Synthesis of Benzoate-Functionalized Phosphanes as Novel Building Blocks for the Traceless Staudinger Ligation

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Abstract: A new synthetic pathway for the preparation of benzoate-functionalized phosphanes for microwave-mediated traceless Staudinger ligations is described. Novel phosphane derivatives based on 4-substituted iodophenyl benzoates were prepared via palladium(II)-catalyzed P–C cross-coupling reaction strategy in high yields. The application of microwave conditions for the ligation reactions reduced the reaction time considerably. An approach to fast and facile labeling strategies using this ligation was established.

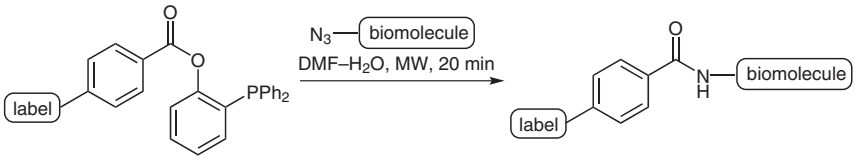
Key words: Staudinger ligation, traceless, click chemistry, P–C cross-coupling, palladium-catalyzed

The Staudinger ligation[1] is widely used in biochemistry and medicinal chemistry for the interconnection of molecular entities like carbohydrates, amino acids, and proteins to give various hybrid-bioconjugates under mild conditions.[2–5] Moreover, the incorporation of molecular probes into biomolecules, as frequently exemplified by fluorescence labels, has gained great interest over the last years to study metabolic pathways in complex biological systems[6] as pointed out in Scheme 1. Despite the desirable bioorthogonal character of the reaction partners through chemoselective reaction between organic azides and phosphanes, and the mild reaction conditions, the major drawback of the Staudinger ligation lies in its very long reaction time of up to 24 hours upon completion. However, in 2008 Bernardi and co-workers demonstrated the beneficial effect of microwave activation to reduce reaction times to less than one hour by synthesizing glycosyl amides via the Staudinger ligation.[7]

Acylated phosphanes are of great interest as versatile building blocks for the traceless Staudinger ligation. Most of these phosphanes were prepared by reacting aliphatic carboxylic acid chlorides or anhydrides with phosphanophenol leading to the corresponding phosphane-functionalized esters.[3] Recently Xian et al. demonstrated a reductive ligation procedure involving *S*-nitrosothiols based on a benzoate-functionalized phosphanes.[8]

Palladium-catalyzed carbon–carbon and carbon–heteroatom cross-coupling reactions are widely used in synthetic organic chemistry for various arylation and acylation reactions involving a broad variety of organic substrates.[9] However, only a few reports in the literature deal with the synthesis of phosphanes using metal-catalyzed P^{III}–C cross-coupling reactions, mainly through Stille-type reactions.[10] The synthetic application of P–C coupling reactions was improved by the direct use of secondary phosphanes as shown by the group of Stelzer and co-workers in 1996.[11] They described a direct route towards tertiary phosphanes containing polar substituents via a palladium(II)-catalyzed P–C cross-coupling reaction between aryl halides and $HPPh_2$ or H_2PPh. Further improvements were implemented by the use of borane-protected phosphanes in ionic liquids as reported by Valette et al.[12] or by the use of triflates as more reactive leaving groups.[13] The high hydrophilicity of these phosphanes is an advantage for their application in reactions in polar or aqueous solvents and in biological systems.

In this paper, we describe an easy access to novel benzoate-functionalized phosphanes as versatile building blocks for traceless Staudinger reaction and their application in microwave-mediated Staudinger ligation. This approach represents an interesting synthesis route for subsequent incorporation of various molecular probes into bioactive molecules. Moreover, an efficient procedure for the protection of phosphanes via borane-phosphane adduct formation is described, which enables subsequent functionalization reactions.



Scheme 1 Labeling strategy via the traceless Staudinger ligation

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The benzoate residue is an important motif for the incorporation of the short-lived positron emitter fluorine-18 (^{18}F, $t_{1/2}$ = 109.8 min) into biologically active molecules due to the high in vivo stability of the ^{18}F–C bond in 4-[^{18}F]fluorobenzoate groups.[14] Incorporation of ^{18}F into benzoates is usually accomplished via nucleophilic aromatic substitution with [^{18}F]fluoride on the activated aromatic system bearing 4-nitro, 4-trimethylammonium, or 4-iodo substituents as leaving group.

Conventional esterification of phosphanol **2** with appropriate benzoyl chlorides **3a–c** in the presence of a base like Et_3N or *t*-BuOK in THF, or via Steglich esterification (for **4d**) was envisaged for the synthesis of substituted phosphanes **4a–d** as shown in Scheme 2. However, application of these reaction conditions sometimes led to low chemical yields of the desired phosphanes and the formation of by-products, which made the purification steps difficult. Furthermore, the corresponding phosphane oxides were also formed in small amount (approx. 0.5–0.9%).

Therefore, we developed an alternative strategy based on palladium-catalyzed P–C cross-coupling reactions[11] between various 2-iodophenyl benzoates and diphenylphosphane. Two possibilities were applied for the preparation of substrates **6a–h** as intermediates for subsequent cross-couplings (Scheme 3). In the first set of reactions (method A) several 2-iodophenyl benzoates **6a–c** were prepared in excellent yields from 83 to 98% through the reaction of benzoyl chlorides **3a–c** with 2-iodophenol (**1**) in the presence of Et_3N as the base. A second approach (method B) was based on the reaction of benzoic acids **5d–h** with 2-iodophenol (**1**) and DCC/DMAP according to Steglich esterification[15] that delivers compounds **6d–h** in good yields of 39 to 81%. The results are summarized in Table 1.

In the next step, synthesis of benzoylated phosphanes **4a**,**b**,**e–h** was performed via palladium-catalyzed cross-coupling reaction of 2-iodophenyl benzoates **6a**,**b**,**e–h** with diphenylphosphane in the presence of KOAc, and

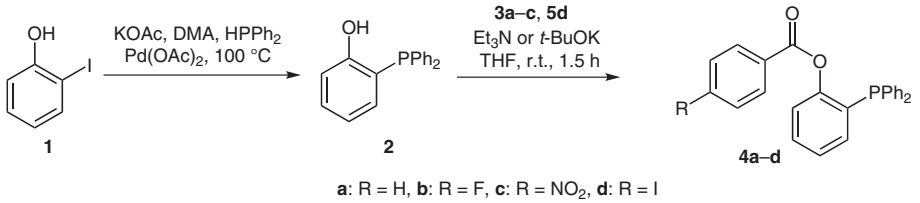
Table 1 2-Iodophenyl Benzoates **6a–h**

Substrate	R	Method	Product	Yield (%)
3a	H	A	**6a**	89
3b	F	A	**6b**	98
3c	NO_2	A	**6c**	83
5d	I	B	**6d**	74
5e	OCH_2CH_2OH	B	**6e**	81
5f	OCH_2CH_2F	B	**6f**	67
5g	OH	B	**6g**	39
5h	NMe_2	B	**6h**	42

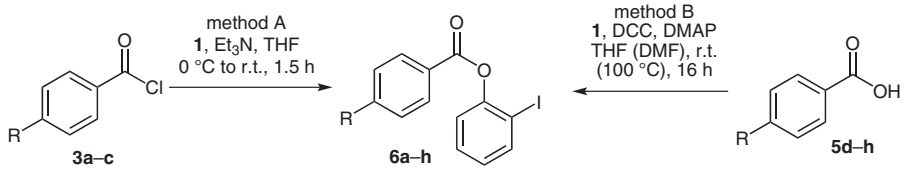
$Pd(OAc)_2$ as the catalyst. The reaction proceeded smoothly, and no protecting group manipulations for the OH groups in compounds **6e** and **6g** were necessary under these reaction conditions. The reactions were accomplished within 4 to 16 hours. After aqueous workup, purification of the crude product was carried out by column chromatography to afford the desired products **4a**,**b**,**e–h** in moderate to high chemical yields of 58 to 89% without the formation of by-products or oxidation products. Most of the studied functions seem to be compatible with these reaction conditions. However, no product formation was observed when the nitro-containing compound **6c** was subjected to palladium-catalyzed cross-coupling reaction. Scope and limitation of this formation are pointed out in Scheme 4 and Table 2.

^{31}P NMR investigations of phosphanes **4a–h** showed signals in the range of $\delta = -15$ indicative of aromatic organophosphanes in the oxidation state +3 (compared to $\delta = 30$[16] for Ph_3PO). The observed singlet indicates that no oxidized species were formed during the reaction.

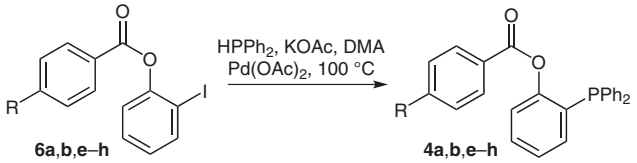
It was possible to obtain crystals from compound **4a** suitable for a single crystal X-ray structural analysis. Figure 1



Scheme 2 Synthesis of substituted phosphanes **4a–d**



Scheme 3 Synthesis of several 2-iodophenyl benzoates **6a–h** as synthons for the palladium-catalyzed P–C cross-coupling



a: R = H, **b**: R = F, **d**: R = OCH_2CH_2OH,
f: R = OCH_2CH_2F, **g**: R = OH, **h**: R = NMe_2

Scheme 4 Palladium-catalyzed cross-coupling of **6a**,**b**,**e–h** with $HPPh_2$

Table 2 Substituted Phosphanes **4a–h**

Substrate	R	Product	Yield (%)
3a	H	**4a**[a]	92
6a	H	**4a**[b]	79
3b	F	**4b**[a]	57
6b	F	**4b**[b]	65
3c	NO_2	**4c**[a]	38
6c	NO_2	**4c**[b]	n.d.[c]
5d	I	**4d**[a]	76
6e	OCH_2CH_2OH	**4e**[b]	89
6f	OCH_2CH_2F	**4f**[b]	67
6g	OH	**4g**[b]	58
6h	NMe_2	**4h**[b]	75

[a] Preparation via esterification (Scheme 2).
[b] Preparation via Pd-catalyzed P–C cross-coupling (Scheme 4).
[c] No formation of the desired product was observed by this method.

depicts the molecular structure of **4a**.[17] The central phosphorus atom has a pyramidal configuration, the P–C distances with an average of 1.83 Å are within the range of normal P–C single bonds (1.87 Å[18]).

