Oxidative Carbon–Carbon Coupling. I. The Oxidative Coupling of α-Substituted Benzyl Cyanides

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Oxidative dimerization of benzyl cyanides α-substituted with an ester (**1**), acyl (**3**), or amide group (**5**) with a Cu–amine–O_2 system or with other oxidants gave the corresponding 2,3-diphenylsuccinonitriles **2**, **4**, and **6** as a mixture of diastereoisomers in high yields. Configurational assignments are made for *dl*- and *meso*-**2** on the basis of cyclization reactions to give mono- or bicyclic succinimides **8** and **9**. Thermal equilibration of the *dl* and meso diastereoisomers takes place in various solvents at 80–130° *via* radical dissociation–recombination along the central C–C bond. For dimers **2a** and **2b**, the equilibrium constant *K* (*dl*/meso) is 13–16. For the meso → *dl* conversion of **2a** and **2b**, $\Delta H^{\ddagger}$ is 22–23 kcal/mol and $\Delta S^{\ddagger}$ is −11 to −12 eu. Thermal treatment of the para-unsubstitued diester **2a**, at 130–170°, gives redistribution to the monomer **1a** and oligomers (tri- to pentamers). Similarly, the oxidative coupling of the para-unsubstituted benzyl cyanides **1a**, **3a**, and **5d** gave rise to various amounts of oligomers (n = 3–8). Both oligomerization reactions are impeded by introduction of a para substituent.

Oxidative carbon–carbon coupling of compounds containing activated CH, CH_2, or CH_3 groups has been reported in the literature with a large variety of oxidants, *e.g.*, di-*tert*-butyl peroxide,[1] H_2O_2,[2,3] $K_3Fe(CN)_6$,[4–7] $KMnO_4$,[5,8] PbO_2,[4,9] persulfates,[10] iodine,[8,11] or anodic oxidation.[12]

Catalytic oxidative C–C couplings with Cu–amine–O_2 systems are known with phenols,[4] acetylenes,[13] and 2-keto-2,5-dihydrofurans;[14,15] uncatalyzed C–C dimerizations are known with indigo,[16] *p*-nitrotoluene,[17,18] and *p*-cymene.[19] Carbon–carbon couplings of aromatics or activated olefins with O_2–Pd^{II}–Cu^{II} systems have also been reported.[20,21]

Dehydrogenation is usually accompanied by a fair amount of oxygenation. Notable exceptions are the oxidative dimerization of acetylenes[13] and of diphenylacetonitrile.[5]

We have succeeded in selecting a class of substrates which undergo exclusive C–C coupling with the Cu–amine–O_2 system. The complex of Cu(OH)Cl with the bidentate diamine *N,N,N′,N′*-tetramethylethylenediamine (TMEDA) was chosen because of its high activity in the oxidative coupling of acetylenes[22] and phenols.[23,24]

Oxidative Coupling of α-Substituted Benzyl Cyanides. A. With Oxygen and a Cu-Amine Complex.—The oxidative coupling of arylcyanoacetic esters **1**, acylbenzyl cyanides **3**, and *p*-tolylcyanoacetamides **5** gave high yields of the carbon–carbon coupled dimers (Scheme I). The yields and analytical data of the dimers **2**, **4**, and **6** are listed in Table I.

The starting materials **1** (except **1e**) **3**, and **5** were prepared from para-substituted benzyl cyanides by the modification of known procedures (see Experimental Section and Table VI). Methyl *p*-nitrophenylcyanoacetate (**1e**) could only be synthesized from *p*-nitrochlorobenzene and methyl cyanoacetate.[25] Compounds **1b–e**, **3b**, and **5a–c** are new.

Most of the oxidative coupling reactions were carried out at 20 or 50° in methanol or chloroform with oxygen and Cu(OH)Cl–TMEDA as a catalyst. Oxygen was consumed rapidly and the reaction was finished in 1–5 min. We have studied the effect of variation of the amine component in the catalyst and of the temperature on the reaction times (see Table II). We are unable to explain the striking difference in activity at low temperatures of the two diamines.

B. With Other Oxidants.—The oxidative coupling of phenylcyanoacetic esters (**1**), α-acylbenzyl cyanides (**3**), and *p*-tolylcyanoacetamides (**5**) could equally well be carried out at room temperature with other oxidants as shown in Table III. A few of these α-substituted benzyl cyanides have been oxidized before to give low yields (7–40%) of the C–C dimers, *viz.*, **1a**[26] (ethyl ester, anodically), **1e**[27] (ethyl ester, CrO_3), and **3a,b**[11] ($NaNO_2$ or iodine). A fair yield (60%) has only been reported in the oxidation of **3** (R_1 = Br; R_2 = CH_3) with H_2O_2.[2]

C. Mechanism.—On the basis of information in the

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[1] (a) K. Schwetlick, J. Jentzsch, R. Karl, and D. Wolter, *J. Prakt. Chem.*, **25** [4], 95 (1964); (b) H. H. Huang and P. K. K. Lim, *J. Chem. Soc. C*, 2432 (1967).

[2] H. J. Barber and R. Slack, *J. Chem. Soc.*, 612 (1944).

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[6] H. D. Hartzler, *J. Org. Chem.*, **31**, 2654 (1966).

[7] F. M. Beringer, S. A. Galton, and S. J. Huang, *Tetrahedron*, **19**, 809 (1963).

[8] E. M. Kaiser, *J. Amer. Chem. Soc.*, **89**, 3659 (1967).

[9] (a) R. Brettle and D. Seddon, *J. Chem. Soc. C*, 1320 (1970); (b) R. Brettle, *Chem. Commun.*, 342 (1970).

[10] (a) A. H. Pagano and H. Shechter, *J. Org. Chem.*, **35**, 295 (1970); (b) H. Bretschneider and R. Lutz, *Monatsh. Chem.*, **95**, 1702 (1964).

[11] G. Heller, *J. Prakt. Chem.*, **120** [2], 193 (1928); see also J. F. M. Wajon and J. F. Arens, *Recl. Trav. Chim. Pays-Bas*, **76**, 69 (1957).

[12] N. L. Weinberg and H. R. Weinberg, *Chem. Rev.*, **68**, 489 (1968).

[13] G. Eglington and W. Mac. Crae, *Advan. Org. Chem.*, **4**, 225 (1963); see also F. Bohlmann, H. Schönowsky, E. Inhoffen, and G. Grau, *Chem. Ber.*, **97**, 794 (1964).

[14] H. C. Volger, W. Brackman, and J. W. F. M. Lemmers, *Recl. Trav. Chim. Pays-Bas*, **84**, 1203 (1965).

[15] H. C. Volger and W. Brackman, *ibid.*, **86**, 243 (1967).

[16] G. A. Russell and G. Kaupp, *J. Amer. Chem. Soc.*, **91**, 3851 (1969), and references therein.

[17] N. Rabjohn, "Organic Syntheses," Collect. Vol. IV, Wiley, New York, N. Y., 1963, p 367.

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[23] A. S. Hay, *Advan. Polym. Sci.*, **4**, 496 (1967).

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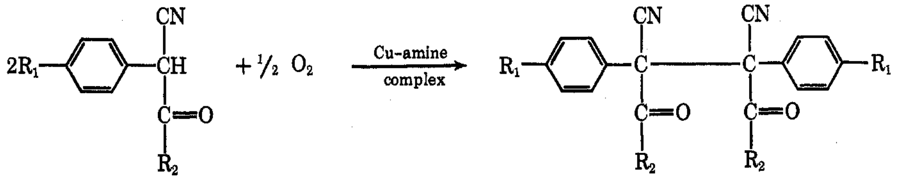
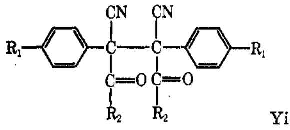
SCHEME I



Compd	R_1	R_2	
1a	H	OCH_3	
b	CH_3	OCH_3	
c	Cl	OCH_3	**2**
d	OCH_3	OCH_3	
e	NO_2	OCH_3	
3a	H	CH_3	
b	CH_3	CH_3	**4**
c	H	C_6H_5	
5a	CH_3	NH_2	
b	CH_3	$NHCH_3$	**6**
c	CH_3		

