It has been confirmed that the autoxidation of dialkyl dixanthyls, at least in the early stages of the reaction, is dependent almost solely upon slow dissociation into free radicals, which are themselves very rapidly oxidized.

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[A CONTRIBUTION FROM THE CHEMICAL LABORATORY OF NORTHWESTERN UNIVERSITY]

The Concentration of Deuterium in Organic Compounds. II. A General Discussion with Particular Reference to Benzene

BY MALCOLM DOLE

The abundance of deuterium in naturally occurring hydrogen compounds has been investigated by a number of workers. These researches may be divided into two classes: the first type of research consists in the investigation of naturally occurring water, while the second type consists in the investigation of water obtained in the combustion of hydrogen-containing organic substances. It is the latter type with which this paper is concerned; hence researches in which water only was investigated will not be discussed further. Table I summarizes data obtained by previous workers in the second type of investigation; that is, organic compounds were burned, and the density of the water obtained was measured after a careful purification of the water. These data, however, are subject to all or some of the following uncertainties which make the calculation of the deuterium concentration entirely unreliable.

TABLE I

RELATIVE DENSITIES OF WATER OBTAINED IN THE COMBUSTION OF HYDROGEN-CONTAINING ORGANIC SUBSTANCES

Author	Substance burned	O_2 Source[a]	γ[b]
Dole[c]	Benzene	Air	7.9
	Oklahoma kerosene	Air	6.2
	Honey	Air	4.1
Dole[d]	Benzene	Electrolysis	0
	Cholesterol	Air	0
Emeléus, James, King, Pearson, Purcell and Briscoe[e]	Alcohol	Air	3
	Beet molasses	Air	2.9
	Yeast from the above	Air	2.1
	Mixed molasses	Air	5.3
	Fusel oil	Air	4.0
	Sucrose	Linde?	8.6
	Cane sugar (Trinidad)	Air	7.56
	Salix caprea, wood	Linde?	3.2
Filippova[f]	Motor petroleum	Linde?	11[g]
Greene and Voskuyl[h]	Corn oil	Air	4.9
	Natural gas	Air	5.7
Moser[i]	Illuminating gas	?	0
	Anthracite coal	?	0
Okabe and Titani[j]	Filter paper	Air	6.3
	Cotton	Air	5.7
	Cedar wood	Air	4.5
	Bamboo	Air	4.4
Snow and Johnston[k]	Natural Oklahoma butane	Linde	6.1 (corr.?)
Titani and Harada[l]	Molasses	Air	2.8
Titani and Harada[m]	Crude cane sugar	Air	7.8
	Cane sugar, purified	Air	7.4
	Beet sugar, purified	Air	6.5
	Grape sugar (dextrose)	Air	6.4
	Milk sugar (lactose)	Air	5.9
	Soluble starch	Air	3.9
	Rice flour (starch)	Air	6.0
	Wheat flour (starch)	Air	6.0
	Potato starch	Air	5.9
	Dextrin	Air	5.4
	Galactan	Air	4.8
	Mannan	Air	5.8
Washburn and Smith[n]	Dry willow wood	Linde	3.2 (corr.?)
Washburn and Smith[o]	Anthracite coal	?	0
	Natural propane	?	0

[a] In this column "Linde" means oxygen obtained from liquid air, "Linde?" means commercial oxygen of unknown origin, "electolysis" means electrolytic oxygen, "corr.?" means a correction has been applied to the density data for the oxygen used but that this correction is uncertain. [b] γ means the density difference between the water under investigation and normal water expressed in p. p. m. [c] M. Dole, *J. Chem. Phys.*, **2**, 337 (1934). [d] M. Dole, *ibid.*, **2**, 548 (1934). [e] H. J. Emeléus, F. N. James, A. King, T. G. Pearson, R. H. Purcell, H. Y. A. Briscoe, *J. Chem. Soc.*, (London), 1207, 1948 (1934). [f] N. S. Filippova, *J. Chem. Phys.*, **3**, 316 (1935). [g] Calculated from Filippova's estimated concentration of deuterium and not corrected for the type of oxygen used. [h] C. H. Greene and R. J. Voskuyl, THIS JOURNAL, **56**, 1649 (1934). [i] H. Moser, *Physik. Z.*, **35**, 682 (1934). [j] K. Okabe and T. Titani, *Bull. Chem. Soc. Japan*, **10**, 465 (1935). [k] R. D. Snow and H. L. Johnston, *Science*, **80**, 210 (1934). [l] T. Titani and M. Harada, *Bull. Chem. Soc. Japan*, **10**, 41 (1935). [m] T. Titani and M. Harada, *ibid.*, **10**, 205, 261 (1935). [n] E. W. Washburn and E. R. Smith, *Science*, **79**, 188 (1934). [o] E. W. Washburn and E. R. Smith, *Bur. Standards J. Research*, **12**, 305 (1934).

