Aromatic Rearrangements in the Benzene Series. Part 3.[1] Rearrangement of Isotopically Labelled Phenyl Benzoates: Intermolecularity of the *ortho*-Directed Rearrangement. Criteria for Determining the Intra-/Inter-molecularity of Aromatic Rearrangements

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The rearrangement of a mixture of $Ph^{13}COOPh$ and $PhCO^{18}OPh$ (with some unlabelled ester) catalysed by anhydrous $AlBr_3$ in homogeneous solution in chlorobenzene has been examined. Contrary to expectations, more of the 2-hydroxybenzophenone is formed intermolecularly than of the 4-hydroxybenzophenone at the beginning of the reaction, contradicting earlier views that a high *ortho*:*para* ratio in such reactions indicates the operation of an intramolecular mechanism. A mechanism is proposed for this stage of the rearrangement involving a cyclic six-membered transition state originating from one molecule of phenyl benzoate and one of $Ph–C(OPh)=\overset{+}{O}–\overset{-}{Al}Br_3$, allowing *C*-acylation by the benzoyl moiety of the catalyst–ester complex to compete with bimolecular ester interchange. This *C*-acylation can only occur at the *ortho*-position of the phenoxy-ring of the (uncomplexed) ester molecule, because of steric requirements. This step of the rearrangement is thus necessarily intermolecular. Criteria for judging the intra- or inter-molecularity of aromatic rearrangements are also briefly discussed.

In Part 1[2] we described the rearrangement of phenyl benzoate, catalysed by anhydrous $AlBr_3$, in homogeneous solution in chlorobenzene; and the acylation of phenol by benzoyl bromide, using the same catalyst and solvent. The reactions described involved one or two moles of $AlBr_3$ per mole of ester (the 1:1 and 2:1 rearrangements, respectively); or one or two moles of $AlBr_3$, one mole of phenol, and one of benzoyl bromide (the 1:1:1 and 2:1:1 acylations, respectively). The 1:1 rearrangement and 1:1:1 acylation led only to 2- and 4-hydroxybenzophenone (and small amounts of the ketoester 4-benzoylphenyl benzoate).

The 2:1 rearrangement and 2:1:1 acylation gave the same products, but solvent acylation also occurred, giving 2- and 4-chlorobenzophenone. In these latter two reactions, the ketoester appeared to be an intermediate rather than a by-product, whereas the reverse was the case in the 1:1 and 1:1:1 reactions. The acylations proceeded to a greater or lesser extent *via* the ester, which subsequently rearranged: over 90% of the maximum possible quantity of phenyl benzoate was formed at the start of the 1:1:1 acylation reaction. Under the conditions used, the most directly informative reactions were the 1:1 rearrangement and 1:1:1 acylation, and reactions involving two moles of $AlBr_3$ per mole of other reactant(s) will not be considered further in this paper.

The *ortho*:*para* (*o*:*p*) ratio of the hydroxybenzophenones formed decreased continuously with increasing time in the 1:1 rearrangement, but remained constant in the 1:1:1 acylation (after the initial stage of the latter reaction). The 1:1 rearrangement was represented as a combination of two reactions, one giving solely 2-hydroxybenzophenone (the first-stage reaction) and the other (which was faster) giving 2- and 4-hydroxybenzophenone in constant ratio (the second-stage reaction). A simple mathematical treatment (involving some approximations) showed that the calculated *o*:*p* ratio for the second-stage reaction was close to the experimental value for that of the 1:1:1 acylation. Our view[2] of the 1:1 rearrangement, therefore, was that it consisted of an intramolecular[3] reaction giving only 2-hydroxybenzophenone, and a competitive reaction giving 2- and 4-hydroxybenzophenone with a constant *o*:*p* ratio of *ca.* 0.78 under the reaction conditions used. In the light of then-current views, the experimental value (0.78) seemed low for a genuinely intramolecular rearrangement; on the other hand, no solvent acylation occurred. Consequently, the second-stage reaction was described[2] as 'pseudo-intramolecular'. The validity of current criteria for establishing the intramolecularity of reactions of this type is discussed later.