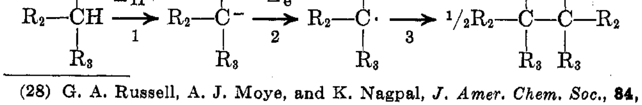
TABLE I

YIELDS, MELTING POINTS, ELEMENTAL ANALYSES, AND NMR DATA OF THE DIMERS **2**, **4**, AND **6**

 Compd	R_1	R_2	Yield,[a] %	Mp of isolated material, °C	Mp of meso isomer, °C	Mp of racemic isomer, °C	Nmr data (δ, ppm, in $CDCl_3$) of R_2 group (CH_3) meso	*dl*	Found, % (calcd) C	H	N	Cl	Mol wt, found (calcd)
2a′	H	OC_2H_5	60	117–123					70.1	5.3	7.6		
									(70.21)	(5.32)	(7.45)		
2a	H	OCH_3	84	147–152	163–165	182–184	3.78	3.92	68.9	4.5	7.8		345[b]
									(68.96)	(4.60)	(8.05)		(348)
2b	CH_3	OCH_3	99	216.5–218[c]	172–175	216.5–218	3.78	3.92	69.9	5.3	7.7		383
									(70.21)	(5.32)	(7.45)		(376)
2c	Cl	OCH_3	91		172–174	207–213	3.78	3.91	57.5	3.4	6.8	17.2	432
									(57.55)	(3.36)	(6.71)	(17.03)	(417)
2d	OCH_3	OCH_3	87	195–196			3.78	3.92	64.7	4.8	6.9		
									(64.71)	(4.90)	(6.86)		
2e	NO_2	OCH_3	49	220–226			3.78	3.91	54.4	3.4	12.8)		
									(54.79)	(3.20)	(12.78)		
4a	H	CH_3	79	174.5–177[d]			2.27	2.41					
4b	CH_3	CH_3	83	168–181	178–181	178–181	2.27	2.41	76.7	5.8	7.9		344[e]
									(76.74)	(5.81)	(8.14)		(344)
4c	H	C_6H_5	68	205–206.5[d]									
6a	CH_3	NH_2	74	218.0–220.0[f]					69.2	5.4	15.8		
									(69.36)	(5.20)	(16.18)		
6b	CH_3	$NHCH_3$	68	192.5–193.5[f]					70.3	5.9	14.7		
									(70.59)	(5.88)	(14.97)		
6c	CH_3	$C_5H_{10}N$	41	231.0–232.2[f]					74.4	7.2	11.5		482[e]
									(74.69)	(7.05)	(11.62)		(482)

[a] Yield of crude crystalline material from the oxidative coupling with oxygen in methanol using Cu(OH)Cl-TMEDA as a catalyst. See also Table III. [b] Determined with a Mechrolab osmometer, Model 301 A. [c] Heating gave a complete conversion to meso dimer **2b** without intermediate melting; see Experimental Section. [d] See lit. ref 11. [e] Determined with a Varian Mat CH-5 mass spectrometer. [f] The mother liquor contained exclusively a noncrystalline mixture of dimer **6** as shown by tlc.

literature[5,28,29] we propose that our oxidative dimerizations take place in three steps.[30] To be successful in catalytic oxidative coupling a substrate should fullfill the following conditions.



$$R_2\text{—}\overset{R_1}{\underset{R_3}{CH}} \xrightarrow[1]{-H^+} R_2\text{—}\overset{R_1}{\underset{R_3}{C^-}} \xrightarrow[2]{-e} R_2\text{—}\overset{R_1}{\underset{R_3}{C\cdot}} \xrightarrow[3]{} {}^1/{}_2R_2\text{—}\overset{R_1}{\underset{R_3}{C}}\text{—}\overset{R_1}{\underset{R_3}{C}}\text{—}R_2$$

(1) pK_a (substrate) < 20. Too high a pK_a or the use of aprotic solvents like dimethyl sulfoxide[31] and dimethylacetamide[32] gives a fast oxygenation of the carbanion.[31]

(2) Groups R_1–R_3 should stabilize the radical more than the carbanion. The phenyl group seems to satisfy this requirement.[28]

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[28] G. A. Russell, A. J. Moye, and K. Nagpal, *J. Amer. Chem. Soc.*, **84**, 4154 (1962).

[29] W. Brackman and H. C. Volger, *Recl. Trav. Chim. Pays-Bas*, **85**, 446 (1966).

[30] The present experimental facts do not exclude an alternative mechanism in which a carbanion coupled with a radical to give the radical ion of a dimer, which is further oxidized to dimer. This possibility was pointed out by Dr. Glen A. Russell, private communication.

[31] G. A. Russell, A. G. Bemis, E. J. Geels, E. G. Janzen, and A. J. Moye, *Advan. Chem. Ser.*, **1**, 174 (1968).

[32] Unpublished results obtained by A. J. Leusink and W. Drenth of the Organisch Chemisch Instituut TNO, Utrecht, The Netherlands.

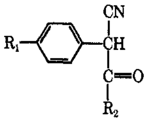
TABLE II

OXIDATIVE COUPLING OF METHYL PHENYLCYANOACETATE (**1a**) WITH OXYGEN AND 10 MOL % $CuCl_2$-AMINE (1:2 MOL RATIO) IN 10% METHANOL SOLUTION. DEPENDENCE ON TEMPERATURE AND DIAMINE

Amine	Temp, °C	Reaction time, min
Pyridine	20	80
$CH_2N(CH_3)_2$ $CH_2N(CH_3)_2$	50	4
	0	5
	−15	14
	−27	30
$CH_2N(C_2H_5)_2$ $CH_2N(C_2H_5)_2$	−27	1
	−50	6
	−70	14

TABLE III

OXIDATIVE COUPLING OF PHENYLCYANOACETIC ESTERS **1** AND α-ACYLBENZYL CYANIDES **3** WITH VARIOUS OXIDANTS (EXCEPT OXYGEN)



Compd	R_1	R_2	Oxidant	Solvent	Reaction time, min (room temp)	Yield of cryst C-C dimer, %
1b	CH_3	OCH_3	$K_3Fe(CN)_6$	Methylene chloride + aqueous NaOH	30	83
1b	CH_3	OCH_3	$K_3Fe(CN)_6$	Methanol + aqueous ammonia	45	91
1b	CH_3	OCH_3	$KMnO_4$	Acetone + aqueous ammonia	45	91
1b	CH_3	OCH_3	Ag_2O	Acetic acid	30	76
1b	CH_3	OCH_3	Ag_2O	Benzene	30	95
1b	CH_3	OCH_3	PbO_2	Acetic acid	60	0
1b	CH_3	OCH_3	$NaNO_2$	Acetic acid	24 hr	65
3a	H	CH_3	PbO_2	Acetic acid	30	45
3b	H	C_6H_5	PbO_2	Acetic acid	45	78
5c	CH_3	$C_5H_{10}N$	$KMnO_4$	Acetone-ammonia	30	63

(3) Conversion of tertiary carbanions to tertiary radicals occurs more readily than conversion of secondary or primary carbanions to the corresponding radicals.[28] Therefore, R_1, R_2, $R_3 \neq H$.

(4) The carbanion, the radical, and the dimer all should be relatively insensitive to oxygen, otherwise oxygenation of any of these intermediates or products will take place.

(5) One of the groups R_1–R_3 should enable the substrate to complex with the Cu catalyst. Complexing of Cu compounds with nitrile groups is well documented in the literature.[33a] In this respect it is interesting to note that arylmalonic esters mainly give a slow oxygenation to arylglyoxylic esters with the Cu–amine–O_2 system. High yields of C–C dimers, however, can be obtained with other oxidants.[33b]

The exclusive catalytic oxidative dimerization found with substrates **1**, **3**, and **5**, selected after extensive screening, can be understood along these lines.

The noncatalytic oxidative coupling is apparently more restricted to specifically activated substrates than it is to special oxidants. Some oxidants are, however, more specific than others. For example, lead dioxide does couple α-acylbenzyl cyanides **3a** and **3b** while it gives no reaction with methyl *p*-tolylcyanoacetate (**1b**) at all (Table III). This difference may be due to the fact that, unlike the cyanoacetic esters **1**, the acylbenzyl cyanides **3** are strongly enolized in polar solvents, as shown by their ir spectra. Accordingly, lead dioxide is an excellent oxidative coupling agent of phenols.[34]

Properties of the Dimers. A. Assignment of *dl* and Meso Configuration.—The dimers obtained by oxidative coupling often crystallized immediately from the reaction mixture and were mostly obtained as an approximately 3:2 mixture of low melting and high melting isomers. In the case of dimers **2a–c**, the pure low melting isomer (running faster on tlc) was obtained from the reaction mixture by fractional crystallization from carbon tetrachloride or methanol. The corresponding high melting isomer was obtained by thermal equilibration to give more than 90% of the higher melting isomer (see part C), followed by fractional crystallization. The isomer ratio could easily be determined from the nmr spectrum by integration of the separate methyl ester peaks (Table I). The higher melting isomer of diester **2a** (mp 184°) has the *dl*, while the lower melting isomer (mp 165°) has the meso configuration. This has been proven as follows.

