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New Synthetic Method of [2.2]Cyclophanes via Diselena[3.3]cyclophanes

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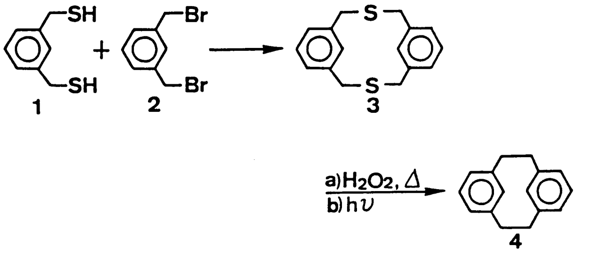
Syntheses of cyclic diselenides through diselenolates and the following deselenation reactions by means of three ways were studied. The preparation of the cyclic diselenides in the presence of excess sodium borohydride gave thirty-eight diselenides containing diselena[3.3]cyclophanes and alicyclic diseleno compounds in high yields in addition to two triple-bridged selenacyclophanes. Photodeselenation of the diselenides in tris(dimethylamino)phosphine afforded series of [2.2]cyclophanes in much higher yields than those of the other two methods, i.e. benzyne-Stevens rearrangement/Raney nickel hydrogenolysis and pyrolytic deselenation at ca. 650 °C. The present study demonstrates that the photodeselenation method, combined with the synthesis of their precursor diselenides, is much superior to the conventional dechalcogenation methods.

The chemistry of cyclophanes has been drastically developed by the emergence of the synthetic methods via various types of desulfurizations of dithia cyclophanes.[1] Especially, pyrolysis of disulfones has been appreciated to be very useful for the preparation of [2.2]cyclophanes.[2] Organoseleniums are also expected to be applicable to the synthesis of cyclophanes in place of the corresponding organosulfur compounds because C–Se bonds undergo more easily bond fission both thermally and photochemically than the corresponding C–S bonds.



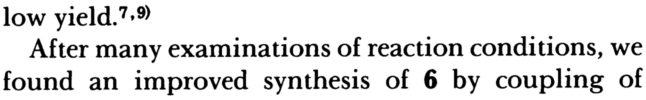
In fact, bis(arylmethyl) selenide and diselenide thermally decomposed with extrusion of elemental selenium to give 1,2-diarylethane.[3] Recently, we reported flash vacuum pyrolysis of a series of dibenzyl selenides and diselenides at 600 °C to give bibenzyl derivatives in high yields[4,5] and the formation (23% yield) of [2.2]paracyclophane by a similar pyrolytic way of 1,4-bis(phenylselenomethyl)benzene.[5,6] An attempt to synthesize cyclophanes via diselenacyclophanes was carried out first by Mitchell but it gave a low yield of [2.2]metacyclophane derivative.[7]

The bibenzyl formation by thermal selenium extrusion stimulated us to develop general synthetic methods for [2.2]cyclophanes via diselena[3.3]cyclophanes.

After various examinations on reaction conditions, we found a general synthesis of diselenacyclophanes in high yields by reductive coupling of bisselenocyanate and dihalide.[8] Here we report general synthetic methods of a variety of [2.2]cyclophanes from diselena[3.3]cyclophanes by a few deselenation ways, i.e. (a) benzyne-Stevens rearrangement/hydrogenolysis, (b) photodeselenation with tris(dimethylamino)phosphine, and (c) flash pyrolysis under reduced pressure.

Results and Discussion

Selenacyclophanes: Synthesis and Properties. Dithia[3.3]cyclophane, a good precursor of [2.2]cyclophane, is generally prepared by coupling of appropriate dithiol and dihalide with potassium hydroxide. On the other hand, diselenol or diselenolate anion is unsuitable to synthesize diselena[3.3]cyclophane **6**, because it is highly air-sensitive under alkaline conditions to give hardly separable diselenide polymer. The first synthesis of **6** was achieved by coupling of dihalide with sodium selenide and by deselenation of tetraselena[4.4]cyclophane with $P(NEt_2)_3$ both in low yield.[7,9]



After many examinations of reaction conditions, we found an improved synthesis of **6** by coupling of bisselenocyanate **5** and dibromide **2** under reductive environment: A mixture of **2** and **5** (1 : 1 ratio) in EtOH–THF is dropwise added to a large excess of $NaBH_4$ in EtOH–THF using high dilution technique.

A wide range of mixing ratio of EtOH–THF is usable as the reaction solvent according to solubilities of reactant and a ratio of 5 : 95 (EtOH–THF) is convenient for the coupling in good yield. A suspension of excess $NaBH_4$ is also effective for high yield of coupling product, by holding the reaction system in reductive condition for suppression of oxidative polymerization.

Table 1. Yields, Melting Points, Crystal Forms, and ^{1}H NMR and Analytical Data of Selenacyclophanes

