Aryliodine(III) Dicarboxylates

By A. Varvoglis
LABORATORY OF ORGANIC CHEMISTRY UNIVERSITY OF THESSALONIKI, THESSALONIKI, GREECE

1 Introduction

Since the last general review on polyvalent iodine compounds by Banks[1] in 1966, a considerable body of research has been published, especially on aryliodine(III) dicarboxylates, [$ArI(OCOR)_2$ abbreviated* to AID]. The multifaced interest of these compounds has been the driving force for this review, which is restricted mainly to the title compounds, with incidental citations of related compounds such as aliphatic and cyclic analogues, iodine(III) tricarboxylates, *etc.*

Nomenclature.—A great variety of names have been used for AID (no less than fourteen!). The nomenclature in *Chemical Abstracts* has been changed several times, *e.g.* for PID* from (dihydroxyiodo)benzene diacetate to iodosobenzene diacetate to phenyliodine(III) diacetate to the current phenyliodine bis(acetato-*O*). The nomenclature used here has been adopted by several journals.

2 Structure and Spectra

The crystal structures of PID (1) and $PhI(OCOCHCl_2)_2$ (2) have been recently determined.[2,3] The first study[2] was performed at $-60\,^{\circ}C$ to avoid decomposition by *X*-rays and revealed a wealth of structural information. Both molecules have in common the T-shaped geometry of dsp^3 hybridized trivalent iodine compounds but the overall geometry of iodine can be described as a pentagonal planar arrangement of three strong and two weak secondary bonds (Figures 1 and 2).

In (1) the two I–O distances of the covalent bonds are equal and the two secondary I···O bonds are intramolecular, forming a four-membered IOCO ring. In (2) the I–O distances differ significantly and the molecule is a dimer: one of the I···O bonds is intramolecular and the other intermolecular, forming a I_2O_2 ring. As a suitable bonding model, the overlap of the I–C antibonding orbital with each one of the oxygen atoms lone-pair orbitals is favoured[2] (Figure 3).

The dipole moments of PID (4.65 D) and other AID have been determined in benzene and compared with theoretical values for various conformations.[4]

*Other abbreviations: PID = phenyliodine(III) diacetate, PIB = phenyliodine(III) bis(trifluoroacetate), LTA = lead tetra-acetate. All these compounds are commercially available.

[1] D. F. Banks, *Chem. Rev.*, 1966, **66**, 243.
[2] N. W. Alcock, R. M. Countryman, S. Esperas, and J. F. Sawyer, *J. Chem. Soc., Dalton Trans.*, 1979, 854.
[3] C.-K. Lee, T.-C.W. Mak, W.-K. Li, and J. F. Kirner, *Acta Cryst.*, 1977, **B33**, 1620.
[4] O. Exner and B. Plesničar, *J. Org. Chem.*, 1974, **39**, 2812.

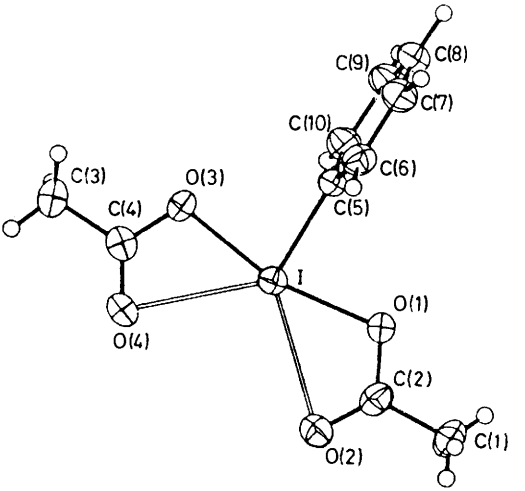


Figure 1 *ORTEP view of* (1)
(Reproduced from *J. Chem. Soc., Dalton Trans.*, 1979, 854)

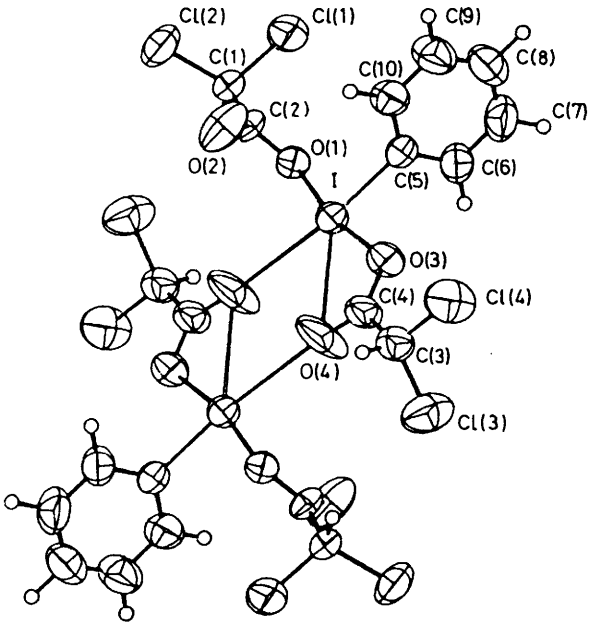


Figure 2 *ORTEP view of* (2)
(Reproduced from *J. Chem. Soc., Dalton Trans.*, 1979, 854)

The results clearly showed that all AID are in the *Z* conformation, essentially identical to their structure in the crystalline state. No evidence has been found

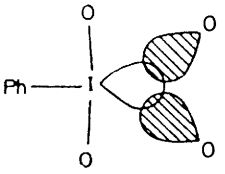


Figure 3 *Pentagonal-plane arrangement around iodide in* (1) *and* (2) (Reproduced from *J. Chem. Soc., Dalton Trans.*, 1979, 854)

in the ^1H n.m.r. spectra between 50 and $-55\,°C$ for the presence of an *E* conformer or a dissociation of the type shown in equation 1.

$$PhI(OCOR)_2 \rightleftharpoons PhI^+OCOR + RCO_2^- \quad (1)$$

It seems that in non-polar solvents there is no appreciable dissociation, an observation borne out by freezing point and conductivity measurements.[5] In polar solvents, however, there is a small degree of dissociation above room temperature, as shown for PID by conductivity studies in acetic acid.[6] The existence of an ionic equilibrium in MeO^2H for a series of AID has been claimed on the basis of n.m.r. spectra at -80 to $-60\,°C$, where two acyloxy-groups were observed and assigned to covalent and ionic forms.[7] In CH_2Cl_2 and $CHCl_3$ no such splitting was observed. This interpretation is open to question since PID in $CDCl_3$, with two equivalents of MeOH, exchanges its acetoxy-groups slowly enough at $-60\,°C$ to be observed by n.m.r.[8] [Equation (2)].

$$PhI(OCOCH_3)_2 + n\text{MeOH} \rightleftharpoons PhI(OCOCH_3)_{2-n}(OMe)_n + nCH_3CO_2H \quad (2)$$

^{19}F n.m.r. spectra of several *meta*- and *para*-X-substituted fluorobenzenes,[9] where X = $I(OAc)_2$, $I(OCOCF_3)_2$ *etc.*, showed that iodine does not interact with the aromatic ring mesomerically and that only the inductive effect operates in the order $I(OCOCF_3)_2 > ICl_2 > IF_4 > IF_2 > I(OAc)_2$.

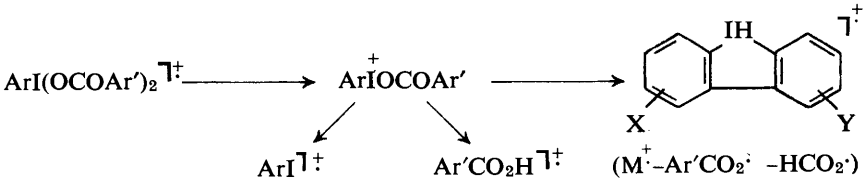
The ^{13}C n.m.r. spectrum of PID gives a value of 122.2 p.p.m. for the C bound to I, far off the value of 94.66 p.p.m. observed for the same C in iodobenzene.[10] It seems that the anomalous 'heavy atom' effect of iodine is restricted to its monovalent compounds.

The i.r. spectra of several AID have been discussed.[11] The carbonyl stretching band is displaced to values *ca.* 100 cm^{-1} less than those of the corresponding C-compounds, *e.g.* for $PhCH(OAc)_2$ νCO = 1755 cm^{-1} and for $PhI(OAc)_2$ νCO = 1660 cm^{-1} (in CCl_4). This remarkable shift has been attributed to inefficient overlap between the oxygen orbitals: electrons shift towards O and

[5] W. D. Johnson and N. V. Riggs, *Aust. J. Chem.*, 1955, **8**, 457.
[6] W. D. Johnson and J. E. Sherwood, *Aust. J. Chem.*, 1971, **24**, 2281.
[7] S. S. Makarchenko, E. B. Merkushev, M. M. Shakirov, and A. I. Rezvukhin, *Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Khim. Nauk*, 1978, 125 (*Chem. Abstr.*, 1978, **89**, 162 876).
[8] A. Seveno, G. Morel, A. Foucaud, and E. Marchand, *Tetrahedron Lett.*, 1977, 3349.
[9] V. V. Lyalin, G. P. Syrova. V. V. Orda, L. A. Alekseeva, and L. M. Yagupolskii, *Zh. Org. Khim.*, 1970, **6**, 1420. (*Chem. Abstr.*, 1970, **73**, 87 298).
[10] K. Friedrich, W. Amann, and H. Fritz, *Chem. Ber.*, 1978, **111**, 2099.
[11] R. Bell and K. J. Morgan, *J. Chem. Soc.*, 1960, 1209.

the C=O bond weakens, while the molecule acquires partially ionic character. A cyclic contribution (as that of Figure 3) was rejected. The fact that PID both in nujol and CCl_4 has low νCO values suggests that the cyclic form of the crystalline state indeed does not contribute significantly to the weakening of the carbonyl bond. Other characteristic bands near 1290 cm^{-1} and 670 cm^{-1} have been tentatively assigned to the stretching of the I–O–(C) system.

The mass spectra of a series of aryliodine(III) dibenzoates have been reported.[12] With the exception of phenyliodine(III) dimesitoate, no molecular ions were detected, but several fragment ions arose from thermal decompositions. The main fragmentation pathways include ions of both benzoic acids and iodobenzene, and a minor fragment has been attributed to the iodole ion in Scheme 1. No molecular ions were seen in the mass spectra of several aryliodine(III) diacetates.[13]



Scheme 1

The u.v. spectra of AID have not been published, but those of some diacetates have been found to exhibit a considerable hypsochromic shift[14] in comparison to iodoarenes, like other polyvalent iodine compounds.[15]

3 Synthesis

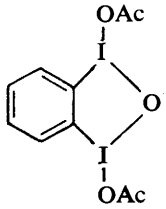
The standard procedure for the preparation of AID with aliphatic acids is the direct oxidation of iodoarenes with peracids, in the presence of the corresponding carboxylic acid [Equation (3)].

$$ArI + RCOOOH + RCOOH \longrightarrow ArI(OCOR)_2 + H_2O \qquad (3)$$

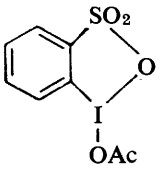
This is especially applicable to the preparation of diacetates, using 30% H_2O_2 and acetic anhydride[16] or 40% peracetic acid.[17] It should be noted that with excess 40% peracetic acid, iodoxybenzene ($PhIO_2$) is formed.[17] This method fails with some *ortho* substituted iodobenzenes: *o*-di-iodobenzene forms diacetoxybenzodi-iodoxole[18a] (3), which was shown by n.m.r. spectroscopy not to be in equilibrium with the isomeric *o*-iodoso-PID;*o*-iodobenzenesulphonamide

[12] E. Malamidou, E. Micromastoras, and A. Varvoglis, *Chim. Chron., New Series*, 1977, **6**, 493.
[13] J. A. Gustafsson, L. Rondahl, and J. Bergman, *Biochemistry*, 1979, **18**, 865.
[14] J. Gallos, Ph.D Thesis, to be submitted to the University of Thessaloniki.
[15] F. M. Beringer and P. Bodlaender, *J. Org. Chem.*, 1968, **33**, 2981.
[16] K. H. Pausacker, *J. Chem. Soc.*, 1953, 107.
[17] J. G. Sharefkin and H. Saltzman, *Org. Synth.*, 1963, **43**, 60, 62, 65.
[18] (a) W. Wolf, E. Chalekson, and D. Kobata, *J. Org. Chem.*, 1967, **32**, 3239; (b) H. Jaffé and J. E. Leffler, *ibid.*, 1973, **38**, 2719; (c), 1975, **40**, 797.