Upon mild treatment (25°) with 96% sulfuric acid the higher melting isomer of **2a** gave the diester diamide **7**, which dissolved rapidly at room temperature in 2 equiv of aqueous sodium hydroxide solution. On acidification a crystalline compound (mp 393°) separated, to which the diimide structure **8** was assigned on the basis of spectral and analytical data (see Experimental Section). Analogous cyclizations of amido esters to succinimides are known in the amino acid field,[35,36a] with succinic acid derivatives[36b] and also starting from tetracyanoethylene derivatives.[37] It can be concluded from these results that the higher melting isomer **2a** has the *dl* configuration.

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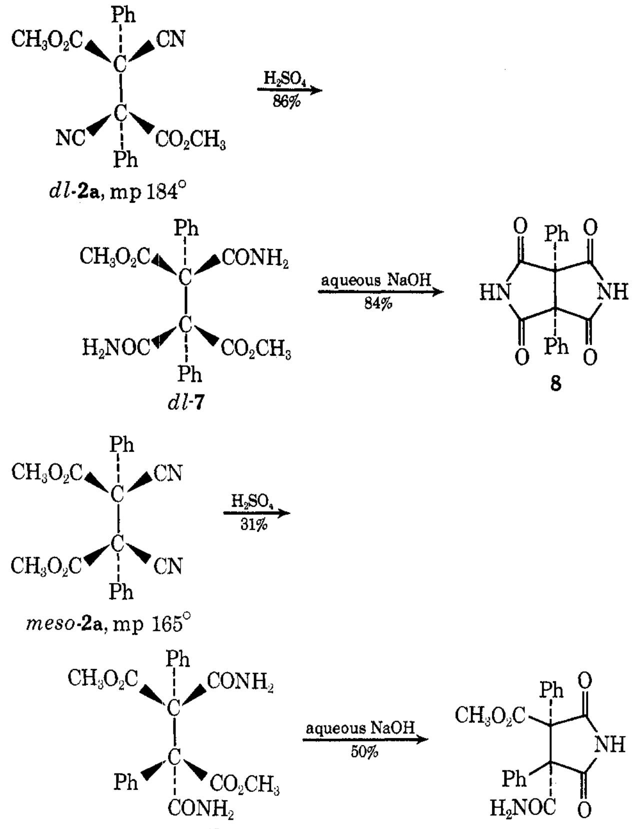
[33] (a) *Gmelins Handbuch Anorg. Chem.*, **60B**, 243 (1958); R. A. Walton, *Quart. Rev., Chem. Soc.*, **19**, 136 (1965). (b) Unpublished work.

[34] H. M. van Dort, C. R. H. I. de Jonge, and W. J. Mijs, *J. Polym. Sci., Part C*, **22**, 431 (1968); C. R. H. I. de Jonge, H. M. van Dort, and L. Vollbracht, *Tetrahedron Lett.*, 1881 (1970).

[35] E. Sondheimer and R. W. Holley, *J. Amer. Chem. Soc.*, **76**, 2467 (1954); **79**, 3767 (1957).

[36] (a) M. K. Hargreaves, J. G. Pritchard, and H. R. Dave, *Chem. Rev.*, **70**, 441 (1970); (b) G. Morel and A. Foucaud, *Bull. Soc. Chim. Fr.*, 3123 (1970), and references therein.

[37] P. G. Farrell and R. K. Wojtowski, *J. Chem. Soc. C*, 1390 (1970).



dl-**2a**, mp 184°

dl-**7**

8

meso-**2a**, mp 165°

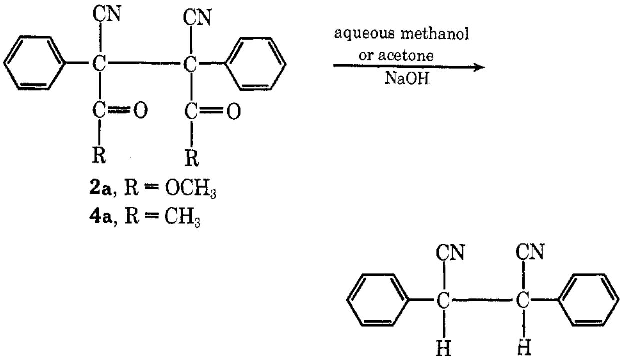
meso-**7**

9

The lower melting isomer of **2a** was treated similarly to give the other stereoisomeric diester diamide **7**, which was now found to undergo only monocyclization to **9** (mp 204°). The trans position of the ester and amide groups in **9** prevents the second cyclization. Accordingly, the meso configuration is assigned to the lower melting isomer **2a**.

From equivalence of nmr spectra (OCH_3 signal at 3.78 ppm) for all lower melting isomers **2a–c**, the meso configuration can be assumed, whereas all higher melting isomers **2a–c** (OCH_3 at 3.91–3.92 ppm) should have the *dl* configuration.

B. Basic Hydrolysis of Dimers 2a and 4a.—The dimers **2a** and **4a** are extremely susceptible to hydrolysis by aqueous base at room temperature to give 2,3-diphenylsuccinonitrile (**10**). The hydrolysis of the para-substituted dimers **2** and **4** has not been investigated but they are expected to show a comparable activity.



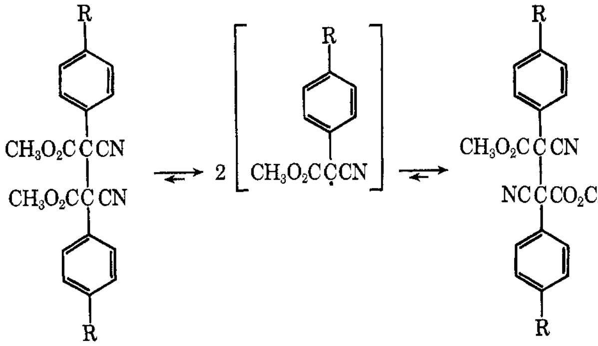
2a, R = OCH_3
4a, R = CH_3

10

With dimer **4a**, even the TMEDA present in the catalyst can effect partial hydrolysis. On treating **4a** with 1 equiv of $[Cu(OH)(TMEDA)]_2Cl_2$ at 50° in methanol, α,α′-dicyanostilbene was formed, apparently by oxidation of the dinitrile **10**, resulting from hydrolysis of **4a**. Dimer **2a** was unreactive under these conditions (see Experimental Section).

C. Thermal Interconversion of Diastereoisomers 2a and 2b.—Thermal interconversion of the meso (low melting) and *dl* (high melting) isomers **2a** and **2b** proceeds very smoothly. *meso*-**2a** and -**2b** by refluxing in toluene or acetic acid gave a 5:95 mixture of meso and *dl* isomers. The same equilibrium mixture could be obtained from pure *dl* isomer.

The interconversion takes place *via* radical dissociation–recombination as evidenced by esr spectroscopy.[38] Solutions of the diesters **2a–d** in 1:1 biphenyl–diphenyl ether exhibited an esr spectrum from 120° upwards. At 150° a pronounced spectrum was produced which has been analyzed.[39a] The signals declined on cooling down and increased again on warming. The facile C–C bond rupture is also observed in the mass spectrum of, *e.g.*, dimer **4b** (M = 344), which shows *m/e* at 172 (intensity 25% of base peak). A radical adduct was obtained in 50% yield from **2b** by trapping with diphenylpicrylhydrazyl at 80°. With thiophenol at 100°, **2b** afforded methyl *p*-tolylcyanoacetate (**1b**) and diphenyl disulfide as the only products. Consistent with this behavior the C–C dimers have been proven to be active initiators in the radical polymerization of vinyl monomers.[39b]



meso-**2**

dl-**2**

Comparable cases of reversible radical dissociation–recombination described in the literature are tetraphenylsuccinonitrile (**11**),[40] 2,3-dicyano-2,3-diphenylsuccinonitrile (**12**),[6] and 2,3-dimethyl-2,3-diphenylsuccinonitrile (**13**).[41]

The radicals resulting from C–C bond scission are surprisingly inert to oxygen. On shaking a solution of **2b** in *o*-dichlorobenzene at 150° with oxygen, no consumption took place. In contrast, tetraphenylsuccinonitrile (**11**) consumed oxygen at 80° (0.5 mol/mol of dinitrile in 1 hr), while diethyl tetraphenylsuccinate quickly reacts with oxygen at room temperature to give a peroxide.[42]

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[38] W. J. van den Hoek and J. Smidt, unpublished results obtained at the Technical University of Delft, The Netherlands.

