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Radiocarbon Dating

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Radiocarbon dating

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[Plates 1 and 2]

1. History

The cosmic ray production of new atoms in matter is the basis of radiocarbon dating. In this case the atom is carbon of mass fourteen made from the most abundant atom in air—nitrogen of mass fourteen. Radiocarbon—carbon-14, ^{14}C—lasts 8300 years on the average (see note on radioactive decay on p. 10 for explanation of 'half life' and 'average life') before reverting in radioactive decay to nitrogen-14 and during this time it enters all living things as well as sea water and air. Chemically carbon dioxide (the product of the combustion of carbon with air—which is 20 % oxygen) is the food of life and presumably the freshly produced ^{14}C atom burns sooner or later (probably in a few days, although this time is not at all well known) to $^{14}CO_2$ which is mixed with the ordinary carbon dioxide (0.03 % in air) which contains mainly non-radioactive carbon atoms of masses 12 and 13 in abundances of 99 % and 1 %, respectively.

The process which converts CO_2 into plants—photosynthesis—is the way in which the radiocarbon is introduced into living beings, for all life on Earth so far as is known either is a plant or lives off plants. In principle and in theory one could understand if organisms were to live off fossil (or primeval, if there be any) organic matter and that radiocarbon dating would not work for them. They would not be in touch with the cosmic rays through recent photosynthesis and the long time that coal or oil has been underground would have required that the original radiocarbon (assuming the cosmic rays were working when the coal and oil deposits were made) would long since have disappeared.

The cosmic rays actually produce radiocarbon only indirectly. In the first instance they strike the air atoms and disintegrate them to tiny fragments (the cosmic rays in some instances have unbelievably high energies) most of which almost immediately transform into long-lived things and radiocarbon is the daughter or product of one of these, the neutron. The neutron which has been with us now since the early thirties (due to Chadwick and Joliot) and has come to be part of our daily life since it is the purveyor of atomic energy as well as radiocarbon dating. It somehow comes out of the maze of strange particles and general debris coming from the collision of a great cosmic ray primary with the nucleus of a nitrogen or an oxygen atom. In fact, the first clue to radiocarbon dating came in 1939 when Korff of New York University sent up neutron sensitive detectors on balloons and found a peak intensity at some 16 km altitude. This, taken together with the previously demonstrated fact that the chief interaction of neutrons with air was to produce radiocarbon was the first hint of radiocarbon dating. However, World War II intervened and our quest which had gelled in theory during the four war years came to test at the University of Chicago in 1945 to 1950. Our first move was to publish the general thought that cosmic ray produced atoms could accumulate in the atmosphere as tritium (radiohydrogen of mass three), its radioactive daughter helium-3 (which also probably is produced directly by the cosmic rays as well), and radiocarbon. Then a strenuous programme to measure the radiocarbon decay rate. (We know the average life of 8300 years

now to about 1 or 2 % but at that time the uncertainty was much larger. One figure was as large as 30000 years!) was undertaken. However, our major objective was to test whether the whole fabric was false in some way by searching for natural radiocarbon.

The theoretical structure was in a sense simple—the cosmic rays make radiocarbon atoms at a steady rate of 2 per square centimetre of area of the Earth per second and have been doing so for tens of millenia so that at present there should be an equilibrium inventory in which 2 radiocarbons revert to nitrogen every second for each square centimetre of area. Therefore we should find 2 disintegrations per second for every 8 g of carbon in living beings or dissolved in sea water or in the atmospheric CO_2 for the total carbon in these three catagories adds to 8 [7.5 in the oceans, $\frac{1}{8}$ in the air, $\frac{1}{4}$ in life forms, and perhaps $\frac{1}{8}$ in humus. Some of these figures are not accurately proven but since the ocean is the largest and is best known (5% error or better) the total is known to about 10%]. Thus we expected to find this concentration of radiocarbon in living matter and the job was to test for it.

