tallized from 95% ethanol yielding 167 mg. (90%) of yellow-orange leaflets, m.p. 304–305°. The reported value[9] for benzo[b]acridone made in another manner is 303°.

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Reactions of Carbon Monoxide with Thiols, Sulfides, and Disulfides

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The literature on reactions of carbon monoxide with thiols is limited to those in which either acetylene[1] or an olefin[2] is present as a third component. The products are the thiol esters of the carbonylated unsaturate. There are no accounts of the direct reaction of carbon monoxide with thiols or their derivatives.

We now wish to report that carbon monoxide reacts with thiols, disulfides, and sulfides to give thiol esters in accordance with Equations 1–3 in the presence of a cobalt carbonyl catalyst or certain metal oxide catalysts at 250–300° and 100–1000 atm. Results are summarized in Table I.

$$2RSH + CO \longrightarrow RCOSR + H_2S \quad (1)$$

$$RSSR + 2CO \longrightarrow RCOSR + COS \quad (2)$$

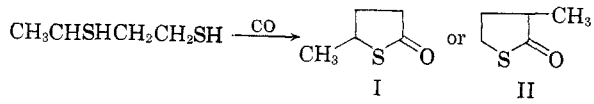
$$RSR + CO \longrightarrow RCOSR \quad (3)$$

$$RSH + CO \longrightarrow RH + COS \quad (4)$$

Carbonylation of thiols. Both aliphatic and aromatic thiols undergo carbonylation according to equation 1 to give thiol esters in yields up to 46% at conversions up to 73%. The catalysts used were dicobalt octacarbonyl and a supported cobalt oxide preparation that presumably was converted to the carbonyl under conditions of the experiment. The temperatures employed were 250–275° at a pressure of 100–1000 atm. of carbon monoxide. The reaction times were two to sixteen hours and the most convenient solvents were benzene and toluene.

No reaction took place between carbon monoxide and thiophenol at 70° in the presence of cobalt carbonyl, nor at 275° with no catalyst. In some runs, carboxylic acids were found. Thus, carbonylation of benzenethiol without solvent gave only benzoic acid. In one benzenethiol run, the gaseous products were collected and found by mass spectrophotometric analysis to contain mainly hydrogen sulfide and carbon oxysulfide.

The carbonylation of 1,3-butanedithiol gave a thiolactone (I or II). The available data do not permit an unequivocal choice between the two possible structures.



I II

Attempted carbonylation of a *gem*-dithiol, 3,5,5-trimethylhexane-1,1-dithiol, at 70° and 150° gave mainly the corresponding monothiol and a small amount of the carboxylic acid. At 250°, the monothiol and the thiol ester derived from the monothiol according to equation 1 were obtained. An attempt to add hydrogen sulfide to an olefin and carbonylate the resulting thiol *in situ* led to only a 1% yield of thiol ester. Benzyl mercaptan was the only thiol which gave products containing no sulfur. 1,2-Diphenylethane and 1,2,3-triphenylpropane were isolated.

An important competing reaction to thiol ester formation apparently was reduction of thiol to hydrocarbon (Equation 4). Attempts were not made to isolate the hydrocarbon in most of the experiments, but in the case of 3,5,5-trimethylhexane-1-thiol approximately as much hydrocarbon was found as thiol ester. With benzothiazole-2-thiol, benzothiazole was the sole product. Similarly, *o*-mercaptobenzoic acid gave benzoic acid.

Carbonylation of disulfides. The conditions for the carbonylation of disulfides were similar to those used for thiols. The cobalt carbonyl–catalyzed reaction of carbon monoxide with *n*-butyl disulfide yielded *n*-butyl thiol-*n*-valerate. Phenyl thiolbenzoate was formed from carbon monoxide and phenyl disulfide using a chromium oxide-on-alumina catalyst, the only catalyst not containing cobalt successfully employed in these reactions. The corresponding sulfides were isolated as by-products.

Carbonylation of sulfides. At 300° and 1000 atm. of carbon monoxide, phenyl sulfide, and *n*-butyl sulfide were converted to thiol esters in small yields using dicobalt octacarbonyl as catalyst. Under the same conditions, phenyl methyl sulfide gave only methyl thiolbenzoate. No evidence for formation of the isomeric phenyl thiolacetate was obtained.

