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CHEMICAL EFFECTS OF NUCLEAR TRANSFORMATIONS
AND THEIR USE IN MAKING LABELED COMPOUNDS

The chemical effects of nuclear transformations can be utilized to introduce the radioactive atoms produced into chemical species useful for tracer studies. Gas chromatography offers a means of separating the tagged compounds with high specific activity. A chromatographic apparatus for separating and identifying labeled compounds is described. Comparisons are made of this with other labeling techniques.

Since 1934 when Szilard and Chalmers (31) reported that radioiodine produced by the irradiation of ethyl iodide with neutrons appears in a form which can be partially extracted with water, it has been recognized that nuclear processes can cause chemical reactions.

Typical such processes which will be considered in this discussion include the following: $\text{Cl}^{37}(\text{n},\gamma)\text{Cl}^{38}$ (37 min.); $\text{Br}^{81}(\text{n},\gamma)\text{Br}^{82}$ (36 hr.); $\text{I}^{127}(\text{n},\gamma)\text{I}^{128}$ (25 min); $\text{N}^{14}(\text{n},\text{p})\text{C}^{14}$ (5600 y); $\text{Li}^6(\text{n},\alpha)\text{H}^3$ (12 y); $\text{He}^3(\text{n},\text{p})\text{H}^3$ (12 y).

The notation signifies that the stable isotope at the left captures a neutron and emits a gamma ray, proton or alpha particle, forming the radioisotope which is indicated at the

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right. The half-life is given in the parentheses at the right. In each case the radioactive product atom is born with high energy which allows it to break its parent chemical bond and subsequently to react with surrounding molecules. As illustrated by Figure 1, a wide variety of radioactively labeled compounds may result. These are a source of tracers for research, development and production use, if they can be separated from each other with sufficiently high specific activity. In the following paragraphs we shall review briefly the evolution of knowledge as to the characteristics and mechanisms of such reactions, shall describe the use of gas chromatography for separating very high specific activity labeled compounds, shall compare this method of labeling with certain other methods, and shall cite references which may be useful to those desiring further acquaintance with the field. A more comprehensive discussion of basic investigations of chemical effects of nuclear transformations has been given in earlier reviews (2,3). References here to work prior to these reviews will be limited to a few examples.

Mechanism

Although it was at first perhaps thought that the rupture of the carbon-iodine bond in ethyl iodide, observed by Szilard and Chalmers (31), resulted from the momentum carried by the neutron as it entered the iodine atom it was soon realized that the process could occur even with neutrons of only thermal energies. The rupture was then ascribed to the recoil energy given to the iodine atom as a result of emission of one or more

gamma rays in the $I^{127}(n,\gamma)I^{128}$ process. For an 8 Mev. gamma ray this recoil energy is 6170 kcal. per mole, which is more than one hundred times greater than the energy of the carbon-iodine bond. Consistent with these ideas was the observation (4) that in some gaseous alkyl halides nearly 100% of the halogen atoms which capture neutrons split the parent bond and appear in inorganic form. These atoms can be distinguished from those which have not captured neutrons, because the (n,γ) process changes them to radioactive isotopes.

In liquid or solid organic media from 20% to nearly 100% of the radioactive atoms which have split their parent bonds reenter organic combination. Early theories ascribed this to a "billiard ball collision" mechanism (22) in which the recoil atom was postulated to lose its energy by a head-on collision with an atom of equal mass, the struck atom being knocked on, leaving behind a radical which combined with the radioactive recoil atom. It was necessary to discard this hypothesis when it was observed in several laboratories that: a) Halogen atoms activated by neutron capture can enter organic combination not only by replacement of halogen atoms but by replacing various other atoms and radicals (4, 11, 12, 23) including hydrogen atoms; b) Low concentrations of atom scavengers alter the chemical fate of radioactive halogen atoms produced by the (n,γ) process in organic compounds indicating that many of the recoil atoms do not enter stable combination until after they have lost their excess energy and diffused in thermal equilibrium with the medium (13).