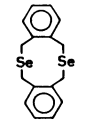
Compound	Yield/%	Mp θ_m/°C	Crystal form (solvent)	^{1}H NMR/δ ($CDCl_3$)	Found/% (Calcd) C	H	MS
6	85	120—122 121—122[c]	Prism (hex.[a])	3.78(s, 8H, CH_2), 6.46(s, 2H, inner ArH), 7.04(m, 6H, ArH)	52.31 (52.46)	4.23 (4.37)	368 (M^+)
7	83	201—202 201—202[d]	Needle (CH_2Cl_2-C_6H_6)	3.66(s, 8H, CH_2), 7.25—7.50(m, 8H, ArH)	52.74 (52.46)	4.37 (4.37)	368 (M^+)
8	78	129—130	Needle (C_6H_6-hex.[a])	3.31(s, 4H, CH_2), 3.66(s, 4H, CH_2), 6.00(bs, 1H, inner ArH), 7.14—7.82(m, 7H, ArH)	52.21 (52.46)	4.41 (4.37)	368 (M^+)
9	81	168—170	Needle (C_6H_6)	3.57(s, 4H, CH_2), 3.94(s, 4H, CH_2), 5.61(bs, 1H, inner ArH), 6.98(s, 4H, ArH), 6.87—7.16 (m, 3H, ArH)	52.35 (52.46)	4.62 (4.37)	368 (M^+)
10	73	214—215	Prism (CH_2Cl_2-C_6H_6)	3.89(s, 8H, CH_2), 6.84(s, 8H, ArH)	52.16 (52.46)	4.70 (4.37)	368 (M^+)
11	78	183—189	Prism (CH_2Cl_2-C_6H_6)	2.98(bs, 8H, CH_2), 3.36, 3.67 (ABq, 4H, $SeCH_2$), 3.71(bs, 4H, $SeCH_2$), 5.25(br, 1H, ArH), 6.23(s, 2H, ArH), 6.41, 6.62 ($A_2'B_2'$m, 4H, ArH), 6.65—6.95 (m, 3H, ArH)	63.18 (62.90)	5.18 (5.24)	498 (M^+)
12	68	182—184	Pale yellow Prism (C_6H_6)	2.34—3.44(m, 8H, CH_2), 3.29 (s, 4H, $SeCH_2$), 3.52, 3.83(ABq, 4H, $SeCH_2$), 5.37(bs, 1H, ArH), 5.87(s, 2H, ArH), 6.32, 6.49 ($A_2'B_2'$m, 4H, ArH), 6.75—6.98 (m, 3H, ArH)	63.08 (62.90)	5.11 (5.24)	498 (M^+)
13	74	177—179	Prism (C_6H_6-hex,[a])	2.42—3.38(m, 8H, CH_2), 3.59, 3.82(ABq, 4H, $SeCH_2$), 3.76(bs, 4H, $SeCH_2$), 5.75(s, 2H, ArH), 6.22, 6.44($A_2'B_2'$m, 4H, ArH), 6.63, 6.67($A_2'B_2'$m, 4H, ArH)	63.23 (62.90)	5.31 (5.24)	498 (M^+)
14[b]	30	>212 (decomp)	Needle (CH_2Cl_2-C_6H_6)	2.24—3.26(m, 16H, CH_2), 3.47, 3.72(ABq, 8H, $SeCH_2$), 5.53(s, 4H, ArH), 6.16, 6.37($A_2'B_2'$m, 8H, ArH)	68.77 (69.01)	5.67 (5.75)	628 (M^+)
15[b]	34	>204 (decomp)	Column (CH_2Cl_2-C_6H_6)	2.29—3.37(m, CH_2, 16H), 3.45, 3.82(ABq, 8H, $SeCH_2$), 5.58(s, 4H, ArH), 6.18, 6.36($A_2'B_2'$m, 8H, ArH)	68.59 (69.01)	5.65 (5.75)	628 (M^+)
16[b]	27	194—198 >190 (decomp)[e]	Powder (C_6H_6-hex.[a])	2.56—3.18(m, 16H, CH_2), 3.42, 3.92(ABq, 8H, $SeCH_2$), 5.78(s, 4H, ArH), 6.24, 6.47($A_2'B_2'$m, 8H, ArH)	68.89 (69.01)	5.58 (5.75)	628 (M^+)
17[b]	36	235—241 (decomp) >235 (decomp)[e]	Needle (CH_2Cl_2-C_6H_6)	2.08—2.82(m, 8H, CH_2), 2.90 (bs, 8H, CH_2), 3.36(s, 8H, $SeCH_2$), 6.15(s, 4H, ArH), 6.29, 6.46($A_2'B_2'$m, 8H, ArH)	68.75 (69.01)	5.38 (5.75)	628 (M^+)
18	80	204—208	Needle (THF)	4.06, 4.74(ABq, 8H, CH_2), 6.30 (s, 4H, NapH), 7.58—7.63(m, 4H, NapH), 8.08—8.14(m, 4H NapH)	61.60 (61.81)	4.61 (4.32)	468 (M^+)
19	41	203.5—204.5	Prism (C_6H_6)	4.01(s, 8H, CH_2), 7.00(s, 4H, NapH), 7.16(bs, 8H, NapH)	61.66 (61.81)	4.23 (4.32)	468 (M^+)

Table 1. (Continued)

Compound	Yield/%	Mp θ_m/°C	Crystal form (solvent)	^{1}H NMR/δ ($CDCl_3$)	Found/% (Calcd)		MS
					C	H	
20	77	139—144	Prism (C_6H_6)	3.83, 4.01(ABq, 4H, CH_2), 4.21, 4.36(ABq, 4H, CH_2), 6.36(m, 2H, ArH), 6.70(s, 2H, NapH), 6.86(m, 2H, ArH), 7.47—7.57 (m, 2H, NapH), 8.00—8.10 (m, 2H, NapH)	57.61 (57.71)	4.29 (4.36)	418 (M$^+$)
21	98	207—209.5	Prism (C_6H_6)	3.46, 3.69(ABq, 4H, CH_2), 4.35 (s, 4H, CH_2), 5.57(bs, 1H, inner ArH), 6.48(t, 1H, ArH, 6.65(d, 2H, ArH), 7.22(s, 2H, NapH), 7.33—7.37(m, 2H, NapH), 8.01—8.04(m, 2H, NapH)	57.66 (57.71)	4.37 (4.36)	418 (M$^+$)
22	79	162.5—163.5	Prism (C_6H_6-hex.[a])	3.74(s, 2H, CH_2), 4.00(s, 6H, CH_2), 5.75(d, 1H, NapH), 7.09 (s, 4H, ArH), 7.35—7.47(m, 3H, NapH), 7.63—7.75(m, 2H, NapH)	57.53 (57.71)	4.51 (4.36)	418 (M$^+$)
23	81	126—127.5	Column (C_6H_6-hex.[a])	3.79(bs, 2H, CH_2), 3.84(bs, 2H, CH_2), 3.88(bs, 2H, CH_2), 4.17 (bs, 2H, CH_2), 6.21(bs, 1H, inner ArH), 6.64(bs, 1H, inner NapH), 7.06—8.04(m, 8H, ArH and NapH)	57.71 (57.71)	4.39 (4.36)	418 (M$^+$)
24	67	>256 (decomp)	Column (C_6H_6)	3.91(s, 12H, CH_2), 6.90(s, 6H, ArH)	46.10 (45.88)	3.90 (3.85)	474 (M$^+$)
25	55	>230 (decomp)	Column (C_6H_6-hex.[a])	3.41—4.04(m, 12H, CH_2), 5.92 (bs, 1H, ArH), 6.91(d, 1H, ArH), 7.07(bs, 1H, ArH), 7.08 (d, 1H, ArH), 7.22(bs, 2H, ArH)	45.75 (45.88)	3.73 (3.85)	474 (M$^+$)
64[b]	(anti) 10	219—221.5 (decomp)	Prism ($CHCl_3$)	3.30(s, 6H, Me), 3.51, 3.87 (ABq, 8H, CH_2), 7.01(t, 2H, ArH), 7.31(d, 4H, ArH)	50.42 (50.72)	4.73 (4.73)	428 (M$^+$)
	(syn) 51	212—214 (decomp)	Prism ($CHCl_3$)	3.42, 4.57(AMq, 8H, CH_2), 3.55(s, 6H, Me), 6.61(t, 2H, ArH), 6.99(d, 4H, ArH)	50.70 (50.72)	4.96 (4.73)	428 (M$^+$)
66[b]	24	173.5—175	Needle (C_6H_6-hex.[a])	3.77(s, 4H, CH_2), 3.81(s, 6H, Me), 3.82(s, 4H, CH_2), 6.48 (d, 2H, inner ArH), 6.66(d, 2H, ArH), 7.01(dd, 2H, ArH) ^{77}Se NMR −2.76(s)	50.48 (50.72)	4.94 (4.73)	428 (M$^+$)
68[b]	18	151.5—152.5	Prism (C_6H_6-hex.[a])	3.71(s, 4H, CH_2), 3.80(s, 4H, CH_2), 3.81(s, 6H, Me), 6.38 (d, 2H, inner ArH), 6.72(d, 2H, ArH), 7.12(dd, 2H, ArH) ^{77}Se NMR 15.7(s), −33.5(s)	50.73 (50.72)	4.49 (4.73)	428 (M$^+$)

