1,3-Dipolar cycloaddition of several azomethine ylides to [60]fullerene: synthesis of derivatives of 2′,5′-dihydro-1′*H*-pyrrolo[3′,4′ : 1,2][60]fullerene [1]

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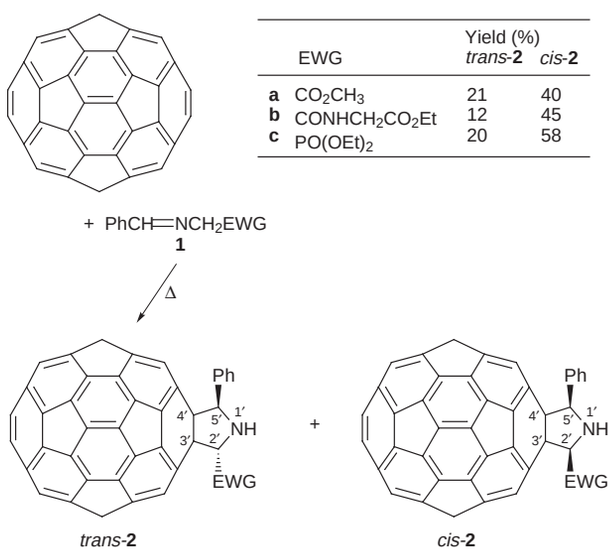
Imines 1 have been prepared by the condensation of benzaldehyde and corresponding primary amines in which the ester group, phosphonate ester group and depsipeptide are introduced. [60]Fullerene reacts with imines 1 to give the corresponding isomers of fullerene-fused proline derivatives 2 *via* a process of 1,3-dipolar cycloaddition. 1,3,5-Tris(ethoxycarbonylmethyl)perhydro-1,3,5-triazine 4, which has been prepared by the condensation of ethyl glycinate with paraformaldehyde, depolymerizes thermally to provide an azomethine ylide which reacts with [60]fullerene to afford ethyl 2′,5′-dihydro-1′*H*-pyrrolo-[3′,4′ : 1,2][60]fullerene-2′-carboxylate 5. 2-Phenyl-4,5-dihydrooxazol-5-one 6 tautomerizes thermally to form the mesoionic oxazolium 5-oxide 6a, which then, as a cyclic azomethine ylide, combines further with [60]fullerene to give 5′-phenyl-2′*H*-pyrrolo[3′,4′ : 1,2][60]fullerene 7 which possesses C_s symmetry.

Introduction

Since the discovery by Wudl's group that some water-soluble fullerene derivatives showed inhibition of HIV-1 protease,[2] much more attention has been paid to the introduction of biologically active groups to [60]fullerene.[3] So far the 1,3-dipolar cycloaddition reactions of [60]fullerene have been shown to be versatile for the functionalization of [60]fullerene in terms of the easily separable and well defined products and good yields.[4] Besides the reactions of [60]fullerene with diazo compounds which lead to the formation of methanofullerene and fulleroid (homofullerene) derivatives,[2,5] the reactions between azomethine ylides and [60]fullerene provide an efficient route for the synthesis of pyrrolidino[60]fullerene. For example, reactions of [60]fullerene with azomethine ylides generated by aziridines,[6] (methoxytrityl)oxazolidinone[7] and *N*-benzyl-*N*-(methoxymethyl)[(trimethylsilyl)methyl]amine[8] have been reported. Imines bearing an electron-withdrawing group at the α position are one kind of important precursor of azomethine ylide, and have been intensively studied and used in the synthesis of pyrrolidine derivatives.[9] In the present work we report the 1,3-dipolar cycloaddition reaction of [60]fullerene with several imines of this kind.



	EWG	Yield (%) *trans*-**2**	*cis*-**2**
a	CO_2CH_3	21	40
b	$CONHCH_2CO_2Et$	12	45
c	$PO(OEt)_2$	20	58

Scheme 1

Results and discussion

Imines were prepared by the condensation of benzaldehyde and corresponding primary amines in which an ester group, phosphonate ester group or depsipeptide were introduced for the purpose of obtaining biologically active fullerene derivatives (Scheme 1). The reaction between ester **1a** and [60]fullerene occurred in refluxing toluene. For substrates **1b** and **1c**, the reaction required a higher temperature: xylene was used as solvent. A nitrogen atmosphere is preferred but was not necessary. The products were obtained by flash column chromatography on silica gel eluted with mixtures of *n*-hexane, toluene, methylene dichloride and ethyl acetate.

All the reactions gave the expected pyrrolidino[60]fullerenes with moderate yields. Since the 6–6 double bonds behave like electron-deficient alkenes, it is reasonable to assume that the addition takes place at the 6–6 ring junction. This conclusion is consistent with the ^{13}C NMR spectra of the products in which the carbon atoms of the addition site appeared at between δ_C 70 and 80 ppm, which revealed they were sp^3-hybridized.

The stereochemistry of the products was confirmed by the nuclear Overhauser (NOE) effects between the two protons on the pyrrolidine ring. In the NOESY spectra of compounds *cis*-**2a** and *cis*-**2c**, correlation peaks were observed between the two protons of the hetero five-membered ring, and no correlations were found between the corresponding protons in the spectra of products *trans*-**2a** and *trans*-**2c**. Table 1 shows the ^1H NMR data of protons located on the pyrrolidine ring for products **2a** and **2c**.