These facts suggested that the recoil atom must form a

track or pocket of radicals of various sorts, with one of which it may combine after becoming thermalized, if it does not first enter stable combination by a "hot" reaction. Concurrently, investigators became aware of the fact that the atoms produced by the (n,γ) process often, and perhaps always, carry a positive charge (33) as a result of some of the energy of the nuclear process being made available for ejecting electrons from the orbits. This charge might lead to reaction as a result of the energy liberated on neutralization or as a result of ion-molecule reactions (28). To explore the relative effectiveness of recoil energy and of charge in causing reaction, the products resulting from activation by the Br^{80} (4.4 hr.) I.T. $\rightarrow$ Br^{80} (18 min.) isomeric transition in several media were compared with those formed by the $\text{Br}^{78}(n,\gamma)\text{Br}^{80}$ process (10). The isomeric transition is known to produce Br^{80} atoms with an average charge of +10 (34). In a number of tests the products of activation by the two processes have been indistinguishable. Unfortunately this result does not distinguish decisively between the charge and recoil mechanisms since atoms from the isomeric transition may acquire some kinetic energy from coulomb repulsion, although this is much lower than the energy acquired from recoil in the (n,γ) process. Recoil atoms of yet much higher energy produced by the $\text{Br}^{78}(n,2n)\text{Br}^{78}$ reaction produce similar results (30). Consequently, the question of the separate contributions of charge and recoil energy is not yet solved although there is evidence from some gas phase reactions that both may be important (21).

Studies of iodine, bromine, and chlorine activated by the

(n, γ) process in the gas phase show that such atoms are able to undergo unique processes unlike those observed for halogen atoms activated in any other way (16). In gaseous hydrocarbons or alkyl halides they can displace hydrogen atoms and organic groups in bimolecular, non-radical reactions to produce a multitude of labeled compounds from a single type of organic gas. It seems probable that these reactions are ion-molecule processes (28), although the possibility cannot be excluded that they are due to atoms in an excited state not encountered in photochemical studies. It is possible that a similar unique mechanism may contribute in part to the formation of the multiplicity of products observed in condensed phases.

Carbon and Hydrogen Labeling

The above outline of the development of knowledge of the chemical effects of nuclear transformations in organic systems has dealt wholly with halogen atoms. These have received predominant attention in such investigations until recently because the radioactive species have suitable half-lives and are conveniently made, with satisfactory capture cross sections, by neutron irradiation of the naturally occurring isotopes. Also, when stabilized in organic combination they do not easily exchange with other molecular forms, or hydrolyze.

From the standpoint of preparing radioactively labeled compounds for use in research, development and production control it would often be desirable to be able to employ carbon, hydrogen, oxygen or nitrogen. Unfortunately nitrogen and oxygen are excluded from such use by the very short half-lives

of their radioisotopes. Carbon and hydrogen each has a naturally occurring isotope which captures neutrons to form a radioactive isotope, i.e. $C^{13}(n,\gamma)C^{14}$ (5600 y) and $H^2(n,\gamma)H^3$ (12 y), but in each case the natural abundance of the capturing isotope is so low, the cross section for neutron capture is so low, and the half life is so long, that it is impractical to use the process for producing useful amounts of the radioactive species. There are however serviceable transmutation processes by which C^{14} and H^3 may be produced from other elements. These are $N^{14}(n,p)C^{14}$, $Li^6(n,\alpha)H^3$ and $He^3(n,p)H^3$. The natural abundance of N^{14} in nitrogen is 99.6% and its cross section for the (n,p) process with thermal neutrons is 1.76 barns; the natural abundance of Li^6 is 7.5% and the cross section 945 barns; He^3 , a decay product of tritium, may be purchased at a reasonable cost, its cross section is 5400 barns. As in the case of the radioactive halogen atoms produced by the (n, γ) process, the C^{14} and H^3 are born with high recoil energy and are presumably positively charged, the recoil energy being much greater because the energetic particle ejected is a massive proton or alpha particle rather than a gamma ray.

It has been shown that by exposing nitrogen compounds in hydrocarbon solvents to neutrons it is possible to form C^{14} -labeled molecules involving replacement of normal C or N atoms by C^{14} , and also to form molecules with larger and smaller carbon skeletons than the substrate (29, 40). Tritons formed by the $Li^6(n,\alpha)H^3$ process in finely ground mixtures of lithium salts with organic compounds form labeled molecules of the substrate as well as other products (26). The distribution of

the label on the different carbon atoms of the molecules formed is selective rather than statistical. When mixtures of He^3 with methane, ethane or propane are irradiated with neutrons the tritium formed is found in compounds requiring both lengthening and shortening of the carbon chains (15, 27).