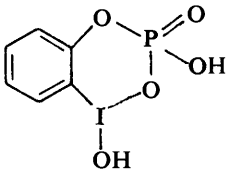
gives the benziodathiazole system[18b] (4) and *o*-iodophenylphosphoric acid the benziodadioxaphosphorin[18c] (5), presumably after hydrolysis of its acetate. *o*-Iodobenzamide[19] reacts similarly.



(3)



(4)



(5)

Pentafluoroiodobenzene has been converted into its bis-trifluoroacetate[20] with $(CF_3CO)_2O$ and HNO_3, in a reaction where CF_3CO_3H was formed *in situ*. Aryliodine(III) dichlorides react with Ag^+ and Pb^{2+} carboxylates[1] and also with aqueous AcOH in pyridine[21] to give AID. Iodosoarenes and carboxylic acids[1] or their anhydrides[20] react to form AID, upon simple stirring in a suitable solvent.

Aliphatic iodocompounds do not normally form dicarboxylates with the exception of *trans*-chlorovinyliodide[22] and certain perfluoroiodides; *e.g.* $CF_3I(OCOCF_3)_2$ has been prepared[23] from CF_3IF_2 or CF_3IO and $(CF_3CO)_2O$. With peracetic acid, alkyliodides form acetyl hypoiodite, which reacts further with the iodide to give an acetate ester and iodine.[24] In the presence of arenes iodination of the aromatic ring takes place. Alkyl iodides with *meta*-chloroperbenzoic acid are converted mainly into alcohols[25] *via* iodosocompounds, which rearrange to alkyl hypoiodites; the latter hydrolyse through formation of carbonium ions, so that the yields of alcohols are not always good. Among other products, depending on the nature of alkyl iodide, are ketones and oxiranes.

AID exchange their acyloxy-groups with stronger acids.[26] Initially a μ-oxo-dicarboxylato-diaryl-di-iodine (6) is formed, which with excess of the acid is transformed to the new AID (Scheme 2).

[19] W. Wolf and L. Steinberg, *J. Chem. Soc., Chem Commun.*, 1965, 449; H. J. Barber and M. A. Henderson, *J. Chem. Soc.* (*C*), 1970, 862.

[20] M. Schmeisser, K. Dahmen, and P. Sartori, *Chem. Ber.*, 1967, **100**, 1633, and 1970, **103**, 307; L. M. Yagupolskii, I. I. Maletina, N. V. Kondratenko, and V. Orda, *Synthesis*, 1977, 574.

[21] B. Karele and O. Neilands, *Latv. PSR Zinat. Akad. Vestis, Kim. Ser.*, 1970, 587. (*Chem. Abstr.*, 1971, **74**, 42033).

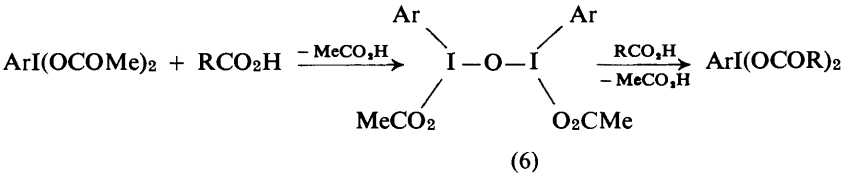
[22] J. Thiele and H. Haakh, *Ann. Chem.*, 1909, **369**, 131.

[23] D. Naumann and J. Baumans, *J Fluorine Chem.*, 1976, **8**, 177.

[24] Y. Ogata and K. Aoki, *J. Org. Chem.*, 1969, **34**, 3974.

[25] H. J. Reich and S. L. Peake, *J. Am. Chem. Soc.*, 1978, **100**, 4888; R. C. Cambie, D. Chambers, B. G. Lindsay, P. S. Rutledge, and P. D. Woodgate, *J. Chem. Soc., Perkin Trans. 1*, 1980, 822; T. L. Macdonald, N. Narasimhan, and L. T. Burka, *J. Am. Chem. Soc.*, 1980, **102**, 7760.

[26] E. B. Merkushev, A. N. Novikov, T. I. Kogai, and V. V. Gluskova, *Zh. Org. Khim.*, 1972, **8**, 436.

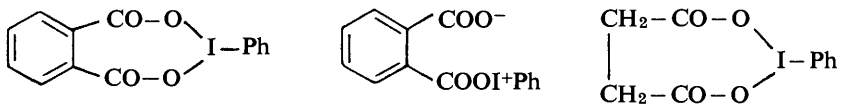


(6)

Scheme 2

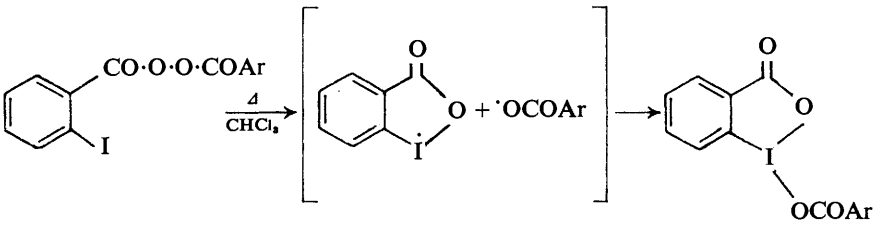
Using the above method with an isolable μ-compound (6), and by careful sequential addition of two different acids, AID with two different acyloxy-groups, *e.g.* PhI(OCOCH$_2$Cl)(OCOCH$_2$Br), have been obtained.[27] Two seven-membered heterocycles were obtained from PID and phthalic acid[28] (7) and from PID and succinic acid[29] (8):

The cyclic structures of (7) and (8) have not been rigorously proven and they



(7) (7′) (8)

may well be internal salts. In fact structure (7′) has been proposed for the product of the reaction between PID and phthalic anhydride.[30] An exchange reaction between PID and acid anhydrides also leads to AID.[30] Cyclic AID are also known with five and six-membered rings.[1] Of special interest are cyclic AID (10) resulting from thermal rearrangement of *o*-iodobenzoyl aroyl peroxides (9), (Scheme 3).



(9) (10)

Scheme 3

[27] E. B. Merkushev, T. I. Kogai, L. G. Polyakova, and A. N. Novikov, *Zh. Org. Khim.*, 1973, **9**, 1077.

[28] E. B. Merkushev, A. N. Novikov, S. S. Makarchenko, A. S. Moskal'chuk, T. I. Kogai, V. V. Glushkova, and L. G. Polyakova, *Zh. Org. Khim.*, 1975, **11**, 1259.

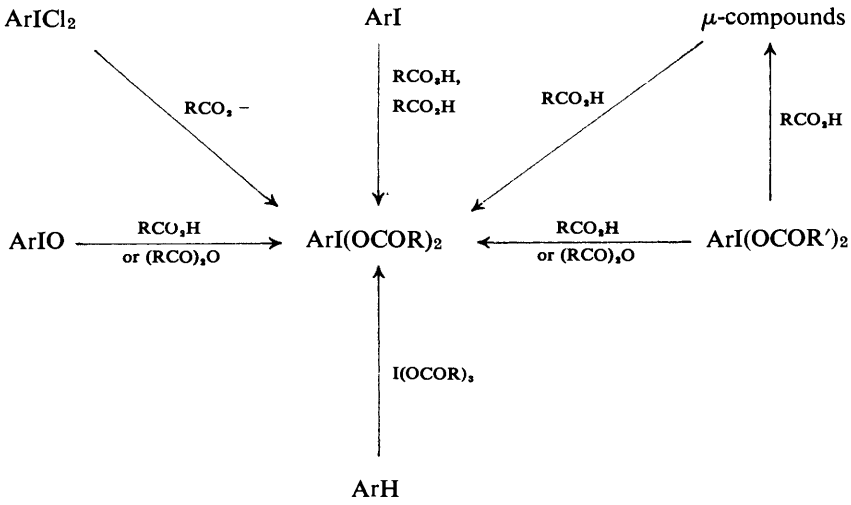
[29] G. P. Baker, F. G. Mann, N. Sheppard, and A. J. Tetlow, *J. Chem. Soc.*, 1965, 3721.

[30] A. N. Moskal'chuk, S. S. Makarenko, and A. N. Novikov, *Dep. Publ. VINITI* 6261-73, 1973 (*Chem. Abstr.*, 1976, **85**, 46116).

The above rearrangement was found to occur *via* a caged radical-pair mechanism.[31] It can also take place in the solid state thermally or upon *X*-irradiation, as revealed during crystallographic studies. Compound (10), ArCO = *o*-iodobenzoyl, appears in two polymorphic forms, whose crystal structures differ significantly; one of them results in a preferentially oriented single-crystal phase (topotaxy). It should be noted that solid-state chemistry of organic polyvalent iodine compounds similar to (10) has been shown to be a fruitful area of research.[32]

A final preparative method for AID is the electrophilic aromatic substitution of various arenes (activated or slightly deactivated) with tris-trifluoroacetoxyiodine.[33] Monosubstituted benzenes give exclusively *para*-isomers, whereas $C_6H_5CF_3$ affords the *meta*-isomer. In the presence of strong acids diaryliodonium salts are formed preferentially.[34] Iodobenzene has also been oxidized electrolytically[35] into PID.

The various preparative methods of AID are summarized in Scheme 4.



Scheme 4

4 Chemical Properties

AID are fairly stable compounds. They decompose only at elevated temperatures (Section 4E) and they are not hydrolysed by atmospheric moisture. They are hydrolysed by alkali into iodosoarenes and this is the method of choice for

[31] J. E. Leffler, R. D. Faulkner, and C. C. Petropoulos, *J. Am. Chem. Soc.*, 1958, **80**, 5435; W. Honsberg and J. E. Leffler, *J. Org. Chem.*, 1961, **26**, 733.

[32] J. Z. Gougoutas and J. C. Clardy, *Acta Cryst.*, 1970, **B26**, 1999 and *J. Solid State Chem.*, 1972, **4**, 226, 230; J. Z. Gougoutas, *J. Am. Chem. Soc.*, 1977, **99**, 127.

[33] I. I. Maletina, V. V. Orda, and L. M. Yagupolskii, *Zh. Org. Khim.*, 1974, **10**, 294.

[34] F. M. Beringer, R. A. Falk, M. Karniol, I. Lillien, G. Masullo, M. Mausner, and E. Sommer, *J. Am. Chem. Soc.*, 1959, **81**, 342.

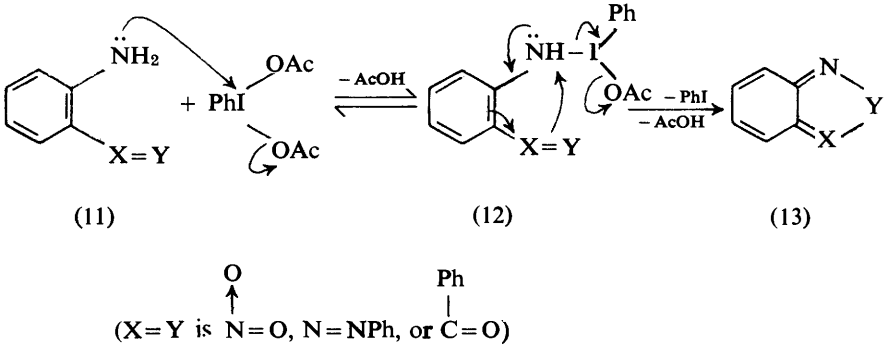
[35] H. Hoffelner, H. W. Lorch, and H. Wendt, *J. Electroanal. Chem.*, 1975, **66**, 183.

the preparation of the latter.[17] They are sensitive to daylight to a small extent but they easily undergo photochemical decomposition (Section 4E).

The reactions of AID are mainly oxidations of various types, where iodine(III) is reduced to iodine(I). They can be classified as 'conventional' oxidations, acetoxylations, and aryliodinations. There are also some substitution reactions at iodine, which is subsequently reduced; sometimes, however, new stable iodine(III) compounds may be formed.