Unfortunately at that time no instrument was sufficiently sensitive, so my colleague, Dr E. C. Anderson and I were stumped for the time, until we recalled that an old friend from World War II days had a carbon isotope separator with which he was making concentrated ^{13}C for isotope tracer work in cancer research. This expensive machine was operating at Marcus Hook near Philadelphia and we enlisted Dr A. V. Grosse's aid to enrich the natural ^{14}C by some hundredfold in concentration so we then could detect the radioactive rays it gives in reverting to nitrogen -14 in our Geiger or methane-filled proportional counters. [A Geiger–Muller counter is a metal cylinder with a fine wire down its axis with perhaps 0.1 atm (10 kN m^{-2}) of some gas mixture. A potential is applied between the wire (positive) and the cylinder (negative) of 1–2 kV depending on the pressure and compositions of the gas. Under these conditions, uniformly sized pulses of voltage (sparks) are delivered whenever ionization (separation of one or more electrons from a neutral atom or molecule) occurs even if it is only one event, i.e. one free electron and one positive ion. This is the most sensitive radiation detector known. The ^{14}C radiation makes about 1500 ion pairs over a path length of about 2.5 cm in air on the average so it is measured best in the counter gas itself since the radiation will not easily traverse the counter wall. Now it happens to be true that the hydrocarbons and carbon dioxide which are the richest carbon-containing gases will not serve in Geiger counters, but will serve as proportional counters. Proportional counters operate below the voltage for the onset of the uniform pulse size required in Geiger counters and give pulses which are approximately proportional to the number of ions delivered by the particular ray being registered, thus qualifying for the term 'proportional'. The voltage pulses are smaller and require stronger amplifying electronics.]

Dr Grosse's equipment operated on methane (CH_4). Therefore it seemed we needed to find a source of live methane. We found it in the gaseous effluent of the sewage disposal plant of the city of Baltimore. Most methane (natural gas) is from oil wells and therefore would be completely devoid of ^{14}C but the sewage gas would of course be very much alive in our sense of recency since leaving the biosphere.

Perhaps at this point we should stop and clearly state the basic principles of radiocarbon dating: (1) The cosmic rays make living things radioactive to a certain level fixed by the environment through the food eaten. (2) At death the intake of food stops so no replenishment of the immutable radioactive decay of ^{14}C can occur and the degree to which decay is observed to have occurred gives the time lapse since death (radiocarbon age). Thus 5730 years (half life) corresponds to 50 % of the concentration in living matter.

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Well, Dr Grosse after obtaining the sewage methane proceeded to enrich it to varying degrees (as measured by the ^{13}C enrichment) and Dr Anderson and I excitedly put the enriched methane in our proportional counter and took the counts behind the heaviest shield we could assemble, since the counter was responding in the main to laboratory radioactivity present in the building and equipment and to the cosmic radiation reaching the Earth's surface at Chicago. Strangely enough this whole thing worked and we did find about the anticipated ^{14}C concentration as a small additional count rate for the enriched methane as compared with the rate for unenriched methane or for petroleum natural gas methane. Further confirmation came when the carbon dioxide formed by burning the methane was found to be radioactive as well and to display a radiation with an average penetrating distance equivalent to 2.5 cm of air just as is true for man-made radiocarbon. This was done by precipitating the carbon dioxide as solid calcium carbonate which then was spread as a thin layer to minimize self absorption of the radiation. Thin aluminum foils were placed over the deposit and the decrease in count rate in a special screen wall counter measured (see figure 1, plate 1). (The special screen wall counter was necessary because the radiation is so soft.) A layer of aluminum weighing some 2.5 to 3 mg cm^{-2} was found to effect a 50 % reduction just as is the case for synthetic reactor produced ^{14}C.