a) Hexane. b) Pairs of selenacyclophanes (**14** and **15**, **16** and **17**, syn and anti **64**, **66** and **68**) were obtained at the same time by appropriate coupling reaction. The structure of **66** and **68** was determined by ^{77}Se NMR measurement. c) Ref. 7. d) Ref. 5. e) Ref. 11.

Table 1 shows yields of a variety of selena[3^n]cyclophanes including triple-bridged compounds. This method is convenient to prepare unsymmetrical diselenacyclophanes as well as symmetrical ones and easy to purify the product because tedious polymer is not formed. The yields of such selenacyclophanes are much higher than those of the corresponding thiacyclophanes,[10] just as multilayered ones and triple-bridged ones. For example, triselena[3^3](1,3,5)-cyclophane **24** is afforded in a good yield by more than 10 times that (5.3% yield) of the corresponding trithiacyclophane.[10m] Two pairs of isomeric quadru-



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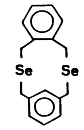

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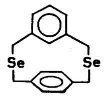

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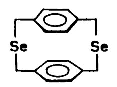

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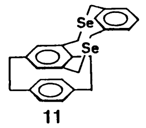

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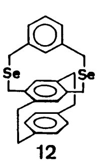

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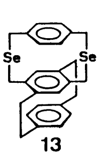

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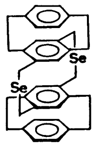

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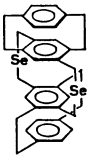

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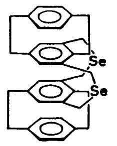

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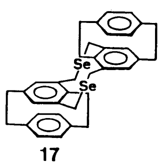

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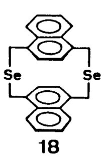

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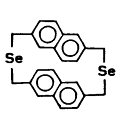

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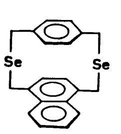

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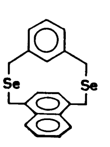

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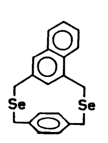

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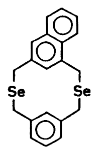

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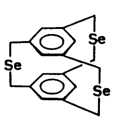

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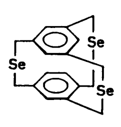

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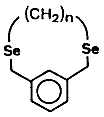

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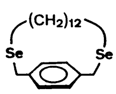
n=5,6,7,8,10



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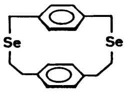

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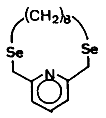

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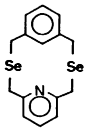

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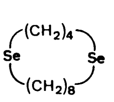

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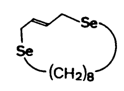

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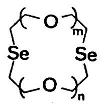
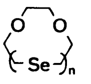


33 a: m=n=1
b: m=1, n=2
c: m=n=2

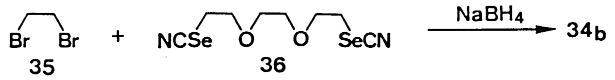


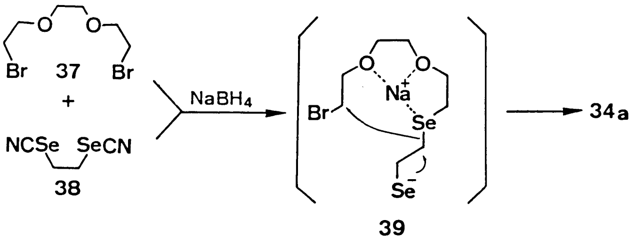
34 a: n=1
b: n=2

ple-layered selenacyclophanes (**14** and **15**; **16**[11] and **17**[11]) are obtained as a mixture of about 1 : 1 isomeric ratio and separated by silica-gel column chromatography.