A. Oxidations.—Most reactions of AID are oxidations bearing a close analogy with the reactions of LTA, as pointed out by Criegee[36] who was the first to explore their chemistry. Although few systematic studies about their structure and reactivity have been performed, acyloxy-moieties from strong acids moderately accelerate reaction rates, whereas substituents in the benzene ring may have a variable role, depending on the reaction mechanism.[37] It is possible in some cases for a substituent to exert a powerful influence on the rate. It must be noted that in several oxidations AID react in a unique way and also that PIB reacts with systems inert to PID.

(*i*) *Oxidation of* N-*Compounds.* The oxidation of aromatic amines with PID is known to give, in poor yields, azocompounds *via* hydrazocompounds in a reaction involving free radicals.[1] Several 2-nitroanilines and heterocyclic *vic*-nitroamines preferentially undergo an oxidative cyclization into furoxans.[1,38] Dyall *et al.*[39] have studied kinetically the reactions of several *ortho*-substituted anilines (11) with PID and have proposed a general mechanistic scheme, different from an earlier one suggested for 2-nitroanilines.[1] A nucleophilic displacement at iodine leads to the formation of intermediate (12), which by neighbouring-group participation is oxidatively cyclized into (13); this is usually a furoxan but it may be also a triazole or an anthranil (Scheme 5).

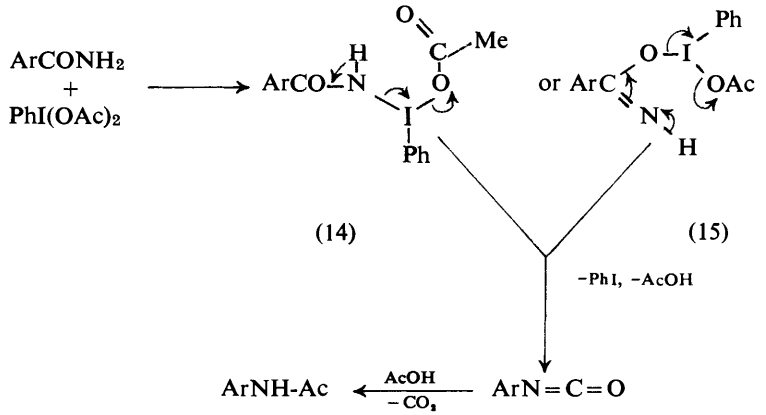


Scheme 5

[36] R. Criegee, 'Oxidation in Organic Chemistry', Academic Press, New York, 1965, p. 365.
[37] D. Barbas, J. Gallos, and A. Varvoglis, *Chim. Chron., New Series*, (in press).
[38] A. J. Boulton and D. Middleton, *J. Org. Chem.*, 1974, **39**, 2956.
[39] L. K. Dyall, *Aust. J. Chem.*, 1973, **26**, 2665 and references therein.

The intermediate (12) accumulated during the reaction as shown indirectly by comparison of the concentration of 2-benzoylaniline (by i.r. spectroscopy) and total iodine(III) species (by titration); the apparent aniline concentration was higher in the early stages of the reaction, resulting from a contribution by (12), supposed to absorb at the same region as the symmetric N–H stretch of the aniline. The activation parameters for the cyclization of eleven *ortho*-substituted anilines with PID fitted an isokinetic relationship, which suggests that a common reaction mechanism is followed in all cases.

Amides undergo with PID an oxidative rearrangement[40] analogous to the Hofmann rearrangement. With acetic acid as solvent, acetanilides are formed. The reaction has been studied kinetically with various substituted amides; electron donors in the benzene ring accelerate reaction rates, whereas electron acceptors retard them, the Hammett ρ value being -0.81. The activation parameters for several benzamides show a good linearity. A mechanism involving the formation of an iodine(III)–amide complex, (14) or (15), which rearranges in a concerted manner into the isocyanate has been proposed (Scheme 6).



Scheme 6

Amides are converted by PID in MeCN–H_2O into amines in high yields,[41] provided that the carboxamido-group is not attached to an aromatic ring, in which case the resulting aniline is further oxidized. Formation of *N*,*N*-dialkyl ureas, which are by-products in the reaction with PID, is here avoided; in addition, trifluoroacetic acid from equation (4) catalyses the hydrolysis of the

$$RCONH_2 + PhI(OCOCF_3)_2 \xrightarrow{-PhI} RN{=}C{=}O + 2CF_3CO_2H \qquad (4)$$

isocyanate [Equation (5)], so that only short reaction times are required with no heating.

[40] K. Swaminathan and N. Venkatasubramanian, *J. Chem. Soc., Perkin Trans. 2*, 1975, 1161.
[41] A. S. Radhakrishna, M. E. Parham, R. M. Riggs, and G. M. Loudon, *J. Org. Chem.*, 1979, **44**, 1746; G. M. Loudon and M. E. Parham, *Tetrahedron Lett.*, 1978, 437.

$$RN{=}C{=}O + H_2O \xrightarrow{H^+} RNH_2 + CO_2 \qquad (5)$$

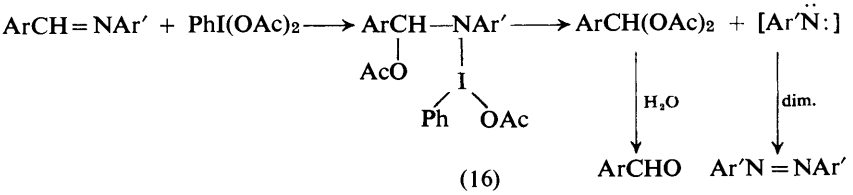
Since secondary amides are inert, the above reaction has been applied to the degradation of peptides, serving as a key step in sequence studies.[41] The peptide is anchored by the free NH_2 of the *N*-terminal amino-acid to a solid support; the CO_2H of the *C*-terminal amino-acid is then converted into $CONH_2$ through a series of reactions and the amide function with PIB is transformed into an amine, which is spontaneously hydrolysed into a new peptide-amine and an aldehyde [Equations (6) and (7)].

$$\cdots\cdots CONH\text{-}CH(R)CONH_2 + PIB \rightarrow \cdots\cdots CONH\text{-}CH(R)NH_3^+ \qquad (6)$$

$$\cdots\cdots CONH\text{-}CH(R)NH_3^+ + H_2O \rightarrow \cdots\cdots CONH_2 + RCHO + NH_3 \qquad (7)$$

PID oxidizes cyanamide at room temperature, forming *in situ* cyanonitrene,[42] which may be added to thioethers, sulphoxides, phosphines, and olefins. The reagent is mild, with low steric demands, and it is effective in cases where conventional reagents fail. 1-Amino-2,5-diphenyl-1,3,4-triazole is also oxidized by PID to the corresponding nitrene, which either decomposes into PhCN and N_2 or may be trapped by an olefin.[43] The course of the reaction was unaltered when $PhI(OCOCHCl_2)_2$ or LTA were used. By contrast, oxidation of 1-amino-benzotriazole with PID gives not the expected biphenylene, as LTA does, but a mixture of azobenzene, 1-phenylbenzotriazole, and other more complex products.[44] Mechanisms where both nitrene and benzyne formation are involved have been proposed. In other similar oxidations[45] both PID and LTA give the same products. Nitrene formation occurs also during the PID oxidation of Schiff's bases.[46] The initial addition product (16) is cleaved with rearrangement into a diacetoxy-derivative hydrolysing into an aldehyde and a nitrene, which dimerizes into an azocompound (Scheme 7).

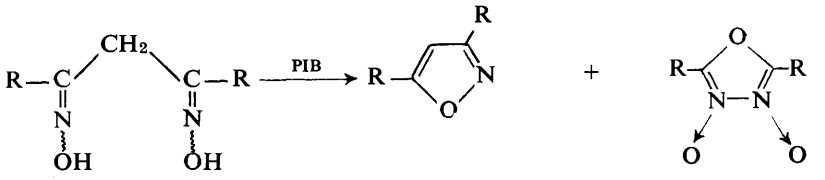
A variety of oximes react with PIB in several ways.[47] Aromatic *syn*-aldoximes



Scheme 7

[42] J. E. G. Kemp, D. Ellis, and M. D. Closier, *Tetrahedron Lett.*, 1979, 3781.
[43] F. Schröppel and J. Sauer, *Tetrahedron Lett.*, 1974, 2945.
[44] C. D. Campbell and C. W. Rees, *J. Chem. Soc.* (*C*), 1969, 752; P. G. Houghton and C. W. Rees, *J. Chem. Res.* (*S*), 1980, 303.
[45] C. D. Campbell and C. W. Rees, *J. Chem. Soc.* (*C*), 1969, 742; C. W. Rees and R. C. Storr, *ibid.*, 1969, 760.
[46] S. Narasimhabarathi, S. Sundaram, and N. Venkatasubramanian, *Indian J. Chem.*, 1977, **15B**, 376.
[47] S. Spyroudis, Ph.D Thesis, University of Thessaloniki, 1981; S. Spyroudis and A. Varvoglis *Synthesis*, 1975, 445; 1976, 837.

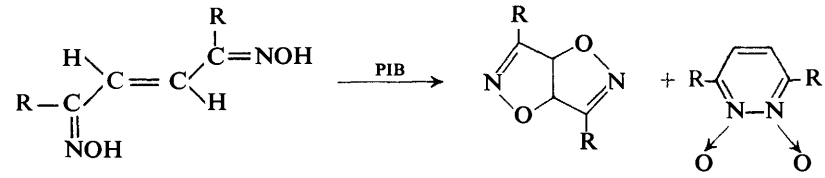
give mixtures of aldazine di-*N*-oxides and nitrile oxides, the latter being the major products, provided they are stable. Aliphatic ketoximes form *gem*-nitroso-trifluoroacetoxy-alkanes, stable only in solution, whereas aromatic ketoximes give mainly the parent ketone. α-Dioximes give furoxans in high yields, whereas β-dioximes (17) form mixtures of isoxazoles (18) and 4-oxo-4*H*-pyrazole-di-*N*-oxides (19) (Scheme 8).



(17) (18) (19)

Scheme 8

trans-2-Unsaturated 1,4-dioximes (10) are oxidized by PIB[47,48] into a mixture of 3*a*,6*a*-dihydroisoxazolo[5,4-*d*]isoxazoles (21) and pyridazine 1,2-dioxides (22) (Scheme 9).



(20) (21) (22)

Scheme 9

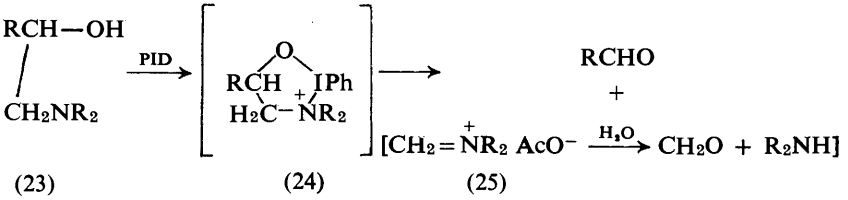
No detailed work has been done so far concerning the mechanism of these oxidations, but it seems that at a first stage an unstable substitution product $\diagdown$C=NOI(OCOCF$_3$)Ph $\diagup$ is formed, which is further transformed, mainly homolytically, with formation of iminoxy-radicals. In some cases, however, a polar or a concerted mechanism may also operate.

Other *N*-compounds oxidized by AID are *N*-benzylhydroxylamine to give the dimeric α-nitrosotoluene[47] and several *N*,*N*-benzylhydroxylamines to give

[48] A. Ohsawa, H. Arai, H. Igeta, T. Akimoto, A. Tsuji, and Y. Iitaka, *J. Org. Chem.*, 1979, **44**, 3254.

nitrones.[49] Again, homolytic pathways are assumed to operate. In the last case various oxidants were shown to produce essentially the same results.

(*ii*) *Oxidation of Alcohols and Ethers.* Perhaps the best known reaction of PID is the cleavage of glycols into carbonyl compounds.[1,36] The reaction is similar to the $NaIO_4$ or LTA oxidation and an analogous mechanism involving a cyclic trivalent iodine intermediate has been proposed.[1] PID has been found to cleave several steroidal glycols[50] at a rate about 100 times slower than LTA. Although again a cyclic intermediate is favoured, the fact that PID reacts with *trans*-decalin-9,10-diol suggests that an alternative mechanism is also available ($NaIO_4$ does not react with this diol). It is pertinent that *d,l*-tartaric acid is oxidized by PID slightly faster than its *meso*-isomer.[51] PIB is a superior reagent to PID and no heating is required for glycol cleavage, which is effected very quickly.[47] In an analogous manner *N,N*-dialkyl-1,2-aminoalcohols (23) are cleaved by PID to aldehydes and an immonium salt (25), which hydrolyses to an amine and formaldehyde; the latter being eventually oxidized to CO_2. A cyclic intermediate (24), as with glycols, is likely to be formed[52] [Scheme (10)].