The question of the rate of burning of the freshly made ^{14}C atom in the high atmosphere remains, for as said previously we really do not know this rate. The main part of the ^{14}C is produced in the stratosphere—the top 20 % or so of the atmosphere lying above the cloud tops at heights of 9150 m or above. We know now (although we only guessed it in 1945) that the stratospheric air mixes downward with the lower air—the troposphere—only in a matter of years. This information has been gained from studies of the radioactive debris of nuclear explosions introduced into the stratosphere by the high rising fireballs. At the present time we still are detecting such fallout from explosions in 1962 and 1963! Thus we see that if the carbon atoms burn in a year or two that is soon enough for our purposes in radiocarbon dating. It seems likely from laboratory experiments that the first step is the formation of carbon monoxide and that this occurs very rapidly. Following on this is a slower oxidation of CO by oxygen or possibly ozone or by sunlight exciting the CO, or what else. More research is needed.

However, there is a great saving grace—the 8300-year average life of radiocarbon. In this great span of time there is adequate opportunity for the CO to burn, for the atmosphere to mix, for the oceans to mix, and for the biosphere to cycle many times, i.e. die, decay to CO_2, and be reborn in photosynthesis. This grand system is continually stirred. Living matter is a part of this until death occurs and thus all living things have the same concentration.

At death isolation occurs and the radiocarbon clock starts ticking. The isolation is complete so we can separate physically and chemically the ancient matter to be dated from modern contamination. The fact that it is possible to do this 'laundry' job so completely ranks with the near constancy of the cosmic rays as one of the real breaks of good fortune in radiocarbon dating. However, both have some basis in scientific principle and fact—the chemistry of death is very different from that of life and the cosmic rays whatever their origin may ultimately prove to be, probably will not prove to be, a recent or transitory phenomenon since they seem more and more to be part of the warp and woof of the cosmos itself which measures its age in a time scale a million times longer than do the radiocarbon atoms.

The laundry of the dating materials is done by common sense and understanding. For example, with charcoal which is a most favourite type of material since man apparently is the only animal ever to make fire at will and charcoal is never attacked chemically except in fire,

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the first move is to examine the material under a low-power glass and to remove foreign materials such as plant rootlets. Then an acid wash is used to remove carbonates and this is followed by an alkaline wash to remove humic acids. Normally this is adequate and the treatment ends with a thorough distilled water washing before drying and burning to give the carbon dioxide for the dating counter (most of the modern daters use carbon dioxide proportional counters operating at 1 atm and about 5 kV although some favour other methods such as methane or acetylene proportional counters or scintillation counters using benzene synthesized from the purified sample and there probably will be other improved methods).

The method of counting contains a story: after Dr Anderson, Dr Grosse and I had found natural radiocarbon we had to face the fact that we could hardly expect Dr Grosse to use his very expensive apparatus on all our analyses.

So we went to work on the problem—how to increase the sensitivity of detection of the soft short-ranged radioactive carbon radiation by two or three orders of magnitude. The task was commanding for the Grosse samples left no serious doubt at this point that natural radiocarbon did exist. The only question was whether we could use it and it was completely clear that if every time we wanted a radiocarbon date we had to isotopically enrich the sample the cost would be prohibitive. Dr Grosse had spent enough money on this Baltimore sewage sample to run many archaeological museums for a month!

The natural count rate for a Geiger or proportional counter is about 5 counts min^{-1} cm^{-2} of cross-sectional area or 30 counts min^{-1} in^{-2}. Thus a counter 15 cm in diameter and 60 cm in length would count at the enormous rate of about 4300 counts min^{-1}, whereas the expected radiocarbon from one atmosphere carbon dioxide or methane filling the counter would be about 45 counts min^{-1} or about 1 %! Furthermore, in order to make meaningful use this 45 counts min^{-1} would have to be measured to better than 1 count min^{-1}.

We began our task by making an analysis of the sources of the background radiation and found them to be many and varied. The material of which the counter itself was made—the metallic cylinder, the central wire, and the insulating end plugs all could contain radioactive materials—uranium and thorium and their radioactive daughters or potassium which is naturally radioactive. In addition the laboratory floor, ceiling and walls, the workbench and the electronic equipment all were potential sources of penetrating γ radiation (very hard X-ray-like radiation emitted by many radioactive substances in addition to the α (helium nucleii) and β (negative electrons) particle radiations).