It is not clear whether 2,11-diselena[3.3]metacyclophane **6** consists of an equilibrating mixture of syn- and anti-conformers in solution at room temperature,[12] whereas the corresponding dithiacyclophane **3** exists only in syn-conformer in both solid state and solution.[13] A conformational equilibrium is expected from molecular model examination also for triple-layered diselenacyclophane **11** and diselenanaphthalenometacyclophane **23**, both of which contain the partial structure, diselena[3.3]metacyclophane. On the basis of ^{1}H NMR data, that is, the chemical shifts of the inner aromatic protons and the coupling pattern of bridge methylene protons, cyclophane **23** is in similar equilibrium, while cyclophane **11**, on the contrary, exists as anti-conformer only.[14] A reasonable explanation for the predominance of anti-conformer is steric repulsion among vicinal three methylenes attached to the inner benzene ring. Both of symmetrical naphthalenophanes, **18** and **19**, exist only in one of two conformers, and the structure of **18** is confirmed to be antiform by comparison of its ^{1}H NMR spectrum with that of the corresponding dithia[3.3]naphthalenophane.[10g]

Diselena[m]cyclophanes (**26** and **27**), diselenapyridinophanes (**29** and **30**), alicyclic diselenides (**31** and **32**), and diselenocrown ethers (**33** and **34**) are similarly prepared in good yields as shown in Table 2. 2,13-Diselena[4.4]paracyclophane **28** is prepared by two ways, i.e. couplings of 1,4-bis(bromoethyl)benzene with 1,4-bis(cyanoselenatomethyl)benzene in 38% yield and of 1,4-bis(2-cyanoselenatoethyl)benzene with 1,4-bis(bromomethyl)benzene in 77% both in the presence of NaBH$_4$. The difference in the yields suggests a preferable S$_N$2 substitution of bromine at benzyl position by selenolate anion. On the other hand, coupling reactions of two pairs of dibromides and diselenocyanates, i.e. **35**+**36** and **37**+**38**, unexpectedly give different selenocrown compounds, **34b** and **34a**, respectively. The formation of unusual ring-contracted compound **34a** seems reasonable to assume a template effect of sodium ion in an intermediate **39**. Similar ring contractions were observed in cyclizations of polythioethers.[15]





The structures of all selenacyclophanes were determined by MS and ^{1}H NMR spectra and elemental analyses as shown in Table 1.

Syntheses of Cyclophanes by Deselenation: Desulfurization of polythia[3^n]cyclophanes to [2^n]cyclophanes has usually been carried out by i) Stevens or Wittig rearrangement and the following Raney Ni hydrogenolysis, ii) irradiation in the presence of P(OR)$_3$, and iii) oxidation to the corresponding sulfone and the following pyrolytic desulfonation. Selenium extrusion reactions are carried out by modifying the above-stated desulfurization methods. A series of [2^n]cyclophanes are obtained from polyselena[3^n]cyclophanes by three methods, (A)—(C), as follows:

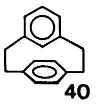
(A) Benzyne-Stevens rearrangement/hydrogenolysis,

(B) Photodeselenation with tris(dimethylamino)phosphine P(NMe$_2$)$_3$,

Table 2. Yields, Mp's, Crystal Forms, and ^{1}H NMR and Analytical Data of Cyclic Selenides

Compound	Yield/%	Mp θ_m/°C	Crystal form (solvent)	^{1}H NMR/δ (CDCl$_3$)	Found/% (Calcd)			MS
					C	H	N	
26 $n=5$	48	>135	Solid (hex.[a])	1.21—1.25(m, 6H, CH$_2$), 2.28 (t, 4H, SeCH$_2$), 3.78(s, 4H, SeCH$_2$), 7.14—7.31(m, 4H, ArH)	46.94 (46.99)	5.75 (5.47)		334 (M$^+$)
$n=6$	Quant.	80—83.7	Solid (pentane)	1.20—1.56(m, 8H, CH$_2$), 2.44 (t, 4H, SeCH$_2$), 3.74(s, 4H, SeCH$_2$), 7.16—7.23(m, 4H, ArH)	48.46 (48.56)	5.92 (5.83)		348 (M$^+$)
$n=7$	Quant.	66.5—72.5	Solid (pentane)	1.10—1.60(m, 10H, CH$_2$), 2.46 (t, 4H, SeCH$_2$), 3.72(s, 4H, SeCH$_2$), 7.04—7.29(m, 4H, ArH)	49.88 (50.00)	6.45 (6.17)		362 (M$^+$)
$n=8$	87	38—43	Semisolid	1.13—1.57(m, 12H, CH$_2$), 2.46 (t, 4H, SeCH$_2$), 3.69(s, 4H, SeCH$_2$), 7.16(bs, 4H, ArH)	51.49 (51.34)	6.73 (6.48)		376 (M$^+$)
$n=10$	53	Colorless oil		1.28—1.73(m, 16H, CH$_2$), 2.46 (t, 4H, SeCH$_2$), 3.73(s, 4H, SeCH$_2$), 7.14—7.25(m, 4H, ArH)	53.79 (53.74)	6.91 (6.48)		404 (M$^+$)
27	79	104—108	Needle (C$_6$H$_6$-hex.[a])	0.95—1.76(m, 20H, CH$_2$), 2.48 (t, 4H, SeCH$_2$), 3.74(s, 4H, SeCH$_2$), 7.19(s, 4H, ArH)	55.62 (55.81)	7.28 (7.44)		432 (M$^+$)
28	77 (38)	152—155	Needle (C$_6$H$_6$)	2.63—3.01(A$_2$B$_2$m, 8H, CH$_2$), 3.46(s, 4H, SeCH$_2$), 6.78(s, 4H, ArH), 6.83(s, 4H, ArH)	55.06 (54.82)	5.22 (5.08)		396 (M$^+$)
29	78	101—102	Needle (hex.[a])	1.27—1.75(m, 12H, CH$_2$), 2.63 (t, 4H, SeCH$_2$), 3.81(s, 4H, SeCH$_2$), 7.15—7.64(m, 3H, PyH)	47.96 (48.00)	6.33 (6.13)	3.81 (3.73)	377 (M$^+$)
30	93	168—168.5	Prism (C$_6$H$_6$-hex.[a])	3.91(s, 4H, CH$_2$), 3.99(s, 4H, CH$_2$), 6.89—7.35(m, 6H, ArH and PyH), 7.06(bs, 1H, inner ArH)	48.88 (49.05)	4.07 (4.09)	3.88 (3.81)	369 (M$^+$)
31	70	47—48	Solid (hex.[a])	1.40—1.87(m, 16H, CH$_2$) 2.54—2.68(dt, 8H, SeCH$_2$)	43.92 (44.17)	7.18 (7.33)		328 (M$^+$)
32	80	48—53	Solid (pentane)	1.24—1.68(m, 12H, CH$_2$), 2.57 (t, 4H, SeCH$_2$), 3.13—3.19(m, 4H, allylic H), 5.52—5.64(m, 2H, olefinic H)	44.22 (44.44)	6.61 (6.78)		326 (M$^+$)
33 a: $m=n=1$	60	Colorless oil		2.87(t, 8H, SeCH_2CH$_2$O), 3.85(t, 8H, SeCH$_2\mathit{CH}_2$O)	31.80 (31.78)	5.50 (5.30)		304 (M$^+$)
b: $m=1$ $n=2$	78	Colorless oil		2.74—2.93(m, 8H, SeCH$_2$), 3.64(s, 4H, OCH$_2$CH$_2$O), 3.72—3.90(m, 8H, OCH$_2$)	34.61 (34.68)	5.85 (5.78)		348 (M$^+$)
c: $m=n=2$	85	98—99.5	Prism (C$_6$H$_6$-hex.[a])	2.85(t, 8H, SeCH_2CH$_2$O), 3.63(s, 8H, OCH$_2$CH$_2$O), 3.79(t, 8H, SeCH$_2\mathit{CH}_2$O)	37.10 (36.93)	6.19 (6.15)		392 (M$^+$)
34 a: $n=1$	40	Colorless oil		2.90(t, 4H, SeCH_2CH$_2$O), 3.65(s, 4H, OCH$_2$CH$_2$O), 4.10(t, 4H, SeCH$_2\mathit{CH}_2$O)	37.36 (36.93)	6.46 (6.15)		196 (M$^+$)
b: $n=2$	76	Colorless oil		2.76(t, 4H, SeCH_2CH$_2$O), 3.17(s, 4H, SeCH$_2$CH$_2$Se), 3.61(s, 4H, OCH$_2$CH$_2$O), 3.96(t, 4H, SeCH$_2\mathit{CH}_2$O)	31.77 (31.78)	5.57 (5.30)		304 (M$^+$)