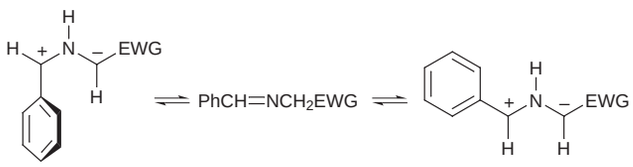
For *trans*-**2b** and *cis*-**2b**, the stereochemistry was determined by comparison of the ^1H NMR spectra with those of compounds **2a** and **2c**. In the ^1H NMR spectra of *trans*-**2b** and *cis*-**2b**, the two protons on the pyrrolidine ring were located at δ_H 6.51, 5.69 and 5.84, 5.41 ppm respectively. It is obvious that the difference in δ_H values between 2′-H and 5′-H in *trans*-**2b**

Table 1 ^{1}H NMR data of compounds **2a** and **2c**

	2a		**2c**	
	trans-**2a**/δ_H	*cis*-**2a**/δ_H	*trans*-**2c**/δ_H	*cis*-**2c**/δ_H
2′-H	5.78 (1 H, s)	5.60 (1 H, s)	5.33 (d, $^2J_{H\text{-}P}$ 10.4 Hz)	5.14 (d, $^2J_{H\text{-}P}$ 10.6 Hz)
5′-H	6.51 (1 H, s)	5.81 (1 H, s)	6.52 (s)	5.75 (s)

($\Delta_{trans} = 0.82$ ppm) is greater than the difference in *cis*-**2b** ($\Delta_{cis} = 0.43$ ppm). This also accords with the data for products **2a** and **2c** for which *trans*-isomers always have larger differences in chemical shifts for the pyrrolidine methine protons than do the *cis*-isomers.

The stereochemistry for reactions of this kind was also in agreement with the reaction mechanism. As shown in Scheme 2, there is a thermal tautomeric equilibrium between imine **1**

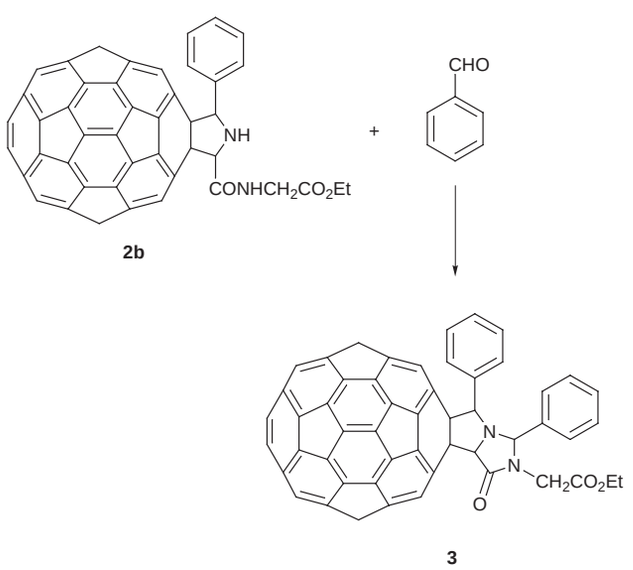


anti-**1** **1** *syn*-**1**

Scheme 2

and *anti*-**1**, or between imine **1** and *syn*-**1**. The intermediates *anti*-**1** and *syn*-**1** react with [60]fullerene to form products *trans*-**2** and *cis*-**2** respectively *via* a concerted process of 1,3-dipolar addition. Tautomer *anti*-**1** is less stable than *syn*-**1** because in *anti*-**1**, interactions between the phenyl group and the hydrogen atom α to the electron-withdrawing group (EWG) prevent the phenyl ring from becoming coplanar with the nitrogen atom. In addition, the out-of-plane phenyl group also increases the energy of the transition state when postulated intermediate *anti*-**1** approaches the fullerene molecule. Therefore, the *cis*-isomer is expected to be the major product. In fact, all the reactions gave the *cis*-isomers as the major products and the *trans*-isomers as the minor ones.

In the reaction of [60]fullerene with depsipeptide **1b**, besides the predicated products *trans*-**2b** and *cis*-**2b**, another (unexpected) product, compound **3**, was also obtained (yield 1%). We suggest that adduct **3** was the secondary reaction product of the main product **2b** with remnant benzaldehyde (as an impurity in the depsipeptide **1b**) (Scheme 3).



2b **3**

Scheme 3

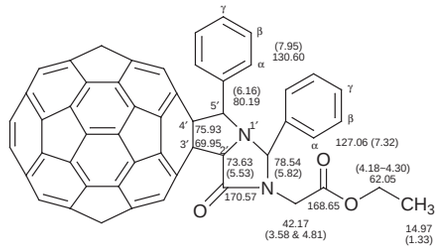
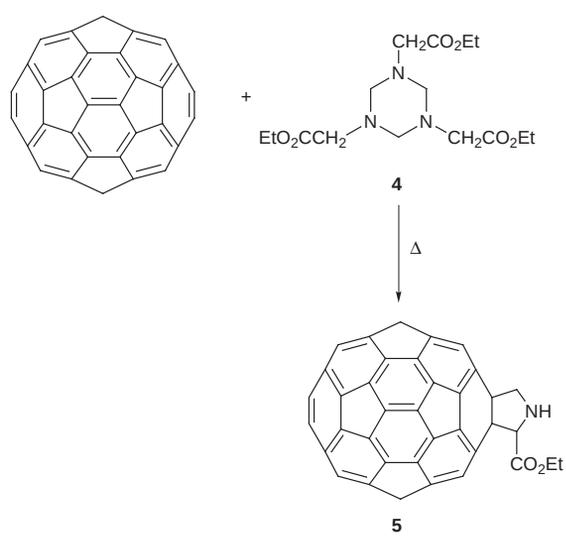


Fig. 1 ^{13}C NMR and ^{1}H NMR (in parentheses) data for compound **3**

The proposed structure of by-product **3** was confirmed by UV-VIS, Fourier-transform IR (FT-IR), field desorption mass spectrometry (FD-MS), ^{1}H NMR and ^{13}C NMR spectroscopic analysis and was further substantiated by the 2D heteronuclear multiple quantum-filtered coherence (HMQC) and 2D heteronuclear multiple-bond coherence (HMBC) NMR spectra. Assignable NMR spectral data are shown in Fig. 1.

Imines that are prepared from paraformaldehyde sometimes suffer trimerization.[10] The condensation of ethyl glycinate with paraformaldehyde in methylene dichloride gave an imine trimer, 1,3,5-tris(ethoxycarbonylmethyl)perhydro-1,3,5-triazine **4**. Compound **4** depolymerized thermally to form azomethine ylide, which reacted with [60]fullerene to give the expected product ethyl 2′,5′-dihydro-1′*H*-pyrrolo[3′,4′ : 1,2][60]fullerene-2′-carboxylate **5** *via* the process of 1,3-dipolar cycloaddition (Scheme 4).