Separation by Gas Chromatography

Prior to the availability of gas chromatography it was impossible to separate without carrier or solvent unweighable amounts of labeled compounds such as are indicated by the peaks of Figures 1 and 2. With gas chromatography, however, the only solvent required is a carrier gas, such as helium, from which the unweighable components can be removed, with appropriate cold traps, as they come off the column. It has been demonstrated that essentially carrier-free components are separated by the chromatographic column as effectively as components present in macro amounts (9, 10). This is illustrated by Figure 1 where all of the radioactivity peaks are for "carrier-free" products, except those under the dotted lines which indicate added carriers detected by thermal conductivity. For those compounds which are sufficiently volatile and stable to be separated by gas chromatography the use of chemical effects of nuclear transformations for producing high specific activity tracers is, then, no longer subject to the stringent limitations formerly imposed by the separation problem.

Identification of Products. Before gas chromatography was available it had been demonstrated that nuclear transformations involving halogen atoms can lead to a variety of labeled compounds in alkyl halide media. This was done by the relatively

laborious process of adding carriers for suspected products to the irradiated sample, distilling and observing the radioactivity in successive fractions of the distillate (6, 11). With gas chromatography one can first determine the number of carrier-free compounds present by making a chromatogram of the radioactivity peaks from say a 50 microliter sample of the irradiated material. To another sample he can then add non-radioactive macro portions of suspected products whose order of emergence from the column has been previously determined. By simultaneously monitoring the radioactivity and heat conductivity changes in the effluent gas from the column, using a two pen chart recorder to give a record such as that of Figure 1, the radioactivity peaks are easily identified. Each of the labeled peaks in Figure 1 has been characterized by this method. Often significant guesses as to the identity of peaks may be made from a knowledge that the compounds come off a particular column in the order of some property. Those of Figure 1 emerge in the order of their boiling points. There is the possibility that two compounds may not be resolved by the column, in which case the superposition of the thermal conductivity and radioactivity peaks may lead to a false conclusion. Where there is doubt, as for example in the " $C_6H_{11}Br$ " peak of Figure 1 the components of the peak should be trapped and run through a column of a different type.

Equipment. The equipment used in obtaining the chromatograms of Figure 1 is diagrammed in Figure 3. The column consisted of 12 feet of 4 mm. I.D. glass tubing coiled into a double spiral eight inches long and four inches in diameter and packed

with 40-60 mesh Johns-Manville C-22 firebrick coated with 40% of its weight of General Electric SF-96 (40) silicone oil. During the 30 minute separation run the temperature of the heating bath around the column was raised gradually from 40° to 200° to allow components of successively higher boiling point to move through the column at a desirable rate. The effluent gas passed to the bottom of a thin walled 1 ml. glass thimble which fit in the well of a NaI (Tl) scintillation crystal. The latter fed through a photomultiplier tube, preamplifier, linear amplifier and rate meter to the chart recorder. From the scintillation counter the gas passed in order through the thermal conductivity sensing cell, a liquid air trap (in which the components under analysis were frozen from the helium stream), the thermal conductivity reference cell, and the flowmeter. The flow rate was maintained at 60 ml./min. by increasing the pressure from 12 to 19 lb./sq. in. as the temperature increased. Placing the reference cell on the effluent side rather than the input side of the system avoided variations in the base line of the chart recorder as the reducing valve was adjusted during a run. The negative peak immediately following the air peak of Figure 1 is due to the fact that air is not removed by the liquid air trap. The tubes from the column to the scintillation counter and from the counter to the cell were wound with nichrome wire and asbestos and electrically heated to prevent condensation of the less volatile components.

Equipment Modifications. Many modifications of the above equipment are of course possible, and in some cases are necessary to allow the separation of different chemical species and

the monitoring of different types and energies of radiation. The aluminum clad scintillation counter with glass thimble in the well gives high efficiency for the counting of gamma rays and high energy beta rays but is useless for counting the weak beta rays from tritium or carbon-14. For tritium it is necessary to have the compound to be counted inside the counter. This was accomplished in the experiment of Figure 2 (15) by using methane, a good counter gas, to carry the sample through the chromatographic column and then allowing it to flow through a proportional counter which consisted of an internally silvered glass sphere of 10 ml. vol. (14). It is interesting to note that the ^{radioactivity} peak for tritiated methane shows up well even with methane as the carrier gas.