a) Hexane.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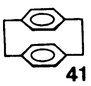
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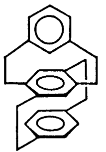
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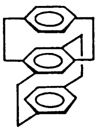
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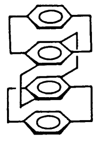
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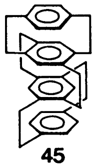
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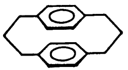
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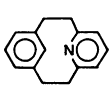
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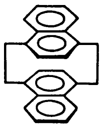
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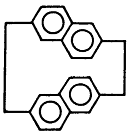
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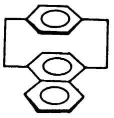
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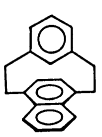
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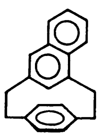
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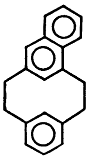
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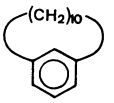

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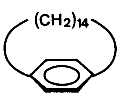

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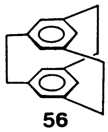
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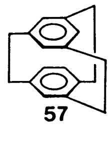
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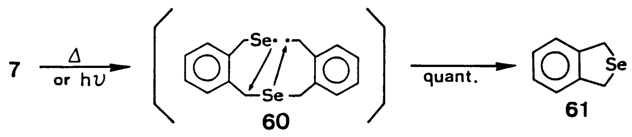
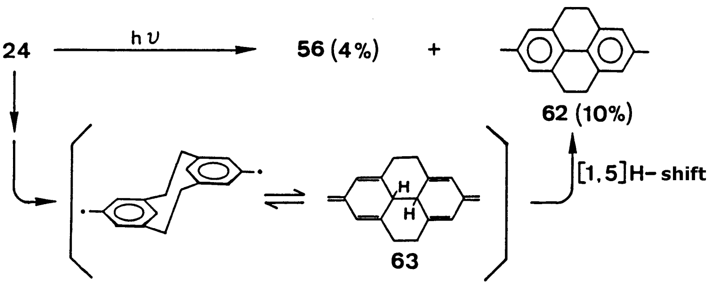
(C) Flash pyrolysis under reduced pressure.

The yields of [2.2]cyclophanes as well as multilayered, naphthaleno-, and pyridino-cyclophanes are shown in Table 3. The table reveals that the benzyne-hydrogenolysis method (A) is obviously superior to the direct extrusion by flash pyrolysis (C) and the yields are comparable to those of the transformation of the corresponding dithiacyclophanes into cyclophanes by benzyne-hydrogenolysis method. Pyrolysis of **28** gives 1,4-divinylbenzene (73% yield) as main product and [2.2]paracyclophane **41**[16] (6%) as a by-product without the desired [3.3]paracyclophane **46**. The reaction seems to proceed via a biradical intermediate **59** which was presumed to generate by pyrolysis of diselenide **58**.[5]

The second method, photodeselenation (B) generally gives higher yield of [2.2]cyclophane than those of the two methods, (A) and (C), as seen in Table 3. Tris(dimethylamino)phosphine is an effective reagent of many well-known reagents for dechalcogenation.[17] The photodeselenation by this reagent proceeds more rapidly than desulfurization with trialkyl phosphite $P(OR)_3$ from the corresponding dithiacyclophane and gives easily separable products. In the case of diselena[3.3]orthometacyclophane, the desired [2.2]-orthometacyclophane is not afforded even by the use of all methods, probably due to highly severe strain predicted in the product. Also, diselena[3.3]orthocyclophane **7**[5] affords quantitative yield of benzoselenophene **61**[5] which may be formed by favorable



intramolecular cyclization of intermediary biradical species **60** into two of the five-membered ring. Both triple-bridged cyclophanes, **56** and **57**, are given in low yield because of more severe strain. Compound **57**, which polymerizes easily at room temperature,[10k,l] is obtained in fairly good yield (11%) at lower temperature in spite of severe strain. On irradiation of triselenacyclophane **24**, an unexpected 2,7-dimethyltetrahydropyrene **62**[10n] is afforded in higher yield (10%) than the normal product **56**[10n] (4%). The formation of **62** is explainable in terms of 1,5-hydrogen shift of transannularly bridged intermediate **63**.



