

Liversidge Research Lecture

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1948

SOME RECENT WORK ON THE SEPARATION AND USE
OF STABLE ISOTOPES

I. LAUDER



The Royal Society of New South Wales



Ian Lauder 1914 -

IAN LAUDER 1914 - 2008

Ian Lauder was born on 6 April 1914 in Christchurch, New Zealand. After secondary education at Christchurch Boy's High School during 1928-32, he studied at Canterbury University College (Christchurch), University of New Zealand (now the University of Canterbury, Christchurch). In his second year (1934) he was awarded the Haydon Prize in Chemistry, and in 1935 he graduated B.Sc. with the award of both the Sir George Grey Scholarship in Chemistry, and the Senior Scholarship in Chemistry. In 1936 he graduated M.Sc. with 1st. class Honours in Organic Chemistry, and the award of the Charles Cook Warwick-House Memorial Fellowship in Chemistry that enabled him to continue research at Canterbury University College during 1937, working under Dr. H.N. Parton on the oxidation-reduction potential of 2,6-dichlorophenol indophenol. The award of an 1851 Exhibition Science Research Scholarship and a Free Passage (England - New Zealand return) in 1937 took him to the University of Manchester where he worked on oxygen-18 exchange reactions between water and oxygen-containing organic compounds under the supervision of Professor M. Polanyi and Mr. J.B.M. Herbert. He was awarded the degree of Ph.D. from the University of Manchester in July 1939, and in that same year he was awarded a Senior Fellowship by the Department of Scientific and Industrial Research (DSIR, United Kingdom). With war apparently imminent, he returned to New Zealand for a short visit before taking up the DSIR award, but war broke out the day he arrived in New Zealand, and he decided to give up the DSIR Fellowship. In January 1940 he applied for and was appointed as Research Officer in the newly established Lubricants and Bearings Section, CSIR, located at the University of Melbourne (see Bowden, Liversidge Research Lecturer No. 5, 1944). While there he worked on the development of a "cutting fluid" which was required by the Commonwealth Aircraft Corporation (CAC) at Fishermen's Bend (Melbourne), because the USA government had prohibited the export of the "cutting fluid" which the CAC was using in machining operations. The preliminary laboratory work on this project was carried out in the Department of Mechanical Engineering, University of Melbourne where Mansergh Shaw was the academic in charge of the workshops. Shaw later became the Professor of Mechanical Engineering at the University of Queensland, and the good liaison which Ian Lauder developed with Shaw at Melbourne proved to be valuable later on in the construction of an isotope-ratio mass spectrometer at the University of Queensland in 1953-5.

In 1940 Ian Lauder accepted the appointment of Lecturer in Chemistry at the University of Queensland where he was promoted to Associate Professor in 1946. His main research interests have concerned the use of oxygen-18 as a tracer in the study of chemical reactions, and in mass spectrometry. In 1952, with both a Carnegie Corporation of New York Travel grant and a Fullbright Travel Grant, he spent a year's Study Leave with Visiting Fellowships, partly at the Department of Physics, University of Minnesota, Minneapolis, Minnesota, USA, and partly at Princeton University, New Jersey, USA. While at Minnesota Lauder studied mass spectrometry with Professor A.O.C. Nier, and after his return to the University of Queensland the isotope-ratio mass spectrometer referred to above was constructed. Later on Lauder had both a small 180° deflection mass spectrometer, and a small quadrupole

instrument constructed. In 1960-61, and also in 1964, he spent study leave as Visiting Professor at the Department of Physical Chemistry, University of Leeds, England, funded by a Royal Society - Nuffield Foundation Travel Grant. He later held Visiting Professorships at the Université Libre de Bruxelles, Belgium (1970-71), and at Universität Erlangen-Nürnberg, Wissenschaften III Glas und Keramik, Erlangen, West Germany (1975-76). In 1967 he participated in two International Conferences - one on Mass Spectrometry in Berlin, Germany, and the other on High Temperature Chemistry in Semmering, Austria; he also spent time at the firm Krupp in Bremen, Germany where additional accessories were then under construction for the Atlas CH4 mass spectrometer which had been made by Krupp for the University of Queensland in the previous year. He retired from his position in the Chemistry Department, University of Queensland in 1979.

In a letter to the author dated 18 July, 2000, Ian Lauder included the following recollection of the evening of his 1948 Liversidge Lecture:

I shall never forget that Liversidge Lecture. Several members of the NSW Royal Society took me to a restaurant for a meal before the lecture which was due to start at 8 pm at Sydney University. We left the restaurant in ample time to get to the University by taxi, but there were none about. War-time conditions still prevailed! Finally David Mellor did get one. We arrived at the University 15 minutes late! The room was full of noise - people shuffling feet and talking. I had brought with me some glass apparatus about one metre long to illustrate the separation of gases by thermal diffusion. Someone set up this apparatus, in working condition, on the lecture bench. Then Professor Le Fèvre, with me in tow, walked rapidly to the lecture dais. I wasn't warned about the step! I almost went sprawling on hands and knees behind the lecture table! No physical damage was done. Despite the initial inauspicious events, the lecture and demonstration went well.

Honours and Awards (Pre-2001)

- 1946 D.Sc., University of Queensland
- 1946 FRACI
- 1948 Liversidge Research Lecture, Royal Society of New South Wales
- 1960 Royal Australian Chemical Institute (RACI) Visiting Lecturer, University of Sydney
- 1962 RACI Visiting Lecturer, University of New South Wales
- 1971 University Medal, Université Libre de Bruxelles, Belgium, in recognition of Ian Lauder's contribution to the re-establishment of the work of the Faculty of Science after a disastrous fire in the Science Building
- 1979 Honorary Fellow, RACI

Biographical Source: Personal communication

Obituary: J. Cotton, "Ian Lauder 1914-2008", *Chemistry in Australia*, 2009, **76** (3), 22.

Scientific Publications of I. Lauder

Forty-eight publications on chemistry between 1938 and 1980.

SOME RECENT WORK ON THE SEPARATION AND USE OF STABLE ISOTOPES*

I. LAUDER

Chemistry Department, University of Queensland, St. Lucia, Queensland

Mr. President, Ladies and Gentlemen,

I wish to express my appreciation of the invitation to deliver this year's Liversidge Research Lecture as this is, indeed, a high honour. The University of Queensland is greatly handicapped by its isolation, and it is not often that a member of its staff is asked to deliver a special lecture at some other university. For this reason, too, I very much appreciate the invitation.