Phosphane-borane adducts[19] are frequently applied to organic chemistry and catalysis. They are used for the synthesis of chiral phoshanes[20] and diphosphanes[21] as well as 'protecting group' for the preparation of key intermediates for the Staudinger ligation.[4] The main application of phosphane-borane adducts is stabilization of phosphorus at the oxidation state +3 to prevent side reactions. For further reactions involving alkyl halides leading to phosphonium salts or under oxidative conditions leading to phosphane oxides, the phosphorous is blocked with the BH_3 group. Two different synthesis pathways for borane-phosphane adducts are described in the literature. McNulty and co-workers reported a strategy based on the conversion of alkylphosphanes with $NaBH_4$ (or $LiBH_4$) as the borane source under acidic conditions.[22] An alternative approach is based on the transfer of the BH_3 group from a weaker $THF{\cdot}BH_3$ or $Me_2S{\cdot}BH_3$ adduct to phosphorus.[23]

In a first experiment, $HPPh_2$ (**7**) was protected with BH_3 according to literature procedures[24] resulting in the diphenylphosphane-borane adduct **8** followed by reaction of compound **8** with 2-iodophenol (**1**) under palladium(II) catalysis. Borane-protected phosphane **9** could not be isolated under these reaction conditions (Scheme 5).

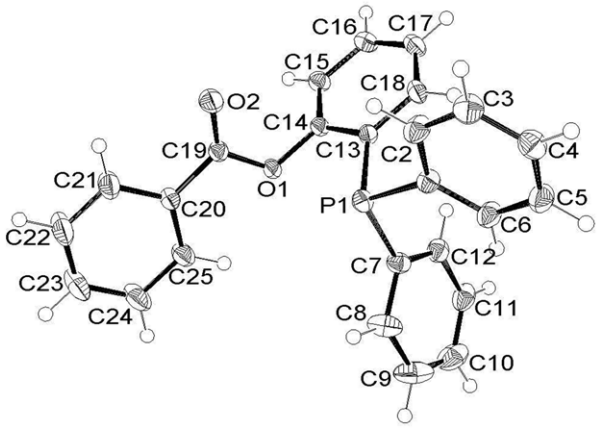
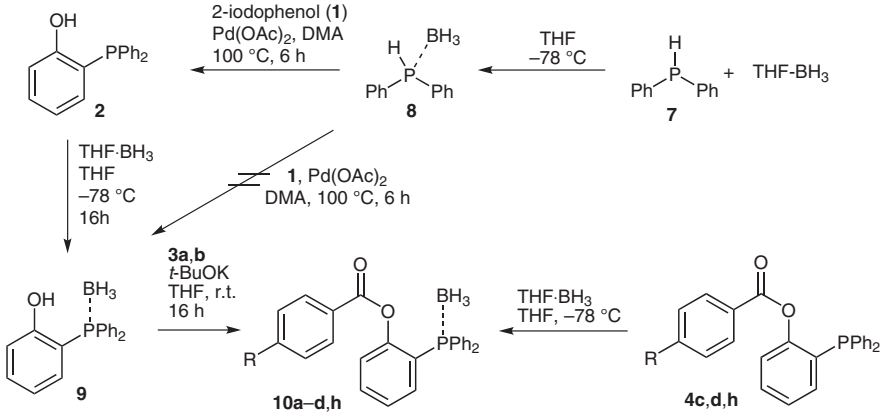


Figure 1 Molecular structure of compound **4a** (ORTEP-Plot, 50% probability level). Selected bond lengths (Å) and angles (°): P1–C1 1.8358(8), P1–C13 1.8339(8), P1–C7 1.8343(9), O2–C19 1.2060(10), O1–C19 1.3618(9), C19–O1–C14 116.01(6), O2–C19–O1 122.88(7), C13–P1–C7 101.65(4), C13–P1–C1 101.11(3).



a: R = H, **b**: R = F, **c**: R = NO_2, **d**: R = I, **h**: R = NMe_2

Scheme 5 Synthesis of phosphane-boranes **8**, **9**, and **10a–d**,**h**

Direct conversion of 2-(diphenylphosphano)phenol (**2**) into the phosphane borane adduct **9** was accomplished by the reaction with a 1 M THF·BH_3 solution at –78 °C. Warming up the reaction mixture to room temperature overnight, removal of the solvent, and subsequent purification of the crude product via column chromatography gave compound **9** as colorless crystals in 95% yield. Compound **9** functions as key intermediate for the preparation of all other substituted phosphane-borane compounds. For this purpose, compound **9** was likewise reacted with the benzoyl chloride derivatives **3a**,**b** in the presence of *t*-BuOK as the base. Products **10a**,**b** were obtained in good yields, respectively. Another possibility consists of the direct treatment of the substituted phosphanophenols **4c**,**d**,**h** with THF·BH_3 solution to give the corresponding phosphane-boranes **10c**,**d**,**h** in 67 to 85% yields. Scheme 5 and Table 3 summarize the synthesis and the obtained chemical yields.

Table 3 Synthesis of Borane Adducts **10a–d**,**h** by Protection with BH_3

Substrate	R	Product	Yield (%)	^{31}P NMR, δ	^{31}P NMR,[a] δ
3a	H	**10a**	60	19.8	–14.8
3b	F	**10b**	95	20.8	–14.6
4c	NO_2	**10c**	84	20.7	–14.7
4d	I	**10d**	67	21.0	–14.7
4h	NMe_2	**10h**	85	21.2	–14.8

[a] The ^{31}P NMR shifts belong to the unprotected phosphane compounds **4a–d**,**h**, respectively.

The presence of the BH_3 group was confirmed by the evaluation of ^{1}H, ^{13}C as well as ^{31}P NMR analysis. A broad multiplet originating from the borane protons was observed as a new signal between δ = 1–2 in the ^{1}H NMR spectra. Furthermore, a multiplet appears for the phosphorus atom that is shifted downfield from δ = ca. –15 for phosphanes to δ = ca. +20 for the phosphane-borane adducts in the ^{31}P NMR spectra. The multiplet results from complex couplings of the central phosphorus with ^{10}B, ^{11}B, and the borane protons. In the ^{11}B NMR spectrum a signal in the range of δ = –36 was observed, which is indicative of the BH_3 group.

In addition, it was possible to obtain crystals from compound **10c** suitable for a single crystal X-ray analysis[17] (Figure 2). The central phosphorus atom of this structure adopts a tetracoordinated configuration with the BH_3 group as fourth ligand. The P–B distance with 1.93 Å lies

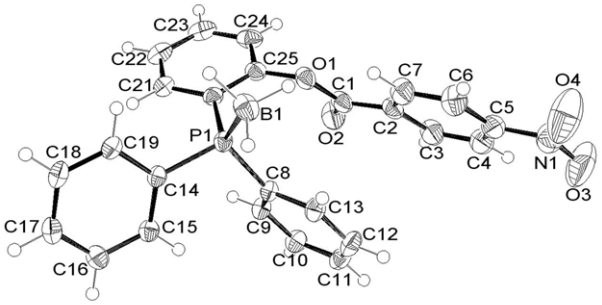


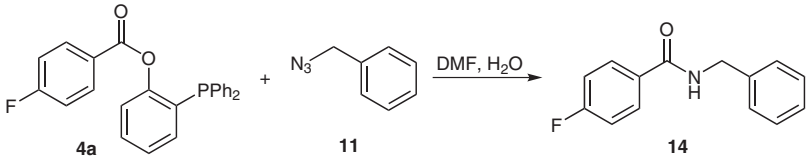
Figure 2 Molecular structure of compound **10c** (ORTEP-Plot, 50% probability level). Selected bond lengths (Å) and angles (°): P1–B1 1.9324(15), N1–O4 1.2178(24), C1–O1 1.3680(15), C1–O2 1.2002(17), B1–P1–C8 115.27(6), O4–N1–O3 123.67(18), C25–O1–C1 118.26(10), O1–C1–O2 123.97(13), O1–C1–C2 110.65(11).

in the range of the values typically found for Me_3PBH_3 (1.901 Å) or H_3PBH_3 (1.937 Å)[25] and an average of 1.81 Å was found for the P–C bonds (1.819 Å for Me_3PBH_3).

A special challenge for the application of Staudinger ligation involving the short-lived positron emitter ^{18}F is the relatively long time required for the reaction. To overcome this obstacle we have performed various attempts to accelerate the ligation procedure. First, as a test reaction phosphane **4a** was reacted with benzyl azide (**11**) at ambient temperature and at 90 °C (Scheme 6). Increasing the temperature was accompanied with a considerable reduction of reaction time from 6.5 hours to 1 hour to reach comparable chemical yields of compound **14**. In addition, the application of microwave activation at 50 Watt further reduced reaction time to 15 to 20 minutes (Table 4).

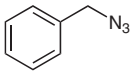
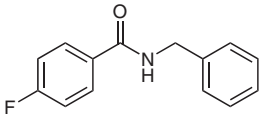
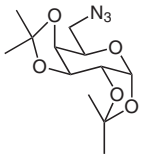
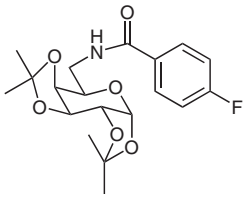
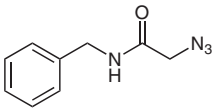
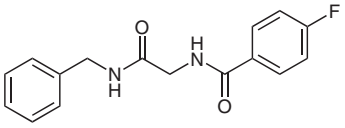
The azide functionalized galactose derivative **12** and amide **13** as biologically relevant compounds were reacted successfully within the Staudinger ligation under microwave conditions to give the corresponding fluorobenzoylated amides in 92 and 78% yields, respectively. The results are summarized in Table 4.

In summary, we have developed a straightforward and convenient synthetic route to substituted phosphanes **4a–h** by the palladium-catalyzed P–C cross-coupling reaction of appropriate 2-iodophenyl esters **6a–h** with $HPPh_2$. The synthesis represents an alternative approach to the commonly employed esterification of substituted phenol derivatives. The starting material for the coupling reaction was easily available through the reaction of 2-iodophenol (**1**) with benzoic acids **5d–h** under Steglich conditions, or by the reaction with the appropriate benzoyl chlorides **3a–c**. The benzoylated phosphane derivatives **4a**,**b**,**e–h** obtained by this method represent as key intermediates for



Scheme 6 Sample Staudinger ligation under different reaction conditions

Table 4 Staudinger Conditions and Substrates

Substrate		Conditions	Time	Product		Yield
11		r.t. 90 °C microwave (50 W)	6.5 h 1 h 15 min	**14**		81% 85% 83%
12		microwave (50 W)	20 min	**15**		92%
13		microwave (50 W)	20 min	**16**		78%

the traceless Staudinger ligation and can be used as starting material for various radiolabeling purposes due to the great variety of introduced functional groups. Treatment of phosphanes with THF·BH_3 solution gave the corresponding phosphane-borane adducts **10a–d**,**h** in excellent yields. Protection of the phosphorous with the BH_3 group enabled further functionalizations of the carbon scaffold. Moreover, a considerable reduction of reaction time from 6 hours to 20 minutes for the Staudinger ligation was achieved through the application of microwave activation.