Consequently, Table 3 shows the photodeselenative synthesis of [2.2]cyclophane to be the most useful method compared to the other ones, (A) and (C). This method is particularly convenient for synthesis of para-para series [2.2]cyclophanes such as **41**,[16] **43**,[18] **44**,[18] **45**,[18] **48**,[19] and **50**,[16a] compared to those of meta-para and meta-meta series. Firstly we assume from this finding that the yield of cyclophane may increase with the increase in rigidity of starting diselena[3.3]cyclophane. In order to confirm such an assumption, three isomeric diselena[3.3]metacyclophane derivatives, **64**, **66**, and **68**, were synthesized and subjected to the photodeselenation reaction. The

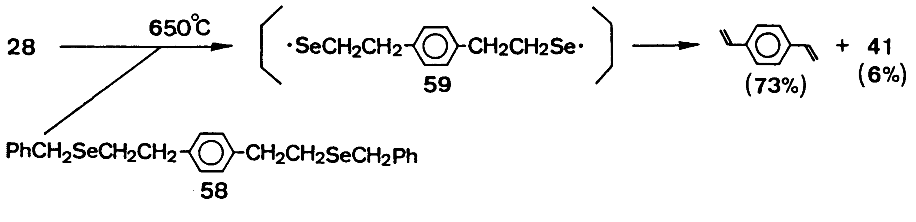


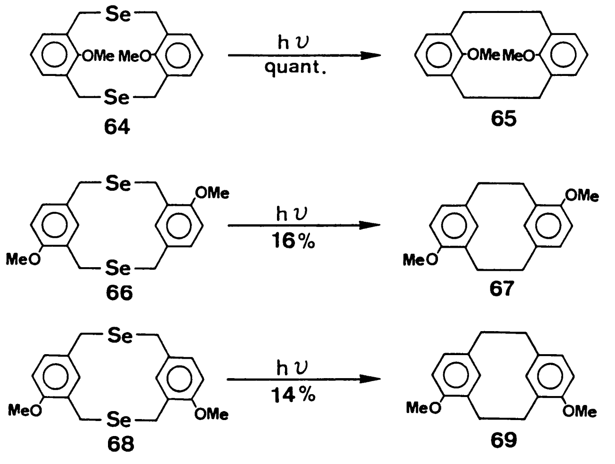
Table 3. Yields by Three Methods, Mp's, Crystal Forms, and ^{1}H NMR, MS, and/or Analytical Data

Compound	Yield/% Method (A) (B) (C)	Mp θ_m/°C	Crystal form (solvent)	^{1}H NMR/δ ($CDCl_3$)	MS and/or analysis
4	49 48 8	 133—134 134.5—135[b]	Prism (hex.[a])	2.08, 2.95(m, 8H, CH_2), 4.16(bs, 2H, inner ArH), 6.90—7.39(m, 6H, ArH)	MS 208 (M^+)
40	42 53 13	 80—81 81—81.5[c]	Plate (hex.[a])	1.96—3.16(m, 8H, CH_2), 5.28(s, 1H, inner ArH), 6.42—6.92(m, 7H, ArH)	MS 208 (M^+)
41	28 93 11	 286—289 285—287[d]	Prism (C_6H_6)	3.06(s, 8H, CH_2), 6.48(s, 8H, ArH)	MS 208 (M^+)
42	37 51 17	 145—146 144—145[e]	Prism (C_6H_6)	1.52—3.62(m, 16H, CH_2) 4.90(s, 1H, ArH of inner benzene), 5.12(bs, 1H, meta inner ArH), 6.17(s, 1H, ArH of inner benzene), 6.24—6.86(m, 7H, ArH)	MS 338 (M^+)
43	26 80 Trace	 >229 (decomp) 230 (decomp)[f]	Plate (C_6H_6-hex.[a])	2.23—3.16(m, 16H, CH_2), 5.40(s, 2H, ArH), 6.07(s, 8H, ArH)	MS 338 (M^+)
44	— 87 —	 >247 (decomp) >250 (decomp)[f]	Prism (C_6H_6)	2.07—3.21(m, 24H, CH_2), 5.12(s, 4H, ArH), 6.01(s, 8H, ArH)	MS 468 (M^+)
45	— 90 —	 >241 (decomp) >240 (decomp)[f]	Needle (hex.[a])	2.08—3.24(m, 24H, CH_2), 5.15(s, 4H, ArH), 5.99(s, 8H, ArH)	MS 468 (M^+)
46	12 None None[g]	 102—103 104.3—105.3[h]	Needle (MeOH)	2.03(m, 4H, CH_2), 2.72(t, 8H, CH_2), 6.66(s, 8H, ArH)	MS 236 (M^+)
47[i]	37 25 17	 >158 (decomp)	Column (hex.[a])	2.23—2.46, 3.08—3.46(m, 8H, CH_2), 4.38(s, 1H, inner ArH), 7.03—7.66(m, 6H, ArH and PyH)	MS 209 (M^+)
48	 — 75 anti : syn	(anti) 295—297 299—301[j]	 Prism (C_6H_6)	3.00—3.75(m, 8H, CH_2), 5.73(s, 4H, NapH), 7.33(m, 4H, NapH), 7.65(m, 4H, NapH)	MS 308 (M^+)
	=9 : 1 —	(syn) 245—245.5 243—245[k]	 Prism (C_6H_6)	3.56(m, 8H, CH_2), 6.72(s, 4H, NapH), 7.15(m, 8H, NapH)	MS 308 (M^+)
49	— 43 —	 365—368 368—369[l]	Needle (C_6H_6-hex.[a])	2.63—3.30(m, 8H, CH_2), 6.44(bs, 4H, NapH), 6.88(dd, 4H, NapH), 7.11(d, 4H, NapH)	MS 308 (M^+)
50	— 78 —	 113—114 114—115[j]	Needle (C_6H_6-hex.[a])	3.03—3.70(m, 8H, CH_2), 5.50(s, 2H, ArH), 6.35(s, 2H, NapH), 6.63(s, 2H, ArH), 7.30(m, 2H, NapH), 7.58(m, 2H, NapH)	MS 258 (M^+)
51	— 78 —	 155.5—156.5	Prism (hex.[a])	2.14—2.34(m, 6H, CH_2), 2.50—2.82(m, 2H, CH_2), 3.96(d, 1H, inner ArH), 6.05(s, 2H, NapH), 6.69—7.12(m, 3H, ArH), 7.50—7.63(m, 2H, NapH), 8.01—8.14 (m, 2H, NapH)	C(%) H(%) Found 93.01 7.13 Calcd 92.98 7.02 MS 258 (M^+)