I have chosen for the title of this address "Some Recent Work on the Separation and Use of Stable Isotopes". There have been many outstanding achievements in science in the past ten to fifteen years, and I think that the development of methods for separating isotopes must come within this category, not only because of its immediate interest to chemistry, but also because a vast amount of important information has been gained by the use of the separated isotopes.

The existence of isotopes of radio-active elements was first established in 1911, and two years later J.J. Thomson demonstrated for the first time the existence of isotopes of a stable element - neon - of mass numbers 20 and 22. With the subsequent development of the mass-spectrograph by Aston, the isotopic compositions of most elements are now known.

Although the basic principles of most of the methods now used for the separation of isotopes have been known for many years, it was not until 1932 and later that any large-scale separations were achieved. It is interesting to note that work on the detection and separation of isotopes was suspended during World War I, whereas during World War II such work reached an immense climax with the development of the atomic bomb.

Part I. Methods of Separation

Except in the case of hydrogen, only small differences in chemical and physical properties of isotopes exist, and these differences decrease relatively with increasing atomic weight, thus increasing the difficulty of separation. The hydrogen isotopes were the first to be separated in an almost pure state. This was achieved in 1933 by Lewis and MacDonald⁽¹⁾ by the continued electrolysis of water. The process is so well known that it need not be considered further, but it may be added that in the case of isotopes of other elements only very small separations have been obtained by electrolysis.

The separation of small amounts of ions of different masses has been achieved by the

*Liversidge Research Lecture delivered before the Royal Society of N.S.W., August 19th, 1948. Reproduced by permission of the Royal Society of New South Wales from *J. Proc. Roy. Soc. N.S.W.*, 1948, **82**, 183-195.

use of the mass-spectrograph and, during the war years, a large-scale development of this method took place for the separation of the uranium isotopes. I am not familiar with this development and may be permitted to exclude it from further consideration

Omitting, then, any discussion on the electrolytic and the electromagnetic methods, the following methods have been used to achieve considerable degrees of separation: (1) diffusion, (2) distillation, (3) chemical exchange, (4) thermal diffusion. The important applications of each of these methods will be considered and, in addition, the centrifugal method of separation may be considered. This latter method has not resulted in any important degree of separation as yet, but it may become of importance in the future, especially for the separation of isotopes of high molecular weight.

(1) *Diffusion Methods*

The rate of gaseous diffusion varies inversely as the square root of the molecular weight, and so isotopic molecules should diffuse at slightly different rates. This method was first applied by Aston in an attempt to separate the isotopes of neon, but only a very limited success was achieved. The atomic weight of neon of normal isotopic ratio is 20.2, while Aston obtained ultimately two fractions with atomic weights 20.15 and 20.28 respectively.

In all methods of separation a quantity known as the separation factor is of interest. This is given by the ratio of the isotopes after applying the separation process to the ratio before applying the separation process. That is, the separation factor with respect to the heavy molecules,

$$S = \frac{N_h / N_l \text{ (after applying separation process)}}{N_h / N_l \text{ (before applying separation process)}} \dots\dots\dots (1)$$

where N_h , N_l stand for the numbers of heavy and light molecules respectively. To achieve a maximum separation by the diffusion method, it is necessary to ensure that there is perfect mixing of the gas on each side of the porous barrier through which diffusion occurs and also that the mean pore diameter of the barrier is small in comparison with the mean free path of the diffusing gas. This is a rather stringent condition, as for most gases at one atmosphere pressure and room temperature the mean free path is of the order 10^{-5} cm. The mean free path varies inversely with pressure, and so by working at lower pressures a barrier with a larger pore diameter may be used.

For a separation by gaseous diffusion under ideal conditions the separation factor (with respect to the heavy molecules) is given approximately by the expression

$$S = \frac{M_2 + M_1}{M_2 - M_1} \sqrt{\frac{\text{Initial Volume}}{\text{Final Volume}}} \dots\dots\dots (2)$$

where M_2 and M_1 stand for the molecular weights of the heavy and light molecules respectively. If half of the initial volume of gas is allowed to diffuse through the barrier, then, for the neon isotopes of molecular weights 22 and 20, $S = 1.034$. Thus only a small degree of separation is achieved in each diffusion unit, but by connecting a sufficient

number of units in series any desired concentration of isotope may be achieved. The over-all separation factor for n units in series equals S^n .

The first successful apparatus for the continuous separation of isotopes by gaseous diffusion at low pressure was devised by Hertz⁽²⁾ in 1932, using porous porcelain tubes as the diffusion barrier. With 48 units operating in series, Hertz⁽³⁾ produced practically pure ^{22}Ne from normal neon. In the same apparatus, starting from hydrogen containing 10% deuterium, spectroscopically pure deuterium⁽⁴⁾ was isolated. Carbon⁽⁵⁾ containing 16% ^{13}C and nitrogen⁽⁶⁾ containing 3% ^{15}N have been isolated by this type of diffusion method.

Later, in 1934, Hertz⁽⁷⁾ produced a still more efficient unit in which a stream of mercury vapour served as the diffusion barrier, and at the same time it served to pump the gas undergoing diffusion from one unit to another. This modification has been used to produce oxygen⁽⁷⁾ containing 0.5% ^{18}O , argon⁽⁸⁾ containing 50% ^{36}Ar , carbon⁽⁹⁾ containing 30% ^{13}C , and nitrogen⁽¹⁰⁾ containing 9% ^{15}N .

Any account of the diffusion method of separation of isotopes could not be regarded as complete without some mention of its recent application to the separation of the uranium isotopes ^{235}U and ^{238}U using uranium hexafluoride, UF_6 as the carrier gas. A limited amount of information on the process is given in the Smythe Report.⁽¹¹⁾ Assuming that the separation factor for a single unit is 1.0013 and that 4,000 units are operated in series, the over-all separation factor comes out to 173.8. If the first unit is fed with UF_6 of normal isotopic ratio (0.7% $^{235}\text{UF}_6$), UF_6 containing approximately 55.5% $^{235}\text{UF}_6$ would be produced in the last unit when equilibrium is established. The concentrating cascade of 4,000 units would be run in combination with a stripping cascade for treating the impoverished gas from stage 1. By a partial removal of $^{238}\text{UF}_6$ in the stripping cascade, the $^{235}\text{UF}_6$ content of the impoverished gas is built up to its normal value. The gas from the first unit of the stripping cascade is then re-circulated to the first unit of the concentrating cascade. If it is economical to discard the UF_6 when the $^{235}\text{UF}_6$ content has been reduced to half the normal value, the stripping cascade would consist of about 538 units operating in series.