1. The atomic weight of the oxygen used in the combustion may not be the same as normal atmospheric oxygen. Both Smith[1] and Klar and Krauss[2] have found that commercial oxygen obtained in the fractional distillation of liquid air has a slightly higher atomic weight than atmospheric oxygen, the increase given by Smith for

(1) E. R. Smith, *J. Chem. Phys.*, **2**, 298 (1934); *Science*, **79**, 454 (1934).

(2) R. Klar and A. Krauss, *Naturwiss.*, **22**, 119 (1934).

Linde oxygen being 2.2 p. p. m. These observations have been confirmed in the present research, as will be seen from data given below. There is also the possibility that oxygen obtained in the commercial electrolysis of water may have an atomic weight slightly less than the oxygen in normal water inasmuch as Washburn and Smith,[3] Greene and Voskuyl,[4] Johnston,[5] and Selwood, Taylor, Hipple and Bleakney[6] have all shown that the isotopes of oxygen are definitely separated by electrolysis, the fractionation factor being of the order 1.008. As Washburn, Smith and Smith point out, the hydrogen and oxygen gases from commercial electrolyzers should be somewhat lighter than normal due to the fact that some water is lost by evaporation in electrolysis, thereby preventing the attainment of a "perfect" steady state in which the evolved gases would have the same atomic weight as the hydrogen and oxygen in the water which is continually being added to the cell. This conclusion is confirmed definitely by data given below (after allowing for the difference between air oxygen and water oxygen).

2. The oxygen in the water under investigation may not have a normal atomic weight if the substance originally burnt already contains oxygen. This uncertainty makes it impossible to calculate the deuterium content of water obtained in the combustion of sugars, starches, wood, honey, etc. This difficulty is realized by Titani and Harada, who have been most active in investigating carbohydrates (see Table I).

3. The oxygen in the water may also be abnormal for another reason. Urey and Greiff[7] have shown very recently from theoretical considerations that the fractionation factor for the exchange reaction

$$2H_2O^{18}(l) + CO_2^{16} = 2H_2O^{16}(l) + CO_2^{18}$$

is 1.047 at 0°, the O^{18} being concentrated in the carbon dioxide. Weber, Wahl and Urey[8] measured the density difference between deuterium-free water made from carbon dioxide which had been passed through the original deuterium-free water and the latter water and found it to be 10.2 p. p. m. This effect is of the same order of magnitude as the values of γ given in Table I and indicates that all of these values of γ may be in error due to isotopic exchange between water and carbon dioxide inasmuch as both of these compounds are necessarily formed in the combustion of hydrogen-containing carbon compounds. If such an exchange took place, the γ values of Table I would be too low and the calculation of the deuterium content correspondingly meaningless.

4. There is the possibility that the isotopes of oxygen may be fractionated in the combustion reaction although there have been as yet no definite theoretical or experimental indications of such an effect. Such an effect might be caused by a difference in the reaction rates of the various oxygen isotopes when oxygen is present in excess, or by a difference in the rates with which the isotopes combine with carbon and hydrogen when oxygen is present either in excess or not.

5. If the substance is not burnt in an excess of oxygen and completely oxidized a separation of the hydrogen isotopes might occur.

6. In burning substances with air a large volume of the uncondensable gases, carbon dioxide, nitrogen and excess oxygen, is passed through the condenser, carrying off an appreciable quantity of water vapor and causing, possibly, a fractionation of the isotopes of water. This difficulty has already been pointed out.[9]

7. The isotopes of water may be fractionated in the purification process; thus Harada and Titani[10] show that there is a density difference of 6.3 p. p. m. between the final distillate and final residue after distilling a distillate and retaining a residue of a residue three times.

