STUDIES ON ENOL TITRATION. II. ENOL CONTENTS OF SOME KETONES AND ESTERS IN THE PRESENCE OF METHANOL

ALEXANDER GERO

The first paper of this series (1) contained a report on an improvement in the Kurt Meyer titration and on the enol contents of a few ketones determined with the improved method. This method has since been applied to a number of ketones and esters in an effort to obtain information on their enolization. The present paper is a report on the results of these determinations, as well as an attempt at theoretical interpretation.

Results. The data reported in the first paper require correction and supplementation inasmuch as they were obtained in the presence of methanol in which the ICl was dissolved, and depending on the amount of enol present and the volume of ICl solution used to titrate it, this methanol made up a greater or lesser proportion of the reaction mixture. It is known, however, that the amount of solvent present in an enol titration is not an indifferent matter; in fact, careful determinations by Kurt Meyer and Kappelmeier (2) have shown that the enol content of ethyl acetoacetate decreases with increasing concentration in every one of several solvents tested. This writer has been able to confirm Meyer and Kappelmeier's observation for ethyl acetoacetate as well as for other β-ketoesters and 1,3-diketones, but in simple ketones he found the opposite behavior: their enolization is highest when they are most concentrated and decreases on dilution. Fig. 1 shows this contrary behavior on two representative examples; the data for ethyl acetoacetate are taken from Meyer and Kappelmeier (2), those for phenylacetone from the writer's work.

The variability of enol content necessitates adoption of a standard concentration at which to state the position of the keto-enol equilibrium. For the present paper 100% was adopted as this standard concentration. In the case of slightly enolized ketones, to which only insignificant amounts of ICl solution had to be added, this concentration could be approximated very closely. With other ketones advantage was taken of the fact that the concentration-enolization curves flatten out and become almost linear at high concentrations so that enol titrations at three or four such concentrations permitted extrapolation to 100%, *i.e.* to the enol content of the pure ketone. These extrapolated enol contents of all ketones and esters investigated by the author, including those reported in the first paper, are assembled in Table I.

A glance at the table shows that generally enol contents are highest—as has long been known—in 1,3-diketones and β-ketoesters, lowest or non-existent in simple esters, and intermediate in simple ketones. The high enolization of 1,3-diketones and β-ketoesters is seen particularly well on comparing such compounds with the homologous 1,4-diketones and γ-ketoesters. Compare, for instance, acetylacetone (no. 26) with acetonylacetone (no. 27), ethyl aceto-
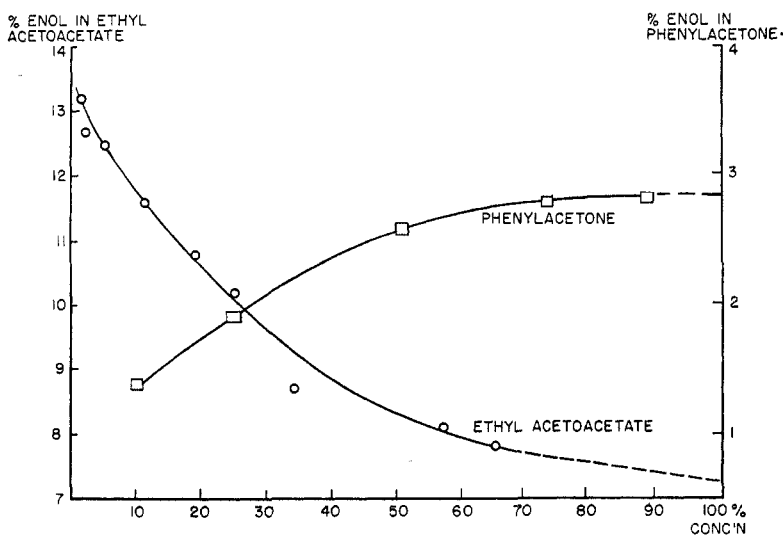
FIG. 1

acetate (no. 28) with ethyl levulinate (no. 29), and ethyl benzoylacetate (no. 30) with ethyl benzoylpropionate (no. 31).