Scheme 4

We have also conducted the reaction of [60]fullerene with a cyclic azomethine ylide. The reaction between 2-phenyl-4,5-dihydrooxazol-5-one **6** and [60]fullerene occurred in refluxing xylene to afford the adduct 5′-phenyl-2′*H*-pyrrolo[3′,4′ : 1,2]-[60]fullerene **7** (Scheme 5).

The structure of product **7** was determined by spectroscopic analysis as described below. The field desorption mass spectrum of compound **7**, which showed a molecular-ion peak at *m*/*z* 837 ($C_{68}H_7N$) as base peak together with a very weak peak at *m*/*z* 720 due to the fragment C_{60}, agreed with the proposed structure. In the IR spectrum of compound **7**, besides the four

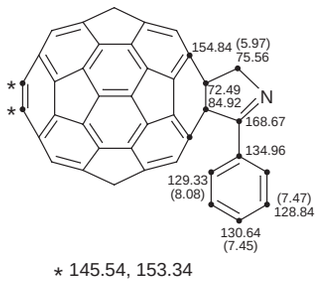
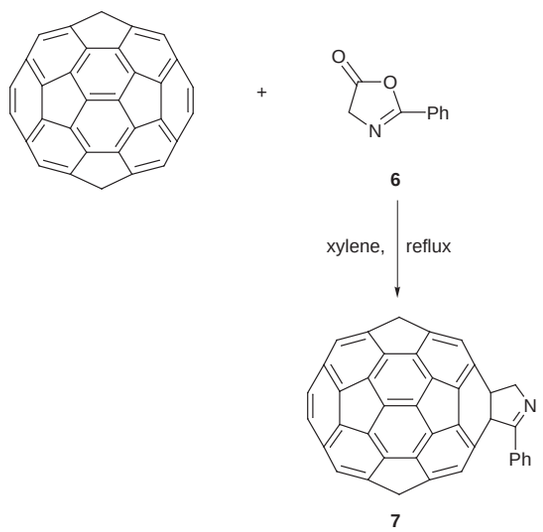


Fig. 2 ^{13}C NMR and ^{1}H NMR (in parentheses) data for compound **7**



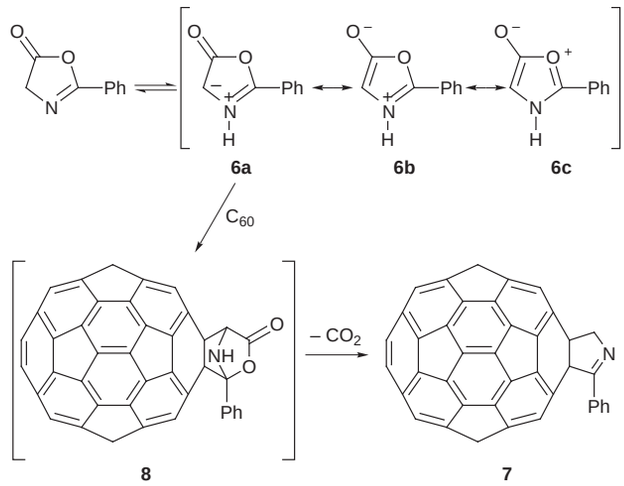
Scheme 5

characteristic bands of the fullerene moiety, a band at 1625 cm^{-1} (C=N) and bands for phenyl were observed. In the ^{1}H NMR spectrum, the methylene protons appeared at δ_H 5.97 as a singlet, and the phenyl protons appeared as three multiplets at δ_H 7.45, 7.47 and 8.08. The ^{13}C NMR spectrum of compound **7** exhibited a total of 36 lines, of which 30 correspond to the [60]fullerene framework. The single-intensity lines corresponding to the two sp^3-hybridized carbon atoms of fullerene appeared at δ_C 72.49 and 84.92, respectively. Two other fullerene lines located at δ_C 145.54 and 153.34 were of single intensity, and 24 fullerene lines were of double intensity. The overlapping signals were observed at δ_C 145.34 and 145.57 and were of quadruple intensity. This is consistent with the C_s symmetry of compound **7**, which requires 32 peaks for the fullerene moiety. The proposed structure of compound **7** was further substantiated by HMQC and HMBC spectra. Assignable NMR spectral data are shown in Fig. 2.

A possible mechanism for the reaction is outlined in Scheme 6:[11] there is a thermal tautomeric equilibration between compound **6** and the mesoionic oxazolium 5-oxides **6a**, **6b** and **6c**, where the resonance formula **6a** indicates a cyclic, aromatic azomethine ylide. Then ylide **6a** and [60]fullerene undergo 1,3-dipolar cycloaddition to afford intermediate product **8**. This species loses CO_2 on heating, rearranging to the final product **7**.

Conclusions

In summary, three kinds of derivatives of [60]fullerene were prepared *via* a process of 1,3-dipolar cycloaddition. [60]Fullerene reacted with imines **1** to give fullerene-fused proline derivatives **2**. All the reactions gave the *cis*-isomers as major products and *trans*-isomers as the minor ones. In the reaction of [60]-fullerene with depsipeptide **1b**, another (unexpected) secondary reaction product, compound **3**, was also obtained besides the predicted products. Thermal depolymerization of 1,3,5-tris-(ethoxycarbonylmethyl)perhydro-1,3,5-triazine **4** generated an



Scheme 6

azomethine ylide. This reactive intermediate reacted with [60]-fullerene to afford ethyl 2′,5′-dihydro-1′*H*-pyrrolo[3′,4′ : 1,2]-[60]fullerene-2′-carboxylate **5**. As a cyclic azomethine ylide, mesoionic oxazolium 5-oxide **6a** was generated from heating of 2-phenyloxazol-5(4*H*)-one **6**. [60]Fullerene reacted with this kind of cyclic azomethine ylide, and 5′-phenyl-2′*H*-pyrrolo-[3′,4′ : 1,2][60]fullerene **7** was prepared.