(23) (24) (25)

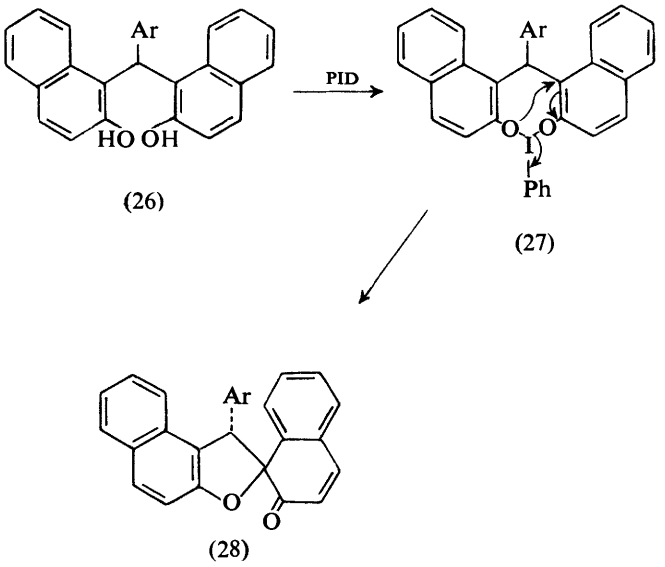
Scheme 10

When the reaction was run in the presence of acidic N–H compounds, such as isatin, derivatives of 1,1-diaminomethane (Mannich's bases) were formed from (25).

The reaction of PID with phenols leads usually to resinous products[1] but upon reaction with 4-X-phenols (X = electron acceptors) *p*-benzoquinones or, mainly, *o*-iodophenyl ethers are formed[53] (Section 4C). Substituted pyrocatechols[54] and hydroquinones[47] are easily oxidized by PID and PIB to the corresponding quinones. A special case is the oxidation of certain bisnaphthols (26) to the spirocompounds (28) (Scheme 11).

Although the reaction proceeds with a great variety of oxidants, only PID gives exclusively the above (R*R*) diastereomer. Its stereospecificity has been

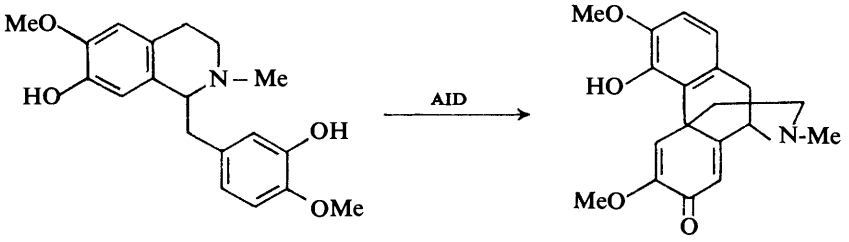
[49] P. A. Smith and S. E. Gloyer, *J. Org. Chem.*, 1975, **40**, 2508.
[50] S. J. Angyal and R. J. Young, *J. Am. Chem. Soc.*, 1959, **81**, 5251.
[51] K. Vaidyanathan and N. Venkatasubramanian, *Indian J. Chem.*, 1973, **11**, 1146.
[52] H. Mohrle and S. Dornbrack, *Pharmazie*, 1974, **29**, 573, 757.
[53] A. R. Fox and K. H. Pausacker, *J. Chem. Soc.*, 1957, 295.
[54] A. T. Balaban, *Rev. Roum. Chim.*, 1969, **14**, 1281; A. Suzuki and K. Sato, *Japan Kokai*, 156863 (1977), (*Chem. Abstr.* 1978, **88**, 152421).



(26) (27) (28)

Scheme 11

attributed to the intermediate formation of (27) from which the less hindered (28) results. Several bisnaphthols and other related diols[55] react in a similar fashion. Another special case, from alkaloid chemistry, is the intramolecular oxidative coupling of reticuline (29) to salutaridine (30) and other analogous reactions[56] (Scheme 12). Many other oxidants failed to effect this oxidation, but several AID were successful.



(29) (30)

Scheme 12

[55] D. J. Bennett, F. M. Dean, G. A. Herbin, D. A. Matkin, and A. W. Price, *J. Chem. Soc., Perkin Trans. 1*, 1980, 1978; F. M. Dean, G. A. Herbin, D. A. Matkin, A. W. Price, and M. L. Robinson, *ibid.*, 1980, 1986.

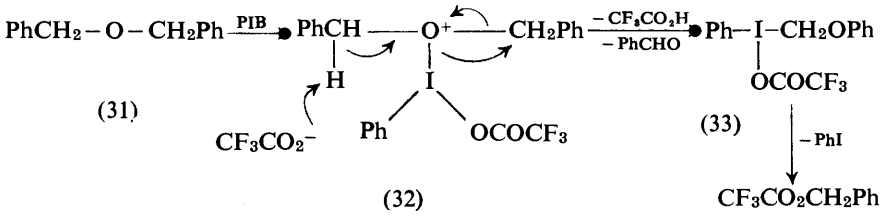
[56] C. Szántay, G. Blaskó, M. Bárczai-Beke, P. Péchy, and G. Dörnyei, *Tetrahedron Lett.*, 1980, **21**, 3509.

Alcohols do not react appreciably with AID at ambient temperature, but they are not suitable as solvents for measurements of u.v. spectra.[14] At 80 °C PIB oxidizes both primary and secondary alcohols into carbonyl compounds; although the presence of pyridine is beneficial, yields are still moderate.[47] Alkoxymagnesium salts, ROMgBr, are oxidized by PID and other oxidants into carbonyl compounds.[57] Although the double bond of a heptenol derivative remained intact, it is doubtful whether the double bond would not react in other cases (Section 4B).

Mandelic acid undergoes oxidative decarboxylation with PID to give benzaldehyde.[58] A kinetic study of several α-hydroxy-acids has shown a similar behaviour for most of them; an iodine(III) 'ester', $RCH(CO_2H)OI(OAc)Ph$, is formed initially, and then is cleaved either directly or through a cyclic intermediate.[51] Esters of α-hydroxy-acids are also oxidized by PID but more slowly than the corresponding acids and evidently to α-keto-esters.

Examples of glycol cleavages can be found also in the chemistry of carbohydrates.[59,60]

An oxidative cleavage of dibenzyl ethers (31) by PIB has been observed with formation of benzaldehyde and benzyl trifluoroacetate.[61] The mechanism of the reaction involves an oxonium ion intermediate (32) and an intermediate (33) with iodonium-like character (Scheme 13).



Scheme 13

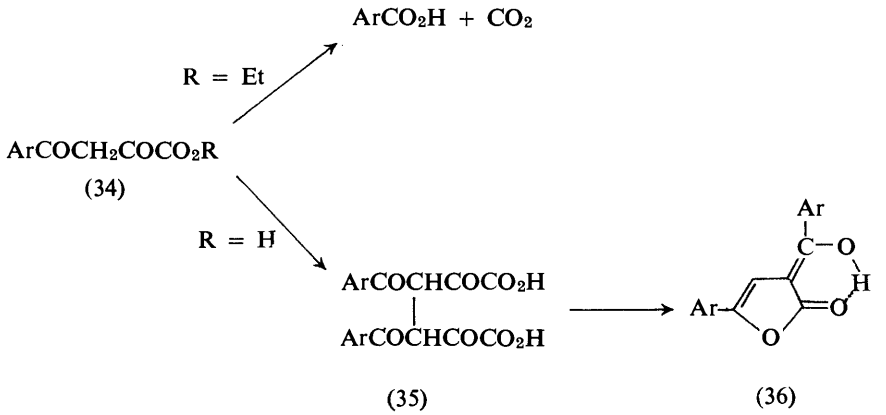
Benzyl alkyl (or benzhydryl, trityl) ethers react analogously to give benzaldehyde and trifluoroacetates; the latter are usually hydrolysed during work up. Thus the reaction may be used for the removal of the protective benzyl group from alcohols containing reducible functions. Benzyl aryl and alkyl aryl ethers give with PIB iodonium salts.[47]

(*iii*) *Oxidation at C.* Apart from the above reactions and acetoxylations and aryliodinations of various substrates (Sections 4B and 4E), oxidations at C are

[57] K. Narasaka, A. Morikawa, K. Saigo, and T. Mukaiyama, *Bull. Chem. Soc. Jpn.*, 1977, **50**, 2773.
[58] R. Criegee and H. Beucker, *Ann. Chem.*, 1939, **541**, 218.
[59] S. Ukai, H. Idemitsu, and T. Takaoka, *Japan. Patent*, 1974, 10933 (*Chem. Abstr.*, 1974, **81**, P63924).
[60] S. C. Pati and R. C. Mahapatro, *Natl. Acad. Sci. Lett.* (India), 1978, **1**, 325 (*Chem. Abstr.*, 1979, **90**, 23444), and *Proc. Indian Acad. Sci., Sect. A*, 1979, **88**, 203 (*Chem. Abstr.*, 1979, **91**, 158004).
[61] S. Spyroudis and A. Varvoglis, *J. Chem. Soc., Chem. Commun.*, 1979. 615.

not common; *e.g.* 9,10-dihydroanthracene is oxidized by PIB under drastic conditions and in poor yield[47] to anthracene, although PID oxidized $\cdots CH_2CH_2COOR$ to $\cdots CH{=}CHCOOR$, when this group was attached to a triazolium ring, in high yield.[62]

Ethyl 4-aryl-2,4-dioxobutanoates (34) are cleaved by PID in AcOH containing a catalytic amount of water into benzoic acids,[63] whereas under similar conditions the corresponding acids give 5-hydroxy-2-aryl-4-aroyl-furans,[64] present in their tautomeric form (36). This unusual reaction is thought to proceed through an initial oxidative coupling to (35), which under loss of CO_2 and H_2O is transformed into (36), (Scheme 14).

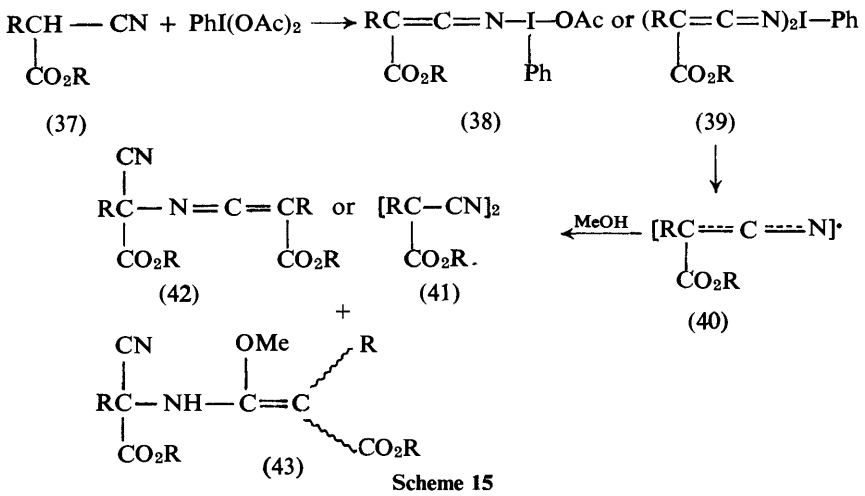


Scheme 14

Related oxidative cleavages have been reported for fluorenyl α-ketoesters and 2-acyl-1,3-indanediones.[65]

Another oxidative dimerization has been observed with α-cyanocarboxylates[8] (37). Initial attack from N to I leads to the intermediates (38) or (39), which *via* free radicals (40), dimerize into (41) or (42). The reaction is carried out in methanol and an enol ether (43) may also be formed (Scheme 15).