The counter contaminants registered mainly by the α and β rays, whereas these would not be able to penetrate the counter wall and the external sources work, therefore only through the much more penetrating γ rays (a typical γ ray may require 7.5 to 12.5 cm of water or a corresponding mass of denser material to be absorbed to 50 % intensity; a typical α, about 50 μm; and a β, 625 μm [^{14}C emits a particularly soft β and has a 'half thickness' of about 25 μm of water or plastic or paper]). Thus we knew that: (*a*) we must build our counter of clean materials, (*b*) we must shield the counter with clean non-radioactive matter, preferably a few metres thick for light materials and 30 cm or so thick for dense materials such as lead or iron.

We tested several samples of metal tubing by cleaning them carefully and building counters with them and using plastic end plugs to avoid glass which contains potassium. Thus we obtained what we thought was a clean counter. We next assembled some lead bricks and built ourselves a little house and lined the inside with iron plates about 2.5 cm thick to avoid radioactivity in the lead which is likely to be present. (The slagging operation in the iron metallurgy seemed

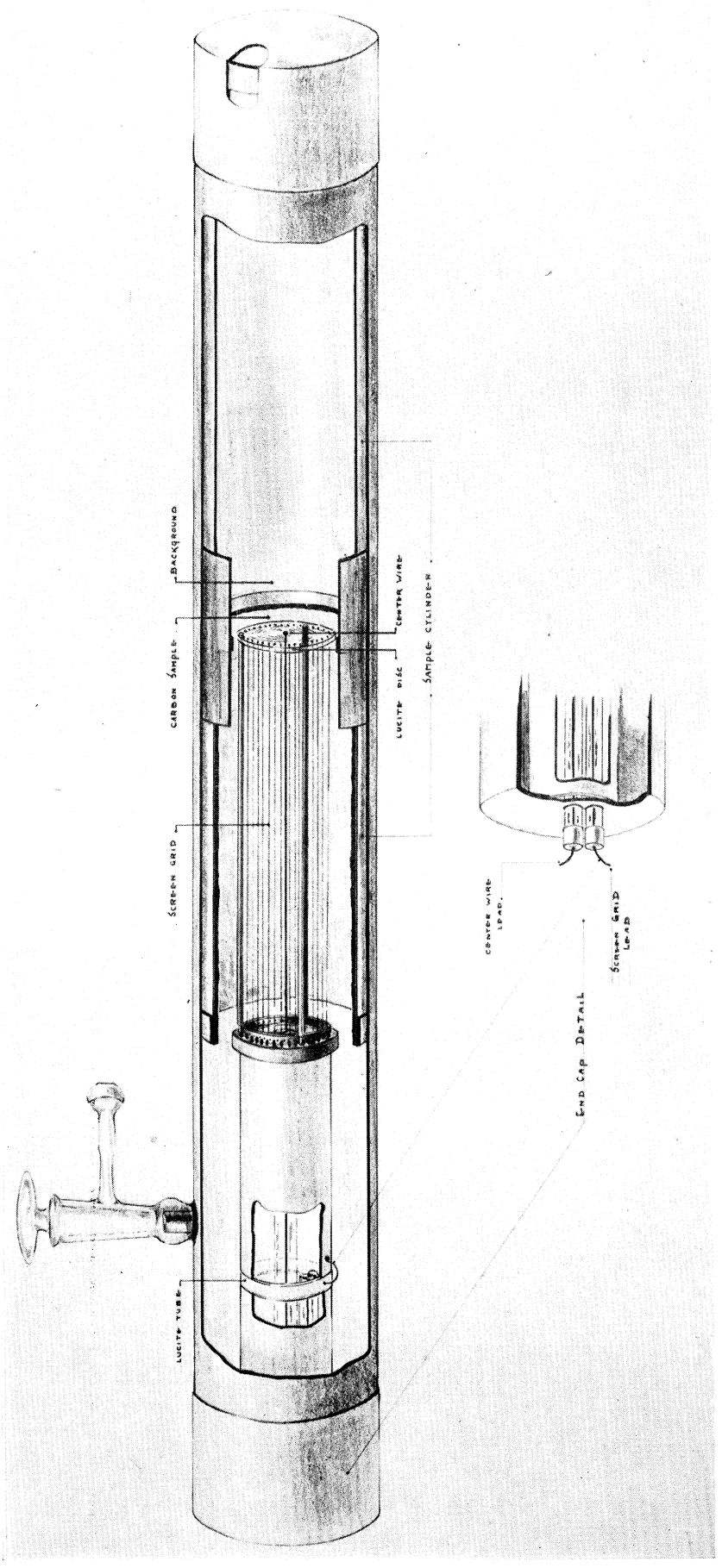

FIGURE 1. Screen wall counter.

(*Facing p.* 4)

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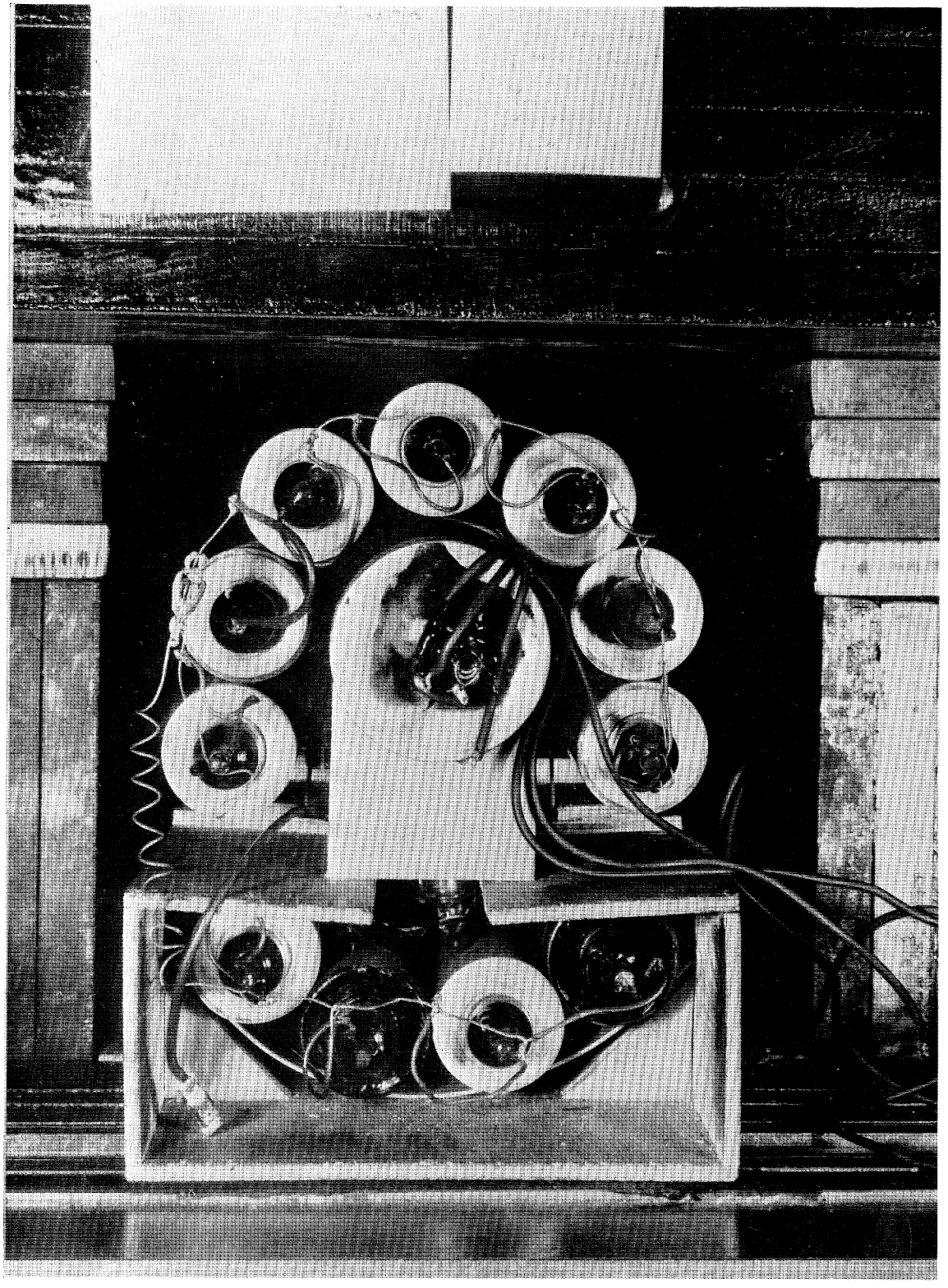

