Electrosynthesis of Amino Acids from a Molybdenum Nitride *via* Nitrogen–Carbon and Carbon–Carbon Bond Formation Reactions involving Imides and Nitrogen Ylides: X-Ray Structure of *trans*-[MoCl(NCHCO$_2$Me)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$]·CH$_2$Cl$_2$

David L. Hughes, Saad K. Ibrahim, Colin J. Macdonald, Hapipah Mohd. Ali and Christopher J. Pickett*

The Nitrogen Fixation Laboratory, AFRC Institute of Plant Science Research, University of Sussex, Brighton BN1 9RQ, UK

Sequential nitrogen–carbon and carbon–carbon bond formation, and an electrochemical Mo–N bond cleavage step, define a pathway to methyl esters of the amino acids glycine and alanine from the molybdenum nitride *trans*-[MoCl(N)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$], a key intermediate being the metallo-nitrogen ylide *trans*-[MoCl(NCHCO$_2$Me)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$], the structure of which has been determined crystallographically.

Nitride can be converted to alkylimide,[1–4] thionitrosyl,[2] methyleneamide, cyanide, heterocumulene, or aminocarbyne groups[5,6] by stepwise reactions at robust {M(R$_2$PCH$_2$-CH$_2$PR$_2$)$_2$} centres (M = Mo or W; R = alkyl or aryl); under other conditions ammonia or methylamine[7] can be released from the metal. In all cases the metal–tertiary phosphorus ligand assembly is conserved.

These transformations suggested that it might be possible to exploit nitrides as reagents in organic synthesis; here we report some first steps in this direction. Sequential nitrogen–carbon and carbon–carbon bond formation, and an electrochemical Mo–N bond cleavage step, define a pathway to amino acids from a molybdenum nitride. A key intermediate in the synthesis is a metallo-nitrogen ylide, which can be viewed as providing the synthetic equivalent **A**.

trans-[MoCl(N)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$] reacts cleanly with the methyl ester of iodoacetic acid to give the cation *trans*-[MoCl(NCH$_2$CO$_2$Me)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$]$^+$ **B** which was isolated as an air-stable, iodide salt (violet crystals, 65% yield) and characterised by ^{1}H, ^{31}P{^{1}H} and ^{13}C{^{1}H}NMR, and FT IR spectroscopy† (Scheme 1).

The electron-withdrawing ester group allows facile deprotonation of **B** at the α-carbon atom by Et$_3$N, and *trans*-[MoCl(NCHCO$_2$Me)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$] **C**‡ was obtained as a moderately air-stable material (olive crystals, 90% yield) (Scheme 1). The X-ray crystallographic structure of **C**§ is

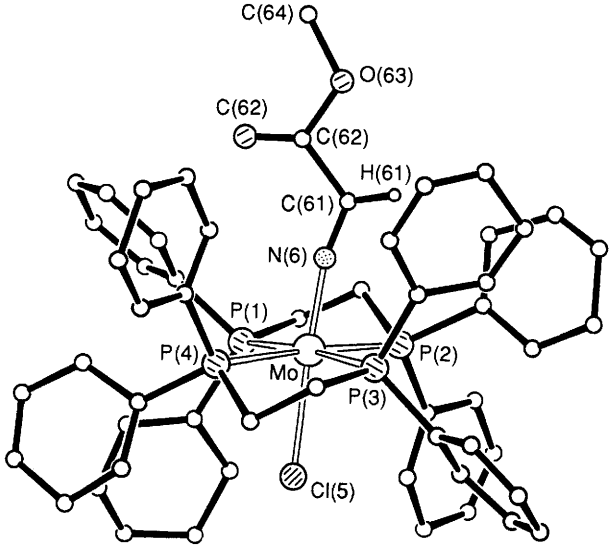
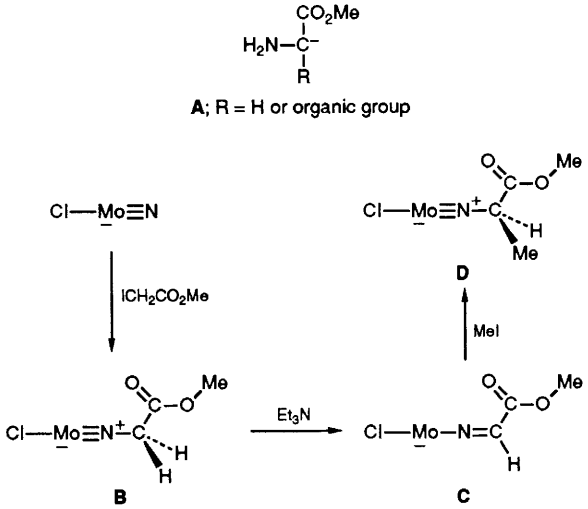