[39] (a) The esr spectrum of the radical derived from **2a** at 140° gave the following hyperfine coupling constants (in Oe): 0.8 (OCH_3), 1.9 (CN), 5.0 (para H), 1.4 (meta H), 4.2 (ortho H). Similar values were obtained for the radicals from **2b** and **2c**.[39b] (b) Forthcoming publication.

[40] G. Wittig and W. Hopf, *Ber.*, **65**, 760 (1932); G. Wittig and H. Petri, *Justus Liebigs Ann. Chem.*, **513**, 26 (1934).

[41] L. J. Peterson, *J. Amer. Chem. Soc.*, **89**, 2677 (1967).

[42] B. Witten and F. Y. Wiselogle, *J. Org. Chem.*, **6**, 584 (1941).

Treating the isomerization as a first-order reversible reaction,[43] rate constants were obtained at each temperature for the meso → *dl* conversion of **2a** and **2b**. The meso/*dl* ratios were measured by integration of the methyl ester signals in the nmr spectrum. Activation parameters were calculated with the transition state theory and are listed in Table IV.

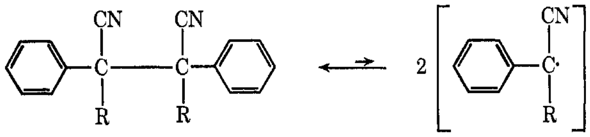
TABLE IV

KINETIC DATA AND ACTIVATION PARAMETERS FOR THE MESO $\underset{k_{-1}}{\overset{k_1}{\rightleftarrows}}$ *dl* CONVERSION OF DIMERS **2a** AND **2b**

	Equil constant		Rate constant		Activation parameters	
Dimer	K (k_1/k_{-1})	Temp, °C	$10^4 \times k_1$ (sec^{-1})	Temp, °C (±0.3°)	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
2a	16	108–127	8.37	107.6	23.1 ± 0.5	−12 ± 2
			18.1	118.1		
			39.7	127.3		
2b	13	84–101	4.35	83.9	22.6 ± 0.5	−11 ± 2
			12.2	95.8		
			19.6	100.9		

There are only two examples of interconversion of racemic and meso isomers *via* carbon radicals in the literature: 2,3,4,5-tetramethyl-3,4-diphenylhexane[44] (*dl*/meso ratio at equilibrium ~0.5; extensive disproportionation of the radicals is reported) and 2,3-dimethyl-2,3-diphenylsuccinonitrile (**13**)[41] (*dl*/meso ratio at equilibrium 1.22, no esr signal observed up to 300°).

Our values for $\Delta H^{\ddagger}$ are much lower than those reported by Peterson[41] with **13** (42.4 kcal/mol). This can be accounted for by the greater stabilization of the radicals from **2a** and **2b**. The activation enthropy $\Delta S^{\ddagger}$ is negative in our case (+17 eu in Peterson's work[41]), meaning some kind of unexplained orientation in the transition state.



11, R = Phenyl
12, R = CN
13, R = CH_3

Assuming purely steric interactions, a meso isomer should always be more stable than *dl* isomer.[45] However, the preference of the *dl* over the meso isomer at equilibrium of **2a** and **2b** (*dl*/meso 13–16) and of **13** (*dl*/meso 1.22) clearly shows that polar interactions are now predominant. The greater stability of a *dl* over a meso isomer has also been reported for α,α′-dialkylsuccinic acids, tartaric acid, butane-2,3-diol, and 2,3-dichlorobutane and is attributed to hydrogen bonding or special attactivre polar interactions.[46]

To explain the *dl*/meso ratio (1.22) with **13**, Peterson postulates London dispersion forces between gauche cyano groups. Similarly, Drefahl assumes attraction between the nitrile groups in 2,3-diphenylsuccinonitrile to explain the larger dipole moment of the meso over the racemic isomer.[47] In contrast, Huang, *et al.*, assume a dipolar repulsion between the nitrile groups in 2,3-dimethyl-2,3-diphenylsuccinonitrile (**13**) on the basis of dipole measurements of the two isomers.[48] Thus specific interactions of polar groups in succinonitriles are too complicated to give rise to any reasonable interpretation of the stability predominance of diastereoisomers of **2**.

D. Formation of Oligomers.—In the catalytic oxidative coupling of para-unsubstituted benzyl cyanides **1a**, **3a**, and **5d**, higher oligomers are also formed. With **1a**, 2–4% trimer was detected by gpc, with **3a** about 15% trimer and at least 6% tetramer, whereas oxidation of **5d** with $KMnO_4$ gave a noncrystallizable foam, consisting mainly of a mixture of hexa- to octamers (by nmr and gpc analysis; see Experimental Section). Substitution at the para position in **1**, **3**, and **5** impedes the formation of oligomers in the oxidation and high yields (>80%) of pure dimer are obtained in most cases.

The same oligomerization was experienced with diester **2a** on heating at 170° *in vacuo* or at 130° in 20% solution in chlorobenzene. Methyl phenylcyanoacetate (**1a**) was distilling, leaving a brown, noncrystallizable residue, which by gpc and tlc (separate spots) consisted of tri-, tetra-, and pentamers (*cf.* Table V). No oligomerization took place on refluxing a dilute solution (0.4% by weight) of *meso*-**2a** in chlorobenzene; 90% of the starting material was recovered after 40 hr. Therefore, the oligomerization of **2a** proceeds bimolecularly (n > 2). Oligomerization was also absent with para-substituted dimers (*e.g.*, **2b**) under conditions where **2a** reacted extensively.

TABLE V

THERMAL TREATMENT OF DIMER **2a**

Conditions			% oligomers after thermal treatment				
Temp, °C	Pressure, mm	Time, hr	Monomer	Dimer	Trimer	Tetramer	Pentamer
130[a]		1		60	20		
130[a]		15	15	25	40	15	5
160	1.5	1.25	[b]	2	35	40	10
170	0.4	3	30[b]	10[c]	5	20	35

[a] 20% solution in refluxing chlorobenzene (bp 130°). [b] Distillate. [c] Sublimate.

The spectral data (ir and nmr; *cf.* Experimental Section), indicating the $NCCHCO_2CH_3$ end group and para substitution, are consistent with that shown in Scheme II (the ratio of structures **14** to **15** could not be determined).

The redistribution reaction of the dimer **2a** bears similarity to the rearrangement of tetraphenylsuccinonitrile (**11**)[40] and 2,3-dicyano-2,3-diphenylsuccinonitrile (**12**)[6] in chloroform at 20–50° to give the para-substituted dimers. We have not been able to detect the presence of rearranged dimer **14** (n = 2).

Experimental Section

Physical Methods and Analyses.—Ir spectra were recorded on a Hitachi EPI-G2 spectrophotometer. Nmr spectra were run on a Varian A-60 or a Jeol nmr spectrometer Model JNM-4S-100-H. Tetramethylsilane (δ = 0 ppm) was used as an internal

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[43] A. A. Frost and R. G. Pearson, "Kinetics and Mechanism," Wiley, New York, N. Y., 1953, p 172.

[44] P. D. Bartlett and J. M. Bride, *Pure Appl. Chem.*, **15**, 89 (1967).

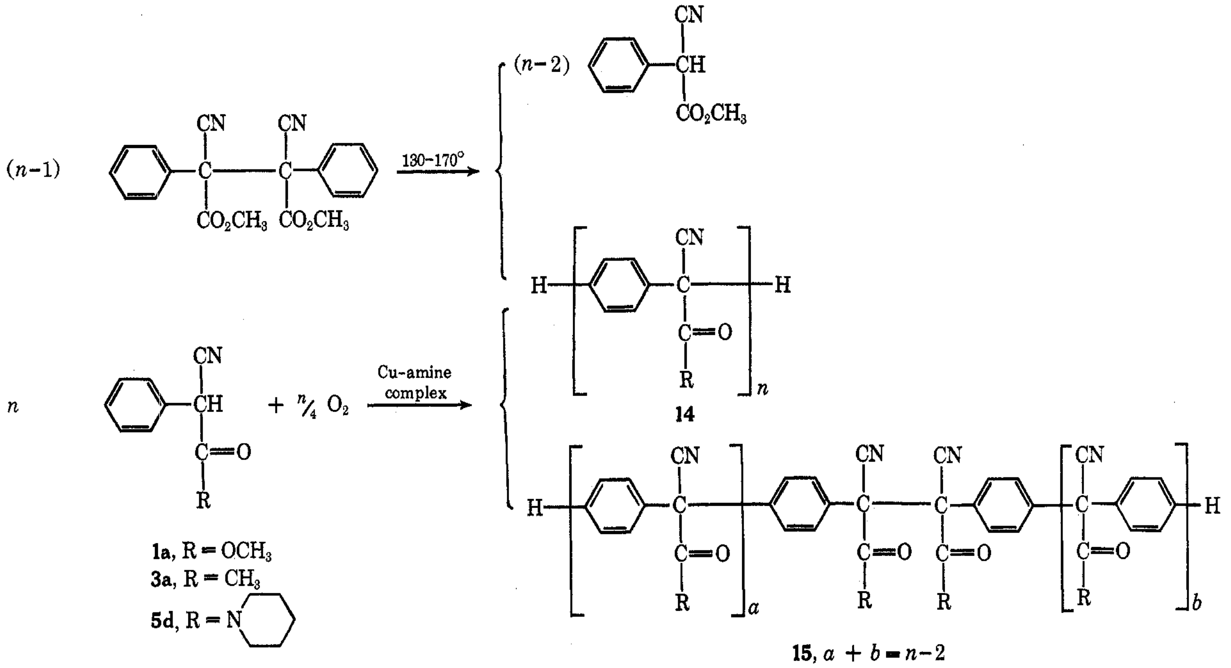
[45] E. L. Eliel, "Stereochemistry of Carbon Compounds," McGraw-Hill, New York, N. Y., 1962, pp 138, 139.