Table 1. Isotopic incorporations

$Ph^{13}COOPh$	87.9% (PhCOOPh 12.1%)
$PhCO^{18}OPh$	73.7% (PhCOOPh 26.3%)

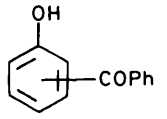
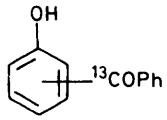
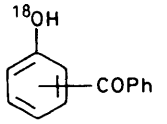
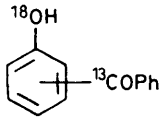
We sought additional firm experimental evidence for the proposals based on our original findings, and it seemed in the light of existing opinion (confused and contradictory as it is) on the mechanism of the Fries rearrangement that use of isotopically labelled compounds offered the best means of finding this. We synthesised $Ph^{13}COOPh$ and $PhCO^{18}OPh$ and rearranged a mixture of these compounds (which also contained unlabelled ester). We isolated unrearranged ester, 2- and 4-hydroxybenzophenone from reactions lasting 15 min and 4 h, and established the isotopic compositions of all these products by mass spectrometry.

Results and Discussion

Results of Mass Spectroscopic Measurements.—These are shown in Tables 1—4. In the following discussion, 'rearrangement' means the conversion of phenyl benzoate into 2- and 4-hydroxybenzophenone; 'scrambling' refers to mixing of isotopic labels by reactions between molecules or fragments of molecules. 'Interchange' means the exchange of PhCO and PhO groups between pairs of molecules to give phenyl benzoate (and is equivalent to scrambling of the ester when isotopically different fragments are involved).

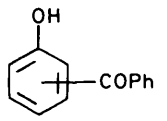
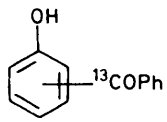
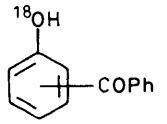
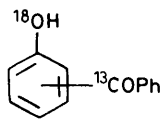
Earlier work[2] established that phenyl benzoate does not undergo a thermal rearrangement in chlorobenzene at 110 °C in the absence of $AlBr_3$. 2-Hydroxybenzophenone and 4-hydroxybenzophenone are not significantly interconverted under the reaction conditions used,[2,4] nor are the hydroxyketones converted back into the ester. [Effenberger[5] has criticised our earlier

Table 2. Rearrangement reaction: 15 min

Molecular weight	Molecule	Composition (%)[a] A	B	C	D	E	F
198	PhCOOPh or 	20.5	20.5	24.2	34.3	26.0	36.3
199	$Ph^{13}COOPh$ or 	39.5	39.7	34.5	27.6	32.7	23.7
200	$PhCO^{18}OPh$ or 	40.0	39.8	34.5	29.1	33.0	24.2
201	$Ph^{13}CO^{18}OPh$ or 	0	0	6.5	9.0	8.0	15.8

[a] An estimate of the errors involved, and the method by which the values in columns A and F were calculated, are given in the Appendix. A, Initial phenyl benzoate mixture (calculated composition); B, initial phenyl benzoate mixture (observed); C, isolated phenyl benzoate; D, isolated 2-hydroxybenzophenone; E, isolated 4-hydroxybenzophenone; F, 100% scrambled material (calculated composition)

Table 3. Rearrangement reaction: 4 h (duplicate run)

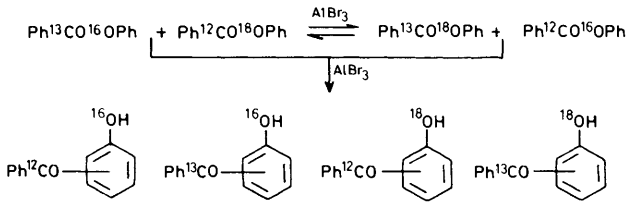
Molecular weight	Molecule	Composition (%)[a] A (1)	A (2)	B (1)	B (2)	C (1)	C (2)	D (1)	D (2)	E (1)	E (2)	F (1)	F (2)
198	PhCOOPh or 	18.3	18.4	18.3	18.2	34.0	34.0	33.4	33.1	33.4	33.8	35.0	35.1
199	$Ph^{13}COOPh$ or 	40.7	40.8	41.3	40.1	24.3	24.7	25.6	26.7	25.4	26.4	24.0	24.2
200	$PhCO^{18}OPh$ or 	41.0	40.8	40.4	41.7	24.0	24.2	26.6	26.1	27.0	25.6	24.3	24.1
201	$Ph^{13}CO^{18}OPh$ or 	0	0	0	0	17.6	17.1	14.4	14.1	14.0	14.2	16.7	16.6