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TABLE I. REACTIONS OF CARBON MONOXIDE WITH SULFUR COMPOUNDS

Sulfur Compound	Solvent	Catalyst	Temp.	Pressure, Atm.	Principal Products	Yield, %	Conversion, %	B.P. or M.P.	Carbon Calcd.	Carbon Found	Hydrogen Calcd.	Hydrogen Found	Sulfur Calcd.	Sulfur Found
Benzenethiol	B[a]	$Co_2(CO)_8$	275[b]	965	Phenyl thiolbenzoate[c]	46	49	54.5–55.5[d,e]	72.87	73.20[f]	4.70	5.10	14.96	14.79
Benzenethiol	T	$Co_2(CO)_8$	275	1000	Phenyl thiolbenzoate	24	65	[g]						
					Benzoic acid	6	65	120[d]						
Benzenethiol	B	$Co_2(CO)_8$	275	100	Phenyl thiolbenzoate	29	52	54[d,f]						
Benzenethiol	B	Cobalt oxide on Al_2O_3	275	990	Phenyl thiolbenzoate	15		[g]						
Benzenethiol	N	$Co_2(CO)_8$	275	995	Benzoic acid	43		120[d]						
o-Toluenethiol	B	$Co_2(CO)_8$	275	1000	*o*-Tolyl thiol-*o*-toluate[c]	18	50	60[d]	74.35	74.24	5.82	5.51		
o-Toluenethiol	B	Cobalt oxide on Al_2O_3	300	950	*o*-Tolyl thiol-*o*-toluate[c]	23	73	50–53[d]						
1-Butanethiol	B	$Co_2(CO)_8$	275	1000	*n*-Butyl thiol-*n*-valerate	19		67 (2.6 mm.)[h]	62.03	62.88[i]	10.41	10.69	18.40	18.80
3-Methyl-1-butanethiol	B	$Co_2(CO)_8$	275	960	Isocaproic acid	17		42 (0.2 mm.)[j]						
1,3-Butanedithiol	B	$Co_2(CO)_8$	250	1000	Methylthiobutyrolactone[k]	15	60	76 (8 mm.)[l]	51.67	51.88[m]	6.94	7.23		
3,5,5-Trimethylhexane-1,1-dithiol	B	$Co_2(CO)_8$	150	950	3,5,5-Trimethylhexane-1-thiol	58		32 (0.8 mm.)[n]	67.43	67.92	12.58	12.40	20.00	19.47
					4,6,6-Trimethylheptanoic acid	10		80–82 (0.6 mm.)[o]						
3,5,5-Trimethylhexane-1,1-dithiol	B	$Co_2(CO)_8$	250	1000	3,5,5-Trimethylhexane-1-thiol	24		75–76 (6 mm.)						
					3,5,5-Trimethylhexyl thiol-4,6,6-trimethylheptanoate	11		123 (0.8 mm.)[p]		[q]			10.20	10.64
					4,6,6-Trimethylheptanoic acid	8		60–76 (0.5 mm.)						
3,5,5-Trimethylhexane-1-thiol	B	Cobalt oxide on Al_2O_3	275	1000	3,5,5-Trimethylhexyl thiol-4,6,6-trimethylheptanoate	17		123–126 (0.8 mm.)						
					2,2,4-Trimethylhexane	15		117–129[r]						
Hydrogen sulfide, cyclohexene[s]	N	$Co_2(CO)_8$	275	1000	Cyclohexyl thiolcyclohexanecarboxylate	1		93 (0.7 mm.)	[t]					
Phenyl disulfide	B	Chromium oxide on Al_2O_3	275	950	Phenyl thiolbenzoate	31		53[d]						
n-Butyl disulfide	N	$Co_2(CO)_8$	250	990	*n*-Butyl thiol-*n*-valerate	30		85 (5 mm.)[u]						
n-Butyl sulfide	N	$Co_2(CO)_8$	300	1000	*n*-Butyl thiol-*n*-valerate	7	17	52 (0.8 mm.)[u]						
Phenyl sulfide	B	$Co_2(CO)_8$	300	1000	Phenyl thiolbenzoate[c]	19	26							
Phenyl methyl sulfide	B	$Co_2(CO)_8$	300	1000	Methyl thiolbenzoate[c]	21	43	117–120 (17 mm.)[v]		[w]				
					Benzoic acid	2	43	120[d]						
Benzothiazole-2-thiol	B	$Co_2(CO)_8$	275[x]	1000	Benzothiazole	80		66 (1.3 mm.)					23.72	23.66

[a] B = benzene; T = toluene; N = none. [b] This experiment was run for only 2 hours. [c] Also characterized by identification of saponification products. [d] Melting point. [e] Reported[3] m.p. 56°. [f] Infrared, carbonyl, 6.0 μ. [g] Mixed m.p. with analyzed sample gave no depression. [h] n_D^{25} 1.4590. [i] Mol. wt. calcd., 174; found, 165, 171; infrared, carbonyl, 5.9 μ. [j] Infrared, consistent with structure. [k] Oxidized by iodine-water to a methylcarboxypropyl disulfide, m.p. 115–116°. Reported[4] for 1-methyl-3-carboxypropyl disulfide, m.p. 118–121°. [l] Reported[4] for γ-thiovalerolactone, b.p. 85–86° (8 mm.), n_D^{20} 1.5028. [m] Infrared, carbonyl 5.8 μ. [n] n_D^{25} 1.4528. Reported[5] b.p. 81° (20 mm.), n_D^{25} 1.4518. [o] n_D^{25} 1.4338. Reported[6] b.p. 132–133° (8 mm.), n_D^{21} 1.4346. [p] n_D^{25} 1.4620. [q] Infrared, carbonyl, 5.9 μ; *gem*-dimethyl, 7.2, 7.3, and 7.35 μ. [r] n_D^{25} 1.4017. [s] 3:1 molar ratio. [t] Infrared, carbonyl, 5.9 μ. [u] Infrared same as analyzed sample. [v] n_D^{25} 1.5813. Reported[7] b.p. 134° (25 mm.), 123–124° (20 mm.).[8] [w] Infrared, carbonyl, 6.05 μ, SCH_3, 7.65 μ. [x] This experiment was run for only 3 hours.