At the other extreme, of lowest enolization, simple esters are not measurably enolic (nos. 23 and 24). Even in ethyl malonate (no. 33), where two carbethoxy groups are in 1,3-position to each other, earlier workers could find no evidence of enol (9, 10). The present writer, however, did find such enolization in malonic ester, although a very feeble one. The fact that an ester is generally less enolic than the corresponding ketone is illustrated by comparing acetone (no. 1) with ethyl acetate (no. 23), benzoylacetone (no. 22) with ethyl benzoylacetate (no. 30), and ethyl acetoacetate (no. 28) on the one hand with ethyl malonate (no. 33), on the other with acetylacetone (no. 26)

The enolizing effect of a β-cyano group is stronger than that of a second carbethoxy group but much weaker than that of a keto group; if we set the enol content of ethyl malonate as 1, that of ethyl cyanoacetate is about 30 (no. 34), and that of ethyl acetoacetate about 1000 (no. 28).

Most of the simple ketones have enol contents in the range 10^{-3} to 10^{-1} %. Only acetone contains less enol than 10^{-3} % while three contain more than 1 %. The most highly enolized simple ketone turned up by this investigation is phenylacetone with almost 3 % enol (no. 21), followed by diacetyl (no. 25) and cyclohexanone (no. 16), both of which contain a little over 1 % enol. It is interesting to compare the enol contents of these three with those of closely related ketones: cyclohexylacetone (no. 17) has an enol content of the same order as many other simple ketones, and less than $\frac{1}{10}$ the enol content of phenylacetone; cyclohexanone is much more enolic than either cyclopentanone (no. 15) or methyl butyl ketone (no. 4) and ethyl propyl ketone (no. 12) which might be considered open-chain analogs of cyclohexanone. This is particularly striking in

TABLE I

Enol Contents of Ketones and Esters, Extrapolated to the Undiluted State

No.	Compound	Enol Content, %	Enol Content, % (Found by Other Investigators)
1	Acetone	1.5×10^{-4}	2.5×10^{-4} (3)
2	Methyl ethyl ketone	1.2×10^{-1}	
3	Methyl propyl ketone	8.6×10^{-3}	
4	Methyl butyl ketone	1.1×10^{-1}	
5	Methyl isobutyl ketone	2.7×10^{-1}	
6	Methyl amyl ketone	9.6×10^{-2}	
7	Methyl hexyl ketone	9.2×10^{-1}	
8	Diethyl ketone	6.7×10^{-2}	
9	Dipropyl ketone	6.2×10^{-3}	
10	Diisopropyl ketone	3.7×10^{-3}	
11	Diisobutyl ketone	7.4×10^{-2}	
12	Ethyl propyl ketone	4.7×10^{-2}	
13	Ethyl butyl ketone	1.7×10^{-1}	
14	Ethyl amyl ketone	1.3×10^{-2}	
15	Cyclopentanone	8.8×10^{-2}	4.8×10^{-3}* (4)
16	Cyclohexanone	1.2	2.0×10^{-2}* (4)
17	Cyclohexylacetone	2.3×10^{-1}	
18	Camphor	1.4×10^{-1}	
19	Acetophenone	3.5×10^{-2}	
20	Propiophenone	1.0×10^{-2}	
21	Phenylacetone	2.9	
22	Benzoylacetone	89.2	90.6† (5)
23	Ethyl acetate	0‡	
24	Ethyl succinate	0‡	
25	Diacetyl	1.1	5.6×10^{-3} (4)
26	Acetylacetone	76.4	76–80 (6)
27	Acetonylacetone	5.7×10^{-2}	
28	Ethyl acetoacetate	8.0	7.3–7.8 (6)
			7.7 (7)
29	Ethyl levulinate	1.9×10^{-2}	
30	Ethyl benzoylacetate	17.7	14.6† (4)
			21.4 (8)
31	Ethyl β-benzoylpropionate	7.1×10^{-1}	
32	Ethyl cyclohexanone-2-carboxylate	62.0	76 (8)
33	Ethyl malonate	7.7×10^{-3}	0 (9, 10)
34	Ethyl cyanoacetate	2.5×10^{-1}	

* In aqueous solution. † In acetone solution. ‡ Within the accuracy of the present method.

view of the fact that the enolization of cyclopentanone (no. 15) is very close to that of its open-chain analog, diethyl ketone (no. 8). As to diacetyl (no. 25), while it is far less enolic than acetylacetone (no. 26), it is far more so than acetonylacetone (no. 27).