Experimental

For starting materials **1**, **4** and **6**: IR spectra were measured on a Shimadzu IR-408 spectrometer; ^{1}H NMR spectra were run on a JNM-PM X 60 Si (JEOL) spectrometer; *J*-values are given in Hz; mass and high-resolution mass spectra were recorded on an HP5989A mass spectrometer. For compounds **2**, **3**, **5** and **7**: IR spectra were measured on a Nicolet FT IR-5DX spectrometer; ^{1}H NMR, ^{13}C NMR, ^{1}H NOESY, HMQC and HMBC spectra were run on a Brucker AMX-600 spectrometer; *J*-values are given in Hz; the ^{13}C NMR data are all 1 C except where noted; UV-VIS spectra were obtained with a Shimadzu UV-240 spectrometer; FD-MS spectra were recorded on a Finnigan MAT 90 mass spectrometer. The yields of products **2**, **3**, **5** and **7** are based on consumed C_{60} ([60]fullerene). Xylene refers to a commercial mixture of the three isomers *o*-, *m*- and *p*-xylene plus ethylbenzene.

1. Preparation of imines 1. Ethyl *N*-(*N*-benzylideneglycyl)-glycinate 1b

A suspension of 3.9 g (0.02 mol) of ethyl glycylglycinate hydrochloride, 2.0 ml (0.02 mol) of freshly distilled benzaldehyde and 3.7 g of anhydrous sodium sulfate in 40 ml of methylene dichloride was cooled to 0 °C and stirred. To this suspension was added dropwise a solution of 2.8 ml (0.02 mol) of triethylamine in 3 ml of methylene dichloride. The reaction mixture was stored overnight at room temperature while being stirred. Then 50 ml of anhydrous diethyl ether was added. The insoluble material was filtered off. The filtrate was washed successively with water and brine, dried over anhydrous sodium sulfate, and concentrated to give title compound **1b** (4.8 g, 96%); ν_{max}(neat)/cm^{-1} 3350, 2950, 2850, 1740, 1690, 1665, 1590, 1575, 1515, 1370, 1300, 1200, 1020, 745 and 680; δ_H(60 MHz; CCl_4) 1.2 (3 H, t, *J* 7, CH_3), 3.8–4.2 (6 H, m, 3 × CH_2), 7.1–7.7 (5 H, m, ArH) and 8.1 (1 H, s, HC=N); *m*/*z* 249 (M^+ + 1, 100%), 247 (M^+ − 1, 1), 118 (37) and 91 (21) (HRMS: Calc. for $C_{13}H_{15}N_2O_3$: *m*/*z*, 247.1083. Found: *m*/*z*, 247.1079).

Methyl *N*-benzylideneglycinate 1a[12,13]

This was prepared from 2.5 g (0.022 mol) of methyl glycinate hydrochloride and 2.0 ml (0.02 mol) of freshly distilled benzaldehyde in a similar procedure to that for compound **1b**, yield

2.6 g (73%); ν_{max}(neat)/cm^{-1} 1740, 1645, 1450, 1430, 1270, 1200, 1170, 1050, 750 and 690; δ_H(60 MHz; CCl_4) 3.3 (3 H, s, OCH_3), 3.6 (2 H, s, NCH_2), 7.1–7.3 (3 H, m, ArH), 7.5–7.7 (2 H, m, ArH) and 8.1 (1 H, s, CH=N).

Diethyl *N*-benzylideneaminomethylphosphonate 1c[14]

This was prepared from 1.67 g (0.01 mol) of diethyl aminomethylphosphonate and 1.0 ml (0.01 mol) of freshly distilled benzaldehyde in a similar procedure to that for compound **1b**, yield 2.5 g (98%); ν_{max}(neat)/cm^{-1} 3450, 3050, 2950, 2900, 2850, 1640, 1575, 1450, 1385, 1310, 1245, 1160, 1025, 960, 750 and 690; δ_H(60 MHz; CCl_4) 1.3 (6 H, t, *J* 7, CH_3), 4.0 (6 H, m, $CH_2P + 2 \times OCH_2$), 7.2 (3 H, m, ArH), 7.5 (2 H, m, ArH) and 8.1 (1 H, d, $^4J_{H\text{-}P}$ 5, CH=N).

2. Preparation of 1,3,5-tris(ethoxycarbonylmethyl)perhydro-1,3,5-triazine 4

A suspension of 2.8 g (0.02 mol) of ethyl glycinate hydrochloride and 6 g (0.2 mol) of paraformaldehyde in 40 ml of methylene dichloride was cooled to 0 °C and stirred. To this suspension was added a solution of 2.8 ml (0.02 mol) of triethylamine in 3 ml of methylene dichloride dropwise. The reaction mixture was stirred while stored for 60 h at room temperature. After removal of solvent, the residue was taken up in 50 ml of anhydrous diethyl ether and the insoluble material was filtered off. The filtrate was washed successively with water and brine, dried over anhydrous sodium sulfate, and concentrated to give title compound **4** (1.6 g, 69%), ν_{max}(neat)/cm^{-1} 2950, 2870, 2840, 1730, 1440, 1420, 1380, 1270, 1180, 1150, 1025, 900 and 845; δ_H(60 MHz; CCl_4) 1.3 (9 H, t, *J* 7, CH_3), 3.3 (6 H, s, CH_2), 3.6 (6 H, s, CH_2) and 4.1 (6 H, q, *J* 7, OCH_2); *m*/*z*, 345 (M^+, 1%), 344 ($M^+ - 1$, 3), 157 (61), 116 (61), 88 (20) and 42 (100). (HRMS: Calc. for $C_{15}H_{26}N_3O_6$: *m*/*z*, 344.1822. Found: *m*/*z*, 344.1788).