EXPERIMENTAL

The reactions, details of which are given in Table I, were carried out in 400-ml. stainless steel shaker tubes for 14–16 hr. unless otherwise noted. The amount of catalyst used was 1–5% of the weight of the sulfur compound. The products were isolated and purified by conventional methods.

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Pyrrolopyridines. III. The Madelung Cyclization of 3-Acylamino-4-picolines[1,2]

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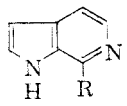
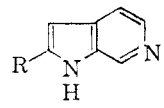
Literature methods for the synthesis of pyrrolo-(2,3-c)-pyridine (6-azaindole, I, R = H) are not very satisfactory. Koenigs and Fulde[4] reported the preparation of 2-methylpyrrolo(2,3-c)pyridine (II, R = CH_3) in 23% yield by a Madelung cyclization of 3-acetamido-4-picoline, the later in turn being made by a tedious route. Clemo and Holt[5]



I

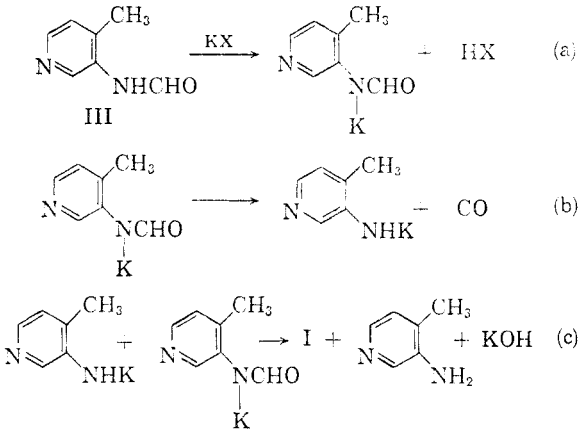


II

were unable to apply the Fischer indole ring closure to 2-methyl-3-pyridylhydrazone. Süs and Möller[6] obtained I (R = H) from the photochemical decomposition of 3-diazo-1,7-naphthyridin-4-(3H)-one and decomposition of the resulting 3-carboxypyrrolo(2,3-c)pyridine, but the multistep synthesis of the required diazo derivative interferes with the utilization of this method for preparative purposes. Somewhat earlier, Herz and Tocker[2] had succeeded in synthesizing I (R = H and CH_3) by the Pomeranz-Fritsch method from readily available starting materials, but the yields were very low.

Recent improvements in the Madelung cyclization of 2-formamidotoluene,[7] the successful preparation of 7-azaindole[8] by an adaptation of this method and the availability of 3-amino-4-picoline[9] suggested that the Madelung cyclization of 3-formamido-4-picoline might give I (R = H) in better yields. The results of such a study are presented here.

3-Amino-4-picoline, prepared by a slightly improved method, was converted to the formamido derivative (III) in 86% yield, but the cyclization, under a variety of conditions, resulted in the isolation of 3-amino-4-picoline only. Tyson's mechanism[7] for the Madelung cyclization as applied to the case at hand (see scheme below) requires the



formation of equivalent amounts of 3-amino-4-picoline and pyrrolo(2,3-c)pyridine by decomposition of the potassium salt of the former; hence it was hoped to direct the reaction toward the formation of I by heating a mixture of the potassium salt of the amine and III in the presence of sodium formate, the latter to repress step *b*. However, the resulting product consisted entirely of 3-amino-4-picoline. It was therefore concluded that the decomposition of the potassium salt of III has a much lower activation energy than the formation of I. In this connection it may be pointed out that while the sodium salt of III, prepared from sodium hydride and III, decomposed below 200°, III itself was stable up to 250°.

It was hoped that cyclization of a diacyl derivative of 3-amino-4-picoline, which cannot form a salt of the amino function and would therefore not undergo decomposition by step *b*, might occur more readily. The diformamido derivative could not be obtained, but diacetyl-3-amino-4-picoline (IV) was prepared by refluxing the amine in acetic anhydride for four hours. Madelung cyclization of IV with potassium ethoxide gave II-(R = CH_3) in 40% yield. Under the same conditions the monoacetyl derivative gave only a 5% yield although Koenigs and Fulde[4] claimed 23%. The fact that the diacetyl compound gave higher yields could, however, be partly accounted for on a statistical basis.

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