8. All the above uncertainties are due to a possible separation of the isotopes of hydrogen or oxygen during the experiment. Rakshit[11] suggests that the γ values of Table I may be due to a shift in the polymer ratios of water saying, "The question is to what extent the observed variation in density is influenced by polymerization and depolymerization with fall and rise in the temperature of water samples under the conditions of the experiment." This question had previously been answered by the work of Dole and Wiener,[12] who

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(3) E. W. Washburn, E. R. Smith and M. Frandsen, *Bur. Standards J. Research*, **11**, 453 (1933); E. W. Washburn, E. R. Smith and F. A. Smith, *ibid.*, **13**, 599 (1934).

(4) C. H. Greene and R. J. Voskuyl, THIS JOURNAL, **56**, 1649 (1934).

(5) H. L. Johnston, *ibid.*, **57**, 484 (1935).

(6) P. W. Selwood, H. S. Taylor, J. A. Hipple, Jr., and W. Bleakney, *ibid.*, **57**, 642 (1935).

(7) H. C. Urey and Lotti J. Greiff, *ibid.*, **57**, 321 (1935).

(8) L. A. Weber, M. H. Wahl and H. C. Urey, *J. Chem. Phys.*, **3**, 129 (1935).

(9) M. Dole, *J. Chem. Phys.*, **2**, 548 (1934).

(10) M. Harada and T. Titani, *Bull. Chem. Soc. Japan*, **10**, 39 (1935); see also N. F. Hall and T. O. Jones, THIS JOURNAL, **56**, 749 (1934).

(11) J. N. Rakshit, *J. Phys. Chem.*, **39**, 303 (1935).

(12) M. Dole and B. Z. Wiener, *Science*, **81**, 45 (1935).

proved that the density of water is in no way a function of its thermal history.

9. Finally, there is the important assumption previously made by all investigators (and tested by none) that normal atmospheric oxygen has the same atomic weight as the oxygen in normal water. Unless this assumption is true the calculation of deuterium abundance ratios from the data of Table I is, of course, meaningless. The density of water made from oxygen of the air has been compared by the author with the density of water made from oxygen originally in water, the difference being 6.0 p. p. m. with the air-oxygen water denser. This work will shortly be published in the *Journal of Chemical Physics;* in this paper all the data will be corrected for the surprising difference between the atomic weight of oxygen from these two natural sources.

The possible sources of error due to dissolved impurities or to errors of density measurement have long been realized and need not be discussed at this point. The difficulties that have been raised are sufficient, however, to indicate that not even the order of magnitude of the concentration of deuterium has been known in any organic compound.

It is the purpose of this paper to determine the concentration of deuterium in benzene, eliminating as far as possible all of the uncertainties listed above. Benzene was chosen for this study because of its importance in organic chemistry, because it contains no oxygen (thereby eliminating uncertainty number 2), because it is a pure compound and not a mixture like honey, for example, because it contains hydrogen that has been held under the surface of the earth for thousands of years and finally because the hydrogen in the benzene cannot exchange with the hydrogen of water during the commercial process of purification.

Experimental

The density measurements were carried out in the manner previously described,[13] except that the Beckmann thermometer was immersed directly in the water with the float, thus enabling the temperature to be brought rapidly to the desired value before observing the motion of the float. The temperature of floating equilibrium with normal water changed during the period January 1, 1934, to October 22, 1935, from 2.703 to 2.763, this change in part being due to a change in the Beckmann thermometer, 2.700 on the Beckmann now being 23.399° instead of 23.412° and in part perhaps to loss of weight of the Pyrex float due to solution of Pyrex glass in water since the float was kept continually submerged in distilled water when not in use.

All the water obtained in the experiments described below was purified according to the following procedure. Since the normal water for comparison was purified in the same way, the volumes, residues, etc., being approximately equal, it is believed that uncertainty number 7 was eliminated. About 450 cc. of water was taken for examination, this water being distilled from alkaline permanganate over copper oxide heated to 500–600°, a small residue containing the permanganate being rejected. A distillation from acid permanganate then followed, rejecting a small residue, and measuring the density of the intermediate water. A third distillation from alkaline permanganate followed and the density measured. Usually the density remained unchanged after this third distillation, but if it had changed, a fourth distillation, from acid permanganate, followed, and the density was finally measured.