Table 3. (Continued)

Compound	Yield/% Method (A) (B) (C)	Mp θ_m/°C	Crystal form (solvent)	^{1}H NMR/δ (CDCl$_3$)	MS and/or analysis
52	— 75 —	132—133	Prism (hex.[a])	2.25—2.35(m, 2H, CH$_2$), 2.47—2.55(m, 1H, CH$_2$), 2.73—2.81(m, 1H, CH$_2$), 2.91—2.97(m, 1H, CH$_2$), 3.17—3.23(m, 2H, CH$_2$), 3.48—3.53(m, 1H, CH$_2$), 5.29—5.62(m, 2H, ArH), 5.61(d, 1H, inner NapH), 7.21—7.33(m, 2H, ArH), 7.38—7.45(m, 3H, NapH), 7.72—7.75(m, 1H, NapH), 7.88—7.91(m, 1H, NapH)	C(%) H(%) Found 92.88 6.85 Calcd 92.98 7.02 MS 258 (M$^+$)
53	— 52 —	171—172	Prism (hex.[a])	2.05—2.33(m, 4H, CH$_2$), 3.12—3.30(m, 3H, CH$_2$), 3.97—4.00(m, 1H, CH$_2$), 4.19(bs, 1H, inner ArH), 4.50(bs, 1H, inner NapH), 7.10—7.17(m, 2H, ArH), 7.30—7.34(m, 1H, ArH), 7.45—7.50(m, 2H, NapH), 7.60(bs, 1H, NapH), 7.86—7.88(m, 1H, NapH), 8.09—8.13(m, 1H, NapH)	C(%) H(%) Found 93.02 7.20 Calcd 92.98 7.02 MS 258 (M$^+$)
54	22 — Trace	Colorless oil[m]		0.76—1.38(m, 12H, CH$_2$), 1.55—1.83(m, 4H, CH$_2$), 2.65(t, 4H, CH$_2$), 6.82—7.21(m, 4H, ArH)	MS 216 (M$^+$)
55	11 None Trace	40.5—42 41—42[m]	Powder (pentane)	0.62—1.87(m, 24H, CH$_2$), 2.55—2.69(m, 4H, CH$_2$), 7.04(bs, 4H, ArH)	MS 272 (M$^+$)
56	Trace 4 —	202—204 204—206[n]	Prism (C$_6$H$_6$-CH$_2$Cl$_2$)	2.74(s, 12H, CH$_2$), 5.71(s, 6H, ArH)	MS 234 (M$^+$)
57	— {Trace {11 (−78°C) —	86—88 87—88[o]	Prism (hex.[a])	1.65—3.51(m, 12H, CH$_2$), 5.04(t, 1H, ArH), 5.85(d, 1H, ArH), 6.32 (t, 1H, ArH), 6.61, 6.83(ABq, 2H, ArH), 6.82(d, 1H, ArH)	MS 234 (M$^+$)
65	— {99[p] {89[q] —		Column (hex.[a])	2.59—2.73(m, 8H, CH$_2$), 2.93(s, 6H, Me), 6.87(t, 2H, ArH), 7.05(d, 4H. ArH)	C(%) H(%) Found 80.34 7.45 Calcd 80.56 7.51 MS 268 (M$^+$)
67	— 16 —	193—194 182[r]	Column (hex.[a])	1.66—1.74(m, 2H, CH$_2$), 2.02—2.10(m, 2H, CH$_2$), 2.94—2.99(m, 2H, CH$_2$), 3.52—3.58(m, 2H, CH$_2$), 3.85(s, 6H, Me), 4.30(d, 2H, inner ArH), 6.84(d, 2H, ArH), 7.04(dd, 2H, ArH)	C(%) H(%) Found 80.84 7.63 Calcd 80.56 7.51 MS 268 (M$^+$)
69	— 14 —	145—146 132—134[r]	Column (MeOH)	1.68, 3.52(AX, 4H, CH$_2$), 2.06, 2.99(AX, 4H, CH$_2$), 3.86(s, 6H, Me), 4.29(d, 2H, inner ArH), 6.83 (d, 2H, ArH), 7.02(dd, 2H, ArH)	C(%) H(%) Found 80.47 7.36 Calcd 80.56 7.51 MS 268 (M$^+$)

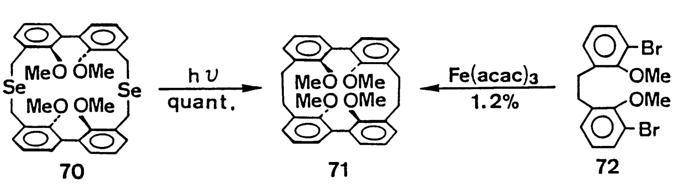
a) Hexane. b) K. Burri and W. Jenny, *Helv. Chim. Acta*, **50**, 1978 (1967). c) D. J. Cram, R. C, Helgeson, D. Lock, and L. A. Singer, *J. Am. Chem. Soc.*, **88**, 1324 (1966). d) Ref. 16b. e) Ref. 1d. f) Ref. 18. g) [2.2]-paracyclophane **41** was obtained about 6% yield. h) D. J. Cram, N. L. Allinger, and H. Steinberg, *J. Am. Chem. Soc.*, **76**, 6132(1954). i) J. R. Fletcher and I. O. Sutherland, *J. Chem. Soc., Chem. Commun.*, **1969**, 1504. j) Ref. 16a. k) Ref. 19. l) Ref. 10i. m) T. Otsubo and S. Misumi, *Synth. Commun.*, **8**, 285 (1978); S. Hirano, H. Hara, T. Hiyama, S. Fujita, and H. Nozaki, *Tetrahedron*, **31**, 2219 (1975). n) Ref. 10n. o) Ref. 10k, l. p) From anti **64**. q) From syn **64**. r) Ref. 20.