For each cubic centimetre of 55.5% $^{235}\text{UF}_6$ withdrawn from the last unit of the concentrating cascade 157 c.c. of 0.35% $^{235}\text{UF}_6$ would be drawn off from the last unit of the stripping cascade. These withdrawals would be balanced by the input of 158 c.c. of normal UF_6 to stage 1. For each cubic centimetre of output from the last unit of the concentrating cascade about 120 litres of UF_6 would pass through the first unit, and so the total circulation in all stages would be very high indeed.

(2) Distillation

The separation of liquids of different boiling points by fractional distillation is a well-understood process. Experiment shows that a fractionation column of the packed type gives concentrations in accordance with the formula

$$\frac{C_t}{1 - C_t} \bigg/ \frac{C_b}{1 - C_b} = \alpha^K \quad \text{-----} \quad (3)$$

where C_t and C_b are the mole fractions of one constituent at the top and bottom respectively. α is the ratio of the vapour pressures and K is the number of theoretical

plates. Values of α for H_2^{16}O and H_2^{18}O forms of water at various temperatures are given in the following table.⁽¹²⁾

TABLE 1

Temperature °C.	α
11.25	1.013
35.6	1.008
46.35	1.007
100.0	1.003

When α is nearly unity, as it is in the case of the separation of most isotopes, K must be large if a large change in the concentration of isotopes is desired. To secure a large K , the length of the column should be made large, and also the efficiency of the column should be made as high as possible by the use of a suitable packing material. The value of α increases with decreasing temperature and so the degree of separation is increased by working at as low a temperature as is conveniently possible.

The method has found its chief application to the separation of the isotopic forms of water. In one column six inches in diameter and 35 feet high set up by Pegram, Huffmann, and Urey⁽¹³⁾ after 300 hours operation water containing 0.85% ^{18}O was produced. If equilibrium had been set up, approximately 20 c.c. of water containing about 2.5% ^{18}O could have been withdrawn daily. In the same still Roberts and Urey⁽¹⁴⁾ fractionated normal methyl alcohol to produce alcohol enriched in the heavy oxygen isotope ^{18}O . No separation of the heavy carbon forms of the alcohol was obtained.

The vapour pressures of the isotopic hydrogen forms of water differ more than the vapour pressures of the isotopic oxygen forms of water.⁽¹²⁾ Accordingly, it is found that deuterium concentrates at a faster rate than the heavy oxygen during the fractionation process. The Smythe Report mentions that one of the methods used for the separation of deuterium required for the work on atomic energy was by the fractionation of water, but no details of the still used are given.

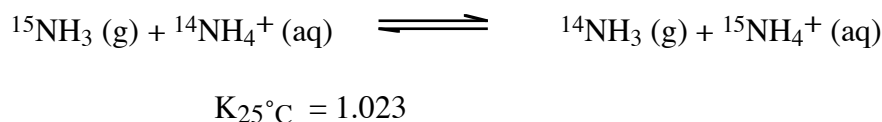
Recently, Dostrovsky and Hughes⁽¹⁵⁾ have published a short note giving details of a very efficient packed column 0.8 inch internal diameter and 12 feet high which produced after 24 hours' operation 500 c.c. of water containing 0.2% D and 0.55% ^{18}O . It is apparent from these figures that the column is highly efficient and is capable of supplying relatively large quantities of the heavy isotopes of hydrogen and oxygen at concentrations usually sufficient for exchange experiments.

(3) *Chemical Exchange*

If the chemical properties of isotopes were identical, the equilibrium constants for isotopic exchange reactions would be unity. That this is not so was first indicated by the calculation of equilibrium constants of certain exchange reactions by Urey and Rittenberg.⁽¹⁶⁾ For reactions involving isotopes of elements of low atomic weight, the constants usually differ from unity by a few per cent., but this difference decreases with increasing atomic weight and also with increasing temperature. The chemical method of

separating isotopes is thus restricted to isotopes of low atomic weight and it is best carried out at as low a temperature as is conveniently possible.

For the separation of ^{15}N the following exchange reaction was used:

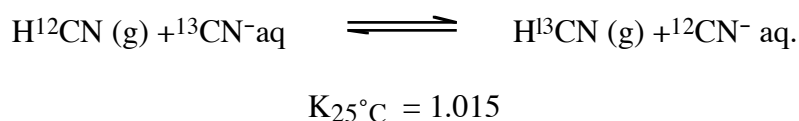


The ^{15}N collects preferentially in the liquid phase.

The technique of the method is to establish a counter-current flow of ammonium nitrate solution and ammonia gas in a packed fractionating column. If several columns are operated in series, the sizes are reduced proportionally so as to keep the transport of the heavy isotope in each column practically the same. If the first column increases the concentration of ^{15}N by a factor of 10, for example, 9/10 of the liquid draining out of the bottom of the column is mixed with sodium hydroxide solution. The ammonia liberated is fed back into the bottom of the first column together with the ammonia issuing from the top of the second column. The remaining 1/10 of the flow from column 1 is fed into the top of the second column, and so on.

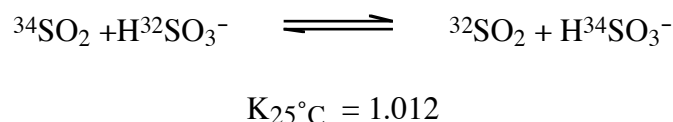
Using a three-stage apparatus of total length 43.5 metres, Urey⁽¹⁷⁾ and co-workers isolated nitrogen containing 70.6% ^{15}N .

Heavy carbon, ^{13}C , has been concentrated by making use of the exchange reaction⁽¹⁸⁾



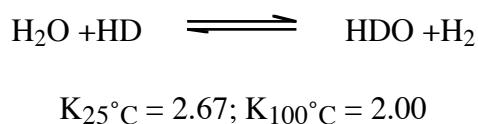
The ^{13}C tends to collect in the gas phase. In a two stage apparatus up to 22% ^{13}C has been produced at the rate of 0.1 gm. ^{13}C per day.