NMR spectra of the compounds were recorded on a Varian Inova-400 and chemical shifts of the ^{1}H, ^{13}C, ^{19}F, and ^{31}P spectra were reported in parts per million (ppm) using TMS as internal standard for ^{1}H and ^{13}C, $CFCl_3$ for ^{19}F, and H_3PO_4 for ^{31}P spectra. ^{11}B NMR spectra were recorded on a Bruker ARX 300 with $B(OMe)_3$ as external standard. Mass spectrometric data were obtained on a Quattro/LC mass spectrometer (MICROMASS) by electron spray ionization or on a Bruker autoflex II TOF/TOF mass spectrometer (Matrix: DHB, reflector mode). Melting points were determined on a Galen III (Cambridge Instruments) melting point apparatus (Leica, Vienna, Austria) and are uncorrected. Microanalyses were carried out with a LECO CHNS 932 elemental analyzer. Anhyd solvents [THF, CH_2Cl_2, *N*,*N*-dimethylacetamide (DMA)] were purchased from Fluka (anhyd, over molecular sieves, 99.7%) and other chemicals used for the syntheses were purchased from Sigma-Aldrich, Fluka, or ABCR and were used as received. Petroleum ether (PE) used refers to the fraction boiling in the range 40–60 °C. Chromatographic separations and TLC detections were carried out with Merck Silica Gel 60 (63–200 μm) and Merck Silica Gel 60 F_{254} sheets, respectively. TLCs were developed by ninhydrin solution (5% in EtOH) and heating (amine-containing compounds) or visualized under UV light (λ = 254 nm). All reactions concerning the Pd-catalyzed coupling of $HPPh_2$ and the borane-phosphane adduct formation were carried out under argon using Schlenk techniques. Phosphanol **2** was synthesized according to a method of Herd and co-workers[11] and carbohydrate **12** was synthesized by a method described in the literature.[26] Crystallographic data were collected with a Bruker-Nonius Apex-X8 CCD-diffractometer with Mo-Kα radiation (λ = 0.71073 Å). The structures were solved by direct methods using SHELXS-97 and refined against F^2 on all data by full-matrix least-squares with SHELXL-97.[27] All non-hydrogen atoms were refined anisotropically; all hydrogen atoms bonded to C atoms were placed on geometrically calculated positions and refined using a riding model. The three H atoms of the BH_3 group in **10c** were refined isotropically.

Substituted Phosphanes 4a–d; General Procedure A

t-BuOK or Et_3N (1–1.2 equiv) was added to a solution of phosphanol **2** (1 equiv) in anhyd THF or CH_2Cl_2 at r.t. and the solution was allowed to stir for 30 min. Afterwards the respective benzoyl chloride **3a–c** (1.2–1.5 equiv) was added at r.t. and the solution was allowed to stir overnight. H_2O (10 mL) was added, the organic layer separated, and the aqueous layer was extracted with Et_2O (3 × 10 mL). The combined organic layers were dried (Na_2SO_4) and concentrated under reduced pressure. The crude product was purified by column chromatography (PE–EtOAc, 20:1).

2-(Diphenylphosphano)phenyl Benzoate (4a)[8]

Following the general procedure A, phosphanol **2** (150 mg, 0.54 mmol), *t*-BuOK (61 mg, 0.54 mmol), and benzoyl chloride (**3a**; 114 mg, 0.81 mmol) yielded compound **4a** as colorless crystals; yield: 190 mg (92%); mp 101 °C; R_f = 0.57 (PE–EtOAc, 10:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 6.84 (t, ^3J = 7.4 Hz, 1 H, $H_{p'}$), 6.93 (t, ^3J = 7.4 Hz, 2 H, H_p), 6.98–7.08 (m, 9 H, H_m, $H_{m'}$, 4-H, 5-H, H-6), 7.25 (dd, $^3J_{H,P}$ = 4.4 Hz, ^3J = 8.2 Hz, 1 H, H-3), 7.34–7.40 (m, 4 H, H_o), 8.06 (d, ^3J = 7.8 Hz, 2 H, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 123.2 (d, $^3J_{C,P}$ = 1.6 Hz, C-6), 126.3 (C-4), 128.4 ($C_{m'}$), 128.9 (d, $^3J_{C,P}$ = 7.1 Hz, C_m), 129.0 (C_p), 130.0 ($C_{ipso'}$), 130.1 (C-5), 130.4 ($C_{o'}$), 131.5 (d, $^1J_{C,P}$ = 16.0 Hz, C-2), 133.2 ($C_{p'}$), 134.0 (d, $^2J_{C,P}$ = 1.1 Hz, C-3), 134.4 (d, $^2J_{C,P}$ = 20.7 Hz, C_o), 136.4 (d, $^1J_{C,P}$ = 11.4 Hz, C_{ipso}), 148.7 (d, $^1J_{C,P}$ = 9.6 Hz, C-1), 164.2 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = –14.8.

MS (ESI+): *m*/*z* (%) = 405 (70, [M^+ + Na]), 383 (100, [M^+ + H]).

Anal. Calcd for $C_{25}H_{19}O_2P$: C, 78.52; H, 5.01. Found: C, 78.44; H, 5.01.

2-(Diphenylphosphano)phenyl 4-Fluorobenzoate (4b)

Following the general procedure A, phosphanol **2** (200 mg, 0.93 mmol), Et_3N (109 mg, 0.72 mmol), and 4-fluorobenzoyl chloride (**3b**; 148 mg, 1.08 mmol) yielded compound **4b** as colorless crystals; yield: 255 mg (87%); mp 94 °C; R_f = 0.37 (PE–EtOAc, 5:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 6.55 (t, $^3J_{o',m'}$ = $^3J_{H,F}$ = 8.6 Hz, 2 H, $H_{m'}$), 6.84 (t, $^3J_{4,5}$ = 7.8 Hz, $^3J_{3,4}$ = 7.0 Hz, 1 H, H-4), 6.97–7.09 (m, 8 H, H_m, H_p, H-5, H-6), 7.27 (dd, $^4J_{H,P}$ = 3.9 Hz, $^3J_{5,6}$ = 7.8 Hz, 1 H,

H-3), 7.32–7.39 (m, 4 H, H_o), 7.84 (dd, $^3J_{o',m'}$ = 8.6 Hz, $^4J_{H,F}$ = 5.4 Hz, 2 H, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 115.6 (d, $^2J_{C,F}$ = 22.1 Hz, $C_{m'}$), 123.2 (C-6), 126.1 (d, $^4J_{C,F}$ = 3.4 Hz, $C_{ipso'}$), 126.4 (C-4), 128.9 (d, $^3J_{C,P}$ = 7.4 Hz, C_m), 129.2 (C_p), 130.1 (C-5), 131.4 (d, $^1J_{C,P}$ = 14.3 Hz, C-2), 133.1 (d, $^2J_{C,F}$ = 8.8 Hz, $C_{o'}$), 134.0 (C-3), 134.4 (d, $^2J_{C,P}$ = 20.6 Hz, C_o), 136.3 (d, $^1J_{C,P}$ = 11.8 Hz, C_{ipso}), 153.6 (d, $^2J_{C,P}$ = 17.8 Hz, C-1), 163.2 (C=O), 166.2 (d, $^1J_{C,F}$ = 253.3 Hz, $C_{p'}$).

^{19}F NMR (376 MHz, C_6D_6): δ = –105.6.

^{31}P NMR (162 MHz, C_6D_6): δ = –14.6.

MS (ESI+): *m*/*z* (%) = 423 (21, [M⁺ + Na]), 401 (19, [M⁺ + H]).

Anal. Calcd for $C_{25}H_{18}FO_2P$: C, 75.00; H, 4.53. Found: C, 75.36; H, 5.08.

2-(Diphenylphosphano)phenyl 4-Nitrobenzoate (4c)

Following the general procedure A, phosphanol **2** (200 mg, 0.72 mmol), *t*-BuOK (100 mg, 0.89 mmol), and 4-nitrobenzoyl chloride (**3c**; 200 mg, 1.08 mmol) in CH_2Cl_2 yielded compound **4c** as colorless crystals; yield: 175 mg (38%); mp 95 °C; R_f = 0.44 (PE–EtOAc, 10:1).

^1H NMR (400 MHz, C_6D_6): δ = 6.83 (t, ^3J = 7.0Hz, ^3J = 7.8 Hz, 1 H, H-4), 6.96–7.02 (m, 7 H, H_m, H_p, H-3), 7.05 (dt, ^3J = 7.8 Hz, ^4J = 1.6 Hz, 1 H, H-5), 7.20 (dd, ^3J = 8.6 Hz, ^4J = 3.9 Hz, 1 H, H-6), 7.30–7.37 (m, 4 H, H_o), 7.58 (d, $^3J_{o,m}$ = 8.6 Hz, 2 H, $H_{o'}$), 7.68 (d, $^3J_{o,m}$ = 8.6 Hz, 2 H, $H_{m'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 122.9 (C-6), 123.4 ($C_{m'}$), 126.8 (C-4), 129.0 (d, $^3J_{C,P}$ = 7.3 Hz, C_m), 129.4 (C_p), 130.2 (C-5), 131.1 ($C_{o'}$), 131.2 (d, $^1J_{C,P}$ = 16.3 Hz, C-2), 134.2 (d, $^2J_{C,P}$ = 1.1 Hz, C-3), 134.4 ($C_{ipso'}$), 134.0 (d, $^2J_{C,P}$ = 1.1 Hz, C-3), 134.4 (d, $^2J_{C,P}$ = 20.7 Hz, C_o), 135.9 (d, $^1J_{C,P}$ = 10.8 Hz, C_{ipso}), 153.2 (d, $^1J_{C,P}$ = 17.6 Hz, C-1), 162.6 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = –14.7.