[46] W. E. Billups and N. C. Deno, *Chem. Commun.*, 12 (1970).

[47] G. Drefahl, G. Heublein, and D. Voigt, *J. Prakt. Chem.*, **23** [4], 157 (1964).

[48] K. K. Chiu, H. H. Huang, and P. K. L. Lim, *Chem. Commun.*, 1336 (1969).

SCHEME II



standard. Mass spectra were determined with a Varian Mat CH-5 mass spectrometer. Gpc measurements were performed on a gel permeation chromatograph, Model 200, manufactured by Waters Associates. The elemental analyses and molecular weight determinations were carried out under the supervision of Mr. W. J. Buis of the Microanalytical laboratory of the Organic Chemical Institute T. N. O. (Utrecht). The melting points were determined with a melting point microscope (Leitz Model 553215) and are uncorrected as are the boiling points. Thin layer chromatography was performed on silica gel layers (Merck, gel F 254, kat 5715/0025) with a mixture of carbon tetrachloride and ethyl acetate (9:1, v/v) unless otherwise specified. The spots were detected with uv light (254 nm) and with phosphomolybdic acid.

Starting Materials and Solvents.—Unless otherwise specified, the solvents and reagents were of reagent grade (puriss) and were not further purified.

General Extraction Procedure.—The reaction mixture was in general diluted with water and extracted three times with chloroform. The combined chloroform layers were washed once with water and dried over MgSO$_4$. After filtration, the chloroform was evaporated *in vacuo*.

Synthesis of the α-Substituted Benzyl Cyanides 1, 3, and 5.—The arylcyanoacetic esters **1a–d** and the α-acylbenzyl cyanides **3a–c** have been prepared according to the following general procedure. Moreover, some of the nitriles **1** and **3** were synthesized[49] with sodium methylate in refluxing toluene. The yields, physical constants, and elemental analyses are listed in Table VI.

General Procedure. Preparation of Methyl Phenylcyanoacetate (1a).—To a suspension of 28.8 g (0.60 mol) of sodium hydride (Fluka, 50% suspension in mineral oil) in 400 ml of dimethoxyethane (distilled over calcium hydride) there was added under nitrogen and while stirring a mixture of 70.2 g (0.60 mol) of benzyl cyanide and 108 g (1.20 mol) of dimethyl carbonate in the course of 20 min. A sudden vigorous hydrogen evolution was slowed down by cooling with ice. In some instances, the reaction was initiated by heating in a water bath kept at 60°.

The reaction mixture was concentrated *in vacuo* and the residue was acidified with 2 *N* acetic acid while cooling in ice. Chloroform extraction followed by distillation gave 82.6 g (87%) of **1a**, bp 154–156° (11 mm).

Preparation of Methyl (*p*-Nitrophenyl)cyanoacetate (1e).—The procedure described for diethyl *p*-nitrophenylmalonate[25] was followed. To a suspension of 72 g (1.5 mol) of sodium hydride (Fluka, 50% suspension in mineral oil) in 800 ml of HMPTA (hexamethylphosphotriamide) there was added a solution of 150 g (1.5 mol) of methyl cyanoacetate. To the suspension there was added 158 g (1.0 mol) of *p*-nitrochlorobenzene in small portions in 30 min with ice cooling to keep the temperature below 60°. After additional stirring for 15 hr at 90°, the reaction mixture was poured on ice and acidified with 2 *N* hydrochloric acid. A sticky precipitate was obtained which after crystallization from methanol–pentane (9:1) yielded 134 g (64%) of colorless product, mp 98.5–100° (see also Table VI).

TABLE VI

YIELDS AND PHYSICAL CONSTANTS OF STARTING MATERIALS **1**, **3**, AND **5**[a]

Compd[b]	Procedure,[c] ref	Yield, %	Bp, °C (mm)	Mp, °C
1a		87	154–156 (11)	
1b		91	124 (1)	
1c		84	112 (0.3)	
1d		80	160 (1)	34–36.5
1e		64		98.5–100
3a	11	68		88–89.5
3b	11	79		90–91
3c	11	55		95.5–97
5a	50	68		168.1–168.4
5b	51	54		125.3–125.6
5c	51	50		140.4–140.6
5d	51	56		128.9–130.1

[a] All new compounds in this table gave satisfactory analyses (±0.4) for C, H, N, and Cl (where relevant). The data were made available to referees and to the Editor. [b] Nmr (chloroform-*d*) of **1**: δ 3.70 (s, 3, OCH$_3$), 4.73 (s, 1, tertiary H). Nmr of **3**: δ 2.25 (s, 3, COCH$_3$), 4.70 (s, 1, tertiary H). Nmr of **5**: δ 5.03 (s, 1, tertiary H). [c] No indication means general procedure described above.

Synthesis of Arylcyanoacetamides 5.—The amides **5a** and **5b** were prepared simply from ester **1b** and ammonia or methylamine at room temperature according to the method described by Hessler.[50] The amides **5c** and **5d** were prepared from esters **1b** and **1a** and piperidine by heating at 110° according to the method described by Pesson, *et al.*[51] See also Table VI.

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(49) Reference 17, p 461.

(50) J. C. Hessler, *J. Amer. Chem. Soc.*, **32**, 122 (1904).

(51) M. Pesson, S. Dupin, and M. Antoine, *C. R. Acad. Sci.*, **256**, 4680 (1963).

Preparation of the Copper-TMEDA Catalyst.—Cu_2Cl_2 (1 mol) and a solution of 2 mol of tetramethylethylenediamine (TMEDA) and 27 ml of water in methanol (500 ml) were shaken in an oblong flask connected with a gas buret for measurements of oxygen uptake. A total amount of 0.5 mol of oxygen was consumed within 30 min. The complex was removed by filtration, washed with acetone, and dried at 40° (12 mm). There was obtained 424 g (90%) of purple powder decomposing at 138–139° (heated from 120°). Elemental analysis and molecular weight determinations suggest this compound to be $[Cu(OH)(TMEDA)]_2Cl_2$.[32]

Anal. Calcd for $C_{12}H_{34}Cl_2Cu_2N_4O_2$: C, 31.04; H, 7.38; Cl, 15.27; Cu, 27.36; N, 12.06; mol. wt, 464.4. Found: C, 31.0; H, 7.3; Cl, 15.2; Cu, 27.2; N, 11.9; mol wt (ebullioscopic determination in boiling ethanol), 320 (apparently the complex is partly dissociated in boiling ethanol).

An identical purple Cu complex has been prepared according to Wasson, *et al.*, by addition of 4 equiv of TMEDA to a saturated aqueous $CuCl_2$ solution.[52] The complex showed an identical ir spectrum (KBr) and decomposition point (138–139°, heated from 120°).

Both of the purple complexes can be converted into a hydrous, deep blue crystalline complex by dissolution in water followed by precipitation with acetone. The blue complexes both show the same ir spectrum (KBr), visible spectrum (max at 625 nm) and decomposition point (142–143°, after evaporation of the water, heated from 130°).

Anal. Calcd for $\{[Cu(OH)(TMEDA)]Cl\cdot 2H_2O\}_n$ (blue complex prepared from $CuCl_2$–TMEDA–H_2O): C, 26.87; H, 7.89; Cl, 13.22; Cu, 23.69; N, 10.44. Found: C, 26.6; H, 7.8; Cl, 13.3; Cu, 24.0; N, 10.2.