For the concentration of ^{34}S use was made of the exchange reaction⁽¹⁹⁾



In a three-stage apparatus sulphur containing 25% ^{34}S was produced at the rate of 3.2 gm. per day.

As mentioned in the Smythe Report, the exchange reaction between water vapour and gaseous hydrogen in the presence of a suitable catalyst was used during the atomic bomb work for concentrating heavy hydrogen. The equilibrium favours the accumulation of deuterium in the water.⁽²⁰⁾



(4) *Thermal Diffusion*

In 1938 Clusius and Dickel⁽²¹⁾ introduced a method of separation of isotopes by thermal diffusion which has proved very effective in many cases. Essentially, the apparatus consists of a vertical water-jacketed tube down the centre of which is stretched a wire which may be heated electrically to the desired temperature. The partial separation of light and heavy molecules which this type of apparatus may produce in a gaseous mixture is due to two effects: (1) due to thermal diffusion, the heavy molecules, in most cases, tend to concentrate near the cool wall of the tube and the light molecules near the hot wire; (2) due to the difference in density between the cold gas and the hot gas, a thermal siphon is set up in the tube which transports the light molecules to the top of the tube and the heavy molecules to the bottom of the tube. The separation produced by these two effects increases until it is just counterbalanced by the remixing effect of ordinary diffusion.

The various factors which influence the efficiency of such separation columns have been investigated by many workers.⁽²²⁾ For a gas containing molecules of weights M_1 and M_2 and mol. fractions C_1 and C_2 respectively, subjected to a thermal gradient (in the absence of convection currents), the relative difference in mol. fraction of either constituent is given by

$$\Delta C = k_T \log_e T_2 / T_1 \quad \dots\dots\dots (5)$$

where T_2 and T_1 ($T_2 > T_1$) represent the temperatures at the two ends of the gradient and k_T is the coefficient of thermal diffusion. For isotopic molecules behaving as elastic spheres,

$$k_T = \frac{105}{118} \times \frac{M_2 - M_1}{M_2 + M_1} \times C_1 C_2 \quad \dots\dots\dots (6)$$

Due to deviations from the perfect gas state, the k_T values for real gases are found to be less than the calculated values. Approximate values of k_T for actual gases may be obtained from viscosity data.⁽²³⁾ If S is the repulsive force index of the molecules and η the coefficient of viscosity, then

$$k_T \text{ (actual gas)} = k_T \text{ (perfect gas)} \times \frac{S - 5}{S - 1} \quad \dots\dots\dots (7)$$

and

$$\log \eta = \frac{S + 3}{2(S - 1)} \log T + \text{constant} \quad \dots\dots\dots (8)$$

If $S > 5$, the heavy molecules tend to concentrate near the cold end of the gradient; if $S < 5$, the separation occurs in the opposite direction; if $S = 5$, no separation by thermal diffusion is possible. Some values for $(S - 5) / (S - 1)$ for various gases are given in Table 2. This data suggests that carbon monoxide would prove more suitable than oxygen for the separation of the oxygen isotopes, but other factors such as ease of preparation in a pure state and thermal stability must be considered.

TABLE 2.

Gas.	S.	$\frac{S-5}{S-1}$
He	13.1	0.67
Cl ₂	5.1	0.02
O ₂	9.7	0.54
CO	11.8	0.63
SO ₂	4.6	-0.10

The concentration of heavy isotope at the bottom of a separation tube when equilibrium is set up is found to be proportional to (1) r^{-4} where r is the radius of the tube, (2) the length of the tube provided the mol. fraction is within the range 0.25 - 0.75, (3) p^{-2} provided the pressure is not too low.

The rate at which equilibrium is established in a column is proportional to r^4 , and to p^2 . In practice, it is found that the time required to establish a given concentration difference may be decreased by starting the apparatus at a pressure greater than the optimum working pressure and subsequently as the separation proceeds by reducing the pressure to the optimum working pressure.⁽²⁴⁾

The separation of the chlorine isotopes ³⁵Cl and ³⁷Cl in an almost pure state using HCl as the carrier was achieved by Clusius and Dickel⁽²⁵⁾ in 1939, using a five-stage apparatus of total length 36 metres and a wire temperature 690°C. The diameter of one tube was 12.8 mm., while all the other tubes had the same diameter, namely 8.4 mm. After 17 days' continuous operation, 8 c.c. H³⁷Cl and 25 c.c. H³⁵Cl could be withdrawn per day. The ³⁵Cl was 99.6% pure and the ³⁷Cl 99.4% pure.

The separation of the chlorine isotopes represents a particularly favourable case, as normal chlorine contains 76% ³⁵Cl and 24% ³⁷Cl. The separation of isotopes of low abundance presents a more difficult problem.

In addition to the separation of the chlorine isotopes, Clusius and Dickel have separated the following isotopes in an almost pure form: ²⁰Ne and ²²Ne⁽²⁶⁾; ⁸⁴Kr and ⁸⁶Kr⁽²⁷⁾; ¹⁸O₂.⁽²⁸⁾ In an attempt to separate heavy nitrogen, Clusius and Dickel⁽²⁸⁾ obtained almost pure ¹⁴N.¹⁵N. The equilibrium $2 \text{ }^{14}\text{N}.\text{}^{15}\text{N} \rightleftharpoons \text{}^{14}\text{N}_2 + \text{}^{15}\text{N}_2$ was not established at the temperature of the wire in the separation tube. Partial separations⁽²⁹⁾ of isotopes of carbon, nitrogen and hydrogen have also been reported.

Recently, a considerable degree of separation of the heavy isotopes of carbon and of oxygen was achieved by Taylor and Bernstein⁽³⁰⁾ by a combination of a chemical exchange process and thermal diffusion in a mixture of CO₂ and CO.

Bramley and Brewer⁽³¹⁾ introduced a slight modification of the Clusius and Dickel apparatus by using two concentric tubes, the inner one being heated and the outer one cooled. A greater volume of gas may be treated by this apparatus but it is not so easy to

maintain the high temperature gradient as is generally used in the Clusius and Dickel apparatus.

(5) *Centrifugation*

The possibility of separating isotopes by a centrifugal method has been considered from time to time, but little advance had been made until the introduction of the Beams⁽³²⁾ air-driven centrifuge.