3. Preparation of 2-phenyl-4,5-dihydrooxazol-5-one 6

2-Phenyl-4,5-dihydrooxazol-5-one **6** was prepared from 5.37 g (0.03 mol) of hippuric acid and 16 ml of acetic anhydride in a similar procedure to that of Ingersoll.[15] Yield 2.1 g (44%), mp 78–83 °C (lit.,[15] 89–92 °C); ν_{max}(KBr)/cm^{-1} 1800, 1750, 1645, 1550, 1445, 1390, 1320, 1140, 1030, 1020, 875, 770 and 685; δ_H(60 MHz; CCl_4) 4.2 (2 H, s, CH_2N), 7.4 (3 H, m, ArH) and 7.8 (2 H, m, ArH).

4. Preparation of methyl 5′-phenyl-2′,5′-dihydro-1′*H*-pyrrolo-[3′,4′ : 1,2][60]fullerene-2′-*trans*-carboxylate *trans*-2a and methyl 5′-phenyl-2′,5′-dihydro-1′*H*-pyrrolo[3′,4′ : 1,2][60]-fullerene-2′-*cis*-carboxylate *cis*-2a †

A mixture of 72 mg of C_{60} (0.1 mmol) and 20 μl of ester **1a** was dissolved in 50 ml of toluene and the solution was heated at 110 °C and stirred for 24 h under nitrogen. Then the solution was concentrated and poured onto the top of a silica gel column. The column was then eluted with *n*-hexane–toluene (1 : 1) first, to give 30.8 mg of unchanged C_{60}, and then with *n*-hexane–methylene dichloride (1 : 1) to afford products *trans*-**2a** (11 mg, 21%) and *cis*-**2a** (20.6 mg, 40%); λ_{max}(CH_2Cl_2)/nm (*trans*-**2a**) 256s, 310s and 428w; (*cis*-**2a**) 256s, 310s and 428w; ν_{max}(KBr)/cm^{-1} (*trans*-**2a**) 3452, 2943, 2918, 2853, 1744, 1456, 1428, 1184, 1153, 753, 734, 697, 575 and 528; (*cis*-**2a**) 3452, 2927, 1853, 1737, 1509, 1459, 1431, 1203, 1181, 762, 734, 575 and 528; δ_H(60 MHz; $CDCl_3$) (*trans*-**2a**) 3.89 (3 H, s, OCH_3), 5.78 (1 H, s, 2′-H), 6.51 (1 H, s, 5′-H), 7.29 (1 H, t, *J* 7.3, ArH), 7.36 (2 H, t, *J* 7.4, ArH) and 7.82 (2 H, d, *J* 7.4, ArH); (*cis*-**2a**) 3.86 (3 H, s, OCH_3), 5.60 (1 H, s, 2′-H), 5.81 (1 H, s, 5′-H), 7.32 (1 H, t, *J* 7.4, ArH), 7.40 (2 H, t, *J* 7.5, ArH) and 7.72 (2 H, d, *J* 7.4, ArH); δ_C[150.9 MHz; $(CD_3)_2CO$–CS_2 (1 : 10)] (*trans*-**2a**) 51.61 (OCH_3), 70.89 and 73.84 (C-2′ and -5′), 73.21 and 75.98 (sp^3-C for C_{60}), 128.30 (aryl, overlapped), 128.50 (aryl), 135.68, 135.72, 136.22, 136.44, 138.05 (2 C), 139.39, 139.45, 139.83, 139.88, 141.38, 141.53, 141.64, 141.87 (3 C), 141.97 (3 C), 142.11 (2 C), 142.42 (2 C), 142.55, 142.85, 142.94, 144.11, 144.36, 144.45, 144.76, 144.96, 145.02 (2 C), 145.09, 145.12, 145.28 (3 C), 145.50, 145.75 (3 C), 145.84, 145.89, 146.02 (2 C), 146.15 (3 C), 146.43 (3 C), 146.99, 147.14, 151.51, 153.21, 153.86, 155.97 and 171.99 (CO); (*cis*-**2a**) 51.90 (OCH_3), 73.02 and 75.89 (C-2′ and -5′), 75.45 and 78.98 (sp^3-C for C_{60}), 128.00 (aryl), 128.46 (aryl), 128.73 (aryl), 135.39, 135.83, 136.17, 136.38 (2 C), 137.09, 139.30, 139.49, 139.56, 139.84, 141.42, 141.51, 141.77 (2 C), 141.85 (2 C), 141.91, 141.96, 142.02, 142.15 (2 C), 142.25, 142.46 (3 C), 142.83, 142.93, 144.08, 144.13, 144.26, 144.36, 144.96 (2 C), 145.04, 145.11 (2 C), 145.27 (2 C), 145.41 (2 C), 145.52, 145.70 (3 C), 145.81 (2 C), 146.03, 146.07, 146.10, 146.17 (2 C), 146.82 (2 C), 146.94, 151.11, 152.33, 152.76, 153.00 and 168.78 (CO); *m*/*z* (*trans*-**2a**) 897 (M^+ of $C_{70}H_{11}NO_2$, 20%) and 720 (C_{60}, 100) (*cis*-**2a**) 897 (M^+ of $C_{70}H_{11}NO_2$, 80%) and 720 (C_{60}, 100).