It may be worth observing that while acetonylacetone is no more enolic than ordinary simple ketones, its enol content is still remarkably high considering that

LOG % ENOL

METHYL
KETONES
$CH_3COC_nH_{2n+1}$

ETHYL
KETONES
$C_2H_5COC_nH_{2n+1}$
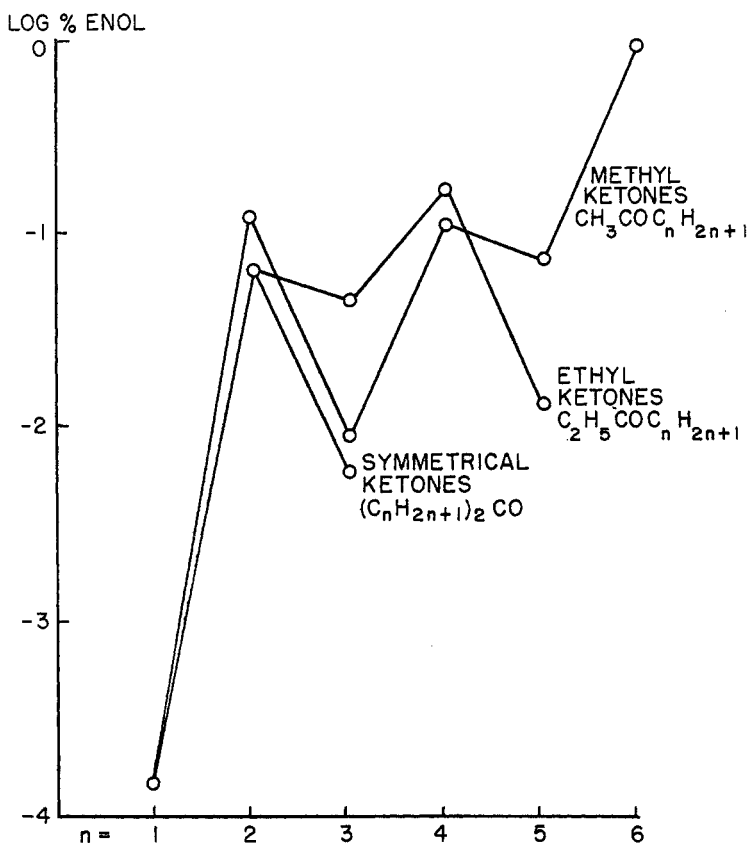
SYMMETRICAL
KETONES
$(C_nH_{2n+1})_2CO$

FIG. 2

the structure of acetonylacetone can be looked upon as being made up of two acetone structures, and the enol content of acetone is less than $\frac{1}{100}$ of that of acetonylacetone. Similar observations can be made regarding other ketones which have the enol-forming groups in 1,4-position to each other: consider ethyl levulinate (no. 29) which may be looked upon as a combination of the structures of acetone (no. 1) and of ethyl acetate (no. 23), and ethyl β-benzoylpropionate which is similarly a combination of the structures of acetophenone (no. 19) and ethyl acetate.

Probably the most interesting phenomenon which can be observed in the data assembled in Table I is the alternation of enol contents in homologous series. This alternation is clearly seen in the series of methyl ketones (nos. 1–7), of ethyl ketones (nos. 8, 12, 13, 14), and also in that of the symmetrical ketones, as far as it goes (nos. 1, 8, 9). The alternation is shown graphically in Fig. 2.

The logarithmic scale in this figure is used in order to make the dimensions of the graph manageable.