The separation factor as already defined is given by the equation

$$S = \exp \frac{(M_2 - M_1)v^2}{2RT} \dots\dots\dots (4)$$

where v is the peripheral velocity and M_2 and M_1 are the molecular weights of the constituents of the gas. It will be noticed that S depends on the difference of the masses of the two isotopes and for a given value of $M_2 - M_1$ the method should be just as effective for the separation of isotopes of high molecular weight as for isotopes of low molecular weight.

TABLE 3

Separations Achieved

Method	Isotope	Normal Abundance of Isotope in Per Cent.	Degree of Separation in Per Cent.	Date Achieved
Electrolysis	² H	0.02	~100	1933
Diffusion	² H	0.02	~100*	1933
	²² Ne	9.73	~100	1934
	¹⁸ O	0.2	0.5	1934
	³⁶ A	0.307	50	1937
	¹³ C	1.1	30	1938
	¹⁵ N	0.38	9	1938
	Distillation	¹⁸ O	0.2	0.85
Chemical exchange	¹⁵ N	0.38	70.6	1939
	¹³ C	1.1	22	1940
	³⁴ S	4.2	25	1940
Thermal diffusion	³⁷ Cl	24	99.4	1939
	³⁵ Cl	76	99.6	1939
	²⁰ Ne	90	~100	1940
	²² Ne	9.73	~100	1940
	⁸⁴ Kr	57.10	~100	1943
	⁸⁶ Kr	17.47	~100	1943
	¹⁸ O	0.2	~100	1943
¹⁵ N	0.38	~ 50	1943	

* This separation was achieved by using hydrogen containing 10% deuterium as the starting material.

For the uranium isotopes ^{235}U and ^{238}U , $M_2 - M_1 = 3$, and with $v = 5 \times 10^4$ cm./sec. and $T = 300^\circ\text{K}$, $S = 1.16$ as compared with the value $S = 1.0013$ for a single stage of the diffusion method already considered. Under the above conditions the separation produced by one centrifugation would equal the separation produced by 115 diffusion units operating in series. A pilot centrifugal plant for the separation of the uranium isotopes was put into operation during the war years, but no large-scale plant was set up.

To achieve large separations a cascade system of centrifuges would be required and it is possible that future development will be along these lines.

The results achieved by the application of the various methods of separation are listed in Table 3.

Part II. Uses of Isotopes

In recent years, both stable and radio-active isotopes of many elements have found extensive application to the study of problems in physics, chemistry and biology. If a suitable radio-active isotope of the element in question is available it is perhaps easier to use as a tracer than a stable isotope. However, in the cases of hydrogen, oxygen, nitrogen and carbon the stable isotopes have so far proved of greater value than the corresponding radio-active isotopes.

The fundamental principle underlying the use of any isotopic tracer element is that the tracer behaves in any reaction in exactly the same way as the normal element. This is true within the usual limits of experimental error provided the concentration of the isotopic tracer is not too great.

The general chemistry of the exchange reactions of heavy hydrogen is well known, and in the remaining discussion we shall consider chiefly applications of the isotopes of oxygen, nitrogen and carbon.

It is not my intention to deal with the biological applications of the separated stable isotopes other than by giving one brief example of the use of heavy hydrogen to study fat-metabolism in rats and mice. In principle, the technique used is as follows: The mice are fed with a fat or fatty-acid labelled with a few per cent. of deuterium and, after a suitable period, the animals are killed. The fatty acids are then isolated and burnt in oxygen. The water formed is collected and, after purification, its isotopic composition is determined usually by a density method.

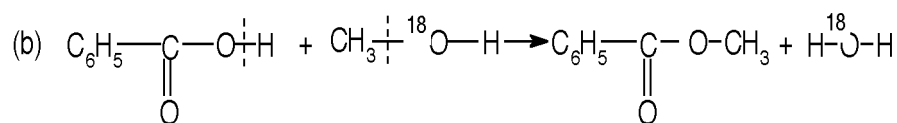
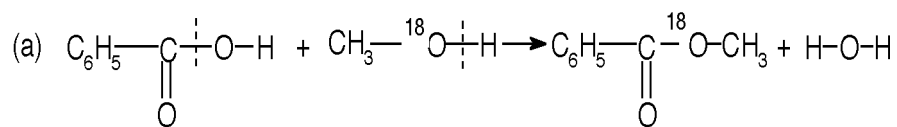
The deuterium-labelled fatty acid is readily prepared. When a fatty acid is heated with D_2SO_4 an exchange of H for D occurs only at the α -carbon atom. On the other hand, when a fatty acid is heated with D_2O at $130\text{--}135^\circ\text{C}$. in the presence of alkali and an active platinum catalyst exchange occurs for all hydrogen atoms on the carbon chain. ⁽³³⁾

In one experiment Stetten and Schoenheimer⁽³⁴⁾ fed the ethyl ester of deuterium-labelled palmitic acid to rats and, subsequently, isolated palmitic, stearic, myristic, lauric, palmitoleic and oleic acids, all containing more deuterium than normal, showing that these acids had been formed from the dietary ethyl palmitate. Work of this type has recently been reviewed in *Science Progress*.⁽³⁵⁾

Many applications of ^{15}N to the study of the metabolisms of proteins and amino-acids have been made and these have been reviewed by Rittenberg and Shemin.⁽³⁶⁾ Numerous papers dealing with the use of ^{13}C as a tracer in the study of fatty acid metabolism, etc., have been published in the *Journal of Biological Chemistry* from 1945 onwards.

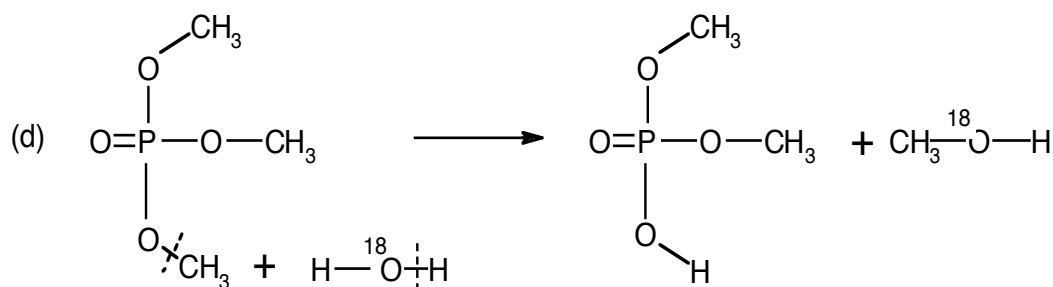
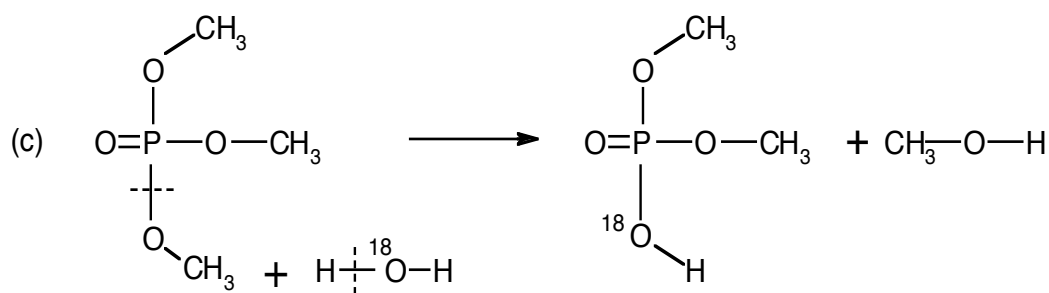
Applications of Heavy Oxygen