MS (ESI+): *m*/*z* (%) = 450 (27, [M⁺ + Na]), 428 (71, [M⁺ + H]).

Anal. Calcd for $C_{25}H_{18}NO_4P$: C, 70.26; H, 4.25; N, 3.28. Found: C, 70.15; H, 4.60; N, 3.26.

2-(Diphenylphosphano)phenyl 4-Iodobenzoate (4d)

Phosphanol **2** (300 mg, 1.08 mmol), 4-iodobenzoic acid (**5d**; 267 mg, 1.08 mmol), and DMAP (50 mg) were dissolved in anhyd THF (5 mL). DCC (334 mg, 1.62 mmol) was added slowly at r.t. and the mixture was allowed to stir overnight. Afterwards, the precipitate was filtered off, the solvent was removed under reduced pressure and purification was done by column chromatography (PE–EtOAc, 10:1); yield: 414 mg (76%); mp 133 °C; R_f = 0.75 (PE–EtOAc, 4:1).

^1H NMR (400 MHz, C_6D_6): δ = 6.83 (t, ^3J = 7.0 Hz, ^3J = 7.8 Hz, 1 H, H-4), 6.95–7.09 (m, 8 H, H-5, H-6, H_m, H_p), 7.20 (dd, ^3J = 7.8 Hz, ^4J = 4,7 Hz, 1 H, H-3), 7.28–7.39 (m, 6 H, $H_{m'}$, H_o), 7.50 (d, $^3J_{o,m}$ = 8.4 Hz, 2 H, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 101.5 ($C_{p'}$), 123.1 (C-6), 126.5 (C-4), 128.9 (d, $^3J_{C,P}$ = 7.4 Hz, C_m), 129.2 (C_p), 130.1 (C-5), 131.5 (d, $^1J_{C,P}$ = 23.5 Hz, C-2), 131.7 ($C_{o'}$), 134.0 (C-3), 134.4 (d, $^2J_{C,P}$ = 20.6 Hz, C_o), 136.2 (d, $^1J_{C,P}$ = 10.3 Hz, C_{ipso}), 137.9 ($C_{m'}$), 153.5 (d, $^1J_{C,P}$ = 16.3 Hz, C-1), 163.8 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = –14.7.

MS (MALDI-TOF): *m*/*z* = 531 [M⁺ + Na], 507 [M⁺ – H].

Anal. Calcd for $C_{25}H_{18}IO_2P$: C, 59.07; H, 3.57. Found: C, 59.49; H, 3.72.

2-Iodophenyl Benzoates 6a–c; General Procedure B

2-Iodophenol (**1**; 1 equiv) and Et_3N (1.5 equiv) were dissolved in THF (30 mL). At 0 °C, the respective benzoyl chloride **3a–c** (1.3 equiv) was added dropwise and the solution was stirred for 30 min at 0 °C and 1 h at r.t. Afterwards, the precipitate was filtered off and the solvent was removed under reduced pressure. Aq 1 M NaOH (30 mL) was added and the aqueous solution was extracted with EtOAc (3 × 10 mL), the combined organic layers dried (Na_2SO_4), and the solvent removed under reduced pressure. Purification was done by distillation under high vacuum (compounds **6a**,**b**) or by column chromatography.

2-Iodophenyl Benzoate (6a)

Following the general procedure B, 2-iodophenol (**1**; 1.00 g, 4.54 mmol), Et_3N (0.95 mL, 6.82 mmol), and benzoyl chloride (**3a**; 0.7 mL, 5.91 mmol) in THF (30 mL) yielded compound **6a** as a colorless liquid after distillation under high vacuum; yield: 1.31 g (89%); bp 155 °C/5·10^{-3} mbar.

^1H NMR (400 MHz, C_6D_6): δ = 6.36 (t, $^3J_{m,p}$ = 7.8 Hz, 1 H, H_p), 6.79 (dt, ^4J = 1.4 Hz, $^3J_{3,4}$ = 7.8 Hz, $^3J_{4,5}$ = 8.0 Hz, 1 H, H-4), 6.89 (dd, ^4J = 1.3 Hz, $^3J_{5,6}$ = 8.2 Hz, 1 H, H-6), 6.99 (t, $^3J_{m,p}$ = 7.8 Hz, $^3J_{o,m}$ = 8.0 Hz, 2 H, H_m), 7.07 (dt, ^4J = 1.3 Hz, $^3J_{5,6}$ = 8.2 Hz, 1 H, H-5), 7.45 (dd, ^4J = 1.2 Hz, $^3J_{3,4}$ = 7.8 Hz, 1 H, H-3), 8.22 (d, $^3J_{o,m}$ = 8.0 Hz, 2 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 91.0 (C-2), 123.6 (C-6), 127.6 (C-4), 128.8 (C_m), 129.4 (C-5), 129.9 (C_{ipso}), 130.7 (C_o), 133.7 (C_p), 139.6 (C-3), 152.0 (C-1), 164.1 (C=O).

MS (ESI+): *m*/*z* (%) = 347 (100, [M⁺ + Na]), 325 (10, [M⁺ + H]).

Anal. Calcd for $C_{13}H_9IO_2$: C, 48.17; H, 2.80. Found: C, 48.33; H, 2.75.

2-Iodophenyl 4-Fluorobenzoate (6b)

Following the general procedure B, 2-iodophenol (**1**; 1.00 g, 4.54 mmol), Et_3N (0.95 mL, 6.82 mmol), and 4-fluorobenzoyl chloride (**3b**; 0.7 mL, 5.91 mmol) in THF (30 mL) yielded compound **6b** as a colorless liquid after distillation under high vacuum; yield: 1.53 g (98%); bp 150 °C/1·10^{-3} mbar.

^1H NMR (400 MHz, C_6D_6): δ = 6.46 (dt, $^3J_{4,5}$ = 7.5 Hz, $^3J_{3,4}$ = 7.9 Hz, ^4J = 1.6 Hz, 1 H, H-4), 6.67 (t, $^3J_{o,m}$ = $^3J_{H,F}$ = 8.9 Hz, 2 H, H_m), 6.89 (dt, $^3J_{4,5}$ = 7.5 Hz, $^3J_{5,6}$ = 8.2 Hz, 1 H, H-5), 6.97 (dd, $^3J_{5,6}$ = 8.2 Hz, ^4J = 1.6 Hz, 1 H, H-6), 7.53 (dd, $^3J_{5,6}$ = 7.9 Hz, ^4J = 1.5 Hz, 1 H, H-3), 7.90 (dd, $^3J_{o,m}$ = 8.9 Hz, $^4J_{H,F}$ = 5.5 Hz, 2 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 90.9 (C-2), 116.0 (d, $^2J_{C,F}$ = 22.1 Hz, C_m), 123.6 (C-6), 125.9 (d, $^4J_{C,F}$ = 3.0 Hz, C_{ipso}), 127.7 (C-4), 129.5 (C-5), 133.3 (d, $^3J_{C,F}$ = 9.5 Hz, C_o), 139.6 (C-3), 151.8 (C-1), 163.1 (C=O), 166.4 (d, $^1J_{C,F}$ = 254.6 Hz, C_p).

^{19}F NMR (376 MHz, C_6D_6): δ = –104.7.

MS (MALDI-TOF): *m*/*z* = 365 [M⁺ + Na], 342 [M⁺ + H], 341 [M⁺].

Anal. Calcd for $C_{13}H_8FIO_2$: C, 45.64; H, 2.36. Found: C, 45.73; H, 2.41.

2-Iodophenyl 4-Nitrobenzoate (6c)

Following the general procedure B, 2-iodophenol (**1**; 1.00 g, 4.54 mmol), Et_3N (0.95 mL, 6.82 mmol), and 4-nitrobenzoyl chloride (**3c**; 0.7 mL, 5.91 mmol) in THF (30 mL) yielded compound **6c** as pale yellow crystals after column chromatography (PE–EtOAc, 20:1); yield: 1.40 g (83%); mp 132 °C; R_f = 0.86 (PE–EtOAc, 3:1).

^1H NMR (400 MHz, C_6D_6): δ = 6.46 (dt, ^4J = 1.6 Hz, $^3J_{4,5}$ = 7.0 Hz, 1 H, H-4), 6.88 (dt, ^4J = 1.6 Hz, $^3J_{4,5}$ = 7.0 Hz, 1 H, H-5), 6.92 (dd, ^4J = 2.3 Hz, $^3J_{5,6}$ = 8.6 Hz, 1 H, H-6), 7.51 (d, $^3J_{3,4}$ = 7.8 Hz, 1 H, H-3), 7.68 (d, $^3J_{o,m}$ = 8.6 Hz, 2 H, H_o), 7.88 (d, $^3J_{o,m}$ = 8.6 Hz, 2 H, H_m).

^{13}C NMR (101 MHz, C_6D_6): δ = 90.5 (C-2), 123.2 (C-6), 123.8 (C_m), 129.6 (C-5), 131.3 (C_o), 134.2 (C_{ipso}),139.8 (C-3), 152.0 (C-1), 151.5 (C_p), 162.4 (C=O).

MS (MALDI-TOF): *m*/*z* = 369 [M⁺], 353 [M⁺ – O], 337 [M⁺ – 2 O].

Anal. Calcd for $C_{13}H_8INO_4$: C, 42.30; H, 2.18; N, 3.79. Found: C, 42.43; H, 2.08; N, 3.78.

2-Iodophenyl Benzoates 6d–h; General Procedure C

2-Iodophenol (**1**; 1.5 equiv), the respective benzoic acid **5d**–**h** (1 equiv), and DMAP (100 mg) were dissolved in anhyd THF (or anhyd DMF for compound **6g**) and DCC (1.2–2 equiv) was added slowly at r.t. The mixture was allowed to stir overnight at r.t. (at 100 °C for compound **6g**). Afterwards, the precipitate was filtered off, the organic layer was diluted with Et_2O (30 mL) and the combined organic layers were washed with aq 1 M HCl (15 mL) and aq 1 M NaOH (15 mL), and dried (Na_2SO_4). The solvent was removed under reduced pressure and purification of the crude product was done by column chromatography.