[a] Footnotes as in Table 2. (1) and (2) refer to duplicate runs.

work[2] on the grounds that he has demonstrated the reversibility of the rearrangement, and stated that we had ignored this possibility. This accusation is groundless. His reactions were performed in $(CH_2Cl)_2$ at 170 °C in a sealed tube, *i.e.* in a closed (and more polar) system. Our reactions are conducted in an open system from which HBr is lost. We sought extensively[2,4] for evidence of the reversibility of the rearrangement under our own and related conditions: we found none.] Finally, the results in Table 4 show that in the absence of $AlBr_3$, the labelled esters had not undergone scrambling after 4 h at 110 °C in chlorobenzene. (In fact, the esters do not undergo scrambling at room temperature over a period of several months, in the absence of a catalyst, as indicated by mass spectrometry.) Thus, the distribution of isotopic labels in the product hydroxyketones

Table 4. Rearrangement reaction: 4 h, no $AlBr_3$

Molecular weight	Molecule	Composition (%)	
198	PhCOOPh	19.2	20.2
199	$Ph^{13}COOPh$	44.8	44.4
200	$PhCO^{18}OPh$	36.0	35.4
t/h		0	4



Scheme 1.

results only from intra- and/or inter-molecular rearrangement of phenyl benzoate catalysed by $AlBr_3$, and scrambling of unrearranged ester also occurs only through the action of $AlBr_3$, *i.e.* we have the situation shown in Scheme 1. Unlabelled ester has no effect on Scheme 1, though it is always present, as the synthetic labelled esters both contained some $Ph^{12}CO^{16}OPh$– see Experimental section.

The rate of ester interchange (scrambling) is crucial to this study. If such interchange is fast relative to rearrangement, then rearrangement would occur from fully scrambled ester, and no useful conclusions could be drawn about the rearrangement mechanism. Little work has been done on ester interchange in the specific context of the Fries rearrangement. Its occurrence in the presence of $AlCl_3$ has been demonstrated,[6] and more recently Ogata and Tabuchi[7] suggested that (at least under their reaction conditions) ester interchange occurred at a rate comparable with that of rearrangement. Our own results enable us to resolve this problem for the early part of our reactions, by using a simple graphical treatment as follows.

Knowing the percentage composition of the original ester mixture (before reaction occurs) the composition of a fully interchanged (scrambled) ester mixture, or of fully scrambled rearrangement products, is easily calculated [see Appendix. We have ignored primary kinetic isotope effects for carbon and oxygen ($^{12}C/^{13}C$, $^{16}O/^{18}O$). They are small at room temperature (*ca.* 1.05[8]) and will be smaller still at 110 °C]. Figure 1 shows these values plotted (for each molecule of nominal molecular weight 198, 199, 200, and 201) as ordinate *versus* % scrambling as abscissa, for the 15 min rearrangement. The experimentally determined relative intensities of the various molecular ions, of unrearranged ester, 2- and 4-hydroxybenzophenone, are also plotted on this graph, with the uncertainty in each value indicated. 2-Hydroxybenzophenone is clearly more scrambled than 4-hydroxybenzophenone, and both hydroxyketones are more scrambled than the unrearranged ester, which has undergone some interchange. Table 5 shows the extent of scrambling of each species for the 15 min and 4 h rearrangement reactions.

Inspection of the figures in columns C—E of Table 3 shows that the reproducibility of the experimental results is very good. The results for run (1) of the 4 h rearrangement are shown in Figure 2: the results for run (2) give a virtually identical graph if plotted. Table 5 shows that at 4 h the ester is virtually completely scrambled, and the hydroxyketones are almost so, so that the 4 h rearrangements plainly cannot provide much

Table 5. Rearrangement reactions: average % scrambling of substrate and rearrangement products

Reaction	Average % scrambling		
	Phenyl benzoate	2-Hydroxy-benzophenone	4-Hydroxy-benzophenone
15 min	33 ± 6	72 ± 11	43 ± 6
4 h (run 1)	100 ± 4	88 ± 2	87 ± 4
4 h (run 2)	98 ± 4	87 ± 2	89 ± 3