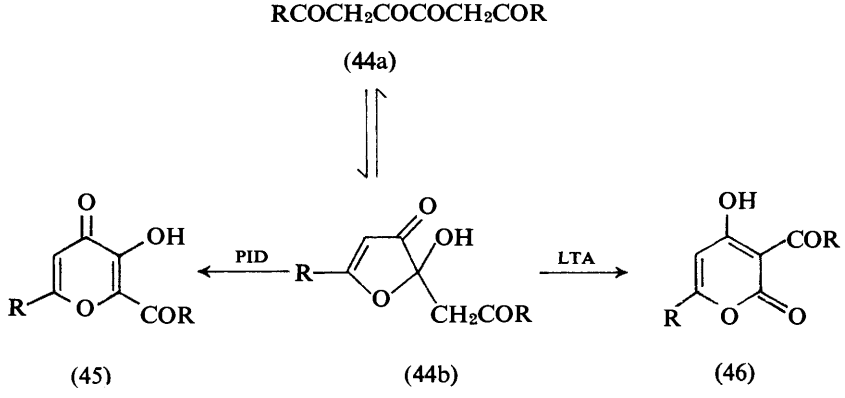
[62] G. Doleschall and G. Toth, *Tetrahedron*, 1980, **36**, 1649.
[63] B. D. Podolesov, *God. Zb., Prir.-Mat. Fak. Univ. Skopje, Mat. Fiz. Hem.*, 1974, **24**, 51 (*Chem. Abstr.*, 1975, **82**, 124993).
[64] N. Bregant, J. Matijevic, I. Sirola, and K. Balenovic, *Bull. Sci. Cons. Acad. Sci. Arts RSF Yougosl., Sect. A*, 1972, **17**, 148 (*Chem. Abstr.*, 1973, **78**, 4047).
[65] M. R. Korunoski and B. D. Podolesov, *God. Zb., Prir.-Mat. Fak. Univ. Skopje, Mat. Fiz. Hem.*, 1974, **24**, 55, and 1978, **28**, 87.



Scheme 15

3-Cyanosuccinimides with PID in methanol are converted into acyl urethans[66] by a mechanism analogous to that of Scheme (15); ketimines like (42) have been detected in the reaction mixture from their i.r. absorption (2030 cm^{-1}).

An interesting case of regiospecificity has been observed in the oxidation of tetraketones[67] (44a), which with PID and LTA give the isomeric pyrones (45) and (46), respectively (Scheme 16), probably through their ring-chain tautomers (44b).



Scheme 16

(*iv*) *Oxidationat S, Se, and P.* Thiols are oxidized with AID into disulphides[47,68]

[66] G. Morel, E. Marchand, A. Seveno, and A. Foucaund, *Tetrahedron Lett.*, 1977, 3353.
[67] M. Poje, *Tetrahedron Lett.*, 1980, **21**, 1575.
[68] T. Mukaiyama and T. Endo, *Bull. Chem. Soc. Jpn.*, 1967, **40**, 2388.

exceedingly easily. Thioethers give with PID sulphoxides in moderate yields,[69] but sometimes the conditions may be drastic. A similar oxygenation occurs in phenothiazines and phenoselenazines.[70] After treatment with PID, followed by hydrolysis, trityl phenyl sulphide and trityl benzyl sulphide give triphenyl carbinol as the only isolable product. Triphenyl phosphine with PIB gives phosphine oxide, whereas trialkyl phosphites give mixtures of complex products,[14] as with LTA. Phosphorus ylides of the type $Ph_3P{=}C(OMe)COR$ are oxidized by PID, LTA, and other oxidants into Ph_3PO and RCOCOOMe.[71] Several mechanistic schemes may be envisaged for these oxidations but no systematic studies have been reported yet.

B. Acetoxylations.—One of the earliest reactions of PID is the addition of two acetoxy-groups to an ethylenic double bond.[58] Cyclopentadiene reacts exothermically with formation of both 1,2- and 1,4-addition products. Anethole (4-MeO-C_6H_4-CH=CHMe) reacts faster with PID's bearing electron donors on the benzene ring than with PID's bearing electron acceptors. PID and catalytic amounts of OsO_4 have been used for effective hydroxylation of the double bonds in several steroids.[72] Alkenes also react with PIB[47] to give mixtures of *cis*- and *trans*-1,2-bis-trifluoroacetoxy-derivatives; when they bear aryl groups other products are formed as well, mainly carbonyl compounds resulting either from scission of the double bond or from rearrangements. With tetraphenylethylene the following products were obtained, besides the normal addition product: Ph_2CO, Ph_3CCOPh, 9,10-diphenylanthracene, and tetraphenyloxirane. The reaction appears to have a close analogy with the reaction of iodine(III) tris-(trifluoroacetate), (47) and alkenes,[73] where 1,2-bis-trifluoroacetoxyalkanes (50) are also the main products. The mechanism of this reaction involves initial addition of $I(OCOCF_3)_2$ and $OCOCF_3$ to the double bond. Thus, with ethylene the aliphatic AID (48) is formed, which expels CF_3CO_2I and is transformed to the isolable dioxolane (49). Under the experimental conditions (49) rearranges to (50) but an acylal (51) may also result as a by-product after a 1,2-shift (Scheme 17). The addition is mainly *cis* for 1,2-disubstituted alkenes but *cis*, *trans*-for tri- and tetrasubstituted alkenes.

PIB adds also its trifluoroacetoxy-groups to alkynes.[74] When the triple bond is internal two equivalents of PIB form a tetra-trifluoroacetoxy-derivative, which on hydrolysis affords an α-diketone. Diynes may give a diketone with the second triple bond intact. When the triple bond is terminal, one equivalent of PIB forms the relatively stable aryl alkynyl iodonium salt (52), detected by i.r.

[69] H. H. Szmant and G. Suld, *J. Am. Chem. Soc.*, 1956, **78**, 3400, K. C. Schreiber and V. Fernandez, *J. Org. Chem.*, 1961, **26**, 2478, 2910, J. P. A. Castrillon and H. H. Szmant, *J. Org. Chem.*, 1967, **32**, 976.

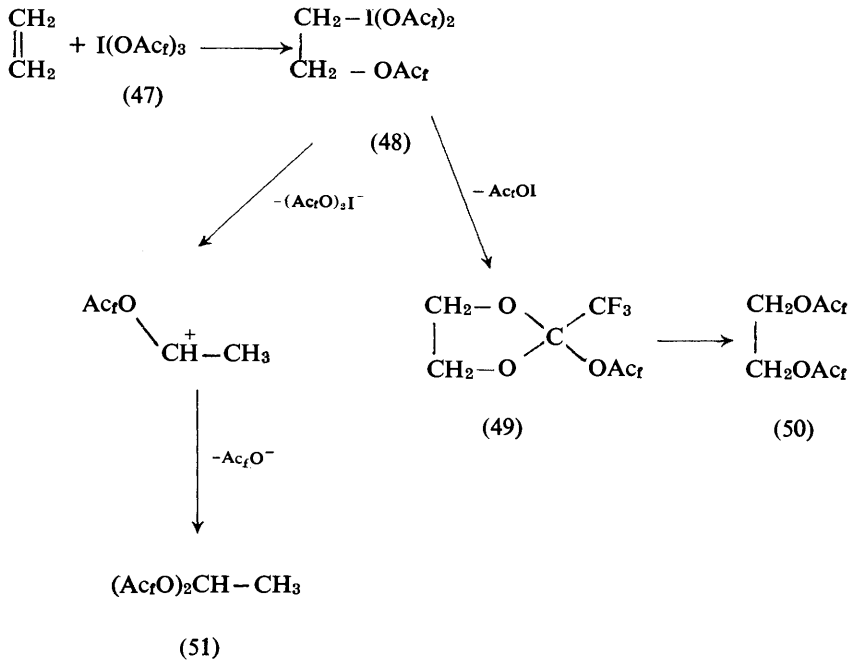
[70] B. D. Podolesov, *Prikl. Maked. Akad. Nauk Umet., Od. Prir.-Mat. Nauk*, 1978, **10**, 49; B. D. Podolesov and V. B. Jordanovska, *Croat. Chem. Acta*, 1972, **44**, 411.

[71] E. Zbiral and E. Werner, *Monatsh. Chem.* 1966, **97**, 1797.

[72] J. A. Hogg *et al.*, *J. Am. Chem. Soc.*, 1955, **77**, 4436, 4438, 6401.

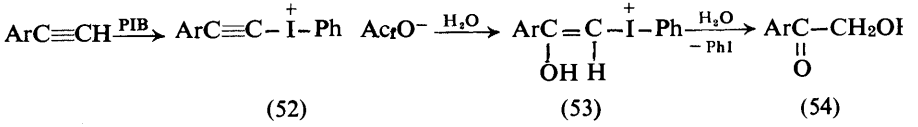
[73] J. Buddrus and H. Plettenberg, *Chem. Ber.*, 1980, **113**, 1494.

[74] E. B. Merkushev, L. G. Karpitskaya, and G. I. Novosel'tseva, *Dokl. Akad. Nauk. SSSR*, 1979, **245**, 607.



Scheme 17

spectroscopy; (52) is hydrated to (53) and then hydrolysed to an α-hydroxy-acetophenone (54), (Scheme 18).



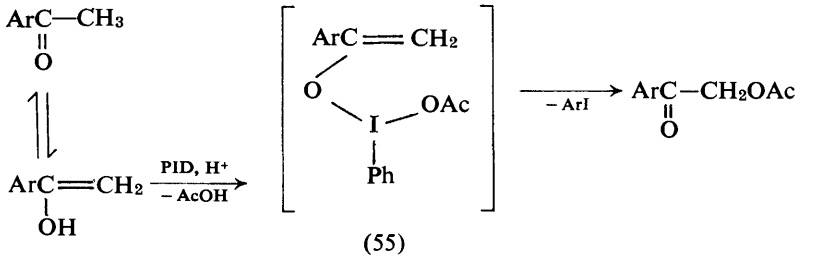
Scheme 18

Acetoxylations also take place at sp^3 carbon atoms. Thus several β-diketones[75] and acetophenones[76] react with PID to give acetoxy-derivatives. The reactions proceed in Ac_2O–AcOH or in aqueous AcOH with H_2SO_4 as a catalyst through the enolic form of the ketones, with intermediate formation of an *O*-phenyliodinated species (55), (Scheme 19). Aliphatic and cyclic ketones react similarly.[77]

[75] O. Neilands and G. Vanags, *Dokl. Akad. Nauk SSSR*, 1960, **131**, 1351 (*Chem. Abstr.*, 1960, **54**, 21 080).

[76] F. Mizukami, M. Ando, T. Tanaka, and J. Imamura, *Bull. Chem. Soc. Jpn.*, 1978, **51**, 335.

[77] S. C. Pati and B. R. Dev, *Indian J. Chem., Sect. A*, 1979, **17**, 92, and 1979, **18A**, 262; V. Mahalingan and N. Venkatasubramanian, *Indian J. Chem., Sect. B*, 1979, **18**, 94, 95; M. Higuchi, and R. Suzuki, *Japan Kokai*, 1973, 68575 (*Chem. Abstr.*, 1974, **80**, 36997).



(55)

Scheme 19

It must be noted that most β-diketones react with PID but they yield iodine ylides rather than acetoxy-derivatives (Section 4C).

PIB reacts with aryldiazomethanes and 1-aryl-1-diazoethanes in a complex way.[78] The main products are esters of trifluoroacetic acid, $ArCH_2OCOCF_3$ or $ArCH(CH_3)OCOCF_3$, resulting from an intermolecular hydrogen transfer, as deuterium labelling has shown. The mechanism of the reaction remains unknown.