The original investigation by Polanyi and Szabo⁽³⁷⁾ of the mechanism of alkaline hydrolysis of esters using the heavy oxygen isotope as a tracer element has been extended to investigations of the mechanisms of acid-catalysed hydrolysis of esters⁽³⁸⁾ and to acid-catalysed esterification reactions.⁽³⁹⁾ Urey and Roberts investigated the mechanism of the acid-catalysed esterification reaction between benzoic acid and methyl alcohol labelled with heavy oxygen. The reaction may occur via the mechanisms illustrated by the following equations:



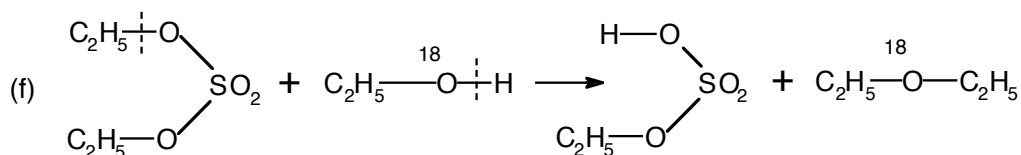
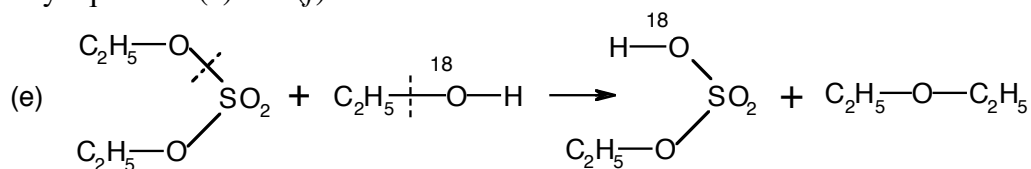
If the reaction occurs by a fission of the bonds, as is illustrated by the dotted lines in equation (a), water of normal isotopic composition would be produced. Mechanism (b), on the other hand, would yield water containing the heavy oxygen originally present in the alcohol. Experiment shows that water with a normal isotopic ratio is produced during esterification, and thus mechanism (a) is correct.

An investigation of the mechanism of hydrolysis of trimethyl phosphate,⁽⁴⁰⁾ the only inorganic ester so far considered, shows that under alkaline conditions behaviour is the same as for organic esters - the alkyl-oxygen bond remains intact.



Under acid conditions, however, the result is not so clear-cut. If the bonds break as is shown by the dotted lines in equation (c), the alcohol formed would contain normal oxygen. The other possibility at which a break may occur is shown by the dotted lines in equation (d); and this would lead to the formation of alcohol containing the heavy oxygen originally present in the water. The experimental results show that both mechanisms are involved during acid hydrolysis or alternatively that the investigation is upset by the occurrence of certain side reactions.

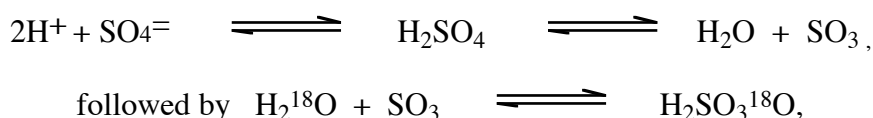
Recently, the mechanism of formation of diethyl ether⁽⁴¹⁾ by reaction between diethyl sulphate and ethyl alcohol has been studied by use of heavy oxygen. In this reaction an alkyl-oxygen bond must break in one of the reagents. The two possible mechanisms are shown by equations (e) and (f).



Experiment showed that the ether formed contained less heavy oxygen than the original alcohol. This dilution was attributed indirectly to the occurrence of two side reactions, namely hydrolysis and alcoholysis. The mechanisms of these reactions had not been investigated, and so their influence was eliminated by variation of the length of the reaction time. On extrapolation of the curve obtained by plotting ¹⁸O-content of the ether against time, the ¹⁸O content of the ether formed from the alcohol originally present in the mixture was obtained. This showed definitely that the ether was formed via mechanism (f).

The mechanisms of the benzil-benzilic acid rearrangement ⁽⁴²⁾ and the Beckmann rearrangement, ⁽⁴³⁾ as well as the alkali fusion ⁽⁴⁴⁾ of certain organic compounds, have been studied by the use of heavy oxygen.

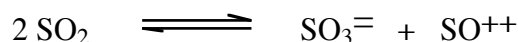
On the inorganic side, most of the applications of heavy oxygen have been for the determination of the rate of exchange of oxygen between water and the various oxy-acid ions.⁽⁴⁵⁾ In general, exchange occurs in acid solution, often in neutral solution and less frequently in alkaline solution. The mechanism of exchange in such reactions may involve addition and subsequent removal of a water molecule or hydroxyl ion to the anion, while in the case of the acid-catalysed exchange the most satisfactory mechanism appears to be reversible anhydride formation. For example, in the acid-catalysed exchange of oxygen between water and sulphate ions the following equilibria are believed to be involved:



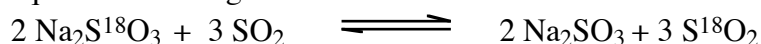
and so on until complete exchange is established.

Some mention may be made of the oxygen tracer work at present under investigation at the University of Queensland.