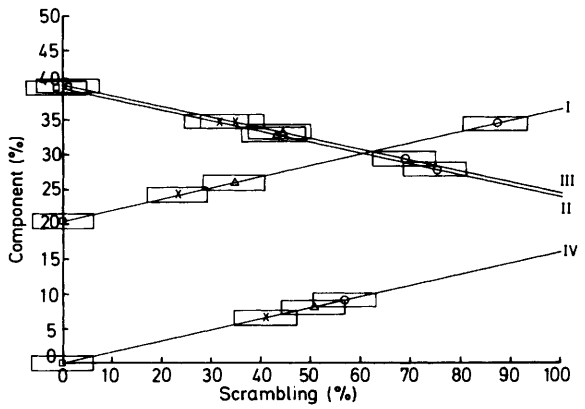


Figure 1. Rearrangement reaction: 15 min. I, mol.wt. 198; II, mol.wt. 199; III, mol.wt. 200; IV, mol.wt. 201. □, Initial phenyl benzoate mixture (observed); ×, isolated phenyl benzoate, ○, isolated 2-hydroxybenzophenone; △, isolated 4-hydroxybenzophenone; ▭, uncertainty

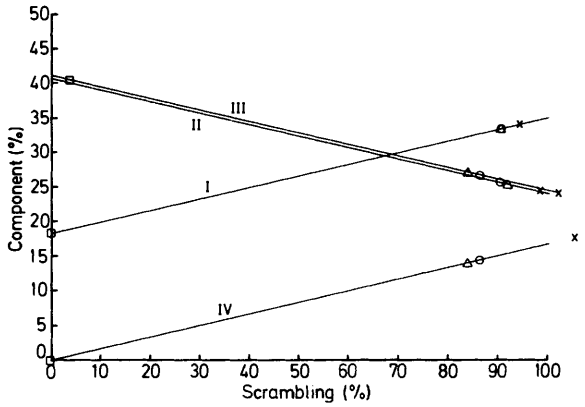
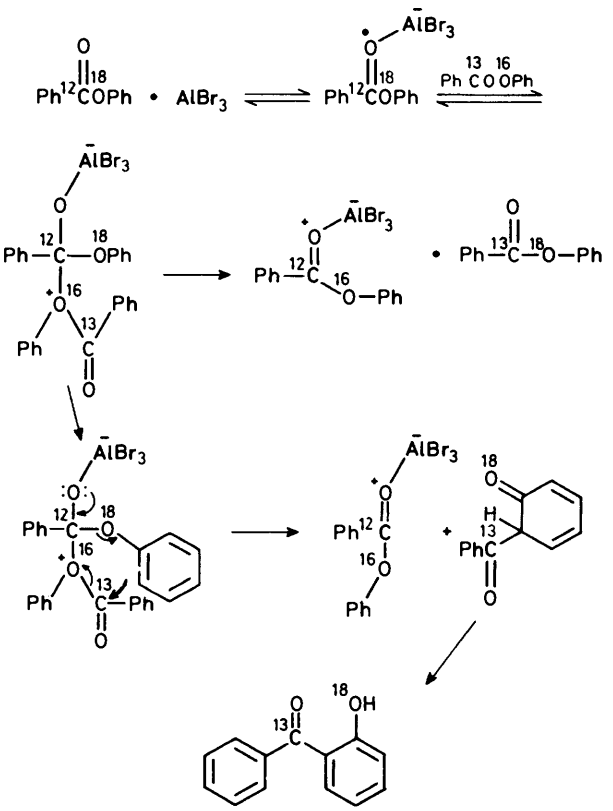


Figure 2. Rearrangement reaction: 4 h [run (1)]. I, mol.wt. 198; II, mol.wt. 199; III, mol.wt. 200; IV, mol.wt. 201. Symbols as in Figure 1 (uncertainties not shown to avoid crowding, but % scrambling values are ±6 for errors of ±1 in % component values)

information about the intra-/inter-molecularity of the reaction in view of the comparable extents of scrambling of the unrearranged ester and of the rearrangement products (though we shall return to this point later). In contrast, the 15 min rearrangement clearly shows that the 2-hydroxybenzophenone is more scrambled than the 4-hydroxybenzophenone, which in turn is more scrambled than the unrearranged ester. The difference in the extent of scrambling is greater than the experimental error and is significant.