Oxidative Coupling. General Procedure (See Also Table I). A. Oxidative Coupling of 1a in Chloroform.—The oxidation was performed in a 250-ml oblong double-walled flask with 7.0 g (40 mmol) of methyl phenylcyanoacetate (**1a**) in 70 ml of chloroform at 50° with oxygen, using 1.0 g (2.2 mmol) of $[Cu(OH)(TMEDA)]_2Cl_2$ (a 1:2 molar mixture of Cu_2Cl_2 and TMEDA gave the same results) as catalyst and 5.0 g of $MgSO_4$ to remove water. The flask was connected with a gas buret and placed on a shaking machine. The whole system was then flushed and filled with oxygen. The reaction was completed within 5 min as shown by a sudden stop in the fast uptake of oxygen (240 ml). The reaction mixture was filtered from $MgSO_4$ and washed with 40 ml of 2 *N* HCl and three times with 40 ml of water. After the usual work-up, a yellow syrup was obtained, which after crystallization from methanol afforded a first crop of 2.75 g (39%) of colorless dimer **2a**, mp 144–149°. Concentration of the mother liquor gave a second crop of 3.72 g (53%) of dimer as a viscous syrup which crystallized slowly on standing and gave two spots (two diastereoisomers) on tlc.

B. Oxidative Coupling of 1b in Methanol.—The oxidation was carried out in the same apparatus as described in procedure A with 7.5 g (40 mmol) of methyl *p*-tolylcyanoacetate (**1b**) in 75 ml of methanol at 50° with oxygen, using 1.0 g (2.2 mmol) of Cu_2Cl_2–TMEDA as catalyst. No $MgSO_4$ was used. Upon addition of **1b** to the catalyst solution, the color changed from blue to deep purple. The purple color persisted until the end of the reaction (2 min) and then suddenly turned blue again. When shaking was stopped at room temperature, the solution became colorless within a few seconds (Cu^I complex). During the reaction the dimer **2b** precipitated. The reaction mixture was acidified with 5 ml of 2 *N* HCl and filtered, and the product was washed twice with 10 ml of water and twice with 10 ml of cold methanol. This yielded 6.93 g of dimer **2b** (92%), mp 217.5–219.0°. Addition of 100 ml of water to the filtrate followed by chloroform extraction afforded a second crop of 0.57 g (7%) of dimer **2b**, mp 214–216°. Tlc of this second portion showed two spots of about equal intensity.

Oxidative Coupling of 1b with Various Oxidants (Table III).—Diester **2b** obtained in the various oxidations consisted of an approximately 3:2 mixture of meso and *dl* isomers as shown by the nmr spectrum.

Oxidation of 1b with Silver(I) Oxide in Benzene and Acetic Acid.—To a solution of 3.8 g (20 mmol) of methyl *p*-tolylcyanoacetate (**1b**) in 40 ml of benzene there was added 4.6 g (20 mmol) of silver(I) oxide and the mixture was stirred for 30 min at room temperature. The mixture was filtered, the benzene was evaporated *in vacuo*, and the residue was recrystallized from methanol. There was obtained 3.6 g (95%) of dimer **2b**, mp 216–218.5°. Repetition of this procedure in acetic acid yielded 2.9 g (76%) of dimer **2b**, mp 216.5–217°.

Oxidation of 1b with $KMnO_4$ in Acetone-Ammonia.—The oxidation of **1b** was performed according to the procedure described earlier by Kharasch and Sosnovsky.[5] Recrystallization from methanol gave a 91% yield of colorless dimer **2b**, mp 216–218°.

Similarly, oxidation of **5c** gave after recrystallization from methanol a 63% yield of **6c**, mp 231–232.2°.

Oxidation of 1b with $K_3Fe(CN)_6$ in Methanol-Ammonia.—The oxidation of **1b** was performed according to the method described by earlier Kharasch and Sosnovsky.[5] Recrystallization from methanol gave a 91% yield of colorless dimer **2b**, mp 216.5–217°.

Oxidation of 1b with $K_3Fe(CN)_6$ in Methylene Chloride-Aqueous NaOH.—To a mixture of 3.8 g (20 mmol) of methyl *p*-tolylcyanoacetate (**1b**) dissolved in 40 ml of methylene chloride and 25 ml of 2 *N* NaOH there was added 25 ml of a 1 *N* $K_3Fe(CN)_6$ solution in water and after shaking for 5 min in a separatory funnel the layers were separated. Further extraction with methylene chloride followed by recrystallization of the residue from methanol yielded 3.1 g (83%) of dimer **2b**, mp 215.5–217°.

Oxidation of 1b with $NaNO_2$ in Acetic Acid.—The oxidation of **1b** was performed according to the method described by Heller.[11] To a solution of 3.8 g (20 mmol) of methyl *p*-tolylcyanoacetate (**1b**) in 40 ml of glacial acetic acid there was added a solution of 1.4 g (20 mmol) of sodium nitrite in 20 ml of water. The reaction mixture was kept for 30 min at 0–5° and then 24 hr at room temperature. The crystals were separated by filtration and recrystallized from methanol, yielding, 2.6 g (65%) of dimer **2b**, mp 216–217°.

Oxidation of 3b with PbO_2.—To a suspension of 7.0 g (40 mmol) of *p*-tolylacetoacetonitrile (**3b**) in 70 ml of acetic acid there was added 9.6 g (40 mmol) of PbO_2 in the course of 5 min. After 30 min at room temperature, a 5% hydrogen peroxide solution was added until the excess of PbO_2 was dissolved. The product crystallized from the solution. There was obtained 5.45 g (78%) of **4b**, mp 168.5–170°.

Similarly there was obtained a 45% yield of **4a** from **3a**.

Preparation of Meso Diester 2a.—Recrystallization of 650 mg of a 3:2 mixture (meso/*dl*) of **2a** (mp 156–161°) from 40 ml of methanol gave, after 20 min at 25°, 290 mg of product, mp 160–166°, with a 91:9 ratio of meso/*dl* (by nmr).

A second crystallization gave 190 mg of dimer **2a**, mp 163–165°, which was pure meso isomer by nmr. Tlc showed one single spot at R_f 0.23.

Preparation of Meso Diester 2b.—Recrystallization of 500 mg of a 3:2 mixture (meso/*dl*) of **2b** from 50 ml of methanol gave, after 17 hr at 25°, 270 mg of a product, mp 207–215°. A second crystallization yielded 130 mg of dimer **2b**, mp 172–175° which was pure meso isomer by nmr.

On further heating, the molten meso diester **2b** quickly recrystallized at 180° and then melted sharply at 216–217°, the melting point of the *dl* isomer. On heating a 3:2 mixture of *meso*- and *dl*-**2b**, a reshuffling of the crystals started at 130° (very fast at 190°) and a sharp melting point was observed at 216–217°.

Preparation of Racemic Diester 2a by Thermal Equilibration.—A solution of 302 mg of diester **2a** (3:2 mixture of meso/*dl*) in 3 ml of toluene was refluxed for 1 hr. Removal of the toluene *in vacuo* gave 283 mg of product, mp 180–183° (93:7 *dl*/meso, by nmr). Tlc showed spots at R_f 0.23 (weak) and 0.20 (intense). Recrystallization from ethanol gave the *dl* isomer, mp 182–184 (pure by nmr and tlc).

Preparation of Racemic Diester 2b by Thermal Equilibration.—Recrystallization of 15.0 g of diester **2b** (3:2 mixture of meso/*dl*) from 175 ml of 1-butanol gave after 1 hr of reflux and 1 hr at room temperature 14.0 g of colorless crystals (94:6 *dl*/meso by nmr). Tlc showed spots at R_f 0.26 (weak) and 0.21 (intense). Recrystallization from ethanol gave 7.2 g (48%) of the *dl* isomer, mp 216.5–217.5° (pure by nmr and tlc).

Preparation of Meso and Racemic Diester 2c.—The oxidation was carried out after procedure B with 4.2 g (20 mmol) of methyl (*p*-chlorophenyl)cyanoacetate (**1c**) in 50 ml of methanol at 20° with oxygen, using 0.5 g (1.1 mol) of Cu_2Cl_2–TMEDA as catalyst. During the reaction, which was completed within 2 min, dimer **2c** precipitated. Filtration gave 3.00 g (71%) of meso

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(52) J. R. Wasson, T. P. Mitchell, and W. H. Bernard, *J. Inorg. Nucl. Chem.*, **30**, 2865 (1968).

dimer **2c**, mp 172–174° (pure by nmr). On further heating, a fast and complete recrystallization took place at 180° and a second mp 207–213° was observed. Acidification of the filtrate with 5 ml of 2 *N* HCl gave, after 18 hr, 0.82 g (20%) of pure *dl* isomer **2c**, mp 207–213°. The nmr spectral data are given in Table I.