The use of methane has the disadvantage that its heat conductivity is not as much different from that of most compounds of interest as is that of helium, and that the potential required for counting is higher than that of mixtures of the rare gases with hydrocarbons. Wolfgang and Rowland (27, 42) have avoided these disadvantages by using helium as the gas to carry the sample through the chromatographic column and heat conductivity cell, following which methane is bled into the stream to make a good counting mixture. The mixed gas is then passed through a cylindrical brass proportional counter. These authors have also given a useful analysis of the effect of chamber volume and flow rate on the sensitivity of detection of the radioactivity peaks. Wilzbach, Kaplan and Riesz (38) have avoided the necessity for a special counter gas by employing as their detector a flow type ionization chamber in conjunction with a vibrating reed electrometer. In addition to

operating at low voltage with any carrier gas this unit should tolerate gaseous species which form negative ions, such as alkyl halides, which stop the operation of proportional counters, although such species may possibly reduce the detection efficiency rates somewhat. When an ionization chamber is used which is small enough so that a significant fraction of the beta particles reach the walls the sensitivity of the chamber will vary as the composition of the flow gas varies; the larger the number of electrons per molecule in the gas the larger will be the number of ion pairs produced per beta emitted in the chamber.

Kokes, Tobin and Emmett (19) were probably the first investigators to separate radioactively labeled compounds by gas chromatography and analyze the effluent by both counting and heat conductivity. They analyzed macro amounts of hydrocarbons labeled with C^{14} . Their radioactivity detector was a mica window Geiger tube arranged so that the gas sample flowed through a compartment enclosing the window.

For many systems an important requisite of the radioactivity detector is that it be able to operate at elevated temperature so that it can be heated to prevent compounds of low volatility from condensing. In taking the data of Figure 1 the thimble in the well of the scintillation counter was maintained at 200° (9). This is not an ideal arrangement because it risks the possibility of cracking an expensive crystal and because the sensitivity of the crystal drops after a prolonged period of heating the well. It has, however, been used successfully for hundreds of experiments. The sensitivity remains

sufficiently constant for the time required for a run. When it drops, due to long heating, it returns to its normal value on cooling. Another method of counting energetic beta particles or gamma rays in a hot flowing gas is to pass the gases through an electrically heated thin walled glass tube adjacent to a thin walled Geiger counter (9, 10). The counter is mounted horizontally below the flow tube and the two are separated by a thin sheet of aluminum foil thus allowing the counter to operate at near room temperature. In general Geiger counters and proportional counters do not operate satisfactorily above about 75° C. Therefore for experiments such as those of Figure 2 the gases from the chromatographic column were passed through a length of unheated tubing before entering the counter tube. Wilzbach and coworkers (38) have operated their flow ionization chamber at 110° but find that the leakage current becomes excessive at higher temperatures. It is to be expected that this may be remedied by using different insulators or by other changes in the materials of construction.

A very promising prospect for the manufacture of flow counters operable at temperatures up to 200° C. or higher is the type of tube developed by L. B. Clarke, Sr. of the Naval Research Laboratories (7). These tubes have cathodes consisting of films deposited by passing a mixture of stannic chloride and methyl alcohol vapors through the heated glass shell.

Collection of Products. The requirements for sample collection are simply a series of small traps which can be cooled with liquid air or other refrigerant and through which the effluent stream from the chromatographic column can be

directed in turn as successive peaks appear. The simplest unit is a small U tube with a ground joint which can attach to the effluent end of the column. Manifolds of various sorts with several traps in position for convenient rapid switching from one to another have been devised.

Specific Activity of Products. Those labeled molecules which are formed by substitution of the recoil atom for a single atom of the same element in the target molecule (as in the formation of labeled n-propyl bromide from n-propyl bromide or of tritiated propane from propane) are limited in specific activity by dilution by the inactive molecules originally present. Attempts to increase the specific activity by longer irradiations at higher fluxes may result in major decomposition by radiolysis. The labeled compounds which are different from the target molecule (as in the formation of methyl bromide from n-propyl bromide or of tritiated methane from propane) would be present in the "carrier-free" state (i.e. undiluted by non-radioactive molecules) if the starting material were absolutely pure and if none of the inactive species in question were formed by the action on the starting compound of gamma rays, fast neutrons and recoil atoms. In practice such radiolytic action cannot be avoided and non-radioactive molecules are produced which are identical to some or all of the species produced by the recoil labeling reaction, thereby lowering the specific activities of these species.