2-Iodophenyl 4-Iodobenzoate (6d)

Following the general procedure C, 4-iodobenzoic acid (**5d**; 1.50 g, 6.05 mmol), 2-iodophenol (**1**; 2.00 g, 9.07 mmol), DCC (1.87 g, 9.07 mmol), and DMAP (100 mg) in anhyd THF (15 mL) and anhyd DMF (3 mL) yielded compound **6d** as colorless crystals after column chromatography (PE–EtOAc, 10:1); yield: 2.02 g (74%); mp 126 °C; R_f = 0.76 (PE–EtOAc, 4:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 6.43 (t, $^3J_{3,4}$ = 7.03 Hz, $^3J_{4,5}$ = 7.8 Hz, 1 H, H-4), 6.85 (t, $^3J_{5,6}$ = $^3J_{4,5}$ = 7.8 Hz, 1 H, H-5), 6.92 (d, $^3J_{5,6}$ = 7.8 Hz, 1 H, H-6), 7.39 (d, $^3J_{o,m}$ = 8.8 Hz, 2 H, H_m), 7.51 (d, $^3J_{3,4}$ = 7.03 Hz, 1 H, H-3), 7.73 (d, $^3J_{o,m}$ = 8.8 Hz, 2 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 91.2 (C-2), 123.5 (C-6), 127.7 (C-4), 129.1 (C_{ipso}), 129.5 (C-5), 131.9 (C_o), 138.2 (C_m), 139.6 (C-3), 151.8 (C-1), 163.7 (C=O).

MS (MALDI-TOF): *m*/*z* = 450 [M^+].

Anal. Calcd for $C_{13}H_8I_2O_2$: C, 34.70; H, 1.79. Found: C, 35.27; H, 1.82.

2-Iodophenyl 4-(2-Hydroxyethoxy)benzoate (6e)

Following the general procedure C, 4-(2-hydroxyethoxy)benzoic acid (**5e**;[28] 500 mg, 2.72 mmol), 2-iodophenol (**1**; 896 mg, 4.07 mmol), DCC (672 mg, 3.26 mmol), and DMAP (50 mg) in anhyd THF (30 mL) yielded compound **6e** as colorless crystals after column chromatography (PE–EtOAc, 20:1 → 10:1); yield: 840 mg (81%); mp 103–104 °C; R_f = 0.49 (PE–EtOAc, 1:2).

^{1}H NMR (400 MHz, C_6D_6): δ = 3.39–3.46 (m, 5 H, CH_2CH_2OH), 6.45 (t, $^3J_{4,5}$ = 7.7 Hz, 1 H, H-4), 6.65 (d, $^3J_{o,m}$ = 8.8 Hz, 2 H, H_m), 6.89 (t, $^3J_{4,5}$ = 7.8 Hz, 1 H, H-5), 7.04 (d, $^3J_{5,6}$ = 8.6 Hz, 1 H, H-6), 7.55 (d, $^3J_{5,6}$ = 8.9 Hz, 1 H, H-3), 8.31 (d, $^3J_{o,m}$ = 8.8 Hz, 2 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 61.0 (CH_2CH_2OH), 69.6 (CH_2CH_2OH), 91.2 (C-2), 114.8 (C_m), 122.4 (C_{ipso}), 123.8 (C-6), 127.5 (C-4), 129.5 (C-5), 133.0 (C_o), 139.6 (C-3), 152.1 (C-1), 163.6 (C_p), 163.9 (C=O).

MS (ESI–): *m*/*z* (%) 383 [M^+ – H], 339 [M^+ – CH_2CH_2OH].

Anal. Calcd for $C_{15}H_{13}IO_4$: C, 46.90; H, 3.41. Found: C, 46.56; H, 3.52.

2-Iodophenyl 4-(2-Fluoroethoxy)benzoate (6f)

Following the general procedure C, 4-(2-fluoroethoxy)benzoic acid (**5f**;[29] 700 mg, 3.80 mmol), 2-iodophenol (**1**; 1.25 g, 5.70 mmol), DCC (1.57 g, 7.60 mmol), and DMAP (50 mg) in anhyd THF (30 mL) yielded compound **6f** as colorless crystals after column chromatography (PE–EtOAc, 20:1 → 10:1); yield: 985 mg (67%); mp 128 °C; R_f = 0.5 (PE–EtOAc, 1:2).

^{1}H NMR (400 MHz, C_6D_6): δ = 3.35 (dt, ^3J = 8.2 Hz, $^3J_{H,F}$ = 27.6 Hz, 2 H, CH_2CH_2F), 4.05 (dt, $^2J_{H,F}$ = 47.6 Hz, ^3J = 8.2 Hz, 2 H, CH_2CH_2F), 6.44 (dt, ^4J = 1.5 Hz, $^3J_{3,4}$ = 8.0 Hz, 1 H, H-4), 6.61 (d, $^3J_{o,m}$ = 9.0 Hz, 2 H, H_m), 6.88 (dt, ^4J = 1.5 Hz, $^3J_{5,6}$ = 8.1 Hz, 1 H, H-5), 7.03 (dd, ^4J = 1.5 Hz, $^3J_{5,6}$ = 8.1 Hz, 1 H, H-6), 7.55 (dd, ^4J = 1.5 Hz, $^3J_{5,6}$ = 8.0 Hz, 1 H, H-3), 8.28 (d, $^3J_{o,m}$ = 9.0 Hz, 2 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 67.1 (d, $^2J_{C,F}$ = 20.8 Hz, CH_2CH_2F), 81.2 (d, $^1J_{C,F}$ = 170.9 Hz, CH_2CH_2F), 91.1 (C-2), 114.7 (C_m), 122.7 (C_{ipso}), 123.8 (C-6), 127.5 (C-4), 129.4 (C-5), 132.9 (C_o), 139.6 (C-3), 152.1 (C-1), 163.1 (C_p), 163.8 (C=O).

^{19}F NMR (376 MHz, C_6D_6): δ = –223.7.

MS (MALDI-TOF): *m*/*z* = 385 [M^+ – H].

Anal. Calcd for $C_{15}H_{12}FIO_3$: C, 46.65; H, 3.13. Found: C, 46.40; H, 3.00.

2-Iodophenyl 4-Hydroxybenzoate (6g)

Following the general procedure C, 4-hydroxybenzoic acid (**5g**; 1.00 g, 7.24 mmol), 2-iodophenol (**1**; 2.33 g, 10.86 mmol), DCC (1.6 g, 7.96 mmol), and DMAP (100 mg) in anhyd DMF (30 mL) yielded compound **6g** as colorless crystals after column chromatography (PE–EtOAc, 10:1); yield: 985 mg (67%); mp 130–134 °C; R_f = 0.54 (PE–EtOAc, 3:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 5.10 (br s, 1 H, OH), 6.42 (dt, ^4J = 1.5 Hz, $^3J_{3,4}$ = 7.8 Hz, 1 H, H-4), 6.47 (d, $^3J_{o,m}$ = 8.5 Hz, 2 H, H_m), 6.85 (dt, ^4J = 1.5 Hz, $^3J_{5,6}$ = 8.0 Hz, 1 H, H-5), 6.98 (dd, ^4J = 1.5 Hz, $^3J_{5,6}$ = 8.0 Hz, 1 H, H-6), 7.53 (dd, ^4J = 1.5 Hz, $^3J_{5,6}$ = 7.8 Hz, 1 H, H-3), 8.22 (d, $^3J_{o,m}$ = 8.5 Hz, 2 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 91.2 (C-2), 115.7 (C_m), 122.0 (C_{ipso}), 123.8 (C-6), 127.5 (C-4), 129.4 (C-5), 133.2 (C_o), 139.6 (C-3), 152.1 (C-1), 161.3 (C_p), 164.0 (C=O).

MS (ESI–): *m*/*z* (%) = 339 (100, [M^+ + H]), 212 (9, [M^+ – HI]).

Anal. Calcd for $C_{13}H_9IO_3$: C, 45.91; H, 2.67. Found: C, 46.00; H, 2.66.

2-Iodophenyl 4-(Dimethylamino)benzoate (6h)

Following the general procedure C, 4-(dimethylamino)benzoic acid (**5h**; 1.50 g, 9.08 mmol), 2-iodophenol (**1**; 3.00 g, 13.62 mmol), DCC (2.25 g, 10.9 mmol), and DMAP (100 mg) in anhyd THF (30 mL) yielded compound **6h** as colorless crystals after column chromatography (PE–EtOAc, 20:1 → 10:1); yield: 1.39 g (42%); mp 126 °C; R_f = 0.54 (PE–EtOAc, 3:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 2.31 [s, 6 H, $N(CH_3)_2$], 6.36 (d, $^3J_{o,m}$ = 9.0 Hz, 2 H, H_m), 6.45 (t, $^3J_{3,4}$ = $^3J_{4,5}$ 7.8 Hz, 1 H, H-4), 6.89 (t, $^3J_{4,5}$ = $^3J_{5,6}$ = 7.8 Hz, 1 H, H-5), 7.12 (d, $^3J_{5,6}$ = 7.8 Hz, 1 H, H-6), 7.58 (d, $^3J_{3,4}$ = 7.8 Hz, 1 H, H-3), 8.41 (d, $^3J_{o,m}$ = 9.0 Hz, 2 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 39.4 [$N(CH_3)_2$], 91.5 (C-2), 111.3 (C_m), 116.6 (C_{ipso}), 124.1 (C-6), 127.1 (C-4), 129.3 (C_o), 132.7 (C-5), 139.5 (C-3), 152.6 (C-1), 153.9 (C_p), 164.4 (C=O).

MS (ESI+): *m*/*z* (%) = 390 (93, [M^+ + Na]), 368 (11, [M^+ + H]), 148 (100, [M^+ – C_6H_4IO]).

Anal. Calcd for $C_{15}H_{14}INO_2$: C, 49.07; H, 3.84; N, 3.81. Found: C, 49.35; H, 3.86; N, 3.78.

Substituted Phosphanes 4a,b,e–h; General Procedure D

KOAc (1.2 equiv), $HPPh_2$ (1 equiv), and $Pd(OAc)_2$ in catalytical amount were added to a solution of 2-iodophenyl benzoate **6a**–**h** (1 equiv) in anhyd DMA (5 mL) at r.t. under argon. The mixture was allowed to stir for 5–8 h at 100 °C (or at 70 °C overnight). Afterwards, H_2O (10 mL) and CH_2Cl_2 (20 mL) were added, the organic layer was separated and the aqueous layer was extracted with CH_2Cl_2 (3 × 10 mL). The combined organic layers were dried (Na_2SO_4) and concentrated under reduced pressure. The crude product was purified by column chromatography (PE–EtOAc, 20:1 → 10:1).