Fig. 1 A view of the major component in the X-ray structure of *trans*-[MoCl(NCHCO$_2$Me)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$] **C**. The hydrogen atom H(61) was located in the final difference map but was not included in the refinement process.



Scheme 1 Formation of N–C and C–C bonds by stepwise alkylation, deprotonation and methylation reactions. The deprotonation is fully reversible. Mo represents the *trans*-{Mo(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$} assembly.

† *trans*-[MoCl(NCH$_2$CO$_2$Me)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$] **I** (**B** iodide): ^{1}H NMR (CD$_2$Cl$_2$, δ relative to tetramethylsilane, tms): 2.65 (2H, quartet, NC*H*$_2$), 2.8–3.1 (8H, br. m, PC*H*$_2$C*H*$_2$P) with superimposed 3.08 (3H, s, OC*H*$_3$) and 6.5–7.5 (40H, m, CH$_2$P*Ph*$_2$); ^{31}P{^{1}H} NMR (CD$_2$Cl$_2$, δ relative to trimethyl phosphite, tmp): −98 (s); ^{13}C{^{1}H$^+$} NMR (CD$_2$Cl$_2$, δ relative to tms): 27.3 (quintet, PCH$_2$), 52.5 (s, OCH$_3$), 63.3 (s, NCH$_2$), 128–135 (m, P*Ph*$_2$) and 164.4 (s, CO); FT IR (Nujol mull; ν/cm^{-1}): 1753 (strong, νCO).

‡ *trans*-[MoCl(NCHCO$_2$Me)(Ph$_2$PCH$_2$CH$_2$PPh$_2$)$_2$] **C**: ^{1}H NMR (CD$_2$Cl$_2$): δ 3.28 (1H, quintet, NC*H*), 2.65–2.8 (8H, 2 × br m, PC*H*$_2$C*H*$_2$P), 3.00 (3H, s, OC*H*$_3$) and 6.5–7.5 (40 H, m, CH$_2$P*Ph*); ^{31}P{^{1}H} NMR (CD$_2$Cl$_2$): δ −86.7 (s); FT IR (Nujol mull; ν/cm^{-1}): 1607, 1622 and 1637 (strong, νCO and νCN).

§ Crystal structure analysis of *trans*-[MoCl(NCHCO$_2$Me)-(Ph$_2$CH$_2$CH$_2$PPh$_2$)$_2$]·CH$_2$Cl$_2$ **C**: C$_{55}$H$_{52}$ClMoNO$_2$P$_4$·CH$_2$Cl$_2$, M = 1099.2. Monoclinic, space group $C2$ (No. 5), a = 21.851(3), b = 14.054(2), c = 17.152(1) Å, β = 101.259(9)°, V = 5165.9 Å^3, Z = 4, D_c = 1.413 g cm^{-3}, F(000) = 2264, μ(Mo-Kα) = 5.7 cm^{-1}. λ(Mo-Kᾱ) = 0.71069 Å. Dichroic green–red prism crystals with diamond cross-section. One, *ca.* 0.12 × 0.21 × 0.26 mm mounted on glass fibre; photographic examination; the CAD4 diffractometer (with monochromated radiation) for accurate cell dimensions (from settings of 25 reflections, θ *ca.* 10.5°, each in four orientations) and measurement of diffraction intensities (θ_{max} 23°). Corrections for Lorentz–polarisation effects and to eliminate (by Bayesian statistics) negative intensity values were made. 3767 Unique reflections entered into SHELX system[12] for structure determination (heavy-atom method) and refinement (large-block-matrix least-squares methods) to R 0.060 and R_w 0.062[12] for 3411 reflections (those with $I > 3/2\sigma I$), weighted w = $(\sigma_F^2 + 0.00047\ F^2)^{-1}$.