The ratio of inactive molecules produced by radiolysis to radioactive molecules produced by the labeled recoil atoms depends on: 1) The G value (molecules formed per 100 ev

absorbed) for the particular radiolysis step; 2) The ratio of neutrons to gamma rays from the neutron source; 3) The recoil energies of the particles from the nuclear process which forms the labeling atom; 4) The neutron capture cross section for the process which produces the labeling atom; 5) The concentration of the neutron capturing atom relative to other atoms.

In carbon and tritium labeling all of the energy of the nuclear process (n, p or n, α) is usually absorbed in the system since the emitted protons or alpha particles, as well as the C^{14} and H^3 atoms have short ranges in matter, whereas in the (n, γ) processes the emitted gamma ray is only weakly absorbed and the recoil energy of the tagged atom is relatively low. In a typical case of labeling by the $Li^6(n, \alpha)H^3$ process the ratio of radioactive tritium atoms formed to molecules of the substrate decomposed by the recoiling particles may be 10^{-5} .

The longer the half life of a radioactive species the more atoms must be produced to give a useful disintegration rate for tracer purposes, i.e. the longer is the required irradiation time. Consequently the longer the half life the lower will be the specific activity expressed as the ratio of disintegration rate to inactive molecules.

For the reasons enumerated above C^{14} and H^3 cannot be prepared by recoil labeling with nearly as high specific activity as can the halogens. Typical specific activities reported in the literature are $2 \times 10^5 H^3$ disintegrations per minute per milligram of galactose from irradiation of a mixture of Li_2CO_3 and galactose (25) and $420 C^{14}$ d.p.m./mg. of acridine from irradiation of that compound (39).

Other Labeling Methods

By Ionizing Radiation. By use of the chemical effects of nuclear transformations it is possible to produce labeled molecules much more complex than can be readily produced by chemical syntheses. The method has the disadvantage that it requires a high intensity neutron source such as a nuclear reactor. Wilzbach (37) has pioneered a new method of labeling with tritium which promises to have all of the advantages of the nuclear activation method for this element while being simpler to carry out and less subject to reduction in specific activity due to radiation damage. He has shown that it is possible to label complex compounds with tritium by simply allowing the desired compound to stand in contact with tritium gas. Rates of formation of the tritiated form of the original compound as high as 2.2 millicuries per curie-day exposure have been observed and yields of tritiated radiolysis products are still greater. When these species can be separated in high purity each is a potentially useful tracer compound. Among the labeled compounds prepared have been cholesterol with a specific activity of 64 mc./g. and digitoxin with a specific activity of 90 mc./g.

In the Wilzbach method the tritium enters combination as a result of the ionization and excitation of molecules of the medium by the beta radiation of the tritium (1, 24). Identical reactions can be induced in shorter times by irradiating a mixture of tritium and the organic compound with an intense external source of gamma radiation (1). Mixtures of tritium with methane yield not only tritiated methane but also tritiated

hydrocarbons of each chain length up to at least C₆, and when tritium is allowed to stand with hexane both chain lengthening and chain degradation occur.

At approximately the same time that the unique reactions noted above have come to light the following observations have been reported: 1) Hydrocarbon ions formed by the electron beam in the ionization chamber of a mass spectrometer show very high cross sections for reactions such as $\text{CH}_3^+ + \text{CH}_4 \longrightarrow \text{C}_2\text{H}_5^+ + \text{H}_2$ (28); 2) Organically bound tritium is formed when gaseous T₂ at about 50 microns pressure is subjected to a field of only 200 volts/cm. between electrodes coated with various organic compounds (for times too short to allow detectable radiation induced labeling)^{4/}(~~14~~); 3) C¹⁴⁺ ions formed in a mass spectrometer and allowed to impinge on solid benzene yield both benzene and toluene labeled with C¹⁴ (20).

Each of the "unconventional" reactions cited in this section as well as those initiated by nuclear transformation, involves a mechanism of activation which produces ions. The suggestion is obvious that it may be possible to discover many useful labeling reactions which can be initiated by allowing alpha, beta or gamma rays or an electrical discharge to ionize mixtures of simple tagged molecules with other molecules. Convenient source molecules may include C¹⁴O, C¹⁴O₂, C¹⁴H₄, C¹⁴H₂, H₂S³⁶, S³⁶O₂, HCl³⁶, Cl₂³⁶, HBr⁸², Br₂⁸², various tritiated compounds, and many others.