Discussion. Sidgwick (11) suggested formation of a six-membered chelate ring in the enol of ethyl acetoacetate:

$$O—H \cdot \cdot O$$
$$| \qquad ||$$
$$CH_3—C{=}CH—C—OC_2H_5$$
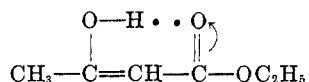
Such chelation, and the conjugated system HO—C=CH—C=O, explains the stability of 1,3-diketones and β-ketoesters, as well as the peculiar decrease with concentration of the enol content of ethyl acetoacetate: the chelated enol is less polar than the ketone and should be more soluble in nonpolar solvents. Hence the shift of the tautomeric equilibrium toward the enol side when acetoacetic ester is dissolved in nonpolar solvents (7). Associating solvents, such as water and alcohols, display two conflicting influences: on the one hand they are still not as polar as the ketone—the solvent of the enol in pure ethyl acetoacetate—hence they also shift the equilibrium toward the enol side though less so than nonpolar solvents, on the other hand they compete with the enolic hydroxyl for hydrogen bonding with the ketone oxygen, thus breaking up the chelate ring and destabilizing the enol (12).

This writer suggests a similar keto-enol hydrogen bond in all ketones:

$$—C—O—H \cdot \cdot \cdot O{=}C—$$
$$||\qquad\qquad\qquad |$$
$$—C—$$
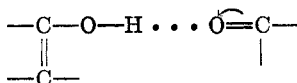
Here, however, the hydrogen bond is *inter*molecular, not *intra*molecular as in ethyl acetoacetate and related compounds. Lacking the stabilizing effect of the chelate ring and of the two conjugated double bonds, simple ketones should be less enolic than the compounds discussed by Sidgwick; also, all consequences of the nonpolarity of the ethyl acetoacetate enol are irrelevant to the enols of simple ketones. In particular, the only solvent effect will be competition of an associating solvent with the enol for hydrogen bonding with the ketone, thus decreasing the stability of the enol. While therefore dilution with an associating solvent has an equivocal effect on the enol content of 1,3-diketones and β-ketoesters, it must always decrease the enol content of a simple ketone. This effect is shown for phenylacetone in Fig. 1; also, there is evidence that dissolution in water decreases the enolization of simple ketones (4).

No six-membered chelate ring can be formed in 1,4-diketones and γ-ketoesters. Yet their relatively high enol contents prove that their carbonyl groups are not completely isolated and that probably conjugation of the double bonds in the dienols is a stabilizing factor. This is borne out by their chemical behavior (13).

In esters the C=O group, apart from ketone resonance, can enter in resonance with an unshared electron pair of the alkoxyl oxygen or tautomerize to an enol. The resonance energy of the ester group is about 24 kcal (14), that of the enol group 3–7 kcal (15). This explains the low enolization of esters (16).

In order to account for the high enol content of phenylacetone, it is assumed that the proton involved in the tautomeric change originates in the methylene

rather than the methyl group. Thus the enol is stabilized by the conjugation of the double bond with the benzene ring (17). Experimental evidence for this position of the double bond is found in the fact that the reaction of phenylacetone with bromine yields Ph-CHBr-CO-CH$_3$ (18). An additional stabilizing factor might perhaps be seen in the fact that in phenylacetone the side chain is *ortho-para* directing (19). This implies a negative charge in the *ortho* positions which might result in a six-membered chelate ring by hydrogen bonding:
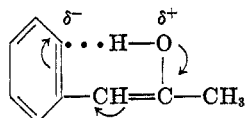
However, if this chelate ring exists, it certainly cannot be strong enough to make the enol molecule nonpolar, otherwise the change of enol content on dilution would be expected to follow the pattern of ethyl acetoacetate rather than that of the simple ketones.

The relatively high enol content of diacetyl must be interpreted in the context of the fact that its cyclic analogs are enormously enolized. In fact, cyclic 1,2-diketones with five-membered rings are known as monoenols only (20). This has been explained by the potential energy which results from the dipole repulsion of two vicinal C=O groups held in *cis* position by the rigidity of a ring (21). The strain is eased by formation of the monoenol—not the dienol, however, in which both oxygens would be positively charged by resonance and therefore cause strain by repulsion.