The Atomic Weight of Commercial Oxygen.—The benzene was burnt three times using three different samples of commercial oxygen, the results indicating that all three tanks contained oxygen of slightly different atomic weight. In order to determine the atomic weight of the first sample of oxygen, Burdette Co. electrolytic oxygen, illuminating gas was burned in two identical apparatuses simultaneously with air and with the Burdette oxygen, the latter being enriched with tank nitrogen to produce an artificial air in order that the two combustions be exactly similar. Illuminating gas was also burned with Burdette oxygen without any added nitrogen, the results of these three combustions are given in Table II.[14] The second and third samples of oxygen, Linde and Air Reduction Co. oxygen, respectively, were burned with tank hydrogen and the water so obtained compared with the water from the combustion of the same tank (number 3) hydrogen with air. It was early realized, due to the discovery of Melville[15] and of Hinshelwood, Williamson and Wolfenden,[16] that protium and deuterium combined at different rates with oxygen that there might be a difference in the density of the water depending on the presence of excess oxygen, air or hydrogen in the flame. This possibility was tested by burning hydrogen (from tank number 2) with air first with roughly 20% excess of hydrogen, then with air in about the same excess and finally with the air and hydrogen in exactly equivalent quantities. The gases were passed through a capillary tube sealed into a larger tube which contained heated copper oxide. The condition of the copper indicated whether air or hydrogen was in excess and enabled the two gases to be passed through the tube in equivalent quantities. When the copper was heated to a white heat by the reaction, the explosion wave traveled back to the tip of the inner glass capillary tube where the gases burned nicely in a flame. This apparatus was used whenever it was desired to burn hydrogen and oxygen in equivalent quantities so that there would be no question

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[13] M. Dole, *J. Chem. Phys.*, **2**, 337 (1934).

[14] γ is easily calculated by multiplying the change in temperature by 231, the p. p. m. decrease in the density of the water per degree rise of temperature at 23.4° corrected for a decrease in the density of the Pyrex float to the extent of 10 p. p. m. per degree rise of temperature.

[15] H. W. Melville, *J. Chem. Soc.*, 797 (1934).

[16] C. N. Hinshelwood, A. T. Williamson and J. H. Wolfenden, *Proc. Roy. Soc.*, **A147**, 48 (1934).

of a separation of the isotopes of either gas. The results of these combustions are summarized in Table II and indicate that there is no appreciable separation of isotopes under the conditions of these experiments. Hall and Johnston[17] find a difference of density of 4 to 5 p. p. m. in the water obtained on burning tank hydrogen in large excess with oxygen from the electrolysis of water and in an excess of air. They attribute this difference to the higher rate at which H_2 reacts with oxygen in comparison with HD, but we know now that the difference is to be explained practically entirely on the difference between the atomic weight of oxygen in water and in air.

The results for the Linde oxygen and the Air Reduction Co. oxygen are also given in Table II. By use below of the correction factors given in Table II which correct the atomic weight of commercial oxygen to that of atmospheric oxygen, uncertainty number 1 above is eliminated.

TABLE II

DATA FOR THE ATOMIC WEIGHT OF COMMERCIAL OXYGEN RELATIVE TO THAT OF ATMOSPHERIC OXYGEN

Source of water	Δt, °C.	γ
Air and illuminating gas	+0.022	
	+ .022	
Average	+ .022	+5.1
Burdette oxygen and nitrogen and illuminating gas	− .013	
	− .012	
Burdette oxygen and illuminating gas	−0.013	
	− .011	
	− .014	
Average of all oxygen data	− .013	−3.0
Correction to Burdette oxygen	+ .035	+8.1
Air + excess tank 2 hydrogen	− .014	
	− .014	
Excess air + tank 2 hydrogen	− .017	
	− .015	
Air + tank 2 hydrogen (equivalent quantities)	− .016	
	− .013	
Air + tank 3 hydrogen (two combustions)	− .016	
	− .016	
	− .016	
	− .019	
	− .018	
	− .017	
Average	− .017	−3.9
Linde oxygen + tank 3 hydrogen (two combustions)	− .011	
	− .011	
	− .008	
	− .007	
	− .009	
Average	− .010	−2.3
Correction to Linde oxygen	− .007	−1.6
Airco oxygen + tank 3 hydrogen (two combustions)	− .015	
	− .013	
	− .016	
	− .016	
Average	− .015	−3.5
Correction to Airco oxygen	− .002	−0.5