2-(Diphenylphosphano)phenyl Benzoate (4a)
Following the general procedure D, 2-iodophenyl benzoate (**6a**; 534 mg, 1.65 mmol), KOAc (194 mg, 1.98 mmol), $HPPh_2$ (0.29 mL, 1.65 mmol), and $Pd(OAc)_2$ (5 mg) yielded compound **4a** as colorless crystals (496 mg, 79%). Analytical and spectral data were in accordance with those shown above (vide supra).

2-(Diphenylphosphano)phenyl 4-Fluorobenzoate (4b)
Following the general procedure D, 2-iodophenyl 4-fluorobenzoate (**6b**; 521 mg, 1.53 mmol), KOAc (180 mg, 1.83 mmol), $HPPh_2$ (0.26 mL, 1.53 mmol), and $Pd(OAc)_2$ (5 mg) yielded compound **4b** as colorless crystals (396 mg, 65%). Analytical and spectral data were in accordance with those shown above (vide supra).

2-(Diphenylphosphano)phenyl 4-Nitrobenzoate (4c)
It was not possible to synthesize compound **4c**. TLC monitoring showed only decomposition of products.

2-(Diphenylphosphano)phenyl 4-(2-Hydroxyethoxy)benzoate (4e)
Following the general procedure D, 2-iodophenyl 4-(2-hydroxyethoxy)benzoate (**6e**; 830 mg, 2.16 mmol), KOAc (254 mg, 2.59 mmol), $HPPh_2$ (402 mg, 2.16 mmol), and $Pd(OAc)_2$ (5 mg) yielded compound **4e** as a colorless syrup; yield: 850 mg (89%); R_f = 0.5 (PE–EtOAc, 1:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 2.39 (br s, 1 H, OH), 3.45–3.56 (m, 4 H, CH_2CH_2OH), 6.58 (d, $^3J_{o,m}$ = 8.4 Hz, 2 H, $H_{m'}$), 6.85 (t, ^3J = 7.8 Hz, 1 H, H-4), 6.97–7.15 (m, 9 H, H_m, H_p, H-3, H-5, H-6), 7.36–7.42 (m, 4 H, H_o), 8.02 (d, $^3J_{o,m}$ = 8.4 Hz, 2 H, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 61.0 (CH_2CH$_2$OH), 69.6 (CH$_2$CH_2OH), 114.5 ($C_{m'}$), 122.4 ($C_{ipso'}$), 123.4 (C-6), 126.3 (C-4), 128.9 (d, $^3J_{C,P}$ = 7.3 Hz, C_m), 129.1 (C_p), 130.2 (C-5), 132.2 (d, $^1J_{C,P}$ = 16.2 Hz, C-2), 132.7 ($C_{o'}$), 134.0 (C-3), 134.4 (d, $^2J_{C,P}$ = 20.6 Hz, C_o), 136.5 (d, $^1J_{C,P}$ = 11.8 Hz, C_{ipso}),153.9 (d, $^2J_{C,P}$ = 17.6 Hz, C-1), 163.3 ($C_{p'}$), 164.1 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = –14.8.

MS (ESI+): *m*/*z* (%) = 426 (58, [M$^+$ + H]).

Anal. Calcd for $C_{27}H_{24}NO_2P$: C, 73.30; H, 5.24. Found: C, 73.32; H, 5.51.

2-(Diphenylphosphano)phenyl 4-(2-Fluoroethoxy)benzoate (4f)
Following the general procedure D, 2-iodophenyl 4-(2-fluoroethoxy)benzoate (**6f**; 437 mg, 1.13 mmol), KOAc (133 mg, 1.36 mmol), $HPPh_2$ (211 mg, 1.13 mmol), and $Pd(OAc)_2$ (5 mg) yielded compound **4f** as a colorless syrup; yield: 337 mg (67%); R_f = 0.24 (PE–EtOAc, 3:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 3.29 (dt, ^3J = 8.4 Hz, $^3J_{H,F}$ = 27.2 Hz, 2 H, CH_2CH$_2$F), 4.02 (dt, $^2J_{H,F}$ = 47.4 Hz, ^3J = 8.4 Hz, 2H, CH$_2$CH_2F), 6.50 (dt, $^3J_{o',m'}$ = 9.2 Hz, 1 H, $H_{m'}$), 6.85 (t, $^3J_{3,4}$ = 7.8 Hz, 1 H, H-4), 7.01–7.10 (m, 8 H, H-5, H-6, H_p, H_m), 7.31 (dd, ^4J = 1.5 Hz, $^3J_{3,4}$ = 7.8 Hz, 1 H, H-3), 7.38–7.44 (m, 4 H, H_o), 8.03 (d, $^3J_{o',m'}$ = 9.2 Hz, 2 H, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 67.0 (d, $^2J_{C,F}$ = 20.6 Hz, CH_2CH$_2$F), 81.2 (d, $^1J_{C,F}$ = 172.1 Hz, CH$_2$CH_2F), 114.7 ($C_{m'}$), 122.7 ($C_{ipso'}$), 123.4 (C-6), 126.3 (C-4), 128.8 (C_p), 129.0 (d, $^3J_{C,P}$ = 20.6 Hz, C_m), 130.1 (C-5), 132.7 (C_o), 134.0 (C-3), 134.5 (d, $^2J_{C,P}$ = 20.6 Hz, C_o), 136.6 (d, $^1J_{C,P}$ = 11.8 Hz, C_{ipso}), 154.0 (d, $^2J_{C,P}$ = 17.5 Hz, C-1), 163.9 (C=O).

^{19}F NMR (376 MHz, C_6D_6): δ = –223.9.

^{31}P NMR (162 MHz, C_6D_6): δ = –14.6.

MS (MALDI–TOF): *m*/*z* = 443 [M$^+$ – H], 428 [M$^+$ – CH_4].

Anal. Calcd for $C_{27}H_{22}FO_3P$: C, 72.97; H, 4.99. Found: C, 72.89; H, 5.50.

2-(Diphenylphosphano)phenyl 4-Hydroxybenzoate (4g)
Following the general procedure D, 2-iodophenyl 4-hydroxybenzoate (**6g**; 830 mg, 2.16 mmol), KOAc (254 mg, 2.59 mmol), $HPPh_2$ (402 mg, 2.16 mmol), and $Pd(OAc)_2$ (5 mg) yielded compound **4g** as colorless syrup; yield: 340 mg (58%); R_f = 0.41 (PE–EtOAc, 3:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 6.27 (d, $^3J_{o,m}$ = 8.6 Hz, 2 H, $H_{m'}$), 6.78 (t, ^3J = 7.8 Hz, 1 H, H-4), 6.91–7.03 (m, 8 H, H_m, H_p, H-5, H-6), 7.17–7.24 (m, 4 H, H-3), 7.28–7.37 (m, 4 H, H_o), 7.89 (d, $^3J_{o,m}$ = 8.6 Hz, 2 H, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 115.5 ($C_{m'}$), 123.4 (C-6), 126.2 (C-4), 128.8 (d, $^3J_{C,P}$ = 7.1 Hz, C_m), 129.0 (C_p), 130.1 (C-5), 132.9 ($C_{o'}$), 133.9 (C-3), 134.5 (d, $^2J_{C,P}$ = 20.6 Hz, C_o), 136.6 (d, $^1J_{C,P}$ = 11.7 Hz, C_{ipso}),154.0 (d, $^2J_{C,P}$ = 17.8 Hz, C-1), 161.3 ($C_{p'}$), 164.1 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = –14.7.

MS (ESI+): *m*/*z* (%) = 421 (94, [M$^+$ + Na]), 399 (52, [M$^+$ + H]).

Anal. Calcd for $C_{25}H_{19}O_3P$: C, 75.37; H, 4.81. Found: C, 75.25; H, 5.15.

2-(Diphenylphosphano)phenyl 4-(Dimethylamino)benzoate (4h)
Following the general procedure D, 2-iodophenyl 4-(dimethylamino)benzoate (**6h**; 924 mg, 2.52 mmol), KOAc (296 mg, 3.02 mmol), $HPPh_2$ (469 mg, 2.52 mmol), and $Pd(OAc)_2$ (5 mg) yielded compound **4h** as colorless crystals; yield: 807 mg (75%); mp 145 °C; R_f = 0.5 (PE–EtOAc, 4:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 2.25 [s, 6 H, N(CH$_3$)$_2$], 6.25 (d, $^3J_{o,m}$ = 8.4 Hz, 2 H, $H_{m'}$), 6.85 (t, ^3J = 7.4 Hz, 1 H, H-6), 7.01–7.11 (m, 8 H, H_m, H_p, H-4, H-5), 7.37 (m, 5 H, H_o, H-3), 8.17 (d, $^3J_{o,m}$ = 8.4 Hz, 2H, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 111.1 ($C_{m'}$), 116.9 ($C_{ipso'}$), 123.7 (C-6), 125.9 (C-4), 128.8 (d, $^3J_{C,P}$ = 6.1 Hz, C_m), 128.9 (C_p), 130.0 (C-5), 131.4 (d, $^1J_{C,P}$ = 16.4 Hz, C-2), 132.3 ($C_{o'}$), 133.9 (C-3), 134.5 (d, $^2J_{C,P}$ = 19.2 Hz, C_o), 137.0 (d, $^1J_{C,P}$ = 11.7 Hz, C_{ipso}), 153.6 ($C_{p'}$), 154.5 (d, $^2J_{C,P}$ = 17.7 Hz, C-1), 164.6 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = –14.8.

MS (ESI+): *m*/*z* (%) = 426 (58, [M$^+$ + H]).

Anal. Calcd for $C_{27}H_{24}NO_2P$: C, 76.22; H, 5.69. Found: C, 76.12; H, 6.11.

2-(Diphenylphosphano)phenol-Borane Complex (9)
2-(Diphenylphosphano)phenol (**2**; 1.00 g, 3.60 mmol) was dissolved in anhyd THF (7 mL) under argon. The solution was cooled down to –78 °C and a 1 M THF·BH_3 complex solution (4.0 mL, 3.96 mmol) was added slowly. The temperature of the reaction mixture was allowed to raise to r.t. overnight. Afterwards, the solvent was removed under reduced pressure and the crude product was purified via column chromatography (PE–EtOAc, 10:1) to yield colorless crystals; yield: 1.0 g (95%); mp 155 °C; R_f = 0.37 (PE–EtOAc, 5:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 1.80–2.70 (m, 3 H, BH_3), 6.52 (t, ^3J = 6.9 Hz, 1 H, H-4), 6.87–7.01 (m, 9 H, H_m, H_p, H-3, H-5, H-6), 7.49–7.56 (m, 4 H, H_o), 8.10 (s, 1 H, OH).