Since diacetyl is free to assume the *trans* arrangement, its diketo form is less strained than a cyclic diketone. Hence its higher ketone content. Still, carbonyl resonance in a 1,2-diketone places positive charges on two vicinal C atoms, thus creating high potential energy even in the *trans* form and destabilizing the ketone. The situation is more favorable in either the monoenol I or the dienol II; hence diacetyl contains more ketone than its cyclic analogs but more enol than simple ketones.
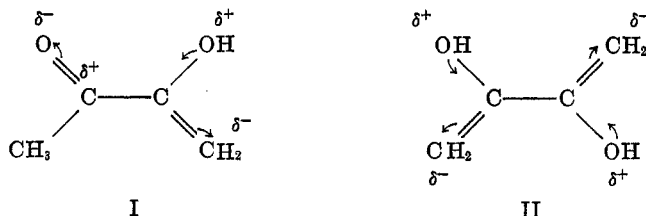
The relatively high enol contents of 1,2-diketones of the type PhCH$_2$CO-COR (22) can be easily interpreted by a combination of the arguments brought forward for 1,2-diketones and for phenylacetone.
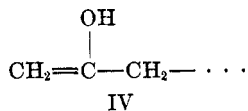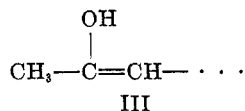
The high enol content of cyclohexanone has already been noted by Schwarzenbach (23) who interpreted it by a consideration based on the relatively low enol content of acetylacetone in water (3, 24). Schwarzenbach reasons that, although

the free energy change favors the enol, the entropy change does not because the enol locks the ends of the carbon chain in position by preventing free rotation around the middle of the molecule. Therefore enolization can occur only when the methyl groups are in certain definite positions so that the transition from ketone to enol is sterically less probable than the transition from enol to ketone. Malonic dialdehyde, which has no terminal methyl groups, can thus enolize more readily and is in fact almost 100 % enol. Rings, because of their rigidity, offer less probability resistance to enolization (25).

The data in Table I do not bear out all of this reasoning. In particular, Schwarzenbach's considerations make no distinction between cyclic ketones, yet, as Table I shows, only cyclohexanone and not cyclopentanone is highly enolic. Much more attractive is a recent suggestion by Brown, *et al.* (26) that quite generally five-membered rings favor an exocyclic double bond and six-membered rings an endocyclic one. Brown's generalization is certainly most interesting but it is restricted to five- and six-membered rings and does not predict the remarkable alternation in the enolization of the homologous 2-carbethoxycycloalkanones (27) where six-, eight-, and ten-membered rings show, respectively, 57, 40, and 50 % enolization, in contrast to 4, 12, 15, and 9 % enol in five-, seven-, nine-, and eleven-membered rings. The crucial phenomenon is therefore not simply a difference between five- and six-membered rings but the fact that all even-membered rings show greater preference for endocyclic double bonds than do odd-membered ones. This alternation is strikingly reminiscent of that in Fig. 2 which may be expressed by the statement that the group —CO—R, R being a straight chain, is more favorable to enolization when the number of C atoms in R is even.

Such alternations are by no means unique. The alternation of the melting points in the homologous series of aliphatic carboxylic acids is well known. Similar alternation effects are found in the carbon-carbon distances in a chain of an even number of carbon atoms between two carboxyl groups (28), in the rates of the reaction of certain alkyl chlorides with potassium iodide (29), in the stabilities of the complexes formed from alkylbenzenes and picric acid (30), and in the yields of isomeric bromoketones obtained from aliphatic methyl ketones. Because of its relevance to the present investigation, this last case will be considered in some detail.