The original proposal[2] that the first-stage reaction of the 1:1 rearrangement, giving 2-hydroxybenzophenone solely, was



Scheme 2.

intramolecular, was based on Dewar's intuitively reasonable arguments[3] that a high (in this case, infinite) *o*:*p* ratio for an aromatic rearrangement indicates an intramolecular pathway. However, the results of our 15 min rearrangement contradict this view. The greater extent of scrambling in the 2-hydroxy- than in the 4-hydroxybenzophenone implies that the 2-isomer is being formed by an intermolecular mechanism which does not permit formation of the 4-isomer (or at least that formation of the 2-isomer is greatly favoured over formation of the 4-isomer by such a mechanism) as otherwise both hydroxyketones would be equally scrambled. One possible mechanism is shown in Scheme 2. In this reaction, a cyclic six-membered transition state is involved, formed from one molecule of ester and one molecule of catalyst-complexed ester, and leading to one molecule of scrambled (interchanged) ester and one molecule of intermolecularly formed (and hence scrambled) 2-hydroxybenzophenone (presumably as its $AlBr_2$ derivative). This mechanism cannot lead to the formation of 4-hydroxybenzophenone, as the 4-position of the relevant benzene ring cannot approach closely enough to the acyl group carbon for reaction to occur (see Scheme 2). Space-filling molecular models indicate that the postulated transition state is entirely feasible, and what we are proposing is a diversion of the normal ester interchange process into a rearrangement leading exclusively, but necessarily intermolecularly, to 2-hydroxybenzophenone.

The other interesting feature of this reaction is that neither of the hydroxyketones is fully scrambled, the 4-hydroxybenzophenone being only about one-third so, whilst even the 2-isomer is only about three-quarters scrambled. In Part 1,[2] the second-stage reaction was described as 'pseudo-intramolecular': our current findings support this early view. If rearrangement in the second-stage reaction to give both 2- and 4-hydroxybenzophenone occurs to some extent within a tight ion-pair, then the hydroxyketones will be produced by this mechanism without scrambling. If the $PhCO^+$ and $PhO\bar{A}lBr_3$ fragments become solvated and escape from the tight ion-pair and then react, the products will be scrambled. Further, rearrangement within the tight ion-pair might be expected to lead to a higher *o*:*p* ratio than reaction of solvated ions: less reorganisation of the tight ion-pair will be needed for *ortho*-substitution than for *para*, and in the absence of steric effects due to solvation *ortho*-substitution should again be easier. Paradoxically, therefore, the unscrambled *ortho*-rearrangement product is being produced by a process which is dissociative, though incompletely so, while the scrambled *ortho*-component is not primarily a result of complete dissociation but of an evidently bimolecular associative mechanism.

Table 6. Products of reaction at 0.25 and 4 h (values from ref. 4)

PhCOOPh (mol %)	96.2	50.0
2-HOC_6H_4COPh (mol %)	2.0	20.5
4-HOC_6H_4COPh (mol %)	1.1	17.7
o:*p* ratio	1.74	1.16
t/h	0.25	4

In the 15 min rearrangement, little of the ester is scrambled: most of the ester has not rearranged. After 4 h, virtually all of the (unrearranged) ester is scrambled. Table 6 shows the quantities of ester and products at the two reaction times used.

If the small difference, in the results for the 4 h rearrangements, between the extent of scrambling of the ester on the one hand and the hydroxyketones on the other (see Table 5) is genuine, then it reflects the fact that whilst ester interchange is necessarily intermolecular, some of the actual rearrangement (as we have argued on the basis of the results of the 15 min rearrangement) appears intramolecular (*via* a tight ion-pair above) though at 4 h, the majority of the rearrangement products have also been formed intermolecularly.

Our work shows, therefore, that the original proposal[2] that the 1:1 rearrangement occurs (under our reaction conditions) *via* two paths is correct; the surprising feature is that the 2-hydroxybenzophenone formed alone in the first-stage reaction results from an intermolecular (*i.e.* bimolecular) reaction rather than from an intramolecular reaction as had been suggested.[2] At least some of the 2- and 4-hydroxybenzophenone must be formed by an *apparently* intramolecular route (see the 15 min reaction results), which we suggest involves a heterolysis to give a tight ion-pair ($PhCO^+$·$PhO\bar{A}lBr_3$) with reaction to give hydroxyketones occurring to some extent before full solvation of the ion-pair occurs. (This cannot, of course, be demonstrated by our labelling experiments.) This possibility was recognised in the original paper,[2] and the mechanism dubbed 'pseudo-intramolecular'. Schofield[9] has coined the term 'extramolecular' for such processes. Reaction to give hydroxybenzophenones must also occur from the solvent-separated ion-pair as indicated by the results of the 4 h rearrangement.