64 65 66 67 68 69

most rigid isomer **64** (syn and anti) gives similarly rigid anti-dimethoxy[2.2]metacyclophane **65** in quantitative yield, whereas isoelectronically substituted, but flexible isomers, **66** and **68**, afford the corresponding dimethoxymetacyclophanes, **67**[20] and **69**,[20] both in low yield.

Furthermore a typical example for our assumption is deselenation of diselena[3.3]biphenylophane **70** to spherand-like macrocyclic compound **71** which is a rigidly constructed molecule and has a cavity suited to encapsulate selectively lithium ion.[21] In fact, the photodeselenation of **70** proceeds with quantitative yield of **71**, compared to low yield (1.2%) by the previous method. Unfortunately, this photodeselenation method is not suitable for cyclic selenides other than dibenzyl selenide form, e.g. diselenides **27**, **28**, and **32**. Consequently, the present synthetic method of [2.2]cyclophanes by means of the photodeselenation of diselenides demonstrates that this method is much more superior to any other conventional dechalcogenation method reported so far.



70 71 72

Experimental

All melting points are uncorrected. ^{1}H NMR spectra were recorded on a JEOL FX-100 (100 MHz) and Bruker WM360 (360 MHz) spectrometers using chloroform-*d* as a solvent and tetramethylsilane as an internal standard. Phenyl selenocyanate (PhSeCN)[22] was employed as the external standard for ^{77}Se measurement of **66** and **68**. Mass spectra were recorded on a Hitachi RMU-7 spectrometer (70 eV) using the direct injection technique and described here for organoselenium compounds.

General Synthetic Method of Selenides, 6—34, 64, 66, and 68. All selenium compounds were prepared by coupling of di- or tri-halides with bis- or tris-selenocyanates,[4] which were easily obtained by treatment of the corresponding halides with potassium selenocyanate, in the presence of large excess of sodium borohydride. The general procedure will be illustrated below by using the synthesis of 2,11-diselena[3.3]paracyclophane **10** as an example.[8]

A solution of 1,4-bis(selenocyanatomethyl)benzene (1.60 g, 5.1 mmol) and 1,4-bis(bromomethyl)benzene (1.32 g, 5.0 mmol) in 100 ml of ethanol and peroxide-free THF (1:1 v/v) was added to a suspension of an excess of $NaBH_4$ (commercial grade, ca. 2 g) in a mixture (1 l) of ethanol and peroxide-free THF (1:19 v/v) under bubbling Ar with vigorous stirring at 40—50 °C for 13 h. After adding a small amount of ice, the reaction mixture was concentrated to ca. 100 ml. Dichloromethane and water were added to the concentrate and the organic layer was separated, washed with sat. NaCl aq, and dried over anhyd magnesium sulfate. The crude colorless residue obtained by evaporation of the solvent was recrystallized from benzene-dichloromethane to give colorless prisms of diselenaparacyclophane **10** (1.35 g, 73% yield).

In the case of oily products, **26** (*n*=10), **33a—b**, **34**, pale yellow oil obtained by solvent evaporation was purified by gel-permeation liquid chromatography with chloroform.

General Procedures of Deselenation. (A) Benzyne-Stevens Rearrangement/Raney Nickel Hydrogenolysis. To a solution of selenacyclophane (1 mmol) and isopentyl nitrite (2 g) in 1,2-dichloroethane (20 ml) was dropwise added a solution of anthranilic acid (4 mmol, 2 equiv.) in dichloromethane (20 ml) with vigorous stirring at reflux for more than 4 h under a nitrogen atmosphere. After removal of the solvent, the residue was chromatographed on silica gel with carbon tetrachloride or benzene to give a pale yellow solid or semisolid. A suspension of this rearranged product and Raney Ni (W-2, ca. 1 g) in ethanol (50 ml) was stirred at gentle reflux for 17—23 h under hydrogen. Worked up the mixture, a semisolid residue was chromatographed on silica gel with benzene-hexane to give cyclophane in a yield shown in Table 3.

(B) Photodeselenation with Tris(dimethylamino)phosphine. A solution of selenacyclophane (50—100 mg) and excess tris(dimethylamino)phosphine (1—1.5 g) in peroxide-free THF (30—80 ml) was irradiated with a 400 W high-pressure mercury lamp at room temperature under bubbling nitrogen until the starting material consumed completely. The residue obtained by solvent evaporation was chromatographed on silica gel with benzene-hexane or purified by gel permeation liquid chromatography to give cyclophane as shown also in Table 3. All of the cyclophanes described in Table 3 were identified by comparison of their ^{1}H NMR spectra, other physical properties and/or elemental analyses.

(C) Flash Pyrolysis under Reduced Pressure. A pyrex tube closed at one end, 45 cm long and 1 cm diameter, was used for pyrolysis. A sample (ca. 100 mg) of selenacyclophane was placed at the closed end of the tube. The other end was connected to a vacuum system (1—5 mmHg (1 mmHg=133.322 Pa)) and cooled with Dry Ice or liq. nitrogen. The middle part was placed in an electric furnace (25 cm long) preheated at 650 °C. After heating for ca. 3 min, the sample part was slidden within the furnace. Pyrolysis immediately occurred and the pyrolysate condensed at the cooled part. The organic products were extracted with dichloromethane and purified by gel permeation liquid chromatography (Nihon Bunseki Kogyo LC-08) with chloroform or column chromatography on silica gel with benzene–hexane to give cyclophane as shown also in Table 3.

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