Racemic Diester Diamide 7.—To 30 ml of 96% sulfuric acid there was added 5.0 g (14.4 mmol) of *dl* diester dinitrile **2a** (mp 183°). The temperature rose from 23 to 30° in 3 min. After stirring for 2 hr at 23°, the colorless solution was slowly added to 200 ml of cold methanol, while cooling in ice–acetone. Slow addition of 300 ml water while cooling with ice–acetone gave a fast crystallization of the product.

Filtration followed by thoroughly washing with water and cold methanol gave 4.75 g (86%) of colorless diester diamine **7**: mp 224–225.8°; ir (KBr) 1740 (ester C≡O), 1680 cm^{-1} (amide C=O); nmr (DMSO-d_6) δ 3.75 (s, 6, OCH_3), 7.08 (broad, 10), 7.55 ppm (broad, 4, NH_2).

Anal. Calcd for $C_{20}H_{20}N_2O_6$: C, 62.50; H, 5.21; N, 7.29; mol wt. 384. Found: C, 62.3; H, 5.4; N, 7.2; mol wt, 384 (mass spectrum).

Bicyclic Diimide 8.—The *dl* diester diamide **7** (3.0 g, 7.8 mmol) dissolved rapidly in 20 ml of 1 *N* aqueous sodium hydroxide. After stirring for 20 min at 23°, the colorless solution was acidified with 2 *N* hydrochloric acid while cooling. Removal of the colorless precipiptate by filtration gave 2.45 g (98%) of crude diimide **8**. Recrystallization from methanol–water (1:1) gave 2.1 g (84%) of pure diimide **8**: mp 393° (determined with differential scanning calorimetry, using a Perkin-Elmer instrument, type DSC-1); ir (KBr) 1780 and 1760 cm^{-1} (imide C=O), no ester or amide C=O; nmr (acetone-d_6) δ 7.05 ppm (m, C_6H_5); mass spectrum (70 eV) *m/e* (rel intensity) 320 (5), 277 (3, NH-CO), 249 (100, O=CNHC=O), 221 (15, NHCO, O=CNH-C=O), 205 (28), 178 (47, PhC≡C-Ph$^+$). No McLafferty rearrangements are observed.

Anal. Calcd for $C_{18}H_{12}N_2O_4$: C, 67.50; H, 3.75; N, 8.75; mol wt, 320. Found: C, 67.4; H, 3.9; N, 8.6.

Meso Diester Diamide 7.—To 15 ml of 96% sulfuric acid there was added 1.90 g (5.5 mmol) of meso diester dinitrile **2a** (mp 163–165°). The temperature rose from 23 to 30° in 3 min. After stirring for 2 hr at 23°, the colorless solution was poured into ice–chloroform. After the usual work-up there was obtained 2.0 g of a colorless foam. Crystallization from 6 ml of methanol gave 650 mg (31%) of diester diamine **7**: mp 159–160°; ir (KBr) 1730 (ester C=O), 1680 cm^{-1} (amide C=O); nmr (acetone-d_6) δ 3.81 (s, 6, OCH_3), 6.83 (broad, 4, NH_2), 7.6 ppm (10, m).

Anal. Calcd for $C_{20}H_{20}N_2O_6$: C, 62.50; H, 5.21; N, 7.29; mol wt, 384. Found: C, 62.4; H, 5.6; N, 7.0; mol wt, 384 (mass spectrum).

Monocyclic Imide 9.—The procedure was identical with the preparation of diimide **8**. From the reaction of 501 mg (1.30 mmol) of meso **7** with 2.6 ml of 1 *N* aqueous sodium hydroxide and 3.4 ml of water there was obtained 460 mg (100%) of crude succinimide **9**. Recrystallization from diethyl ether gave 217 mg (50%) of pure imide **9**: mp 216–217.5°; ir (KBr) 1780 (imide C=O), 1760 (sh, imide C=O), 1730 (ester C=O), 1690 cm^{-1} (amide C=O); nmr (DMSO-d_6) δ 3.25 (s, 3, OCH_3, shifted upfield, due to position above phenol ring), 7.0 (broad, 2, NH_2), 7.7 ppm (m, 10); mass spectrum (70 eV) *m/e* (rel intensity) 352 (5), 309 (51, –CONH), 294 (10, $-CO_2CH_2$), 251 (32, $-CO_2CH_2$, –CONH), 250 (100, $-CO_2CH_2$, $-CONH_2$, or $-CO_2CH_3$, –CONH), 179 (71, PhC≡CPh + H$^+$), 178 (74, PhC=CPh$^+$). Most of the fragments originate *via* McLafferty rearrangements.

Anal. Calcd for $C_{19}H_{16}N_2O_5$: C, 64.77; H, 4.54; N, 7.95; mol wt, 352. Found: C, 64.7; H, 4.7; N, 7.7.

Alkaline Hydrolysis of Diester 2a.—A solution of 350 mg (1.0 mmol) of a 3:2 mixture of meso/*dl* isomer **2a** in a mixture of 9 ml of acetone and 4 ml of 1 *N* aqueous NaOH was kept for 1 hr at 50°. After acidification with 2 *N* hydrochloric acid followed by chloroform extraction there was obtained 310 mg of a mixture of *dl*- and *meso*-2,3-diphenylsuccinonitrile[52] (**10**), mp 141–232°. Crystallization from methanol gave pure meso dinitrile **10**, mp 240° (reported 240°;[53] mmp 240° with an authentic sample from Aldrich Chemical Co.). The nmr spectrum of the reaction mixture showed two singlets at δ 4.81 and 4.84 ppm (tertiary H), while the methyl ester protons at δ 3.78 and 3.92 ppm were absent.

Hydrolysis of Dimer 4a by the Cu–Amine Catalyst.—To a solution of 3.16 g (10 mmol) of dimer **4a** in 30 ml of chloroform there was added 5.00 g (11 mmol) of Cu_2Cl_2–TMEDA and 5.00 g of $MgSO_4$. The reaction mixture was shaken for 1 hr under nitrogen at 50°. The reaction mixture was filtered and washed with 2 *N* hydrochloric acid and water. After the usual work-up there was obtained 3.02 g of a yellow syrup. Crystallization from methanol yielded 0.80 g (35%) of *trans*-α,α′-dicyanostilbene: mp 158–160° (reported mp 160–161°[54]); ir ($CHCl_3$) 2210 cm^{-1} (CN), no C=O; nmr only aromatic H.

When dimer **2a** was treated identically, it remained unchanged as shown by tlc.

Rate Measurements of the Meso → *dl* Conversion of Dimers 2a and 2b.—The nmr measurements were carried out as follows. A 5% solution of one pure isomer was placed in a nmr tube which was then evacuated and sealed under nitrogen. The nmr spectra were then run at regular time intervals (from 20 sec to 3 min) at various temperatures. A *k* value was calculated[43] from 20 to 25 measurements (see Table IV). The equilibrium was approached from both directions.

Reaction of Dimer 2b with DPPH (Diphenylpicrylhydrazyl).—A solution of 380 mg (1 mmol) of dimer **2b** and 790 mg (2 mmol) of DPPH in 40 ml of acetonitrile was stirred at 80° under nitrogen for 2 hr. Evaporation under reduced pressure left 1.06 g of a solid. Recrystallization from ethanol gave material which melted at 106.5–109°.

Anal. Calcd for $C_{29}H_{22}N_6O_8$: C, 59.8; H, 3.78. Found: C, 59.3; H, 3.79.

Reaction of Dimer 2b with Thiophenol.—A solution of 100 mg of dimer **2b** in 1 ml of thiophenol was heated in an nmr tube at 100°. After 1.5 hr the reaction mixture was completely converted into a mixture of methyl *p*-tolylcyanoacetate (**1b**) and diphenyl disulfide as shown by the nmr spectrum (disappearance of methyl ester singlets of **2b** at δ 3.78 and 3.91 ppm; appearance of methyl ester singlet of **1b** at δ 3.70 ppm) and by glc comparison with authentic samples.

Partial Oligomerization of Diester 2a in Refluxing Chlorobenzene.—A solution of 300 mg (0.86 mmol) of diester **2a** (mixture of diastereoisomers, mp 150–170°) in 1.5 ml of chlorobenzene (redistilled, bp 129–132°) was refluxed for 1 hr under nitrogen in an oil bath. After cooling there was added *n*-hexane until the solution turned slightly turbid (3–4 ml). After one night at room temperature there was obtained by filtration 146 mg (49%) of slightly yellow crystals, mp 161–169°. Tlc showed two badly separated spots at R_f 0.32 and 0.27, corresponding to dimer. The mother liquor showed two additional spots, a medium one at R_f 0.10 (trimer) and a very weak one at R_f 0.03 (tetramer).