Isotopic Exchange between Water and Carbon Dioxide.—The possibility of isotopic exchange of the oxygen atoms between carbon dioxide and water in the direction of an increased concentration of O^{18} in the carbon dioxide during the process of condensing the water from the hot gases was investigated by passing carbon dioxide over water at 75° and later condensing the water vapor and measuring the density of the water. Since it was known that commercial carbon dioxide is scrubbed with water during its purification, thereby possibly bringing the O^{18} concentration to its equilibrium value,[18] it was necessary to prepare fresh carbon dioxide containing oxygen of the same isotopic composition as the oxygen in the water. Accordingly tank hydrogen was burned with air and charcoal also with air, the carbon dioxide then being passed over the water kept at 75°; the water vapor and the carbon dioxide with a small volume of added air to complete the combustion of the carbon monoxide were next passed over hot copper oxide and the mixed gases finally flowed through a condenser where the water was recondensed. A total of 265 cc. of water was obtained from the evaporation of 290 cc. and 244 g. of charcoal burned. The ratio of carbon dioxide to water was thus 20 moles to 14 moles whereas in the combustion of benzene the ratio would be 2 to 1. After purification of the water, no difference in density could be observed between this water and some of the water originally obtained from the tank hydrogen and air. The data are given in Table III and should not be interpreted as contradicting the findings of Urey and co-workers inasmuch as equilibrium between the carbon dioxide and water was not obtained. The results prove, however, that isotopic exchange in the condensation of the water as carried out here does not occur to any appreciable extent, thereby eliminating uncertainty number 3 listed above.

TABLE III

DATA PROVING THE ABSENCE OF THE FRACTIONATION OF THE OXYGEN ISOTOPES DURING COMBUSTION REACTIONS, AND THE ABSENCE OF THE FRACTIONATION OF THE ISOTOPES OF WATER ON PARTIAL CONDENSATION OF ITS VAPOR

Source of water	Δt, °C.
Special water not exposed to carbon dioxide	−0.017
	− .017
Special water exposed to carbon dioxide	− .017
	− .017
Special water ($H_2{}^TO^{T,E}$) after electrolysis	− .023
	− .023
Water ($H_2{}^TO^{T,C,E}$) from the benzene combustion after electrolysis	− .023
	− .022
Evaporated and condensed water	− .001
	− .003

Fractionation of Oxygen Isotopes during the Combustion.—The possibility of the fractionation of the isotopes of hydrogen, uncertainty number 5, was eliminated by burning the benzene in an excess of oxygen. However, the presence of an excess of oxygen suggested the possibility of the fractionation of its isotopes. Another possibility is that the isotopes of oxygen might react separately with carbon and hydrogen at different rates producing an increased concentration of O^{18} in the carbon dioxide or the

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(17) W. H. Hall and H. L. Johnston, THIS JOURNAL, **57**, 1515 (1935).

(18) W. H. Hall and H. L. Johnston *ibid.*, **57**, 1515 (1935)) have recently discovered that this actually occurs.

water. To answer these questions it was first planned to burn acetylene made from calcium carbide and water; the density of the water obtained from the combustion on comparison with the original water would demonstrate the existence or non-existence of a fractionation of the oxygen isotopes. Some orienting experiments soon showed, however, that deuterium-free water would have to be used to eliminate errors caused by a separation of the hydrogen isotopes. A method suggested by Professor Urey for the investigation of the atomic weight of oxygen in water by electrolyzing the water and combining the oxygen with known hydrogen was then adopted, water from the benzene combustion being electrolyzed, the oxygen combined with tank hydrogen and the density of the resulting water compared with water similarly treated in regard to the electrolysis and originally made from the same oxygen used in the benzene combustion. These experiments are best outlined by the following reactions where the superscripts T, B, C, E, mean from tank, from benzene, from combustion, from electolysis, respectively.