^{13}C NMR (101 MHz, C_6D_6): δ = 118.9 (d, $^3J_{C,P}$ = 6.1 Hz, C-6), 120.6 (d, $^3J_{C,P}$ = 7.7 Hz, C-4), 128.5 (C_p), 129.1 (d, $^2J_{C,P}$ = 10.4 Hz, C_o), 131.4 (C-5), 131.5 (d, $^1J_{C,P}$ = 10.3 Hz, C-2), 133.3 (d, $^3J_{C,P}$ = 10.3 Hz, C_m), 134.2 (C-3), 134.7 (d, $^1J_{C,P}$ = 4.5 Hz, C_{ipso}), 161.6 (d, $^2J_{C,P}$ = 10.2 Hz, C-1).

^{31}P NMR (162 MHz, C_6D_6): δ = 14.8 (m).

^{11}B NMR (96 MHz, C_6D_6): δ = –35.5 (m).

MS (ESI–): *m*/*z* = 291 (100%, [M$^+$ – H]).

Anal. Calcd for $C_{18}H_{18}BO_2P$: C, 74.01; H, 6.21. Found: C, 74.24; H, 6.46.

2-(Diphenylphosphano)phenyl Benzoate-Borane Complex (10a)

t-BuOK (74 mg, 0.66 mmol) was added to a solution of 2-(diphenylphosphano)phenol-borane complex (**9**; 160 mg, 0.55 mmol) in anhyd THF (10 mL) and the mixture was stirred for 30 min. Subsequently, benzoyl chloride (**3a**; 115 mg, 0.82 mmol) was added slowly and the mixture was stirred overnight. The precipitate was filtered off, the solvent removed under reduced pressure, and the resulting crude product was purified by column chromatography (PE–EtOAc, 20:1 → 10:1) to yield colorless crystals; yield: 130 mg (60%); mp 137 °C; R_f = 0.25 (PE–EtOAc, 5:1).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.79–1.73 (m, 3H, BH_3), 7.23–7.70 (m, 19 H, H_{arom}).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 124.3 (d, $^3J_{C,P}$ = 5.9 Hz, C-6), 126.1 (d, $^3J_{C,P}$ = 8.9 Hz, C-4), 128.1 (C_p), 128.5 ($C_{ipso'}$), 128.9 (d, $^3J_{C,P}$ = 10.3 Hz, C_m), 130.4 ($C_{m'}$), 131.3, 131.4 ($C_{o'}$, C-5), 131.6 (d, $^1J_{C,P}$ = 20.3 Hz, C-2), 132.9 (C-3), 133.2 (d, $^2J_{C,P}$ = 10.3 Hz, C_o), 133.6 ($C_{p'}$), 134.9 (d, $^1J_{C,P}$ = 7.1 Hz, C_{ipso}), 152.7 (C-1), 163.9 (C=O).

^{31}P NMR (162 MHz, $CDCl_3$): δ = 19.8 (m).

^{11}B NMR (96 MHz, C_6D_6): δ = –36.7 (m).

MS (MALDI–TOF): *m*/*z* = 396 [M^+], 382 [$M^+ - BH_3$].

Anal. Calcd for $C_{25}H_{22}BO_2P$: C, 75.78; H, 5.60. Found: C, 75.85; H, 5.69.

2-(Diphenylphosphano)phenyl 4-Fluorobenzoate-Borane Complex (10b)

t-BuOK (192 mg, 1.72 mmol) was added to a solution of 2-(diphenylphosphano)phenol-borane complex (**9**; 334 mg, 1.14 mmol) in anhyd THF (15 mL) and the mixture was stirred for 30 min. Subsequently, 4-fluorobenzoyl chloride (**3b**; 272 mg, 1.72 mmol) was added slowly and the mixture was stirred overnight. The precipitate was filtered off, the solvent removed under reduced pressure and the resulting crude product was purified by column chromatography (PE–EtOAc, 20:1 → 10:1) to yield colorless crystals; yield: 450 mg (95%); mp 130 °C; R_f = 0.53 (PE–EtOAc, 5:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 1.39–2.55 (m, 3 H, BH_3), 6.51 ('t', $^3J_{H,F}$ = $^3J_{o,m}$ = 8.6 Hz, 2 H, $H_{m'}$), 6.73 ('t', $^3J_{3,4}$ = 7.0 Hz, $^3J_{4,5}$ = 7.8 Hz, 1 H, H-4), 6.84–6.93 (m, 6 H, H_m, H_p), 7.03 ('t', $^3J_{4,5}$ = 7.8 Hz, 1 H, H-5), 7.15 (m, 1 H, H-6), 7.25 (ddd, $^3J_{H,P}$ = 11.7 Hz, ^3J = 7.8 Hz, ^4J = 1.4 Hz, 1 H, H-3), 7.67–7.75 (m, 6 H, H_o, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 115.4 (d, $^3J_{C,F}$ = 22.1 Hz, $C_{m'}$), 124.7 (d, $^3J_{C,P}$ = 4.4 Hz, C-6), 125.3 (d, $^4J_{C,F}$ = 2.9 Hz, $C_{ipso'}$), 126.0 (d, $^3J_{C,P}$ = 8.9 Hz, C-4), 128.8 (C_p), 128.9 (d, $^3J_{C,P}$ = 10.3 Hz, C_m), 129.4 (C-5), 131.6 (d, $^1J_{C,P}$ = 10.3 Hz, C-2), 133.3 (d, $^2J_{C,F}$ = 8.8 Hz, $C_{o'}$), 132.6 (C-3), 133.5 (d, $^2J_{C,P}$ = 8.8 Hz, C_o), 134.8 (d, $^1J_{C,P}$ = 7.3 Hz, C_{ipso}), 153.0 (d, $^2J_{C,P}$ = 3.1 Hz, C-1), 162.7 (C=O), 166.2 (d, $^1J_{C,F}$ = 254.4 Hz, $C_{p'}$).

^{19}F NMR (376 MHz, C_6D_6): δ = –105.2.

^{31}P NMR (162 MHz, C_6D_6): δ = 20.8 (m).

^{11}B NMR (96 MHz, C_6D_6): δ = –36.9 (m).

MS (MALDI–TOF): *m*/*z* = 415 [M^+ + H], 414 [M^+].

Anal. Calcd for $C_{25}H_{21}BFO_2P$: C, 72.49; H, 5.11. Found: C, 72.69; H, 5.37.

2-(Diphenylphosphano)phenyl 4-Nitrobenzoate-Borane Complex (10c)

Phosphane **4c** (340 mg, 0.80 mmol) was dissolved in anhyd THF (5 mL) under argon. The solution was cooled down to –78 °C and a 1 M THF·BH_3 complex solution (0.79 mL, 0.80 mmol) was added slowly. The temperature of the reaction mixture was allowed to raise to r.t. overnight. Afterwards, the solvent was removed under reduced pressure and the crude product was purified by column chromatography (PE–EtOAc, 20:1 → 5:1) to yield pale yellow crystals; yield: 520 mg (84%); mp 175 °C; R_f = 0.22 (PE–EtOAc, 5:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 1.53–2.57 (m, 3 H, BH_3), 6.71 (dt, ^3J = 7.8 Hz, ^4J = 1.5 Hz, 1 H, H-4), 6.83–6.91 (m, 6 H, H_m, H_p), 7.03 (dt, ^3J = 8.4 Hz, ^4J = 1.6 Hz, 1 H, H-5), 7.09–7.16 (m, 2 H, H-3, H-6), 7.59 ('t', $^3J_{o',m'}$ = 8.8 Hz, 3 H, $H_{o'}$, $H_{m'}$), 7.62–7.70 (m, 4 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 123.2 ($C_{ipso'}$), 124.4 (d, $^3J_{C,P}$ = 6.0 Hz, C-6), 126.4 (d, $^3J_{C,P}$ = 8.8 Hz, C-4), 129.0 (d, $^3J_{C,P}$ = 10.3 Hz, C_m), 129.1 (C_p), 131.3 ($C_{o'}$), 131.4 (C-5), 132.6 (C-3), 133.5 (d, $^2J_{C,P}$ = 10.3 Hz, C_o), 133.8 ($C_{ipso'}$), 134.7 (d, $^1J_{C,P}$ = 5.9 Hz, C_{ipso}), 150.8 ($C_{p'}$), 152.6 (d, $^2J_{C,P}$ = 3.8 Hz, C-1), 162.1 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = 20.7 (m).

^{11}B NMR (96 MHz, C_6D_6): δ = –36.4 (m).

MS (MALDI–TOF): *m*/*z* = 440 [M^+], 426 [$M^+ - BH_3$].

Anal. Calcd for $C_{25}H_{21}BFO_4P$: C, 68.05; H, 4.80; N, 3.17. Found: C, 68.00; H, 4.86; N, 3.10.

2-(Diphenylphosphano)phenyl 4-Iodobenzoate-Borane Complex (10d)

Phosphane **4d** (355 mg, 0.66 mmol) was dissolved in anhyd THF (6 mL) under argon. The solution was cooled down to –78 °C and a 1 M THF·BH_3 complex solution (0.66 mL, 0.66 mmol) was added slowly. The temperature of the reaction mixture was allowed to raise to r.t. overnight. Afterwards, the solvent was removed under reduced pressure and the crude product was purified by column chromatography (PE–EtOAc, 10:1) to yield colorless crystals; yield: 244 mg (67%); mp 186 °C; R_f = 0.72 (PE–EtOAc 3:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 1.47–2.63 (m, 3 H, BH_3), 6.73 (t, $^3J_{3,4}$ = 7.0 Hz, $^3J_{4,5}$ = 7.8 Hz, 1 H, H-4), 6.83–6.93 (m, 6 H, H_m, H_p), 7.02 (t, $^3J_{4,5}$ = 7.8 Hz, 1 H, H-5), 7.12 (dd, $^3J_{5,6}$ = 7.8 Hz, ^4J = 4.0 Hz, 1 H, H-6), 7.25 (dd, $^3J_{3,4}$ = 7.0 Hz, 1 H, H-3), 7.27 (d, $^3J_{o',m'}$ = 8.6 Hz, 1 H, $H_{m'}$), 7.37 (d, $^3J_{o',m'}$ = 8.6 Hz, 2 H, $H_{o'}$), 7.64–7.73 (m, 4 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 101.7 ($C_{p'}$), 124.6 (d, $^3J_{C,P}$ = 5.8 Hz, C-6), 126.1 (d, $^3J_{C,P}$ = 8.9 Hz, C-4), 128.8 ($C_{ipso'}$),128.9 (d, $^3J_{C,P}$ = 10.3 Hz, C_m), 129.1 (C-5),131.2 ($C_{o'}$), 131.9 (C_p), 132.6 (C-3), 133.5 (d, $^2J_{C,P}$ = 10.3 Hz, C_o), 134.8 (d, $^1J_{C,P}$ = 5.8 Hz, C_{ipso}), 137.7 ($C_{m'}$), 152.9 (C-1), 163.3 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = 21.0 (m).