Cardwell and Kilner (31) found that in ketones CH_3—CO—R bromination generally yielded both isomeric α-bromoketones, but when R contained a chain of an even number of C atoms, the bromine preferentially went to C_3 while when R contained an odd number of carbon atoms in the chain the distribution of bromine between C_1 and C_3 was close to randomness. Assuming that the reaction of a ketone with bromine proceeds by way of the enol the relative yields of the two isomeric α-bromoketones are an indication of which of the two isomeric enols III and IV is formed more rapidly:

$$OH \qquad\qquad\qquad\qquad OH$$
$$| \qquad\qquad\qquad\qquad\qquad |$$
$$CH_3—C{=}CH—\cdots \qquad\qquad CH_2{=}C—CH_2—\cdots$$
$$III \qquad\qquad\qquad\qquad\qquad IV$$

Thus, while the present writer's experiments inquire into the position of the keto-enol equilibrium, Cardwell and Kilner provide information on the rate at which both isomeric enols are formed after equilibrium has been disturbed. Interestingly, the author finds the highest enol content in just those ketones in which Cardwell and Kilner find preferential enolization involving C_3 rather than random enolization with C_1 and C_3. This means that a chain of an even number of C atoms attached to a carbonyl group is more favorable to formation of an enol than an odd number; or, to put it differently, that a chain with an odd number of C atoms attached to a double bond is favored, the double bond being either the $C=O$ group of the ketone or the $C=C$ group of the enol; or, again differently, that the favored structure contains *a chain of an even number of C atoms between the terminal methyl group and a double bond*.

This suggests that the enolization of ketones may be governed by the super-position of two factors: one is the greater thermodynamic stability of the ketone (32), the other, much weaker one, is hyperconjugation. The first factor operates in the same way in all ketones and is responsible for their generally low enol contents. To the extent, however, that hyperconjugation contributes to the degree of enolization, its influence varies. In acetone the methyl groups enter into hyperconjugation with the carbonyl double bond so that enol formation involves loss of hyperconjugation energy. In this case, therefore, the influence of hyperconjugation is contrary to enolization. But in methyl ethyl ketone it favors the enol in which two methyl groups are in hyperconjugation with a double bond, against one in **the ketone:**

$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-CH_2-CH_3 \qquad\qquad CH_3-\overset{\overset{\displaystyle OH}{|}}{C}=CH-CH_3$$

This explains the relatively high enol content of methyl ethyl ketone. It also explains why the enol content of diethyl ketone is higher than that of acetone but lower than that of methyl ethyl ketone (no hyperconjugation of a methyl group in the ketone, and hyperconjugation with only one methyl group in the enol).

However, as the alkyl chain is lengthened the enol contents of the methyl ketones continue to alternate as they do in acetone and methyl ethyl ketone, although the methyl group is now separated from the double bond by a saturated chain. The only effect which explains and indeed postulates alternation in a saturated chain is second-order hyperconjugation (33), a concept introduced on quantum-mechanical grounds by Mulliken (34) and supported with exper-imental evidence by Berliner and Berliner (35). Cardwell and Kilner reached the same conclusion. The author's work may thus be considered as further con-firmation of the reality of second-order hyperconjugation.

The pronounced alternation of enol contents in rings forces us to call on second-order hyperconjugation here, too, even in the absence of a methyl group. It is indeed only logical that if a chain of an even number of C atoms can enter in second-order hyperconjugation with a double bond, it should do so also when both its ends are attached to the same double bond. Hence in cyclic ketones with an odd number of ring members second-order hyperconjugation favors the ketone,

where the ends of the saturated chain of an even number of C atoms are attached to the C=O group, while in cyclic ketones with an even number of ring members it favors the enol, where the ends of such a chain of C atoms are attached to the ends of the C=C group.

It is quite surprising that the enol content of cyclohexanone is about ten times higher than that of methyl butyl ketone. This may mean that second-order hyperconjugation is more effective in a ring than in an open chain, just as resonance is greater in benzene than in hexatriene, but it may also be that steric effects (proton-proton interactions) are responsible. This has been suggested by Brown (26) without further detail. It may be made clear by the inspection of models. A model of cyclohexanone shows that while the axial (36) protons of two neighboring C atoms are perfectly staggered and their two equatorial protons are in skew constellation to each other, the axial proton of one C and the equatorial proton of its neighbor are close to being eclipsed. However, a model of

cyclohexenol shows that the proton of the =CH group is in the equatorial belt and in rather good skew constellation to both protons of the neighboring CH_2. The elimination of a nearly eclipsed constellation may mean a gain of perhaps 2 kcal/mole and thus might explain the relatively high enolization of cyclohexanone. Nevertheless, in the absence of more experimental material probably no further conclusions should be drawn.