Jander's theory⁽⁴⁶⁾ of reactions in liquid sulphur dioxide is based on the idea that liquid SO₂ ionises to a small extent giving rise to sulphite ions and thionyl ions according to the equation



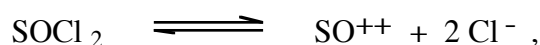
Recently Ingold and co-workers⁽⁴⁷⁾ have questioned the validity of certain of Jander's conclusions. It occurred to us that some useful information might be obtained by determining whether or not exchange of oxygen occurs between liquid sulphur dioxide and a dissolved alkali metal sulphite labelled with heavy oxygen. The above equilibrium would necessarily require an exchange to occur.



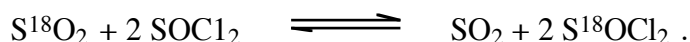
Jander gives the solubilities of various alkali metal sulphites as varying from 16 to 32 mg. per 100 gm. of SO₂, but we cannot verify these figures. We have investigated the solubilities of the sulphites of sodium, potassium and ammonium as well as several other sulphur oxy-acid salts of these elements, but find virtually no solubility at all for any of these salts. We have used sulphur dioxide which has been dried very thoroughly and also sulphur dioxide containing small traces of water, but without any affect on the solubility.

It would be possible to carry out the exchange investigation by shaking liquid sulphur dioxide with the solid sulphite labelled with heavy oxygen, but it is preferable to use a sulphite which shows some degree of solubility.

While the original exchange investigation is held up pending the results of our solubility investigations, the possibility of exchange of oxygen between liquid sulphur dioxide and thionyl chloride is being investigated. According to Jander, thionyl chloride ionises in liquid SO₂



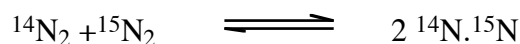
and, if SO₂ ionises, an exchange of oxygen would be expected.



Another problem being investigated is the interchange of oxygen between metal oxides and oxygen gas. There have not been many applications of isotopes to the study of chemical reactions in solids and it is expected that this type of work will have important bearings on the theory of such reactions. In addition to obtaining exchange results at various temperatures and pressures it will also be necessary to determine such factors as dissociation pressures of the oxide at various temperatures, surface area of oxide prepared under varying conditions and also dissociation of oxygen molecules on the surface of the oxide. Little is known about these various factors, and thus in this field alone there is sufficient research to keep several investigators occupied for quite some time.

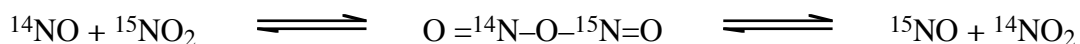
Applications of Heavy Nitrogen and Heavy Carbon

In the presence of a synthetic ammonia catalyst exchange between deuterium and ammonia occurs freely even at room temperature, leading to the formation of the substituted ammonias NH₂D, NHD₂, and ND₃. Taylor and Jungers⁽⁴⁸⁾ from these results conclude that, at the temperatures used in the synthetic ammonia process, the rate controlling step is probably the dissociation of nitrogen molecules to atoms on the surface of the catalyst. This view was confirmed by showing that the equilibrium



is only slowly established on synthetic ammonia catalysts.⁽⁴⁹⁾ The reaction rate first becomes measurable at 450°C.

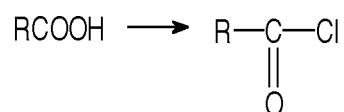
An interchange of nitrogen between nitric oxide and nitrogen dioxide in the gaseous phase at 2.5 cm. Hg pressure and -35°C occurs at a very rapid rate.⁽⁵⁰⁾ This is presumably accounted for by the intermediate formation of nitrogen trioxide.



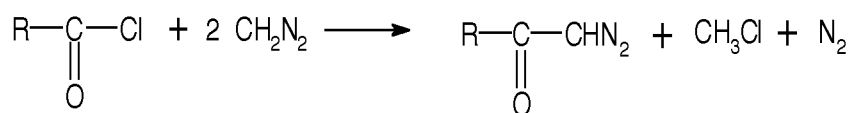
The chances of breaking either the ¹⁴N–O bond or the ¹⁵N–O bond would be about equal and the fission of the latter bond would lead to exchange.

The heavy carbon isotope, ¹³C, has been used to study the Arndt-Eistert reaction.⁽⁵¹⁾ This reaction is used for the conversion of a carboxylic acid to its next higher homologue and it involves three stages:

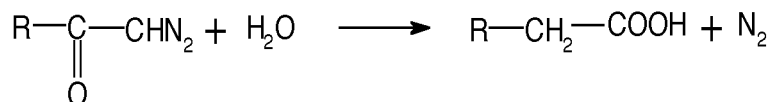
(i) Formation of the acid chloride:



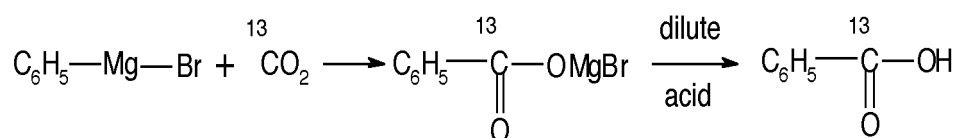
(ii) Reaction of the acid chloride with diazomethane:



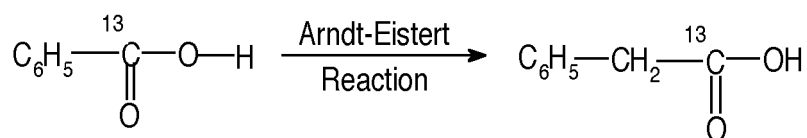
(iii) Rearrangement of the diazoketone with water in the presence of colloidal silver:



The problem to be decided is whether the carbon atom of the $-\text{COOH}$ of the original acid becomes the carbon atom of the $-\text{COOH}$ group of the final acid. This was demonstrated as follows: Benzoic acid containing an excess of ^{13}C in the $-\text{COOH}$ group was prepared by reaction between phenyl magnesium bromide and carbon dioxide labelled with heavy carbon.



After carrying out the Arndt-Eistert reaction the heavy carbon was found associated with the carboxyl group of the phenylacetic acid formed.



The significance of this demonstration in connection with the mechanism of the reaction is discussed in the original paper.