The *trans*-Cl and -N ligands and the solvent molecule are disordered in *ca.* 4:1 ratio in opposing directions. All non-N atoms except those in minor sites of the N ligand and solvent molecule were refined anisotropically. H atoms were included in idealised positions on the diphosphine ligands. Highest peaks in final difference map were *ca.* 0.45 e Å^{-3} near disordered ester group/solvent atoms. Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre. See Notice to Authors, Issue No. 1.

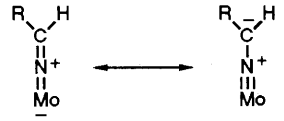


Fig. 2 Canonical representations of bonding in the alkenylamide showing how metallo-nitrogen ylide character might account for the incipient carbanionic behaviour of **C**

shown in Fig. 1. The Cl–Mo–N–C framework is essentially linear and the N–C–C bond angle is 121(1)°; this, together with the bond length data, is consistent with Mo–N and N–C multiple bond character and with sp and sp^2 hybridisation at the nitrogen and α-carbon atoms, respectively (Fig. 2). The Mo–N distance in **C** of 1.853(8) Å is significantly shorter than in $[Mo(\eta^5\text{-}C_5H_5)(CO)_2\{NC(Bu^t)_2\}]$ [1.892(5) Å], which also has the linear Mo–N–C arrangement;[8] the difference in the N–C distances in the two molecules [1.22(2) and 1.26(1) Å, respectively] is not statistically significant.

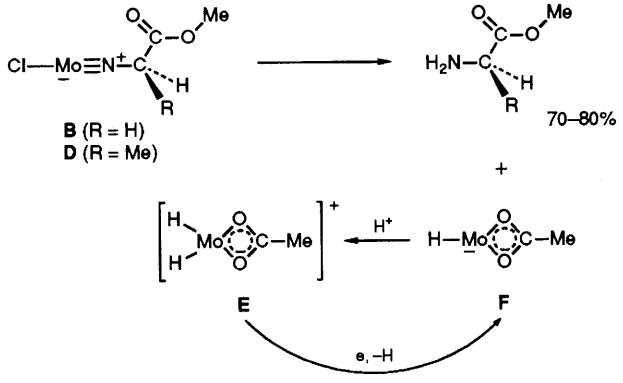
The reactivity of **C** suggests that it has incipient carbanion character and it can be considered as a metallo-nitrogen ylide (Fig. 2). Thus, it reacts cleanly with MeI at the α-carbon atom to give the cationic methyl derivative *trans*-$[MoCl\{NCH(Me)CO_2Me\}(Ph_2PCH_2CH_2PPh_2)_2]^+$ **D**, which was isolated as the iodide salt and characterised by ^1H, $^{31}P\{^1H\}$ and $^{13}C\{^1H\}$NMR, and FT IR spectroscopy (violet crystals, 74% yield¶ (Scheme 1). The pK_a of **B** is *ca.* 12 which places the α-carbon acidity between that of ethyl acetoacetate and diethyl malonate.[9]

The imides **B** and **D** are electroactive and each undergoes a reversible one-electron oxidation at $E_{1/2}^{ox}$ 0.64 and 0.68 V (CH_2Cl_2, 0.2 mol dm^{-3} $[NBu_4][BF_4]$), and a partially reversible reduction at $E_{1/2}^{red}$ −2.12 and −2.21 V {tetrahydrofuran (thf), 0.2 mol dm^{-3} $[NBu_4[BF_4]$, *vs.* ferrocenium–ferrocene (fc^+–fc)}, respectively. Controlled potential electrolysis of **B** {vitreous carbon cathode, −2.3 V *vs.* fc^+–fc, 10% $MeCO_2H$ (v/v) in thf, 0.2 mol dm^{-3} $[NBu_4][BF_4]$} liberated glycine methyl ester in 70% yield. The ester was identified by TLC and the yield determined spectrophotometrically by reaction with ninhydrin.[10] Correspondingly, electrolysis of **D** under identical conditions gave alanine methyl ester in 80% yield (Scheme 2).