Our results are of rather wider significance in the context of determining whether aromatic rearrangements of this type are intramolecular or not. The various criteria[10] on which such a decision has formerly been based have successively been shown to be invalid, or at least questionable, and we are left finally with the long established[11] use of isotopic labelling experiments as the ultimate test of validity, applicable only when the effects of scrambling do not obscure the process being investigated.

Experimental

Materials.—Anhydrous $AlBr_3$, chlorobenzene, phenyl benzoate (unlabelled), and 2- and 4-hydroxybenzophenone were all

synthesised and/or purified as described previously.[2] Benzoic acid ($Ph^{13}COOH$, 90 atom %) and $^{18}O_2$ (99 atom %) were both obtained from Prochem.

$Ph^{13}COOPh$.—Phenyl [*carboxy*-^{13}C]benzoate was synthesised from $Ph^{13}COOH$. The optimised procedure was as follows. Labelled benzoic acid (0.989 g, 8.1 mmol) was refluxed for 4 h with freshly distilled $SOCl_2$ (10 ml). The excess of $SOCl_2$ was removed on a rotary evaporator and the flask cooled to 0 °C. Phenol (0.832 g, 8.8 mmol; recrystallised from distilled hexane) dissolved in pyridine (1 ml) was added dropwise with shaking. An exothermic reaction occurred with formation of a precipitate, and HCl (2M; 10 ml) was added. The mixture was extracted with ether (3 × 10 ml), the extract was washed with water (2 × 10 ml), dried ($MgSO_4$), and the ether was removed. The crude ester was chromatographed on Al_2O_3 with CH_2Cl_2 as eluant. The yield of $Ph^{13}COOPh$ was 0.97 g (60%), m.p. 71 °C (lit.,[12] 71 °C). Mass spectrometry (see later) showed that the incorporation of ^{13}C was 87.9%.

$PhCO^{18}OPh$. –Phenyl [^{18}O]benzoate was prepared as follows. [Tetrahydrofuran (THF) was found to be the best solvent for the reaction (superior to Et_2O and PhOEt) giving $Ph^{18}OH$ in good yield.] Oven-dried magnesium (1.2 g, 50 mmol) and THF (30 ml; sodium-dried) were placed in a flask (50 ml) fitted with a septum and reflux condenser plus drying tube. Dry nitrogen was bubbled through the THF for 15 min to displace oxygen, and the remainder of the process was carried out under nitrogen. PhBr (4 ml, 38 mmol; redistilled from CaH_2) was added to THF (15 ml) and nitrogen passed through the solution for 15 min, when the solution was injected into the flask (above) and the contents were refluxed and stirred magnetically for 3 h. The PhMgBr solution was cooled in an ice-bath and injected into a glass bulb (100 ml; in which the labelled oxygen was supplied) containing the $^{18}O_2$ at 1 atm. pressure, which was suspended in an ice–acetone bath at *ca.* −20 °C. Before this step, a ball-bearing had been carefully placed in the neck of the bulb, which was then fitted with a septum. The bulb was shaken so that the ballbearing broke the internal glass seal. After addition of the (excess of) PhMgBr solution, the bulb was rotated in a cooling bath at a moderate speed for *ca.* 4 h. The contents of the bulb were then added to HCl (20 ml) in a separating funnel, shaken, and extracted with CH_2Cl_2 (5 × 20 ml). The extract was reduced in volume to give *ca.* 20 ml of a yellow liquid. This was then extracted with NaOH (2M, 3 × 10 ml). The alkaline aqueous layer was washed with CH_2Cl_2 (3 × 10 ml) and then acidified, with cooling, to pH 1, using concentrated HCl. The acidified solution was then extracted with CH_2Cl_2 (5 × 10 ml), the extract was dried ($MgSO_4$), reduced to *ca.* 5 ml, and transferred to a round-bottomed flask (100 ml). Pyridine (5 ml, 62 mmol) was added, followed by PhCOCl (AnalaR; 1.3 ml, 11.2 mmol) dropwise, with cooling and swirling. The work-up and purification were similar to those used in the preparation of $Ph^{13}COOPh$ (above). The yield of $PhCO^{18}OPh$ was 1.304 g (73% calculated on the $^{18}O_2$ used), m.p. 70.5 °C (lit.,[12] 71 °C). Mass spectrometry (see later) showed that the incorporation of ^{18}O was 73.7%. This relatively low figure is most probably due to access of atmospheric oxygen through the septum during the reaction of PhMgBr and $^{18}O_2$.