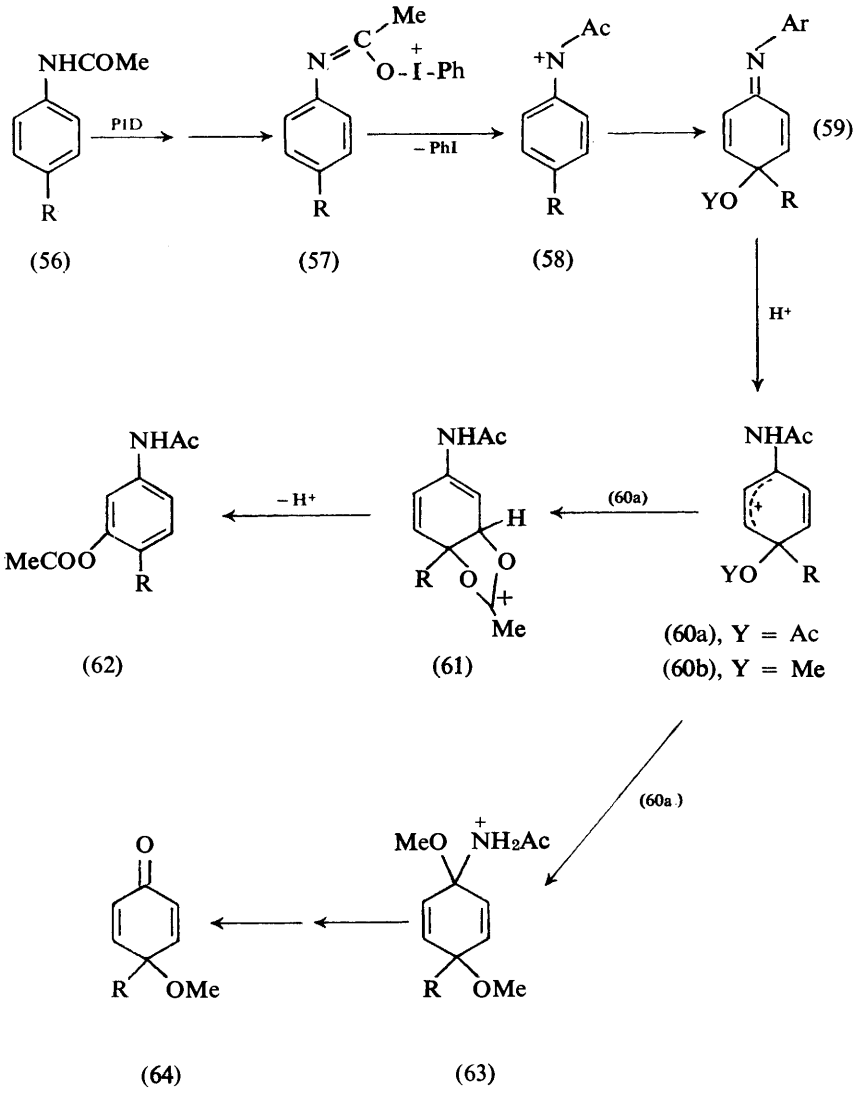
The reaction of 4-R-C_6H_4NHAc (R = electron donor), (56), with PID affords 3-acetoxy-derivatives[1] (62) and it was initially thought to proceed *via* free radicals. It has subsequently been suggested that it is an electrophilic displacement involving direct transfer of acetoxy-cation (from Ph–I^+–OAc) to the acetanilide.[79] The mechanism of this interesting reaction has now been elucidated and the acetoxy-group actually enters the aromatic ring as a nucleophile.[80] Initially (56) attacks PID at iodine with formation of an iodonium salt (57). This expels iodobenzene and gives a nitrenium ion (58), which in the presence of MeOH (solvent) or AcOH forms the dienoneimine (59), the protonated form of which (60a) rearranges, possibly intermolecularly through (61), to the final product (62). In MeOH (60b) gives the addition product (63), which eventually solvolyses to the stable cyclohexa-2,5-dien-3-one (64). In the presence of $MeNH_2$ (60a) forms 3-methylamino-acetanilide. The same dienone (64) is also formed from PID and *N*-t-butyl-*p*-toluidine (Scheme 20).

The reaction between PID or PIB and iodine leads initially to acetoxylation of iodine,[81] with formation of an unstable hypoidite, [Equation (8)].

$$PhI(OCOR)_2 + I_2 \longrightarrow PhI + 2RCO_2I \qquad (8)$$

The hypoiodite may add to alkenes with formation of 2-iodoalkyl acetates or may react with several aromatic compounds to give mono-, di-, or tri-iodo

[78] B. Axiotis, S. Spyroudis, and A. Varvoglis, *Chim. Chron., New Series*, in press.
[79] W. D. Johnson and N. V. Riggs, *Aust. J. Chem.*, 1964, **17**, 787; W. D. Johnson and J. E. Sherwood, *ibid.*, 1972, **25**, 1213.
[80] P. Kokil, S. Partil, T. Ravidranathan, and P. Madhavan Nair, *Tetrahedron Lett.*, 1979, 989.
[81] Y. Ogata and K. Aoki, *J. Am. Chem. Soc.*, 1968, **90**, 6187, and *Bull. Chem. Soc. Jpn.*, 1968, **41**, 1976; E. B. Merkushev, N. D. Simakhina, and G. M. Koveshnikova, *Synthesis*, 1980, 486.



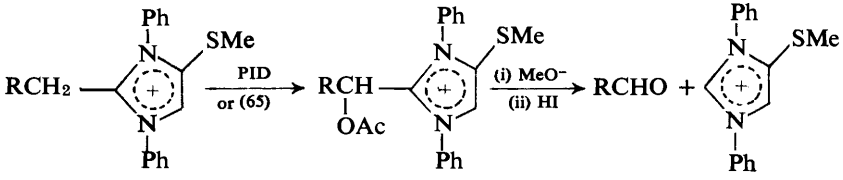
Scheme 20

derivatives; halobenzenes are also iodinated, exclusively at the *para*-position. Good yields, mild conditions, and simple isolation procedures make these reactions synthetically attractive. PID may acetoxylate the iodine anion also, forming acetyl hypoiodite, which equilibrates with AcO^- to give a diacetoxyiodate(I) anion, [Equations (9) and (10)].

$$PhI(OAc)_2 + I^- \rightarrow PhI + IOAc + AcO^- \quad (9)$$

$$IOAc + AcO^- \rightleftharpoons I(OAc)_2^- \quad (10)$$

Upon mixing of tetraethylammonium iodide and PID in $CHCl_3$ the stable salt $Et_4N^+I(AcO)_2^-$ (65) is isolated in high yield.[62] Compound (65) acetoxylates the triazolium salts (66) into (67); the same acetoxylation takes place with PID and iodides or, better, tri-iodides of (66). Kinetics established that $I(AcO)_2^-$ is the active species in both cases rather than IOAc. The salts (67) on hydrolysis are converted into an aldehyde (68) and the salt (69). Since (66) are easily prepared from carboxylic acids and *S*-methyl-1,4-diphenylthiosemicarbazide, their acetoxylation and hydrolysis has served as a convenient method for the conversion of acids into aldehydes with one carbon atom less[62] (Scheme 21).



(66) (67) (68) (69)

Scheme 21

Compound (65) acetoxylates several active CH_2 compounds, introducing one (diethyl malonate) or two (acetophenone) acetoxy-groups. It also reacts with cyclohexene to give *trans*-1-acetoxy-2-iodocyclohexane. In all these cases $I(OAc)_2^-$ is the active species. The bulkiness of $I(OAc)_2^-$ is probably the reason why with diethyl n-butylmalonate it does not act as an acetoxylating but as a halogenating agent, affording n-butyliodomalonate. In this reaction, and also in the reaction of (65) with 4-hydroxybenzaldehyde to give its 3,5-di-iodo derivative, IOAc is probably the iodinating agent. Another reaction of (65) is the oxidation of secondary alcohols into ketones; curiously, primary alcohols do not react.

Trialkylboranes react with PID and boron is acetoxylated into R_2BOAc with formation of an alkyl acetate.[82] A polar mechanism has been proposed, [Equations (11) and (12)].

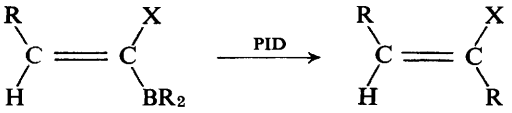
$$PhI(OAc)_2 + R_3B \xrightarrow{\Delta} \overset{+}{PhI}OAc + R_3\bar{B}OAc \quad (11)$$

$$\overset{+}{PhI}OAc + R_3\bar{B}OAc \rightarrow R_2BOAc + [Ph\text{-}I(R)OAc \rightarrow ROAc + PhI] \quad (12)$$

LTA reacts similarly but prefentially with boranes bearing secondary alkyl

[82] Y. Masuda and A. Arase, *Bull. Chem. Soc. Jpn.*, 1978, **51**, 901.

groups, whereas PID converts only the primary ones. Thus the two reagents have a complementary action. It is of interest to note that the reaction with LTA follows a homolytic pathway. With 1-alkenyl dialkylboranes, both PID and LTA react similarly affording alkenes[83] (Scheme 22).



X = H, Cl, or Br

Scheme 22

The reaction is stereoselective, *E*-isomers being formed in a high proportion (*E*:*Z*~9:1). Similarly, 1-bromo- and 1-chloro-1-hexenyl dialkylboranes react to give haloalkenes. Bulky alkyl groups and low temperatures favour *Z*-isomers for the bromo-compounds, while *Z*-isomers are formed from the chloro-compounds almost exclusively. The mechanism of these reactions is not yet known.

C. Transfer of the Aryliodine Group.—The reaction of AID with activated aromatic compounds is one of the various methods developed by Beringer for the preparation of iodonium salts (70), [Equation (13)].

$$ArH + ArI(OCOR)_2 \xrightarrow{H^+} \underset{(70)}{Ar{-}I^+{-}Ar\ RCO_2^-} + RCO_2H \qquad (13)$$

This reaction has been studied in detail, mainly with benzene, toluene, and polymethylbenzenes[84–87] and it is a typical electrophilic aromatic substitution. Sulphuric acid is necessary for the reaction to proceed and it exerts a marked catalytic effect. Electron donors in the benzene ring of AID accelerate slightly the reaction rate, which is considerably greater with toluene than with benzene. The product distribution with toluene is approximately 90% for the *para*- and 10% for the *ortho*-isomer, in contrast to earlier observations where exclusive formation of the *para*-isomer was claimed. There is a primary hydrogen isotope effect in the reactions of PID with C_6H_6 and $C_6{}^2H_6$, $K_H/K_{^2H}$ = 1.4. A decrease of basicity for AID (when there are electron acceptors in the ring) and an increase of basicity for the arene both lead to a decrease of the activation energy, which varies between 40 and 80 kJ mol^{-1}. These findings have been explained by assuming that sulphuric acid protonates PID rather than promoting its dissociation [Equation (14)].

[83] Y. Masuda and A. Arase, *Bull. Chem. Soc. Jpn.*, 1980, **53**, 1652.
[84] D. J. LeCount and J. A. W. Reid, *J. Chem. Soc.* (*C*), 1967, 1298.
[85] J. M. Briody, *J. Chem. Soc.* (*B*), 1968, 93.
[86] H. Hoffelner, H. Schneider, and H. Wendt, *Chem.-Ztg.*, 1978, **102**, 53.
[87] N. 1. Nogina and V. A. Koptyng, *Zh. Org. Khim.*, 1972 **8**, 1495.

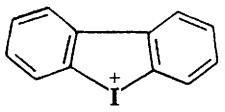
$$PhI^+OAc + AcOH \overset{H^+}{\rightleftharpoons} PhI(OAc)_2 \overset{H^+}{\rightleftharpoons} [PhI(OAc)_2H]^+ \quad (14)$$

The protonated PID[6] rather than PhI^+OAc is the active electrophilic species which gives with the arene first a π-complex and then a σ-complex. The latter is transformed irreversibly into the iodonium salt and this is the rate determining step of the reaction,[96] [Equations (15) and (16)].