5. Preparation of ethyl *N*-(5′-phenyl-2′,5′-dihydro-1′*H*-pyrrolo-[3′,4′ : 1,2][60]fullerene-2′-*trans*-ylcarbonyl)glycinate *trans*-2b and ethyl *N*-(5′-phenyl-2′,5′-dihydro-1′*H*-pyrrolo[3′,4′ : 1,2][60]-fullerene-2′-*cis*-ylcarbonyl)glycinate *cis*-2b

A stirred solution of 73.5 mg (0.10 mmol) of C_{60} and 151.8 mg (0.61 mmol) of depsipeptide **1b** in 50 ml of xylene was heated to 130 °C under nitrogen for 9 h. The solution was poured onto a silica gel column and eluted with *n*-hexane–toluene (1 : 1), first, to give 29.8 mg of unchanged C_{60}, and then with methylene dichloride–ethyl acetate (20 : 1) to afford by-product **3** (0.7 mg, 1%) and major products *cis*-**2b** (26.4 mg, 45%) and *trans*-**2b** (7.0 mg, 12%); λ_{max}(CH_2Cl_2)/nm (*cis*-**2b**) 256s, 310s, 330sh and 430w; (*trans*-**2b**) 256s, 310s, 330sh and 430w (**3**) 256s, 310s, 330sh and 430w; ν_{max}(KBr)/cm^{-1} (*cis*-**2b**) 3409, 2973, 2924, 2847, 1744, 1687, 1516, 1456, 1428, 1375, 1203, 1094, 1025, 762, 700, 575, 547 and 528 (*trans*-**2b**) 3423, 2973, 2924, 2861, 1744, 1712, 1422, 1394, 1372, 1203, 1172, 1094, 1028, 750, 700, 644, 566 and 525 (**3**) 3437, 1747, 1716, 1494, 1456, 1425, 1375, 1262, 1200, 1100, 1059, 1028, 766, 737, 700, 575, 547 and 528; δ_H[600 MHz; $(CD_3)_2CO$–CS_2 (1 : 10)] (*cis*-**2b**) 1.26 (3 H, t, *J* 7.1, CH_3), 3.95–3.99 and 4.05–4.09 (2 H, m, J_{AB} 17.9, J_d 5.4, CH_2CO_2), 4.12 (2 H, q, *J* 7.1, OCH_2), 5.41 (1 H, s, 2′-H), 5.84 (1 H, s, 5′-H), 7.28 (1 H, t, *J* 7.4, ArH), 7.35 (2 H, t, *J* 7.4, ArH), 7.81 (2 H, d, *J* 7.4, ArH) and 7.95 (1 H, t, *J* 5.4, CONH) (*trans*-**2b**) 1.33 (3 H, t, *J* 7.1, CH_3), 4.25 (2 H, q, *J* 7.1, OCH_2), 4.68 (2 H, s, CH_2CO_2), 4.75 (1 H, s, CONH), 5.69 (1 H, s, 2′-H), 6.51 (1 H, s, 5′-H), 7.24 (1 H, t, *J* 7.4, ArH), 7.32 (2 H, t, *J* 7.4, ArH) and 7.76 (2 H, d, *J* 7.4, ArH) (**3**) 1.33 (3 H, t, *J* 7.1, CH_3), 3.58 and 4.81 (2 H, AB, J_{AB} 18.0, CH_2CO_2), 4.18–4.24 and 4.25–4.30 (2 H, m, J_{AB} 17.8, J_q 7.1, OCH_2), 5.53 (1 H, s, 2′-H), 5.82 (1 H, s, NCHN), 6.16 (1 H, s, 5′-H) and 7.32–7.95 (10 H, m, ArH); δ_C[150.9 MHz; $(CD_3)_2CO$–CS_2 (1 : 10)] (*cis*-**2b**) 15.00 (CH_3), 41.44 ($NHCH_2$), 61.69 (OCH_2), 75.43 and 73.66 (C-2′ and -5′), 76.85 and 74.02 (sp^3-C for C_{60}), 128.88 (aryl), 129.06 (aryl), 129.21 (aryl), 135.91, 136.21, 137.12, 137.36, 137.80, 139.73, 139.88, 140.20, 140.36, 141.92, 142.15, 142.28 (2 C), 142.39, 142.42, 142.48, 142.61 (2 C), 142.78, 142.96, 142.99 (2 C), 143.02 (2 C), 143.36, 143.45, 144.65, 144.81, 144.89, 145.04, 145.50, 145.51, 145.60 (2 C), 145.64, 145.84 (2 C), 145.93, 146.04, 146.09, 146.28, 146.33, 146.36 (2 C), 146.43, 146.61, 146.64, 146.68, 146.70, 146.87, 146.89, 147.57 (2 C), 147.82, 152.37, 153.23, 153.36, 153.82, 168.73 (CO) and 169.34 (CONH) (*trans*-**2b**) 14.96 (CH_3), 43.89 ($NHCH_2$), 62.17 (OCH_2), 76.78 and 70.68 (C-2′ and -5′), 73.63 and 70.02 (sp^3-C for C_{60}), 129.06 (overlapped, aryl), 129.25 (aryl), 134.94, 135.89, 136.59, 137.64 (2 C), 138.02, 139.36, 141.24, 141.58, 141.84, 142.77, 142.90 (2 C), 143.08, 143.26 (2 C), 143.53, 144.01, 144.13, 144.24, 144.28, 144.46, 144.61 (2 C), 144.75 (2 C), 144.80, 144.91 (2 C), 144.93 (2 C), 145.15, 145.31, 145.43 (2 C), 145.84 (2 C), 146.05, 146.14, 146.48, 146.81 (2 C), 147.07,

† *cis* and *trans* in compounds **2** refer to the relationship between the 2′ and 5′ substituents.

147.24, 147.47 (2 C), 147.51 (2 C), 147.56, 148.04, 148.38, 148.74, 149.09, 149.62, 149.73 (2 C), 150.44, 151.84, 168.35 (CO) and 170.88 (CONH) (**3**) 14.97 (CH_3), 42.17 (NCH_2), 62.05 (OCH_2), 69.95 (C-1, sp^3-C for C_{60}), 73.63 (C-2′), 75.93 (C-2, sp^3-C for C_{60}), 78.54 (NCHN), 80.19 (C-5′), 127.06 (aryl), 129.29 (aryl), 129.45 (aryl), 129.64 (aryl), 129.81 (aryl), 130.60 (aryl), 135.72, 136.55, 137.11 (2 C), 137.18, 137.57, 139.94, 140.12, 140.23, 140.50, 141.92, 142.07, 142.12, 142.18, 142.36, 142.41, 142.45, 142.51 (2 C), 142.88 (2 C), 142.92, 142.96, 143.06, 143.37, 143.50, 144.68, 144.92, 144.96, 145.10, 145.17, 145.47, 145.57, 145.63, 145.81 (2 C), 145.85, 145.91, 146.01, 146.11, 146.17, 146.38 (2 C), 146.42, 146.48, 146.55, 146.64 (2 C), 146.73, 146.76, 146.78, 146.89, 147.73 (2 C), 153.00, 153.19, 153.24, 156.04, 168.65 (CO) and 170.57 (NCO); *m*/*z* (*cis*-**2b**) 969 ($M^+ + 1$ for $C_{73}H_{16}N_2O_3$, 96%) and 720 (C_{60}, 100) (*trans*-**2b**) 969 ($M^+ + 1$ for $C_{73}H_{16}N_2O_3$, 100%) and 720 (C_{60}, 88) (**3**) 1056 (M^+ for $C_{80}H_{20}N_2O_3$, 84%) and 720 (C_{60}, 100).