By Chemical Synthesis and By Exchange. The preparation of labeled compounds by the use of nuclear transformations and by ionizing radiation both involve equipment and techniques which

are unfamiliar to many chemists. These methods generally produce complex mixtures of labeled compounds from which the desired components must be scrupulously purified before use. Furthermore, if the molecule desired has several atoms of the element to be tagged the label is usually randomly or semi-randomly distributed. For such reasons the great majority of all labeled compounds produced for tracer studies to date have been those which are simple enough for chemical synthesis. In order to obtain high yields from the radioactive starting compound, to prevent unnecessary dilution of the tagged element with non-radioactive isotopes, and to avoid contamination of the laboratory, it is often desirable to design synthetic procedures suitable for use with milligram quantities of reagents, using vacuum line techniques (5). In an extensive review of chemical and biosynthetic labeling methods Thomas and Turner (31) have cited over four hundred illustrative references. In such syntheses of compounds labeled with carbon or hydrogen it is customary to start with $\text{BaC}^{14}\text{O}_3$ or H_2^3 gas, which are available from the atomic energy commission laboratories in several countries, or with simple compounds of C^{14} or H_2^3 available from commercial suppliers.

Illustrative of simple chemical labeling processes which have been found useful in our laboratory are the following.

1) Many organic chlorides may be easily labeled with Cl^{36} by exchange with AlCl_3^{36} (2). AgCl^{36} is precipitated from a solution of HCl^{36} obtained from the Oak Ridge National Laboratory, dried by fusion under vacuum, and heated with Al metal to produce AlCl_3^{36} to which the organic chloride is exposed on the vacuum system. 2) Labeling of organic bromides with Br^{82} may be

accomplished in an analogous fashion, the AlBr_3^{82} being conveniently produced by reaction of Al with Br_2^{82} which has been formed by irradiation of liquid elemental Br_2 in a nuclear reactor.

3) Photochemical reactions have been used to produce HBr^{82} and $\text{CCl}_3\text{Br}^{82}$ by illuminating mixtures of H_2 and Br_2^{82} , and of CCl_3Br and Br_2^{82} , at elevated temperatures with a Mazda lamp. 4) HBr^{82} may be prepared by the rapid exchange which occurs on mixing tank HBr and Br_2^{82} followed by removal of the Br_2 by contact with mercury. 5) Organic iodides appear to be quantitatively converted to the corresponding radiobromides by simple replacement reactions with Br_2^{82} (17). 6) H^3I and H^2Cl (8) have been prepared by heating mixtures of H_2^5 and I_2 and of $\text{H}_2^5 + \text{HCl}$ over a hot platinum wire. 7) Aromatic compounds may be labeled with tritium by heating with H^3Cl in the presence of a catalyst such as SnCl_4 (8). 8) Ethyl benzenes labeled with C^{14} are produced by passing a gaseous mixture of benzene and C^{14} ethyl chloride over anhydrous aluminum chloride (3).

Biosynthesis. Labeled compounds too complex to be prepared by chemical synthesis have in a number of instances been made by feeding C^{14}O_2 to growing plants. Rather high specific activities of randomly labeled compounds can be obtained by starting with young plants. The use of other growing organisms for incorporating C^{14} and other radioelements, particularly P^{32} and S^{35} , has been reported by many investigators. Some of their results are cited by Thomas and Turner (32) and by Kamen (18).

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Figure 1. Gas chromatogram of radioactive products of neutron irradiation of n-propyl bromide plus 5 mole % bromine; dotted line shows compounds added for identification of trace amounts of radioactive species.

Figure 2. Gas chromatogram of tritiated products from $\text{He}^3(n,p)\text{H}^3$ reaction in C_3H_8 . (56 cm. C_3H_8 , 6 mm. He^3 , 5 mm. H_2 ; 1 hr. irradiation in Argonne CP5 reactor at 2×10^{12} neutron cm^{-2} sec^{-1} ; separated on silica gel column).

Figure 3. Gas chromatographic apparatus for identification of radioactive compounds produced as a consequence of nuclear reactions.