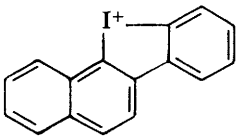
$$[PhI(OAc)_2H]^+ + ArH \rightarrow \rightarrow [PhI(OAc)ArH]^+ + AcOH \quad (15)$$

$$[PhI(OAc)ArH]^+ \rightarrow PhI^+Ar + AcOH \quad (16)$$

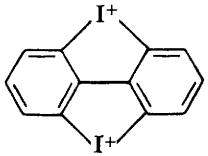
Numerous iodonium salts have been prepared by the above reaction, especially with thiophene,[88] because thienyl iodonium salts are potential antimicrobial agents. Bifunctional AID, such as p-$(AcO)_2IC_6H_4I(OAc)_2$, may give not only bis-iodonium salts, but also polymeric iodonium salts.[89] Of special interest are various heterocyclic iodonium salts, resulting from *in situ* I-acetoxylation of suitable iodoarenes, which subsequently cyclize with H_2SO_4, *e.g.* (71),[1] (72),[90] (73),[91] and (74).[92]



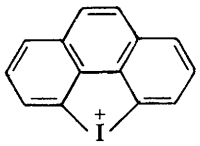
(71)



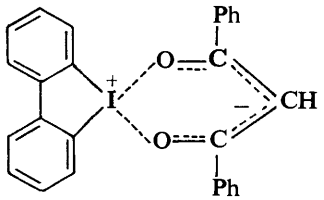
(72)



(73)



(74)



(75)

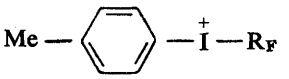
Such iodonium salts have been used in the preparation of 5-aryl-5*H*-dibenziodoles[93] and other compounds such as carbazole from (71), 2,2′,6,6′-tetra-

[88] Y. Yamada and M. Okawara, *Bull. Chem. Soc. Jpn.*, 1972, **45**, 1860, 2515.
[89] Y. Yamada, K. Kashima, and M. Okawara, *J. Polym. Sci., Polym. Lett. Ed.*, 1976, **14**, 65.
[90] D. Hellwinkel, W. Lindner, and W. Schmidt, *Chem. Ber.*, 1979, **112**, 281.
[91] R. B. Sandin, *J. Org. Chem.*, 1969, **34**, 456.
[92] F. M. Beringer, L. L. Chang, A. N. Fenster, and R. R. Rossi, *Tetrahedron*, 1969, **25**, 4339.
[93] F. M. Beringer and L. L. Chang, *J. Org. Chem.*, 1971, **36**, 4055; H. J. Reich and C. S. Cooperman, *J. Am. Chem. Soc.*, 1973, **95**, 5077.

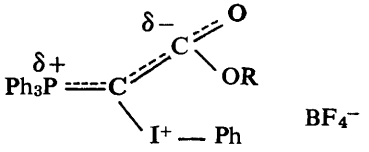
iodobiphenyl from (73),[91] and the chelate complex (75) of dibenziodolium cation.[94]

Perfluoroalkyliodine(III) bis(trifluoroacetates) react with toluene[95] to give the stable iodonium salts (76), where there is an I–C bond to the sp^3 carbon atom. These salts react under mild conditions with various nucleophiles,[96] which attack exclusively the sp^3 carbon atom.

An interesting case of phenyliodination has been reported[97] in the reaction of the phosphorane $Ph_3P{=}CHCOOR$ with PID in the presence of HBF_4, leading to the double salt (77).

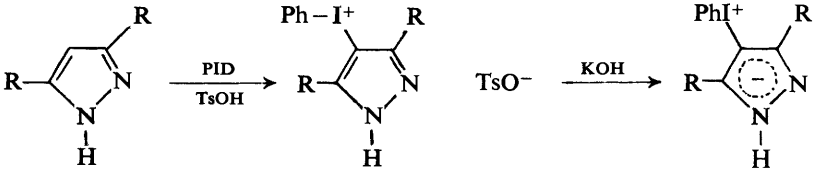


(76), R_f = C_3F_7, or C_6F_{13}



(77)

In certain favourable cases the iodonium salt of a heterocycle may be converted by alkali into an inner salt, *i.e.* an ylide of iodine (iodinane). Pyrazole (78) gives, for example, the salt (79) with PID and *p*-toluenesulphonic acid and this is converted into the ylide (80),[98] Scheme 23.

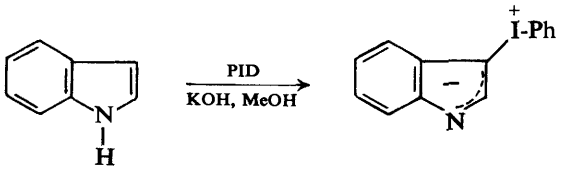


(78) (79) (80)

Scheme 23

With activated heterocycles iodine ylides are formed directly in an alkaline medium, *e.g.* (82) from indole (81),[99] in Scheme 24.

[94] R. E. Lee and R. H. Soderberg, *J. Am. Chem. Soc.*, 1972, **94**, 4132.
[95] V. V. Lyalin, V. V. Orda, L. A. Alekseyeva, and L. M. Yagupolskii, *Zh. Org. Khim.*, 1971, **7**, 1473.
[96] L. M. Yagupolskii, I. I. Maletina, N. V. Kondratenko, and V. V. Orda, *Synthesis*, 1978, 835.
[97] O. Neilands and G. Vanags, *Dokl. Akad. Nauk SSSR*, 1964, **159**, 373 (*Chem. Abstr.*, 1965, **62**, 6510).
[98] B. Karele, S. V. Kalnin, I. Grinberga, and O. Neilands, *Khim. Geterosikl. Soedin.*, 1973, 245.

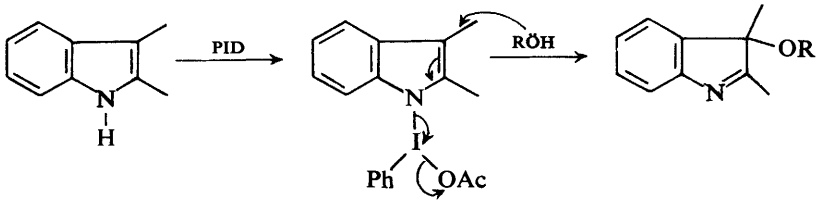


(81) (82)

Scheme 24

It is of interest that indole and PID in MeOH without alkali give intractable tars, while 2,3-dimethylindole (83) reacts to give initially a N–I intermediate (84), which reacts further with alcohols to give a 3-alkoxyindolenine[100] (Scheme 25). Reserpine reacts similarly.

Iodine ylides may also come from substrates with sp^3 carbon atoms *i.e.*



(83) (84) (85)

Scheme 25

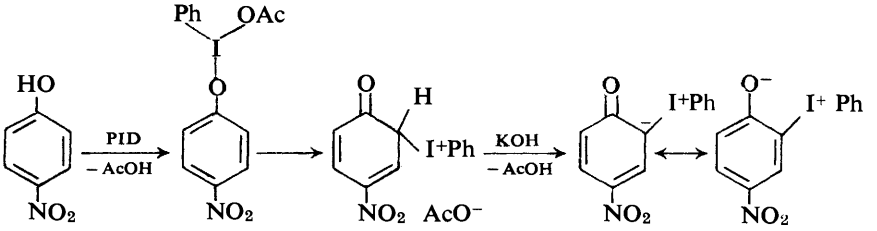
compounds with active methylene groups. A comprehensive list of iodine ylides prepared up to 1978 mostly from PID has been published.[101] Among the various substrates used, the following are mentioned: barbituric acid, Meldrum's acid, dimedone, 4-hydroxycoumarins, uracil, and acetoacetic and malonic esters. Several ylides have also been prepared from cyclopentadiene salts and PID or $ClCH{=}CHI(IOAc)_2$.[10] A new type of I–N ylide is formed from PID and *p*-toluenesulphonamide,[102] [Equation (17)].

$$PhI(OAc)_2 + TsNH_2 \xrightarrow[MeOH]{KOH} PhI^+N^-Ts \qquad (17)$$

An interesting reaction leading to an iodine ylide is that between 4-nitrophenol and PID.[1] An ester (86), is initially formed which rearranges to the iodonium

[99] B. Karele, L. Treigute, S. Kalnina, I. Grinberga, and O. Neilands, *Khim. Geterosikl. Soedin*, 1974, 214.
[100] D. V. C. Awang and A. Vincent, *Can. J. Chem.*, 1980, **58**, 1589.
[101] T. Kappe, G. Korbuly, and W. Stadlbauer, *Chem. Ber.*, 1978, **111**, 3857.
[102] Y. Yamada, T. Yamamoto, and M. Okawara, *Chem. Lett.*, 1975, 361.

salt (87); this can be isolated but on storage over KOH in a desiccator it is transformed into the stable ylide (88). Crystallographic studies favour the betainic form (88b)[103] rather than the ylidic (88a),[104] (Scheme 26).



(86) (87) (88a) (88b)

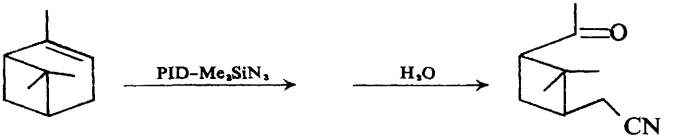
Scheme 26

Like other iodine ylides, (88) and related compounds with an electron acceptor X instead of NO_2 rearrange thermally into 2-iodo-4-NO_2 (X)-diphenyl ethers, which may be used for the preparation of dibenzofurans.[103]

D. Substitutions at Iodine.—A fruitful area of PID chemistry deals with its reactions with alkenes in combination with Me_3SiN_3. In a series of papers Zbiral and co-workers[105] have shown that the double bond of both nucleophilic and electophilic alkenes reacts with PID–Me_3SiN_3, which are in equilibrium, as shown by i.r. spectroscopy, according to equation (18).

$$PhI(OAc)_2 + nMe_3SiN_3 \rightleftharpoons PhI(OAc)_{2-n}(N_3)_n + nMe_3SiOAc \qquad (18)$$

The above system is very reactive; it reacts at −15 to −55 °C in two main ways: either the double bond is cleaved and a ketonitrile is formed (Scheme 27)



Scheme 27

or only the π bond is cleaved with formation of an α-azidoketone (Scheme 28).

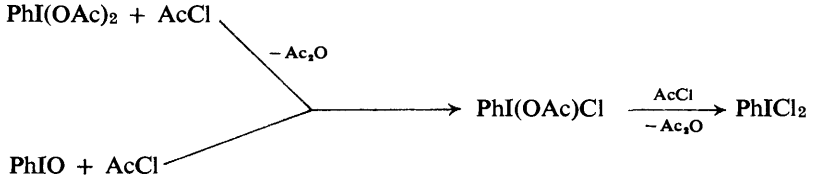
[103] S. W. Page, E. P. Mazzola, A. D. Mighell, V. L. Himes, and C. R. Hubbard, *J. Am. Chem. Soc.*, 1979, **101**, 5858.
[104] P. B. Kokil and P. M. Nair, *Tetrahedron Lett.*, 1977, 4113.
[105] E. Zbiral and G. Nestler, *Tetrahedron*, 1970, **26**, 2945; E. Zbiral and J. Ehrenfreund, *ibid.*, 1971, **27**, 4125; J. Ehrenfreund and E. Zbiral, *ibid.*, 1972, **28**, 1967; J. Ehrenfreund and E. Zbiral, *Ann. Chem.*, 1973, 290; E. Cech and E. Zbiral, *Tetrahedron*, 1975, **31**, 605.

$$ArCH{=}CH_2 \xrightarrow{PID + Me_3SiN_3} \xrightarrow{H_2O} ArCOCH_2N_3$$

Scheme 28

Various mechanistic schemes are possible for these reactions, the addition of PhIOAc and N_3 being always the initial step. With 1,3-dienes 1,4-addition prevails but the final products are often the result of further transformation, *e.g.* from 2,3-dimethylbutadiene a mixture of 3,4-diazido-3-methylbutan-2-one and 2,3,5-trimethyl-3,6-diazidomethylohepta-1,5-diene has resulted.

The ternary system PID + Me_3SiN_3 + AcCl forms *in situ* $PhI(N_3)Cl$ which adds to alkenes, with eventual formation of 1,2-chloro-azidoalkanes.[105] It is noted that PID with acyl chlorides alone[105] as well as PhIO and acyl chlorides[106] react to give phenyliodine(III) dichloride and acid anhydrides, probably through a common intermediate (Scheme 29).



Scheme 29

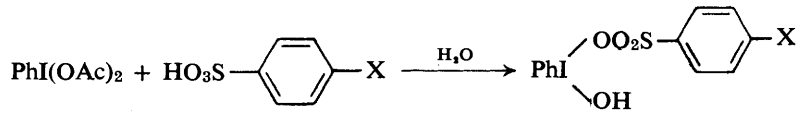
Apart from its exchange with carboxylic acids (Section 3), PID may form, with certain dicarboxylic acids, polymeric AID with unusual properties,[107] Equation (19).

$$n\text{PhI(OAc)}_2 + n\text{HO}_2\text{C}\cdots\cdots\text{CO}_2\text{H} \rightarrow [\text{—OI(Ph)OCO}\cdots\text{CO—}]_n \qquad (19)$$

An interesting exchange of PID with substituted benzenesulphonic acids leads curiously to the hydroxy-derivatives (89)[108] (Scheme 30). Attempts to obtain the bis-tosyloxy-derivative were unsuccessful. The crystal structure of (89), where X = Me, has been determined and some of its reactions examined, mainly with $ArSiMe_3$ to iodonium salts. With aryl iodides metathetical redox reactions take place.