$$H_2^{T} + O_2^{T} \xrightarrow[\text{Equiv. quantitites}]{} H_2^{T}O^{T} \tag{1}$$

$$C_6H_6^{B} + O_2^{T}\ (\text{Excess}) \longrightarrow H_2^{B}O^{T,C} \tag{2}$$

$$H_2^{T}O^{T} \xrightarrow[\text{Electrolysis}]{} H_2^{T,E} + O_2^{T,E} \tag{3}$$

$$O_2^{T,E} + H_2^{T} \xrightarrow[\text{Equiv. quantities}]{} H_2^{T}O^{T,E} \tag{4}$$

$$H_2^{B}O^{T,C} \xrightarrow[\text{Electrolysis}]{} H_2^{B,E} + O_2^{T,C,E} \tag{5}$$

$$H_2^{T} + O_2^{T,C,E} \xrightarrow[\text{Equiv. quantities}]{} H_2^{T}O^{T,C,E} \tag{6}$$

A comparison of the densities of the two waters, $H_2^{T}O^{T,E}$ and $H_2^{T}O^{T,C,E}$, enables an estimate of the extent to which the oxygen isotopes are fractionated in reaction (2). The results given in Table III prove that any such fractionation is inappreciable if it exists at all, thereby eliminating uncertainty number 4.

Fractionation of the Isotopes of Water on Partial Condensation.—The author[19] has already pointed out that partial condensation of water may result in an increased density of the water so condensed. This effect is important where relatively large volumes of uncondensable gases pass through the condenser; in the experiments, for example, on burning benzene at a wick in a rapid stream of air. To overcome this difficulty the combustions described below were performed using pure oxygen, the water being obtained about seven times as rapidly. Nevertheless, it was deemed necessary to prove that even this latter method was free of error. Nitrogen gas was passed through normal water kept at 84° at about the same rate as the uncondensable gases in the benzene combustion passed through the condenser for roughly an equal period of time, obtaining an equal volume of condensed water. (All the sample of normal water was evaporated.) The data for this evaporated and condensed water are also given in Table III, and prove that no appreciable separation of the isotopes of water occurred, thereby eliminating uncertainty number 6 listed above. The other data of Table III also show this statement to be true.

Combustion of Benzene.—After all the above questions concerning this type of research had been eliminated it became possible to proceed with the combustion of benzene and to calculate the concentration of deuterium in benzene with some degree of certainty. Two samples of benzene, C. P. thiophene-free benzene (Mallinckrodt from coal) and practical benzene, were used as the source of benzene and three commercial brands of oxygen served as the source of oxygen. The benzene was heated to 65° in a water-bath, its vapors being swept into a hand torch by nitrogen from a commercial tank. The experiments on the combustion of acetylene mentioned above indicated that the nitrogen also served to prevent the mixed benzene-oxygen gas from "back-firing" into the hand torch. The hand torch was sealed into a glass cylinder (after the benzene flame was lighted) provided with a side arm loosely plugged to act as a safety vent in case of an explosion in the cylinder and the cylinder was also surrounded with wire gauze as a further precaution. The benzene burnt with a blue flame, the vapors being passed through a water-cooled condenser where the water vapors condensed. The water was purified and the density measured as described above. Table IV contains the data for the three series of experiments. The exact agreement between the last two series is considered rather fortuitous in view of the number of density measurements involved in the calculation of the final data. The final average of all probably involves an error not greater than 1γ; *i. e.*, 1 p. p. m. in the density.

Calculation of the Concentration of Deuterium in Benzene.—Before the calculation of the concentration of deuterium in benzene can be made it is necessary to correct the data of Table IV for the difference between the atomic weight of oxygen in air and in Lake Michigan water. As explained above, this correction is −6.0

TABLE IV

DATA OBTAINED IN THE COMBUSTION OF BENZENE

Source of water	Δt, °C.	γ
1. Benzene Burned with Burdette Oxygen		
Benzene + Burdette oxygen	−0.010	
	− .009	
Average	− .009	−2.1
Correction for Burdette oxygen	+ .035	+8.1
Corrected result	+ .026	+6.0
2. Benzene Burned with Linde Oxygen		
C. p. Benzene + Linde oxygen	+0.035	
	.035	
	.036	
Prac. benzene + Linde oxygen	.038	
	.037	
	.036	
Average	+ .036	+8.3
Correction for Linde oxygen	− .007	−1.6
Corrected result	+ .029	+6.7
3. Benzene Burned with Airco Oxygen		
Benzene + Airco oxygen	+0.032	
	.030	
	.031	
Average	+ .031	+7.2
Correction for Airco oxygen	− .002	− .5
Corrected result	+ .029	+6.7
Average of three series	+ .028	+6.5