6. Preparation of diethyl (5′-phenyl-2′,5′-dihydro-1′*H*-pyrrolo-[3′,4′ : 1,2][60]fullerene-2′*trans*-yl)phosphonate *trans*-2c and diethyl (5′-phenyl-2′,5′-dihydro-1′*H*-pyrrolo[3′,4′ : 1,2][60]-fullerene-2′-*cis*-yl)phosphonate *cis*-2c

A stirred solution of 100 mg (0.14 mmol) of C_{60} and 100 mg (0.39 mmol) of phosphonate **1c** in 60 ml of xylene was heated at reflux under nitrogen for 16 h. Then the solution was concentrated to ~10 ml and poured onto the top of a silica gel column. The column was then eluted with *n*-hexane–toluene (1 : 1), first, to give 74 mg of unchanged C_{60}, and then with methylene dichloride–ethyl acetate (20 : 1) to afford products *trans*-**2c** (7.2 mg, 20%) and *cis*-**2c** (20.6 mg, 58%); $\lambda_{max}(CH_2Cl_2)$/nm (*trans*-**2c**) 230s, 257s, 310s and 432w (*cis*-**2c**) 230s, 257s, 310s and 432w; ν_{max}(KBr)/cm^{-1} (*trans*-**2c**) 2971, 2915, 2851, 1454, 1435, 1430, 1389, 1243, 1186, 1161, 1093, 1046, 1022, 964, 877, 761, 699, 570 and 532 (*cis*-**2c**) 2971, 2915, 2851, 1454, 1430, 1389, 1364, 1243, 1186, 1161, 1093, 1046, 1022, 964, 871, 761, 749, 707, 699, 583, 570, 545 and 532; δ_H[600 MHz; $(CD_3)_2CO$–CS_2 (1 : 10)] (*trans*-**2c**) 1.26 (3 H, t, *J* 7.0, CH_3), 1.45 (3 H, t, *J* 7.0, CH_3), 4.05–4.19 (2 H, m, OCH_2), 4.35–4.45 (2 H, m, OCH_2), 5.33 (1 H, d, $^2J_{H\text{-}P}$ 10.4, 2′-H), 6.52 (1 H, s, 5′-H), 7.27 (1 H, t, *J* 7.4, ArH), 7.34 (2 H, t, *J* 7.7, ArH) and 7.73 (2 H, d, *J* 7.2, ArH) (*cis*-**2c**) 1.33 (3 H, t, *J* 4.9, CH_3), 1.34 (3 H, t, *J* 4.9, CH_3), 4.23–4.33 (4 H, m, OCH_2), 5.14 (1 H, d, $^2J_{H\text{-}P}$ 10.6, 2′-H), 5.75 (1 H, s, 5′-H), 7.28 (1 H, t, *J* 7.4, ArH), 7.35 (2 H, t, *J* 7.6, ArH) and 7.77 (2 H, d, *J* 7.3, ArH); δ_C[150.9 MHz; $(CD_3)_2CO$–CS_2 (1 : 10)] (*trans*-**2c**) 16.52 (d, $^3J_{C\text{-}P}$ 5.4, CH_3), 16.87 (d, $^3J_{C\text{-}P}$ 5.4, CH_3), 61.69 (d, $^2J_{C\text{-}P}$ 7.2, OCH_2), 63.46 (d, $^2J_{C\text{-}P}$ 6.9, OCH_2), 67.85 (d, $^1J_{C\text{-}P}$ 157.5, C-2′), 73.19 (C-2, sp^3-C for C_{60}), 74.60 (C-5′), 78.60 (C-1, sp^3-C for C_{60}), 128.32 (overlapped, aryl), 128.60 (aryl), 135.12, 136.09, 136.98, 137.46 (2 C), 137.94, 139.12, 139.38, 139.91 (2 C), 141.60, 141.72, 141.83, 141.89, 141.94, 141.97, 142.00, 142.12 (2 C), 142.22, 142.31 (2 C), 142.52 (3 C), 142.67, 142.99, 143.05, 144.29, 144.39, 144.48 (2 C), 144.72, 145.05, 145.08, 145.09, 145.20, 145.25 (3 C), 145.58, 145.64, 145.84 (2 C), 145.87, 145.89, 146.09, 146.12, 146.19, 146.23, 146.83, 146.96, 146.99, 147.11, 152.03 (1 C, d, $^3J_{C\text{-}P}$ 1.6), 153.64, 143.82 and 156.82 (1 C, d, $^3J_{C\text{-}P}$ 9.0) (*cis*-**2c**) 16.58 (overlapped, CH_3), 62.83 (d, $^2J_{C\text{-}P}$ 6.5, OCH_2), 62.91 (d, $^2J_{C\text{-}P}$ 6.5, OCH_2), 68.62 (d, $^1J_{C\text{-}P}$ 163.9, C-2′), 73.41 (C-2, sp^3-C for C_{60}), 77.44 (d, $^3J_{C\text{-}P}$ 22.0, C-5′), 78.79 (d, $^2J_{C\text{-}P}$ 11.5, C-1, sp^3-C for C_{60}), 128.37 (aryl), 128.45 (aryl), 128.67 (aryl), 135.38, 135.85, 136.50, 136.67, 137.20, 138.75, 139.13, 139.43, 139.88, 141.44, 141.50, 141.83, 141.85, 141.91, 141.94, 141.96, 142.07, 142.13, 142.14, 142.24, 142.33, 142.51, 142.57 (2 C), 142.62, 142.85, 143.09, 144.21, 144.48, 144.61, 145.05 (2 C), 145.07, 145.12, 145.16, 145.24 (2 C), 145.47, 145.55, 145.75, 145.79, 145.81, 145.90, 145.94, 146.02, 146.13, 146.18, 146.21, 146.24, 146.33, 146.55, 146.97, 147.04, 147.59, 152.68, 153.11, 153.37 (1 C, d, $^3J_{C\text{-}P}$ 5.3) and 153.94; *m*/*z* (*trans*-**2c**) 975 (M^+ for $C_{72}H_{18}NO_3P$, 5%) and 720 (C_{60}, 100) (*cis*-**2c**) 975 (M^+ for $C_{72}H_{18}NO_3P$, 26%) and 720 (C_{60}, 100).