FIGURE 2. The first anti-coincidence counter.

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likely to us to be a good way of purifying iron for radioactivity since most natural radioactivities have a stronger reducing potential than iron and would naturally occur as oxide or silicate in the molten slag floating on the liquid iron.) Placing our counter in this shield (which had a heavy door on rails so we could close it) we obtained a count rate corresponding for the counter described above to 800 counts min^{-1}!

This was discouraging but not unexpected since we knew the cosmic rays were able to penetrate many metres of rock. We took our apparatus to the cyclotron building and placed it underneath the magnet yoke which was 3 m of iron thick and found about 600 counts min^{-1}. So it was clear that we either had to put our counter in a deep mine or we had to do something about these penetrating rays. The water table in the City of Chicago is only a metre or so below the surface so we would have had to move our laboratory by many kilometres to some abandoned mine.

We were on the point of doing just that when we had an idea which solved the problem. The cosmic ray muon (the muon is a transitory particle of 3 μs lifetime which is produced high in the atmosphere) has the very strange property of not reacting readily with atomic nuclei and yet, it ionizes matter easily. So it is the culprit which trips the counters deep in the atmosphere and has a great range. This was the clue which gave the way around our hurdle. If it moves in essentially straight lines then all we need do is to surround our counter by a layer of protecting counters set to switch off the central counter whenever they are activated. In other words, an anti-coincidence arrangement. Since the radiocarbon radiation is too soft to pass through the counter walls it will not trip the shield counters and therefore will register except during that certain small fraction of the time when the dater counter will be deactivated by the shield counters and this will constitute a loss factor which fortunately is small. By putting the bundle inside the heavy shield the muon rates are essentially all that is left for the shield counters to handle. The deactivation time need be only a fraction of a millisecond so the loss fraction is about 1 % or less.

Well we tried it. Figure 2, plate 2, is a picture of the first apparatus and it was successful immediately. In terms of the hypothetical counter (actually the present U.C.L.A. dater) the background now dropped from 600 to 13 counts min^{-1}.

The nature of the remaining counts is not known at present. They may be due to a number of effects. In our U.C.L.A. laboratory over the last eight years or so the background has decreased rather steadily from 15 down to something between 12 and 13 as though some slow decay were involved.

Well, having acquired a sufficiently sensitive and practical technique we went to work to test the main assumption first. This actually was Dr Anderson's doctoral thesis—the natural distribution and concentration of radiocarbon. He took wood samples collected about the turn of the century from widely dispersed places as well as seal meat and oil from Antarctica (Admiral Byrd's last expedition was the source). All gave the same result (cf. table 1). This result still stands. At the Nobel Symposium XII on Radiocarbon Dating held this past August in Uppsala several papers once again reaffirmed Dr Anderson's conclusions. The mixing is excellent.

The next step was to try the dating method. Dr J. Arnold of Princeton joined us for this test. He was a physical chemist as were both Dr Anderson and I but his father, a lawyer, was an enthusiastic amateur archaeologist and this brought him to us in the proper mood.