On terminating the electrolysis of either **B** or **D**, the dark orange catholyte solutions slowly turned bright magenta. Cyclic voltammetry, TLC, $^{31}P\{^1H\}$NMR and the characteristic electronic absorption at 514 nm established that the metal product so formed was the η^2-acetate dihydride $[MoH_2(\eta^2\text{-}MeCO_2)(Ph_2PCH_2CH_2PPh_2)_2]^+$ **E**, first reported by Ito *et al.*[11]

The precursor to **E** is the known orange monohydride *trans*-$[MoH(\eta^2\text{-}MeCO_2)(Ph_2PCH_2CH_2PPh_2)_2]$ **F**.[11] This species is oxidised reversibility at $E_{1/2}^{ox}$ −1.00 V *vs.* fc^+–fc and was detected in the reductive cyclic voltammetry under argon of either **B** or **D** in the presence of $MeCO_2H$, and as an intermediate that builds up during the course of the bulk electrolysis of either imide. It is generated by reduction or by deprotonation of **E** with base, and is also produced by the reaction of *trans*-$[Mo(N_2)_2(Ph_2PCH_2CH_2PPh_2)_2]$ with $MeCO_2H$.

¶ *trans*-$[MoCl\{NCH(Me)CO_2Me\}(Ph_2PCH_2CH_2PPh_2)_2]I$ (**D** iodide): ^1H NMR (CD_2Cl_2): δ 0.27 (3H, d, NCH*Me*; see below), 2.87 (3H, OCH_3), 2.9–3.1 (9H, br m, PCH_2CHP with superimposed NC*H*; irradiation of multiplet of 3.0 causes collapse of doublet at δ 0.27 to a singlet) and 6.5–7.5 (40H, m, CH_2PPh); $^{31}P\{^1H\}$ NMR (CD_2Cl_2): δ −99.4 (m); deprotonation of **D** leads to a singlet at δ −90.75; $^{13}C\{^1H\}$ NMR (CD_2Cl_2): δ 18.2 (s, NCH*Me*), 26.8 and 27.5 (m, PCH_2), 52.8 (s, OCH_3), 70.9 [s, NCH(CH)], 128–135 (m, PPh_2) and 167.5 (s, CO); FT IR (Nujol mull; ν/cm^{-1}): 1748 (strong, νCO).



Scheme 2 Electrochemical cleavage of the Mo–N bond in the presence of acetic acid to release amino acid esters and form η^2-acetatomolybdenum hydrides. Mo represents the $\{Mo(Ph_2PCH_2CH_2PPh_2)_2\}$ assembly. *Conditions*: glassy carbon electrode, −1.8 V *vs.* standard calomel electrode, 10% v/v $MeCO_2H$ in thf containing 0.2 mol dm^{-3} $[NBu_4][BF_4]$.

That **E** is reduced to **F** at E_p^{red} −1.88 V *vs.* fc^+–fc, a potential positive to that of **B** or **D**, accounts for the steady-state current observed during bulk electrolyses. Reduction of **E** generates **F**, which is slowly re-protonated by $MeCO_2H$, thus establishing a proton-discharge cycle (Scheme 2).

In conclusion, amino acid esters can be synthesised from a molybdenum nitride *via* formation of imide and nitrogen ylide intermediates. It is noteworthy that the methylated product *trans*-$[MoCl\{NCH(Me)CO_2Me\}(Ph_2PCH_2CH_2PPh_2)_2]$ **D** also is deprotonated to give a nitrogen yield and this offers the prospect of further derivatisation at the α-carbon atom. Asymmetric tertiary phosphine co-ligands might allow access to optically active products.

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