Rearrangement Reactions.—Detailed descriptions of these appear in ref. 13. They were carried out largely as described in ref. 2, but a brief summary of the essential points follows. Weight-in-weight (molal) solutions of $AlBr_3$ and PhCOOPh in chlorobenzene were used to ensure sufficient accuracy and avoid the uncertainty caused by temperature variations when molar solutions are used. Reactions were performed in a Tamson TE45-250 constant-temperature oil-bath at 110 ± 0.2 °C. An $AlBr_3$ solution (1.0 molal) was prepared and *ca.* 0.5 ml weighed accurately and used for a rearrangement reaction. The quantity of $AlBr_3$ present in this weight of solution was calculated and a 1.0 molal solution of the labelled esters prepared in a 20% molar excess of this amount. (The labelled esters were used in equimolar proportions, *i.e.* taking into account the isotopic incorporations.) The excess of solution was then removed, using a finely drawn glass tube, to within ±0.0005 g of the required weight for a 1:1 molar ratio of $AlBr_3$:ester. The excess of the ester solution was analysed by mass spectrometry (see below) to give the data in column B of Tables 2 and 3 (see above). Rearrangements using this procedure were carried out for 15 min and 4 h. (The reactant solutions were separately heated to 110 °C before being mixed in the case of the 15 min rearrangement.) The reactions were quenched in the usual way,[2] and ester, 2- and 4-hydroxybenzophenone, and ketoester, were separated as follows. The mixture of reaction products was subjected to t.l.c. on silica gel GF_{254} (two plates; 200 × 200 × 0.8 mm; previously pre-eluted with redistilled EtOAc) using redistilled CH_2Cl_2 as the mobile phase. This separated 4-hydroxybenzophenone (R_F 0.08) and the ketoester (R_F 0.51) completely, but gave only partial separation of ester and 2-hydroxybenzophenone (R_F 0.8—0.9). The compounds were eluted from the silica with 75:25 v/v CH_2Cl_2–MeOH. The mixture of ester and 2-hydroxybenzophenone was then chromatographed on a column of Al_2O_3 (B.D.H., Brockmann activity II) using CH_2Cl_2 as eluant. The ester was eluted rapidly, leaving the 2-hydroxybenzophenone as a narrow yellow band at the top of the column. The hydroxyketone was removed from the alumina by shaking the yellow layer with concentrated HCl (AnalaR; 2 ml) in redistilled MeOH (2 ml). The acidified methanolic layer was extracted with redistilled hexane (3 × 10 ml) and this was then reduced in volume. The ester and the two hydroxyketones were shown to be pure by g.l.c. (see below). Most importantly, each individual compound was completely uncontaminated by the other two.

Analytical Work.—G.l.c. analysis of the ester and hydroxyketones was performed on a Perkin-Elmer F-33 chromatograph fitted with a flame-ionisation detector. A glass column (1 m × 3 mm i.d.) packed with 5% Dexsil 300GC on 100—120 mesh Gas Chrom Q (Applied Science Labs.) was used at 220 °C with detector and injector at 275 °C, and a carrier gas (N_2) inlet pressure of 10 lb in^{-2} (giving a flow rate of 24 ml min^{-1}). The hydroxyketones were trimethylsilylated [using $MeC(OSiMe_3)=NSiMe_3$] before analysis (see ref. 2). The retention times (min) under these conditions were: ester, 3.8; 2-trimethylsilyloxybenzophenone, 6.0; 4-trimethylsilyloxybenzophenone. 13.0.