<center>EXPERIMENTAL</center>

Most of the compounds used came from commercial sources. The author gratefully acknowledges the generosity of Carbide & Carbon Chemicals Corp., E. I. du Pont de Nemours & Co., Shell Chemical Corporation, and Smith, Kline & French Laboratories in supplying him with many ketones. The only compounds which the author synthesized were methyl butyl ketone (by acetoacetate synthesis from propyl iodide), ethyl propyl ketone (by pyrolysis of a mixture of the manganese salts of butyric and propionic acids), and ethyl β-benzoylpropionate (by esterification of the acid). For purification, liquid compounds were distilled and solid compounds recrystallized.

The method has been described in the first paper, therefore only a few details will be given in the following.

The ketones or esters and the required amount of sodium bicarbonate were placed in glass-stoppered weighing bottles of appropriate size. The ICl solution was added in the beginning from a microburet; however, this was soon found not be advantageous because the microburet was not accurate enough for the small amounts used, and at the same time the flow of liquid from the narrow tip of the microburet was too slow for the required speed of titration. Therefore micropipets were constructed as sketched in Fig. 3. The rubber bulb was permanently kept on the pipet and its perforation was closed with a finger in order to suck up ICl solution to a level above the constriction, then the finger was lifted so that the ICl solution could flow out of the pipet until its level had reached the constriction. It then stopped flowing; the perforation was again covered and by squeezing the bulb the ICl solution was expelled rapidly into the ketone. Micropipets of various sizes were constructed and calibrated by titrating the ICl they held with a standard thiosulfate solution. The calibrations showed perfect reproducibility.

In order to assure rapid and complete addition of the ICl to the enol, the conditions reported in the first paper were changed to a ratio of 0.25 ml. of 6–8 N ICl solution to 1/10 millimole of enol. This excess is probably far more than necesary but no effort was made to find the exact minimum ratio.

After adding the ICl solution to the ketone and mixing thoroughly and rapidly, the mix-

ture was poured into NaI solution which was being stirred mechanically, and immediately titrated with $N/10$ thiosulfate. For the reasons given in the first paper it is important that the titration be carried out rapidly. With a little practice, it can easily be performed in a matter of seconds since the solution is being stirred mechanically and both of the operator's hands are free to handle the buret stopcock.

Since only a few of the ketones are soluble in water, 75% methanol was used as a solvent for the NaI in order to titrate in a homogeneous system. This eliminates the use of starch as an indicator because the blue starch-iodine color does not develop in the presence of so much organic material. However, with a strongly lighted white background there was no difficulty in titrating sharply to disappearance of the yellow color of iodine.
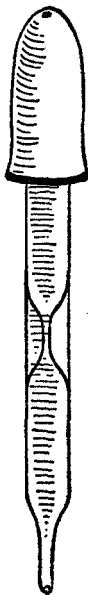

FIG. 3

Although, as mentioned in the first paper, the ICl solution was quite stable, it was nevertheless standardized daily, using the same 75% methanol solution of NaI as for the enol titrations.

In the author's opinion, the advantage of his method—apart from replacing bromine by the more reliable and convenient iodine monochloride—is that it is not much more complicated than a simple titration and thus permits examination of a great many ketones in relatively little time. Its accuracy is probably modest and certainly does not compare with that of an electrometric method. For this reason it would be most desirable if the admirable method of Schwarzenbach (15) could be adapted to the use of ICl in neutral solution, rather than Br_2 in acidic solution.

SUMMARY

The enol contents of 34 ketones and esters were determined. The well-known high enolization of 1,3-diketones and β-ketoesters was confirmed, as was also the increase of their enol content on dilution. But in simple ketones the enol content was found to decrease on dilution.