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[19] M. Dole, *J. Chem. Phys.*, **2**, 548 (1934).

p. p. m.; hence, we have as the difference of density between water made from the hydrogen of benzene and normal water only 0.5 p. p. m. This difference is so small that it can hardly be considered as significant. If it is accepted, it is possible to calculate that there is about 3% more deuterium in the hydrogen in benzene than in the hydrogen of Lake Michigan water. Such a slight difference might possibly arise in the process of producing benzene from coal or in the later purification procedures. But since the experimental error involved in the many density measurements necessary to arrive at this result may be as large or even larger than 0.5 p. p. m., we are led to the conclusion that the atomic weight of hydrogen in benzene does not differ significantly from that of the hydrogen in Lake Michigan water.

Discussion of Other Data.—A calculation of the concentration of deuterium in the other organic compounds listed in Table I would be more or less uncertain due to the fact that the exact correction to apply for the difference between the atomic weight of oxygen in air and water is unknown in each case. In some work to be reported in *Science*, it will be shown that there is a slight but nevertheless significant difference between the atomic weight of oxygen in water from Lake Michigan and from Nevada. The datum of Snow and Johnston can be corrected with some certainty since the water of Ohio is probably the same as the water of Illinois; if a correction of $-6.0\ \gamma$ is applied to their figure of $6.1\ \gamma$, there is no excess density left. This means that the atomic weight of hydrogen in Oklahoma butane is normal (within the experimental errors involved). Probably an accurate determination of the atomic weight of hydrogen in most of the other compounds listed in Table I would also show it to be normal, or at least much more nearly normal than has previously been thought.

Summary

The abundance of deuterium in benzene has been measured by burning benzene with oxygen and comparing the density of the resulting water with normal water. It is demonstrated that the atomic weight of the oxygen used in the combustion must be determined in order for the data to have any significance. Other possible sources of error such as exchange of the oxygen isotopes between carbon dioxide and water, fractionation of the oxygen isotopes during combustion, fractionation of the isotopes of water during the condensation process, etc., are shown to be negligible. When the important correction is made for the difference between the atomic weight of oxygen in water and in air, the excess density of the benzene water over that of Lake Michigan water is only 0.5 p. p. m. which is not considered to be significant. Data obtained by other workers is discussed and the conclusion is reached that the atomic weight of hydrogen in organic compounds is more nearly normal than has hitherto been suspected.

EVANSTON, ILLINOIS RECEIVED OCTOBER 31, 1935

[CONTRIBUTION FROM THE LILLY RESEARCH LABORATORIES]

The Relation of the Structure of Dialkyl Barbituric Acids to the Length of their Action[1]

BY H. A. SHONLE, J. H. WALDO, A. K. KELTCH AND H. W. COLES[2]

Over fifty dialkyl barbituric acids have been studied in an investigation correlating the structure to the length of action, effectiveness, depth of anesthesia, and toxicity, as determined by the intraperitoneal injection of solutions of their sodium salts in white rats.[3] During this investigation a number of new barbituric acids were prepared in order to determine the specific effect of certain desired alkyl groups. A brief pharmacological report already has appeared.[3,4]

These new barbituric acids were prepared as previously described.[5] The primary alcohols were converted into bromides, using phosphorus tribromide, or hydrobromic acid in sulfuric acid solution, while the secondary bromides were prepared by the action of dry hydrogen bromide,[6] or in a few instances by phosphorus tribromide.[7]

These alkyl bromides, after being carefully fractionated in vacuum, were condensed with an absolute alcoholic solution of sodio-ethyl ethylmalonate. The alkyl malonic esters so obtained were purified by fractional distillation under vacuum. The various alkyl ethyl malonic esters

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(1) Presented at the St. Petersburg, Florida, meeting of the American Chemical Society, March 25–30, 1934.

(2) Present address: Mellon Institute, Pittsburgh, Pennsylvania.

(3) E. E. Swanson, *Proc. Soc. Exptl. Biol. Med.*, **31**, 961 (1934).

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