Mass Spectrometry.—Although the molecular ion of phenyl benzoate is weak when electron impact (e.i.) ionisation is used, this mode was eventually employed after investigation of other techniques (chemical and field ionisation) which were found, for various reasons, to be less satisfactory.[13] A magnetically focussing spectrometer was used, giving much better resolution of the ion peaks, though it could not scan as quickly as a quadrupole mass spectrometer, use of which was also examined. Spectra were eventually recorded on a VG Micromass–AEI MS9 spectrometer linked to a VG2035 data-processing system. E.i. ionisation (70 eV) was used, with a source temperature of 180—200 °C. At least 40 scans of the molecular ion cluster were obtained for each compound and averaged using the data-processing unit. A computational program modified from Benz's[14] program was used to calculate isotopic incorporations and distributions. This program substracted contributions due to the presence of naturally abundant carbon-13, and this required the mass spectra of unlabelled ester and 2- and 4-hydroxybenzophenone. The system proved stable with time, *i.e.*

Table 7. 15 min rearrangement

Label	Ester (t 0)	Ester (t 15 min)	2-Hydroxy-benzo-phenone	4-Hydroxy-benzo-phenone	Mean relative intensity	Range
PhCO	60.3	58.7	63.4	59.0	60.4	4.7
$Ph^{13}CO$	39.7	41.0	36.6	40.7	39.5	4.4
PhO	60.2	58.7	61.9	58.7	59.9	3.2
$Ph^{18}O$	39.8	41.0	38.1	41.0	40.0	2.9

the relative intensities of ions in the molecular ion clusters did not vary significantly when measured at different times. Recorded relative intensities were accurate to within ± 1. Apart from the spectra of the unlabelled materials (above) spectra of the labelled esters were recorded, as were spectra of the unrearranged mixed labelled esters, and of the ester and hydroxyketones isolated from rearrangements of 15 min and 4 h duration. (Two 4 h rearrangements were performed to check the reproducibility of the results – see Table 3.)

Appendix

A detailed description of the treatment of the results of the 15 min rearrangement is given below, showing how the estimated errors have been calculated.

The relative amounts of the fragments PhCO, $Ph^{13}CO$, PhO, and $Ph^{18}O$ are constant throughout the reaction. Thus, using the experimentally determined values for the 15 min rearrangement (columns B—E of Table 2) we derive the values shown in Table 7.

The average values of relative intensities of PhCO, $Ph^{13}CO$, PhO, and $Ph^{18}O$ have been used to calculate the relative proportions of PhCOOPh, $Ph^{13}COOPh$, $PhCO^{18}OPh$, and $Ph^{13}CO^{18}OPh$ when ester interchange has reached equilibrium. At t 0, the mixture of labelled esters is given by a PhCOOPh + b $Ph^{13}COOPh$ + c $PhCO^{18}OPh$, where a—c are the respective numbers of moles. Thus the total amount of PhCO = $(a + c)$, of $Ph^{13}CO = b$, of PhO = $(a + b)$, and of $Ph^{18}O = c$. When ester interchange is complete, the relative amounts of differently labelled esters are expressed by relations (1)—(4).

$$\text{PhCOOPh: } \frac{(a + b)(a + c)}{(a + b + c)^2} \quad (1)$$

$$\text{Ph}^{13}\text{COOPh: } \frac{b(a + b)}{(a + b + c)^2} \quad (2)$$

$$\text{PhCO}^{18}\text{OPh: } \frac{c(a + c)}{(a + b + c)^2} \quad (3)$$

$$\text{Ph}^{13}\text{CO}^{18}\text{OPh: } \frac{bc}{(a + b + c)^2} \quad (4)$$

From Table 7, $(a + c) = 60.4$, $b = 39.5$, $(a + b) = 59.9$, and $c = 40.0$. From these values, the figures in columns A and F of Table 2 have been calculated, and these enable the lines in Figure 1 to be plotted. The (experimental) values in columns C—E of Table 2 have then been plotted in Figure 1, the error ranges being based on the fact that measured intensities are accurate to ± 1 (see Experimental section). Because the equation of each line is known, the percentage scrambling (x value) corresponding to each relative intensity (y value) is readily calculated, and an average figure obtained. The results are shown in Table 5. Exactly the same procedure has been followed for the 4 h reactions [runs (1) and (2)].

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