^{11}B NMR (96 MHz, C_6D_6): δ = –37.1 (m).

MS (MALDI–TOF): *m*/*z* = 521 [M^+ – H].

Anal. Calcd for $C_{25}H_{21}BIO_2P$: C, 57.51; H, 4.05. Found: C, 57.54; H, 4.21.

2-(Diphenylphosphano)phenyl 4-(Dimethylamino)benzoate-Borane Complex (10h)

Phosphane **4h** (250 mg, 0.59 mmol) was dissolved in anhyd THF (5 mL) under argon. The solution was cooled down to –78 °C and a 1 M THF·BH_3 complex solution (0.59 mL, 0.59 mmol) was added slowly. The temperature of the reaction mixture was allowed to raise to r.t. during 14 h. Afterwards, the solvent was removed under reduced pressure and the crude product was purified by column chromatography (PE–EtOAc 5:1) to yield colorless crystals; yield: 220 mg (85%); mp 173 °C; R_f = 0.33 (PE–EtOAc, 3:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 6.22 (d, $^3J_{o',m'}$ = 8.6 Hz, 2 H, $H_{m'}$), 6.77 (t, $^3J_{3,4}$ = 7.7 Hz, 1 H, H-3), 6.88–7.01 (m, 6 H, H_m, H_p), 7.05 (t, $^3J_{5,6}$ = 8.6 Hz, 1 H, H-5), 7.28 (dd, ^4J = 4.1 Hz, $^3J_{3,4}$ = 7.7 Hz, 1

H, H-4), 7.45 (dd, $^3J_{5,6}$ = 8.6 Hz, 1 H, H-6), 7.77–7.88 (m, 4 H, H_o), 7.99 (d, $^3J_{o',m'}$ = 8.6 Hz, 1 H, $H_{o'}$).

^{13}C NMR (101 MHz, C_6D_6): δ = 39.3 (NMe_2), 110.8 ($C_{m'}$), 116.0 ($C_{ipso'}$), 125.0 (d, $^3J_{C,P}$ = 4.4 Hz, C-6), 125.4 (d, $^3J_{C,P}$ = 10.3 Hz, C-4), 128.8 (d, $^3J_{C,P}$ = 10.3 Hz, C_m), 129.4 (C-5), 129.9 (C-3), 131.0 (C_p), 132.6 ($C_{o'}$), 133.8 (d, $^2J_{C,P}$ = 10.3 Hz, C_o), 135.0 (d, $^1J_{C,P}$ = 8.8 Hz, C_{ipso}), 153.6 ($C_{p'}$), 154.2 (C-1), 164.0 (C=O).

^{31}P NMR (162 MHz, C_6D_6): δ = 21.2 (m).

^{11}B NMR (96 MHz, C_6D_6): δ = –36.3 (m).

MS (MALDI–TOF): *m*/*z* = 439 [M^+], 438 [M^+ – H].

Anal. Calcd for $C_{27}H_{27}BNO_2P$: C, 73.82; H, 6.20; N, 3.19. Found: C, 73.80; H, 6.15; N, 3.26.

CAUTION! Hazard warning for organic azides: risk of explosion by shock, friction, fire upon heating. Store azides in a cool location.

N-Benzyl-4-fluorobenzamide (14)[30]

Benzyl azide (**11**;[31] 60 mg, 0.45 mmol) and phosphane **4b** (150 mg, 0.37 mmol) were dissolved in a DMF–H_2O mixture (0.5 mL:0.05 mL) and heated under microwave conditions (50 Watt) for 20 min. After removal of the solvent under reduced pressure, the crude product was purified by column chromatography (PE–EtOAc, 20:1); yield: 71 mg (83%); colorless crystals; mp 143–144 °C; R_f = 0.41 (PE–EtOAc, 1:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 4.40 (d, ^2J = 5.6 Hz, 2 H, CH_2), 5.71 (br s, 1 H, NH), 6.64 (t, $^3J_{o,m}$ = $^3J_{H,F}$ = 8.6 Hz, 1 H, H_m), 7.02–7.13 (m, 5 H, C_6H_5), 7.37 (dd, $^3J_{o,m}$ = 8.6 Hz, $^4J_{H,F}$ = 5.5 Hz, 1 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 44.0 (CH_2N), 115.4 (d, $^2J_{C,F}$ = 22.1 Hz, C-3/C-5), 127.6 (C_p), 128.1 (C_m), 128.8 (C-1), 129.7 (d, $^3J_{C,F}$ = 8.8 Hz, C-2/C-6), 139.2 (C_{ipso}), 165.5 (C=O), 167.4 (d, $^1J_{C,F}$ = 250.5 Hz, C-4).

^{19}F NMR (376 MHz, C_6D_6): δ = –109.5.

MS (ESI+): *m*/*z* (%) = 230 (12, [M^+ + H]), 252 (100, [M^+ + Na]).

Anal. Calcd for $C_{14}H_{12}FNO$: C, 73.35; H, 5.28; N, 6.11. Found: C, 73.61; H, 5.45; N, 6.14.

6-(4-Fluoro)benzamino-6-deoxy-1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose (15)

6-Azido-6-deoxy-1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose (**12**;[26] 100 mg, 0.35 mmol) and phosphane **4b** (117 mg, 0.29 mmol) were dissolved in a DMF–H_2O mixture (0.5 mL:0.05 mL) and heated under microwave conditions (50 Watt) for 20 min. After removal of the solvent under reduced pressure, the crude product was purified by column chromatography (PE–EtOAc, 20:1); yield: 190 mg (92%); colorless syrup; R_f = 0.57 (PE–EtOAc, 4:1).

^{1}H NMR (400 MHz, C_6D_6): δ = 1.01, 1.13, 1.39, 1.46 [4 s, 3 H each, 2 × C(CH_3)$_2$], 3.44–3.52 (m, 1 H, H-6a), 3.81 (dd, $^3J_{3,4}$ = 7.8 Hz, 1 H, H-4), 4.02–4.07 (m, 1 H, H-6b), 4.15 (dd, $^3J_{1,2}$ = 4.7 Hz, $^3J_{2,3}$ = 2.3 Hz, 1 H, H-2), 4.12–4.16 (m, 1 H, H-5), 4.42 (dd, $^3J_{2,3}$ = 2.3 Hz, $^3J_{3,4}$ = 7.8 Hz, 1 H, H-3), 5.45 (d, $^3J_{1,2}$ = 4.7 Hz, 1 H, H-1), 6.33 (br s, 1 H, NH), 6.64 ('t', $^3J_{o,m}$ = $^3J_{H,F}$ = 8.6 Hz, 2 H, H_m), 7.55 (dd, $^3J_{o,m}$ = 8.6 Hz, $^4J_{H,F}$ = 5.5 Hz, 2 H, H_o).

^{13}C NMR (101 MHz, C_6D_6): δ = 24.3, 25.0, 26.1, 26.3 [4 × CH_3 of C(CH_3)$_2$)], 41.2 (C-6), 66.9 (C-5), 71.2 (C-2), 71.4 (C-3), 72.0 (C-4), 96.8 (C-1), 108.8, 109.3 [2 × C of C(CH_3)$_2$], 115.3 (d, $^2J_{C,F}$ = 22.1 Hz, C_m), 128.7 (C_{ipso}), 129.7 (d, $^3J_{C,F}$ = 8.8 Hz, C_o), 164.8 (d, $^1J_{C,F}$ = 250.4 Hz, C_p), 166.2 (C=O).

^{19}F NMR (376 MHz, C_6D_6): δ = –109.5.

MS (MALDI–TOF): *m*/z = 380 [M^+ – H].

Anal. Calcd for $C_{19}H_{24}FNO_6$: C, 59.83; H, 6.34; N, 3.67. Found: C, 59.78; H, 6.30; N, 3.78.

N-(2-(Benzamino)-2-oxoethyl)-4-fluorobenzamide (16)

2-Azido-*N*-benzylacetamide (**13**;[32] 67 mg, 0.35 mmol) and phosphane **4b** (118 mg, 0.29 mmol) were dissolved in a DMF–H_2O mixture (0.5 mL:0.05 mL) and heated under microwave conditions (50 Watt) for 20 min. After removal of the solvent under reduced pressure, the crude product was purified by column chromatography (PE–EtOAc, 20:1); yield: 66 mg (78%); colorless crystals; mp 194 °C; R_f = 0.13 (PE–EtOAc, 1:1).

^{1}H NMR (400 MHz, CD_3OD): δ = 4.06 (s, 2 H, CH_2CO), 4.42 (s, 2 H, PhCH_2), 7.20 ('t', $^3J_{o,m}$ = $^3J_{H,F}$ = 8.6 Hz, 2 H, H-3/H-5), 7.26–7.35 (m, 5 H, C_6H_5), 7.83 (dd, $^3J_{o,m}$ = 8.6 Hz, $^4J_{H,F}$ = 4.7 Hz, H-2/H-6).

^{13}C NMR (101 MHz, CD_3OD): δ = 44.0, 44.1 (2 × CH_2N), 116.4 (d, $^2J_{C,F}$ = 22.1 Hz, C-3/C-5), 128.1 (C_p), 128.5 (C_o), 129.5 (C_m), 131.1 (d, $^3J_{C,F}$ = 9.1 Hz, C-2/C-6), 139.8 (C_{ipso}), 166.3 (d, $^1J_{C,F}$ = 250.4 Hz, C-4), 169.4, 171.7 (2 × C=O).

^{19}F NMR (376 MHz, CD_3OD): δ = –110.8.

MS (MALDI-TOF): *m*/*z* = 287 [M^+ + H].

Anal. Calcd for $C_{16}H_{15}FN_2O_2$: C, 67.12; H, 5.28; N, 9.78. Found: C, 67.01; H, 5.23; N, 9.70.

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