7. Preparation of ethyl 2′,5′-dihydro-1′*H*-pyrrolo[3′,4′ : 1,2][60]-fullerene-2′-carboxylate 5

A stirred solution of 71.6 mg (0.099 mmol) of C_{60} and 68.1 mg (0.20 mmol) of trimer **4** in 50 ml of toluene was heated to 90 °C for 32 h. The solution was poured onto a silica gel column and eluted with *n*-hexane–toluene (1 : 1), first, to give 30.7 mg of unchanged C_{60}, and then with methylene dichloride–ethyl acetate (12 : 1) to afford title compound **5** (36.4 mg, 77%); $\lambda_{max}(CH_2Cl_2)$/nm 256s, 310s and 430w; ν_{max}(KBr)/cm^{-1} 3444, 2973, 2924, 2861, 1741, 1428, 1369, 1250, 1187, 794, 766, 575, 553 and 528; δ_H[600 MHz; $(CD_3)_2CO$–CS_2 (1 : 10)] 1.25 (3 H, t, *J* 7.1, CH_3), 4.18–4.23 and 4.28–4.33 (2 H, m, J_{AB} 18.0, J_q 7.1, OCH_2), 4.69 and 5.03 (2 H, AB, J_{AB} 12.2, CH_2N) and 5.34 (1 H, s, $CHCO_2$); δ_C[150.9 MHz; $(CD_3)_2CO$–CS_2 (1 : 10)] 15.51 (CH_3), 62.52 and 63.95 (pyrrolidine ring), 75.91 (OCH_2), 76.11 and 78.03 (sp^3-C for C_{60}), 136.30, 136.34, 136.68, 137.66, 140.33, 140.59, 141.09, 141.19, 142.55, 142.62, 142.70, 142.86, 142.92 (3 C), 143.03 (2 C), 143.23, 143.26, 143.48 (3 C), 143.50 (2 C), 143.89, 143.99, 145.09, 145.13, 145.18, 145.36, 145.98, 146.03 (2 C), 146.11 (2 C), 146.17, 146.22 (2 C), 146.32, 146.47, 146.58, 146.77 (5 C), 146.81, 147.01, 147.06 (2 C), 147.12, 147.44, 147.79, 147.88, 151.79, 154.36, 154.75, 155.91 and 169.39 (CO); *m*/*z* 836 ($M^+ + 1$ for $C_{65}H_9NO_2$, 100%).

8. Preparation of 5′-phenyl-2′*H*-pyrrolo[3′,4′ : 1,2][60]fullerene 7

A stirred solution of 76 mg (0.10 mmol) of C_{60} and 76 mg (0.47 mmol) of the oxazolidone **6** in 50 ml of xylene was heated to 155 °C under nitrogen for 12 h. Then the reaction mixture was concentrated to 20 ml and poured onto the top of a silica gel column. The column was then eluted with *n*-hexane–toluene (1 : 1), first, to give 58.7 mg of unchanged C_{60}, and then with *n*-hexane–methylene dichloride (1 : 2) to afford title compound **7** (18.0 mg, 90%); $\lambda_{max}(CH_2Cl_2)$/nm 230s, 256s, 310s, 330sh and 428w; ν_{max}(KBr)/cm^{-1} 1625, 1428, 1303, 1261, 1184, 1040, 1028, 996, 765, 759, 650, 603, 575 and 528; δ_H[600 MHz; $(CD_3)_2CO$–CS_2 (1 : 5)] 5.97 (2 H, s, CH_2N), 7.45 (1 H, m, ArH), 7.47 (2 H, m, ArH) and 8.08 (2 H, m, ArH); δ_C[150.9 MHz; $(CD_3)_2CO$–CS_2 (1 : 5) with 3 mg of $Cr(acac)_3$ as relaxant reagent] 72.49 (1 C, sp^3-C for C_{60}), 75.56 (1 C, CH_2), 84.92 (1 C, sp^3-C for C_{60}), 128.84 (2 C, arom *m*-C), 129.33 (2 C, arom *o*-C), 130.64 (1 C, arom *p*-C), 134.50 (2 C), 134.96 (1 C, quaternary arom), 136.33 (2 C), 140.23 (2 C), 140.64 (2 C), 141.86 (2 C), 142.19 (2 C), 142.27 (2 C), 142.39 (2 C), 142.48 (2 C), 142.72 (2 C), 142.86 (2 C), 142.94 (2 C), 143.39 (2 C), 144.24 (2 C), 144.61 (2 C), 145.34 (4 C), 145.54, 145.57 (4 C), 145.99 (2 C), 146.05 (2 C), 146.12 (2 C), 146.21 (2 C), 146.48 (2 C), 147.10 (2 C), 147.30 (2 C), 148.04 (2 C), 153.34, 154.84 (2 C) and 168.67 (1 C, C=N); *m*/*z* 837 (M^+ for $C_{68}H_7N$, 100%).

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