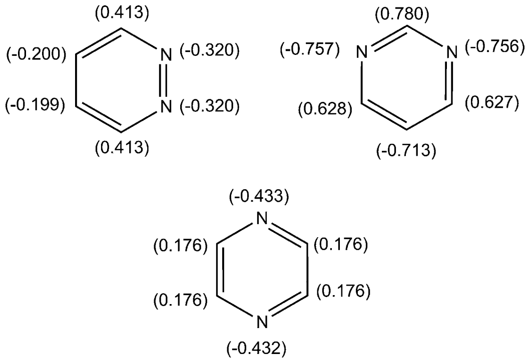
Our choice to target products retaining an N–N bond merits further examination. Clearly more mechanistic steps are required to break the N–N bond completely. Moreover, breaking the N–N bond has generally led to metal nitride species, and these have demanded a highly electropositive early transition metal. Once such a nitride is formed, it takes highly electrophilic reagents to further transform the nitrogen atom, limiting the overall product spectrum. In addition, consider the relative thermodynamic stability of the three positional isomers of cyclic $C_4N_2H_4$. We find, computationally (Scheme 3, energies in kcal mol^{-1}), that the 1,2-isomer is the least stable, with 1,3- and 1,4-isomers nearly degenerate (the 1,3-isomer is less stable than the 1,4- isomer by 4 kcal mol^{-1}, and more stable than the 1,2-isomer by ca. 19 kcal mol^{-1}); these relative stabilities are also found in the experimental database.[31] This situation means that, with our constraint to focus on the retention of N–N bonds, we are targeting a product which is not the thermodynamic one, but one chosen instead for kinetic simplicity, hence also probably involving faster formation rates. We have tried to find the origin of these relative diazabenzene thermodynamic stabilities. One destabilizing factor is lone pair/lone pair repulsion (and highest dipole moment) in the 1,2-isomer. Another aspect is that the electronegative nitrogen atoms build up N–N Coulomb repulsion which is maximal in the 1,2-isomer. The calculated electrostatic charges[69] in Scheme 4 clearly show accumulation of electron density on all the N atoms, so when these are adjacent (in the 1,2-isomer), destabilizing repulsion is maximized. In addition, in this isomer, two adjacent carbon atoms also accumulate negative charge, which uniquely destabilizes this isomer compared to the others.



Scheme 3. Isomer stabilities.

Conclusions

Of course, organic chemistry shows that thermodynamics is not the only guiding principle in synthesis, since most organic compounds are metastable with respect to other isomers, or to CO_2, N_2, and H_2O; this is a caveat that thermodynamics, the guide that we have employed herein, is not only and always the determinant of products formed. On the other hand, catalytic turnover is impossible using a derivatizing reagent that has no foreseeable thermodynamically favorable product, so a preliminary thermodynamic survey is essential. It is the endothermic character of alkynes that makes their hydroxylation and hydroamination thermodynamics so favorable, thus making them attractive targets for catalytic processing.[70] Moreover, some of the reagents we consider for derivatization could react in other ways with metal complexes, so controlling the order of addition of three-component reactions is also challenging; however that challenge has been conquered in catalyzed reactions of alkene, H_2, and CO (i.e., alkene hydroformylation), and in butadiene hydrocyanation, and most impressively in cyclotrimerization of alkynes with nitriles to make pyridines.



Scheme 4. Electrostatic charges on the C and N atoms of $C_4N_2H_4$ isomers.

This Essay is intended to broaden the range of derivatization reagents to be surveyed in N_2 functionalizations. In particular, introducing formaldehyde, or ketones, becomes of interest on moving away from the electropositive early transition metals towards the later, less oxophilic and less azaphilic transition elements, where hydrogenolysis of metal–heteroatom bonds is facile, and thus closing a catalytic cycle with H_2 warrants evaluation. Finally, use of the currently appealing "earth-abundant" 3d elements from Mn to Cu has a special attraction for developing strategic independence from imported platinum metals. Since all the reactions targeted herein are examples of "click" reactions, it can only be hoped that they prove to be as broadly useful as the azide/alkyne click coupling has become. Since viewing an endothermic molecule as a fuel is also a generally useful approach to improving reaction exothermicity that too has broad potential for targeting reagents for small-molecule activation generally.

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