PID also exchanges with hydroperoxides.[109] The reaction at room temperature is highly exothermic and CH_4, C_2H_6, Me_2CO, and CO_2 are among the products when Bu^tOOH is used. At −80 °C, however, in CH_2Cl_2 a peroxy-derivative of

[106] J. Wicha, A. Zarecki, and M. Kocór, *Tetrahedron Lett.*, 1973, 3635.
[107] H. K. Livingston, J. W. Sullivan, and J. I. Musher, *J. Polym. Sci.* (*C*), 1968, 195; J. Kresta and H. K. Livingston, *Macromolecules*, 1972, **5**, 25.
[108] O. Neilands and B. Karele, *Zh. Org. Khim.*, 1970, **6**, 885; G. F. Koser and R. H. Wettach, *J. Org. Chem.*, 1977, **42**, 1476, 1980, **45**, 1542, 4988; G. F. Koser, R. H. Wettach, J. M. Troup, and B. A. Frenz, *ibid.*, 1976, **41**, 3609; G. F. Koser, R. H. Wettach, and C. S. Smith, *ibid.*, 1980, **45**, 1543.
[109] N. A. Milas and B. Plesničar, *J. Am. Chem. Soc.*, 1968, **90**, 4450.



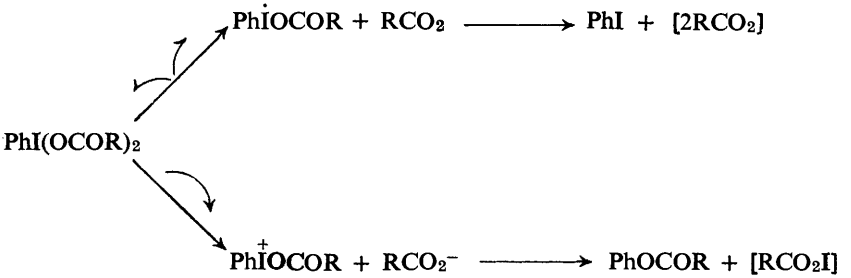
(89)

X = H, Me, NO_2, or Cl

Scheme 30

I^{III} is formed, $PhI(OOBu^t)_2$, which is unstable and by expelling $Bu^tOO\cdot$ is reduced to PhI. The radicals combine initially to a tetroxide and then after a multistep process Bu^tOOBu^t is eventually formed with O_2 evolution. PID and 3-nitro-PID form, with dilute HNO_3, stable μ-oxo-dinitrato-diaryl-di-iodine(III) derivatives,[110] $Ar(ONO_2)I\cdot O\cdot I(ONO_2)Ar$, while PID in fuming HNO_3 has been claimed[89] to give $PhI(ONO_2)_2$. The crystal structure of the μ-phenyl compound has been reported.[111]

E. Thermal and Photochemical Decomposition.—Early work on AID established that on heating they produce alkyl or aryl radicals.[1] The thermal decomposition of AID poses interesting mechanistic problems and has been studied in detail by Leffler and his co-workers.[112] Two major pathways have been recognized, involving heterolysis and homolysis (Scheme 31).



Scheme 31

The homolytic reaction is the minor one. The $RCO_2\cdot$ radicals (aroyloxy or acetoxy) lose CO_2 and dimerize into R–R, or $RCO_2\cdot$ and R· may combine to RCO_2R. Another possibility is the reaction of R· with the solvent. The hypo-

[110] W. E. Dasent and T. C. Waddington, *J. Chem. Soc.*, 1960, 3350; W. E. Dasent and L. E. Sharman, *ibid.*, 1964, 3492.

[111] N. W. Alcock and R M. Countryman, *J. Chem. Soc., Dalton Trans.*, 1979, 851.

[112] J. E. Leffler, W. J. M. Mitchell, and B. C. Menon, *J. Org. Chem.*, 1966, **31**, 1153; J. E. Leffler and L. J. Story, *J. Am. Chem. Soc.*, 1967, **89**, 2333; T. T. Wang and J. E. Leffler, *J. Org. Chem.*, 1971, **36**, 1531; J. E. Leffler, D. C. Ward, and A. Burduroglu, *J. Am. Chem. Soc.*, 1972, **94**, 5339.

iodites formed in the heterolytic reaction decompose homolytically to CO_2 and RI or they can be trapped with added alkene. In chlorobenzene, phenyliodine(III) dibenzoate gives chlorobiphenyls (all isomers) in fair yield. The reaction is catalysed by benzoyl peroxide, which with chlorobenzene forms reactive phenylchlorocyclohexadienyl radicals serving as chain-transfer agents. When substituted PID's are used the reaction is accelerated with electron-withdrawing groups (ρ Hammett value +0.8). By introducing aroyloxy- instead of acetoxy-groups the decomposition is accelerated and the reaction shifts towards the radical pathway; both 4-nitrophenyl and 4-methoxyphenyl groups accelerate the reaction rate.

The thermolysis of $PhI(OCOPh)_2$ was also studied in bromobenzene at relatively high temperatures.[113] In this system $PhCO_2I$ reacts with the solvent, furnishing 2- and 4- (but not 3-) bromoiodobenzenes. Also, the homolytic path produces $PhCO_2H$, bromobiphenyls, and I_2 as additional products. Iodine results from homolysis of $PhCO_2I$, while $PhCO_2H$ comes from both the reaction of $PhCO_2I$ with PhBr and the reaction of PhI·OCOPh with PhC_6H_4Br. Mechanistic details are beyond the scope of this article but it is of interest to note that at least twelve individual steps are necessary to account for the experimental data.

In AcOH the decomposition of PID is very slow, even at 100 °C, but it is greatly enhanced in the presence of perchloric acid, which effectively protonates PID, as has been shown by u.v. spectroscopy and conductivity studies.[6] The protonated PID is equilibrated with phenyl acetoxyiodonium ion by a series of ion-pair equilibria and through a concerted reaction with AcOH gives the observed products, [Equations (20)–(22)].

$$PhI(OAc)_2 + H^+ \rightleftharpoons [PhI(OAc)_2H]^+ \quad (20)$$

$$[PhI(OAc)_2H]^+ \rightleftharpoons PhI^+OAc + AcOH \quad (21)$$

$$PhI^+OAc + AcOH \rightarrow PhI + CO_2 + MeCO_2Me \quad (22)$$

The thermolysis of $ArI(OAc)_2$, where Ar = mesityl, duryl, and pentamethylphenyl, was found to proceed in the absence of solvents at 130—170 °C *via* the polar mechanism.[114] The aryl acetates initially formed do not always survive the drastic conditions and in the case of pentamethyl PID, for example, the isolated products were 2,3,5,6-tetramethyl-4-iodophenyl acetate and 1,4-diacetoxy-2,3,5,6-tetramethylbenzene.

In connection with the thermolysis of AID[113] it was found that $PhI(OCOPh)_2$ when irradiated with u.v. light in the presence of 2,3-dimethylbutane forms almost exclusively the 2-benzoyloxy-derivative as in Equation (23).

$$Me_2CH{\cdot}CHMe_2 + PhI(OCOPh)_2 \xrightarrow{h\nu} Me_2CH{\cdot}CMe_2OCOPh \quad (23)$$

Since benzoyl peroxide under similar conditions gives $Me_2CH{\cdot}CMe_2OCOPh$ and $Me_2CH{\cdot}CHMeCH_2OCOPh$ in a ratio of about 2:1, it was concluded

[113] C. J. Grill, G. B. Gribb, and H. A. R. El-Jamali, *J. Chem. Soc., Perkin Trans. 2*, 1977, 860.
[114] E. B. Merkushev, A. N. Novikov, and L. F. Kharitonova, *Zh. Org. Khim.*, 1971, **7**, 519.

that both in photolysis and thermolysis the active species is PhI·OCOPh rather than PhCOO·. PID is decomposed photochemically[6] in AcOH into C_6H_5I, CO_2, $MeCO_2Me$, and probably ethane, with a quantum yield of 0.62. Kinetic studies established that the rate determining step of the reaction is the activation of PID.

5 Analytical Applications

AID normally oxidize iodide to iodine (see however the reaction with $Et_4N^+I^-$, p. 397). This reaction can serve as an assay of their purity and also in kinetic measurements where unreacted AID liberates iodine, which is titrated with thiosulphate. Quantitative determination of AID may be effected also by automatic potentiometric titration.[115] PID has been proposed as a redox titrant[116] in oxidations of As^{3+}, Fe^{2+}, $[Fe(CN)_6]^{4-}$, Tl^+, Sb^{3+}, and N_2H_4. Organic reductants undergoing quantitative oxidation include hydroquinone and ascorbic acid; phenol, aniline, and oxine (8-hydroxyquinoline) were also oxidized in the presence of bromide, which is first oxidized to bromine and then forms a tri- or dibromo-derivative. The use of PID as a redox titrant has been extended to the determination of thiols, dithiocarbamates, and xanthates.[117] Volumetric determinations of thiols, thioureas, and other sulphur compounds have also been reported.[118–120] Determinations of AID and iodonium salts in mixtures have been performed by polarography.[86]

6 Miscellaneous

An interesting property of AID is their action as hydroxylating agents in biochemical reactions.[13,121] It has been found that, in addition to NADPH, several AID can effect steroid and fatty acids hydroxylations in rat-liver microsomes, by acting as oxygen donors to cytochrome P-450. The most efficient was 2-nitro-PID, (several hundred times as active as NADPH), whereas 2-cyano-PID was inactive.

PID can induce polymerization of 2,6-dimethylphenol.[122] Poly-*p*-styryliodine(III) diacetate may be used as a polymer reagent.[123] PID has been proposed as an oxidant for leuco anthraquinone dyes in colour photography,[124] for the dissolution of cellulose ethers in water,[125] and as a component of a thermal

[115] S. S. Makarchenko, A. N. Novikov, and G. M. Kropacheva, *Dep. Doc. VINITI*, 1975, 239-75 (*Chem. Abstr.*, 1977, **87**, 95045).
[116] V. N. Pilai and C. G. R. Nair, *Talanta*, 1975, **22**, 57.
[117] K. K. Verma, J. Ahmed, M. P. Sahasrabuddhey, and S. Bose, *J. Indian Chem. Soc.*, 1977, **54**, 699.
[118] K. K. Verma, *Fresenius' Z. Anal. Chem.*, 1975, **275**, 287.
[119] K. K. Verma and S. Bose, *J. Indian Chem. Soc.*, 1973, **50**, 542.
[120] K. K. Verma and S. Bose, *Philipp. J. Sci.*, 1974, **103**, 187 (*Chem. Abstr.*, 1976, **84**, 25586).
[121] J. A. Gustafsson and J. Bergman, *FEBS Lett.*, 1976, **70**, 276.
[122] J. Kresta and H. K. Livingston, *J. Macromol. Sci., Chem.*, 1970, **4**, 1719 (*Chem. Abstr.*, 1970, **73**, 99300).
[123] Y. Yamada and M. Okawara, *Makromol. Chem.*, 1972, 153; M. L. Hallensleben, *Angew. Makromol. Chem.*, 1972, **27**, 233.
[124] S. J. Ciurca, jun., *Fr. Demande* 2251841 (*Chem. Abstr.*, 1976, **84**, 128747).
[125] C. D. Callihan and J. R. Boudreaux, *U.S.P.* 337628 (*Chem. Abstr.*, 1968, **68**, 106207).

reaction battery.[126] The most unexpected entry in *Chemical Abstracts* was the 'effect of PID on the pacemaker action-potential and contraction in isolated guinea-pig atria'.[127]

Acknowledgment. I wish to thank Mr. E. Kritsis for his assistance in the preparation of the manuscript.

[126] A. A. Benderly and D. R. Hartler, *U.S.P.* 3819415 (*Chem. Abstr.*, 1974, **81**, 108466).
[127] M. Tani, *Acta Med. Nagasaki*, 1968, **12**, 99 (*Chem. Abstr.* 1969, **70**, 95115).