Simple ketones generally have enol contents of the order 10^{-3} to 10^{-1}%, except

acetone with 1.5×10^{-4} and cyclohexanone, diacetyl, and phenylacetone, with 1–3 % enol content. The enol contents of simple open-chain ketones show alternation: if R in —CO—R contains a chain of an even number of C atoms, the ketone shows greater readiness to tautomerize to enol than with an odd number of C atoms.

Simple esters are not noticeably enolic but ethyl malonate does contain 7.7 $\times 10^{-3}$ %, and ethyl cyanoacetate 2.5×10^{-1} % enol.

The theoretical assumptions made to account for the foregoing observations include a hydrogen bond between the carbonyl group of any ketone and the hydroxyl group of its enol, and second-order hyperconjugation in all ketones and enols.

PHILADELPHIA 2, PENNA.

REFERENCES

(1) GERO, J. Org. Chem., **19**, 469 (1954).
(2) MEYER AND KAPPELMEIER, Ber., **44**, 2718 (1911).
(3) SCHWARZENBACH AND FELDER, Helv. Chim. Acta, **27**, 1044 (1944).
(4) SCHWARZENBACH AND WITTWER, Helv. Chim. Acta, **30**, 669 (1947).
(5) MEYER, Ber., **47**, 826 (1914).
(6) CONANT AND THOMPSON, J. Am. Chem. Soc., **54**, 4039 (1932).
(7) MEYER AND KAPPELMEIER, Ann., **380**, 212 (1911).
(8) DIECKMANN, Ber., **55**, 2470 (1922).
(9) MEYER, Ber., **45**, 2864 (1912).
(10) ARNDT AND EISTERT, Ber., **74**, 437 (1941).
(11) SIDGWICK, J. Chem. Soc., 907 (1925).
(12) BRANCH AND CALVIN, The Theory of Organic Chemistry, Prentice-Hall, New York, 1941, p. 297.
(13) WHELAND, Advanced Organic Chemistry, John Wiley & Sons, New York, 1949, p. 612.
(14) Ref. 12, p. 283.
(15) Ref. 12, p. 289.
(16) Ref. 12, p. 293.
(17) Ref. 12, p. 296.
(18) EMDE AND RUNNE, Arch. Pharm., **249**, 360 (1911).
(19) NEBER, HARTUNG, AND RUOPP, Ber., **58**, 1234 (1925).
(20) SCHWARZENBACH AND WITTWER, Helv. Chim. Acta, **30**, 663 (1947).
(21) WHELAND, J. Chem. Phys., **1**, 731 (1933).
(22) MOUREU, Ann. chim., [10] **14**, 283 (1930).
(23) SCHWARZENBACH AND WITTWER, Helv. Chim. Acta, **30**, 663 (1947).
(24) NACHOD, Z. physik. Chem., [A] **182**, 193 (1938).
(25) SCHWARZENBACH AND FELDER, Helv. Chim. Acta, **27**, 1701 (1944).
(26) BROWN, BREWSTER, AND SHECHTER, J. Am. Chem. Soc., **76**, 467 (1954).
(27) SCHWARZENBACH, ZIMMERMANN, AND PRELOG, Helv. Chim. Acta, **34**, 1954 (1951).
(28) MORRISON AND ROBERTSON, J. Chem. Soc., 980 (1949).
(29) CONANT AND KIRNER, J. Am. Chem. Soc., **46**, 232 (1924); CONANT, KIRNER, AND HUSSEY J. Am. Chem. Soc., **47**, 488 (1925); MURRAY, **60**, 2662 (1938).
(30) ANDERSON AND HAMMICK, J. Chem. Soc., 1089 (1950).
(31) CARDWELL AND KILNER, J. Chem. Soc., 2430 (1951).
(32) WHELAND, ref. 13, p. 613.
(33) DEWAR, The Electronic Theory of Organic Chemistry, Oxford, 1949, p. 157.
(34) MULLIKEN, RIEKE, AND BROWN, J. Am. Chem. Soc., **63**, 41 (1941).
(35) BERLINER AND BERLINER, J. Am. Chem. Soc., **71**, 1195 (1949).
(36) BARTON, HASSEL, PITZER, AND PRELOG, Science, **119**, 29 (1954).