Applications of ^{18}O , ^{13}C and ^{15}N to Analytical Problems

The per cent. oxygen content of an organic compound is usually obtained by deducting the percentages of all other elements present from 100. Thus any errors in the estimations of other elements present will affect the accuracy of the estimation of the oxygen. A direct method of estimation of oxygen has recently been introduced by making use of heavy oxygen.⁽⁵²⁾

A few milligrammes of the organic compound are burnt with a definite amount of oxygen containing a known excess of ^{18}O . The dilution of the heavy oxygen by the normal oxygen originally present in the compound is then determined. The results are then sufficient to enable the per cent. oxygen to be calculated. Using oxygen containing about 2% ^{18}O , the oxygen contents of acetic acid, formic acid, nitromethane and diethyl ether respectively were obtained within $\pm 3\%$. This accuracy is not all that might be desired, but by improving the technique or by using oxygen containing a larger proportion of ^{18}O the accuracy could be improved.

The same type of procedure has been applied to the estimation of carbon (⁵³) and of nitrogen(⁵⁴) in organic compounds. With the higher percentages of ¹³C and ¹⁵N available the estimated values showed a lower average error, namely $\pm 0.3\%$.

Conclusion

Although isotopic tracer work has been in progress for a comparatively short time, it may be seen from the examples considered that much has been added to our knowledge of the way in which many chemical reactions occur. In certain cases this new knowledge could not have been gained other than by the use of a separated isotope as a tracer element.

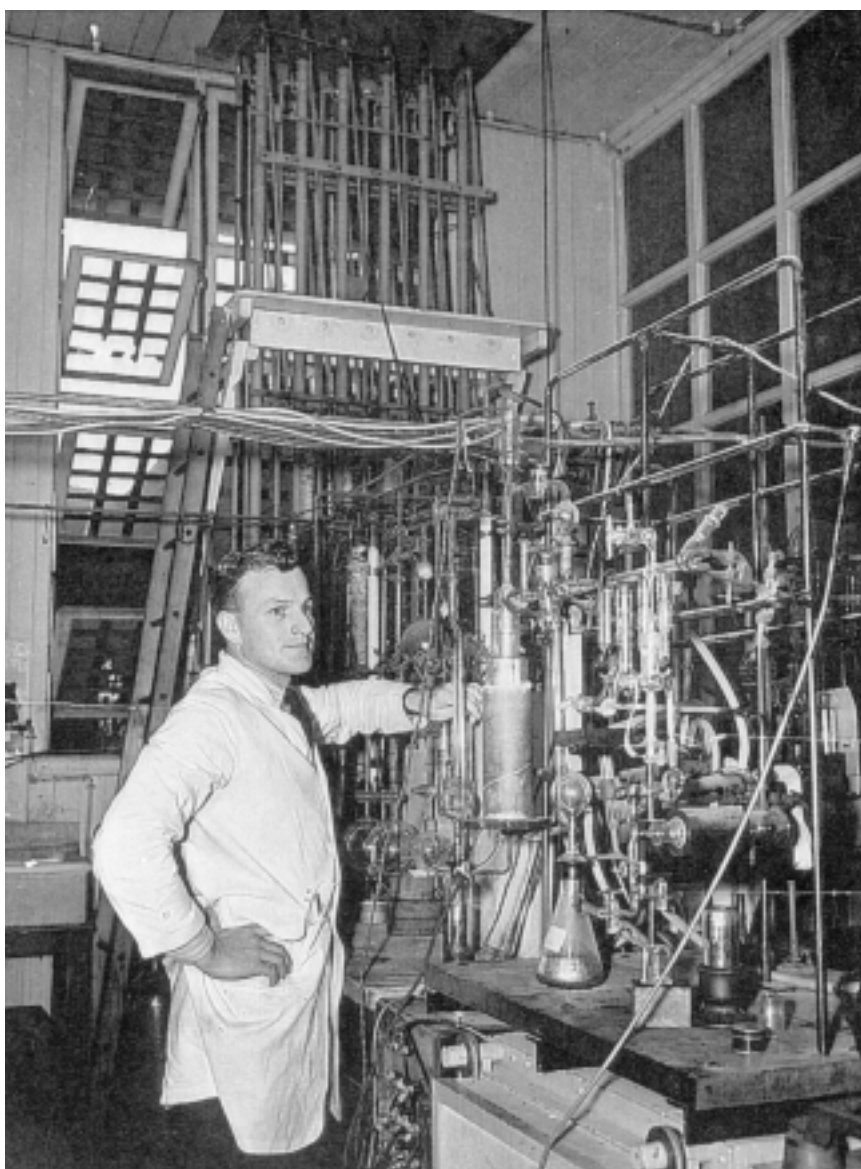
It is, perhaps, fortunate that for the elements H₂, N₂, O₂ and carbon which play such an important part in the chemistry of everyday processes the stable isotopes may now be separated by comparatively simple means as these have proved more useful as tracers than the corresponding radio-active isotopes.

The measurement of the isotopic composition of a sample of oxygen or of hydrogen is readily carried out by the accurate measurement of the density of water formed from the sample. For carbon and nitrogen, however, the measurement requires the use of a mass-spectrograph. The absence of this latter equipment, which is highly expensive, is probably the limiting factor to the uses of the heavy isotopes of carbon and of nitrogen in Australian universities. This, perhaps, is unfortunate, as these two isotopes would appear to be of particular value to the study of the mechanisms of many organic reactions.

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This photograph, taken in 1947, was kindly provided by Ian Lauder

Background: The thermal diffusion separation system for concentrating ^{18}O . Each column (length 3.96 m) consisted of a water-cooled vertical tube, (I.D. 15 mm), down the centre of which a nichrome wire, (D. = 0.071 mm), was suspended. In operation, the wire was heated to 810°C and oxygen flowed continuously into the bottom of the first column and out the top. This gas, now deficient in ^{18}O was removed from the system by recombination with hydrogen from the electrolytic cell. The horizontal temperature gradient, $1080^\circ\text{C}/\text{cm}$, between the wire and the surrounding tube combined with the vertical convection, (gas near the hot wire rising, near the cooled wall falling), produced increasing concentrations of $^{16}\text{O}^{18}\text{O}$ towards the bottom of the column, and *vice versa*. Oxygen gas at the bottom of each column was circulated to the top of the next column. Using four columns in the series, oxygen containing up to 20% ^{18}O was produced from ordinary water (0.2% ^{18}O).

Foreground: The glass apparatus was used for filling the Polanyi-Gilfillan micropyknometer which enabled the density of 10 mg of water to be determined with an accuracy of ± 3 parts per million. Ian Lauder did all of the construction himself, and at his private home!!