A solution of 400 mg of diester **2a** in 2 ml of chlorobenzene was refluxed for 2 hr under nitrogen. Evaporation *in vacuo* followed by crystallization of the residue (overall composition, see Table V) from 5 ml of methanol gave 16 mg of slightly yellow crystals, mp 190–192°. Concentration of the mother liquor afforded 12 mg of product, mp 150–175°.

Gpc of the first crop showed the presence of about 5% dimer, 75% trimer, and 20% tetramer. Tlc showed mainly trimer (R_f 0.16): nmr ($CDCl_3$, corresponding to structure **15a**, $a = 1$, $b = 0$) δ 3.88 (s, 3, OCH_3), 3.92 (s, 6, $2OCH_3$, ester groups of *dl* succinic ester part), 7.17 (m, 14), *no* singlet at 4.7–4.8 ppm (tertiary H).

Oligomerization of Diester 2a at 172° in Bulk.—A bulb-to-bulb distilling apparatus was charged with 401 mg (1.15 mmol) of diester **2a** (mixture of diastereoisomers, mp 150–152°). The distilling bulb was then heated for 3 hr at 172–174° (0.4 mm).

At first the diester **2a** melted, followed by resolidification (transformation into *dl* isomer). Mainly during the first 30 min a total amount of 112 mg (28%) of methyl phenylcyanoacetate (**1a**) distilled over (identified with ir). After 3 hr there was obtained 45 mg (11%) of colorless sublimate, mp 150–160°, identical with the *dl* diester **2a** as shown by nmr and tlc (R_f value 0.29). The residue consisted of a yellow brown glassy resin (244 mg, 61%). Tlc of this resin showed separate spots at R_f 0.09 (trimer), 0.05 (tetramer), and a heavy spot at R_9 0.01 (pentamer). Gpc of the resin showed the presence of about 10% trimer, 30% tetramer, and 60% pentamer. Nmr ($CDCl_3$, corresponding to a

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mixture of **14**, $n = 4$ and 5) showed ester OCH_3 signals at δ 3.68, 3.87, and 3.92 ppm; and tertiary H at δ 4.72 (s, 7.2% relative to the OCH_3 signals; calcd 8.3% for tetramer **14a** and 6.3% for pentamer **14a**).

Oxidative Oligomerization of Cyanamide 5d.—To a solution of 4.56 g (20 mmol) of cyanamide **5d** (mp 128.9–130.1°) in 120 ml of acetone there was added 3.6 g of $KMnO_4$ followed by 40 ml of concentrated ammonia. After stirring for 1 hr the mixture was acidified with 4 *N* hydrochloric acid and the MnO_2 was dissolved by the addition of $Na_2S_2O_3$. Chloroform extraction gave 4.2 g of a noncrystallizable foam, the gpc and nmr analysis of which corresponds with **14d** (n = 6–8).

Oxidation of **5d** in $CHCl_3$ at 20° with O_2 and Cu_2Cl_2–TMEDA as a catalyst and $MgSO_4$ as anhydrant gave an oxygen uptake of 0.5 mol/mol of **5d** in 45 min. The oxygen uptake time curve did not show a discontinuity at the oxygen amount required for oxidative C–C coupling (0.25 mol of O_2/mol of **5d**). A similar mixture of oligomers **14d** was obtained in 93% yield: gpc (oxidized with $KMnO_4$) found $\overline{M}_n = 1500$ $\overline{M}_w = 2100$ $\overline{M}_v = 2000$; nmr ($CDCl_3$) ratio of aromatic protons/CH_2 protons, found 0.41 [calcd 0.50 for monomer and C–C dimer, 0.433 for the trimer, 0.413 for the hexamer, and 0.400 for the polymer (based on structure **14d**)].

Registry No.—**1a**, 30698-30-7; **1b**, 30698-31-8; **1c**, 30758-60-2; **1d**, 30698-32-9; **1e**, 30698-33-0; **2a′**, 30698-34-1; *meso*-**2a**, 30698-35-2; *dl*-**2a**, 30698-36-3; *meso*-**2b**, 30698-37-4; *dl*-**2b**, 30698-38-5; *meso*-**2c**, 30698-39-6; *dl*-**2c**, 30698-40-9; *meso*-**2d**, 30698-41-0; *dl*-**2d**, 30698-42-1; *meso*-**2e**, 30698-43-2; *dl*-**2e**, 30698-44-3; **3a**, 4468-48-8; **3b**, 27243-91-0; **3c**, 5415-07-6; *meso*-**4a**, 30698-48-7; *dl*-**4a**, 30698-49-8; *meso*-**4b**, 30698-50-1; *dl*-**4b**, 30698-51-2; **5a**, 30698-52-3; **5b**, 30698-53-4; **5c**, 30698-54-5; **5d**, 1440-29-5; **6a**, 30758-62-4; **6b**, 30698-55-6; **6c**, 30698-56-7; *meso*-**7**, 30698-57-8; *dl*-**7**, 30698-58-9; **8**, 30698-59-0; **9**, 30698-60-3; **14a** ($n = 4$), 30698-61-4; **14a** ($n = 5$), 30698-62-5; **15a** ($a = 1$; $b = 0$), 30698-63-6; $[Cu(OH)(TMEDA)]_2Cl_2$, 30698-64-7; DPPH monomer, 30698-65-8.

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Asymmetric Reductions. XIV. Reductions of Phenyl Trimethylsilyl Ketone and Phenyl Triphenylsilyl Ketone and Configurational Studies on the Corresponding Carbinols[1]

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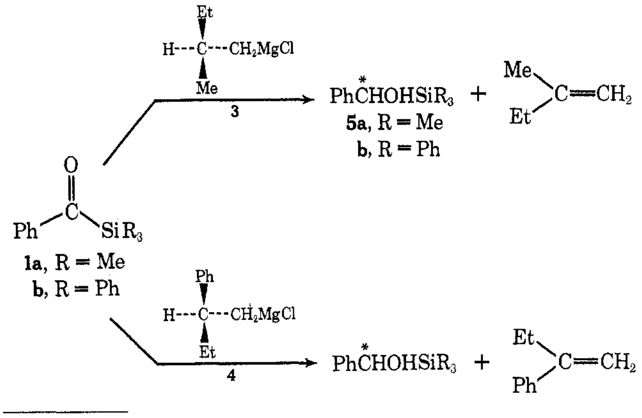
The asymmetric reduction of phenyl trimethylsilyl ketone (**1a**) and phenyl triphenylsilyl ketone (**1b**), by the Grignard reagent **3** from (*S*)-(+)-1-chloro-2-methylbutane, gave the corresponding (*R*)-phenylsilylcarbinols **5a** and **5b** in 3.1 and 10.6% enantiomeric excess (% ee), respectively. Reduction of the same two silyl ketones by the Grignard reagent **4** from (*S*)-(+)-1-chloro-2-phenylbutane gave the corresponding *S* carbinols in 33 and 13.7% ee, respectively. These results are rationalized in terms of steric and electronic interactions in competing six-membered transition states for the hydrogen transfer step and are compared with the results from the reduction by the same chiral reagents of the corresponding carbon ketones. The configurational assignments of these silyl carbinols are consistent with the results from the asymmetric reductions, with the ORD and CD spectra, with application of the Freudenberg rule of shifts to the benzoate and *p*-bromobenzoate derivatives but were not in accord with Horeau's kinetic resolution method.

We sought to extend our studies on asymmetric reductions[3] to include more groups which possessed C_{3v} symmetry. This has led to an investigation of the asymmetric reduction of phenyl trimethylsilyl ketone[4a] (**1a**) and phenyl triphenylsilyl ketone[4b] (**1b**). The corresponding carbon compound phenyl *tert*-butyl ketone (**2a**) had been investigated previously but phenyl trityl ketone[3,5] (**2b**) had not and is included in the present study.

Since α-silyl ketones are readily reduced by Grignard reagents with the requisite β hydrogen, by virtue of their exceptionally polar carbonyl function,[4a,6] they are well suited to such a study. These two silyl ketones **1a** and **1b** were each reduced by the chiral Grignard reagents **3** and **4** from (*S*)-(+)-1-chloro-2-methylbutane and (*S*)-(+)-1-chloro-2-phenylbutane, respectively.



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[1] We acknowledge with gratitude support of these studies by the National Science Foundation, NSF GP 9432.

[2] From the Ph.D. thesis of M. S. Biernbaum, Stanford University, Aug 1970.

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