Straight off we had to face the question: 'How can you expect a museum keeper to give precious invaluable materials for you to destroy?' We worried about this a great deal and finally decided there was nothing for it but to enlist the aid of recognized experts to advise us and

acquire the materials for us. So we appealed to the American Archaeological Association and the Geological Society of America to give us a committee of experts which they did. The chairman was Frederick Johnson of the Peabody Museum at the Phillips Academy in Andover, Froelich Rainey of the Philadelphia Museum at the University of Pennsylvania, Donald Collier of the Field Museum in Chicago, and Richard Foster Flint the geologist from Yale. Three archaeologists and one geologist. These gentlemen did it right. They immediately got us pointed toward the Breasted Egyptian collection in the Oriental Institute at the University of Chicago and John Wilson, a senior professor in the Institute. Through Professor Wilson we obtained precious materials from the earliest pyramids and proceeded to burn and date them. (About 30 g of material were used in each case.)

TABLE 1. ACTIVITY OF TERRESTRIAL BIOSPHERE SAMPLES

source	geomagnetic latitude	absolute specific activity / d min^{-1} g^{-1}
white spruce, Yukon (Frederick Johnson)	60° N	14.84 ± 0.30
Norwegian spruce, Sweden (Donald Collier, Chicago Natural History Museum)	55° N	15.37 ± 0.54
elm wood, Chicago (author)	53° N	14.72 ± 0.54
Fraximus excelsior, Switzerland (Donald Collier)	49° N	15.16 ± 0.30
honeysuckle leaves, Oak Ridge, Tennessee (C. H. Perry, Clinton Laboratory)	47° N	14.60 ± 0.30
pine twigs and needles (3650 m alt.) Mount Wheeler, New Mexico (Robert Fryxell)	44° N	15.82 ± 0.47
North African briar (John Hudson Moore, Inc.)	40° N	14.47 ± 0.44
oak, Sherafut, Palestine (Donald Collier)	34° N	15.19 ± 0.40
unidentified wood, Teheran, Iran (M. Hessaby)	28° N	15.57 ± 0.34
Fraximus mandshurica, Japan (Donald Collier)	26° N	14.84 ± 0.30
unidentified wood, Panama (John Simpson)	20° N	15.94 ± 0.51
Chlorophora excelsa, Liberia (Donald Collier)	11° N	15.08 ± 0.34
Sterculia excelsa, Copacabana, Bolivia (9000 ft alt) (Donald Collier)	1° N	15.47 ± 0.50
ironwood, Majuro, Marshall Islands (Donald Collier)	0°	14.53 ± 0.60
unidentified wood, Ceylon (Donald Collier)	2° S	15.29 ± 0.67
beech wood ('Nothafagus') Tiera del Fuego (Junius Bird)	45° S	15.37 ± 0.49
Eucalyptus, New South Wales, Australia (Donald Collier)	45° S	16.31 ± 0.43
seal oil from seal meat from Antarctic (Byrd Expedition through H. J. Deason)	65° S	15.69 ± 0.30
average	—	15.3 ± 0.1†

† Error of calibration of counter raises error on absolute assay to 0.5.

The agreement obtained was well within our counting uncertainty of a few centuries (1 % in the count is 83 years in the radiocarbon age since the average life is 8300 years). So we began, and now 20 years later with perhaps 30 000 dates and some 70 dating laboratories we can take a reviewing look at the method.

One additional point in the story—we actually used carbon black and the screen wall counter instead of the present carbon dioxide proportional counter and we had to be extremely careful of contamination of the highly absorbent carbon black (obtained by reacting the CO_2 from the combustion with hot metallic magnesium). This nearly derailed us because the errors and uncertainties could be substantial. The carbon black had a tendency to retain magnesium oxide in a strangely adherent way which protected it from the hydrochloric acid leach applied routinely after the magnesium treatment and this ash correction was large. As a final step we mounted the carbon black on the inside of the screen wall counter wall by moistening it with ethyl alcohol to make a slurry which then was dried in a stream of warm air. However, a certain amount of the alcohol usually remained on the highly absorbent carbon black and this contributed an error due to the counts in the grain alcohol used. Only one other laboratory (New

Zealand, Dr G. Fergusson) ever used the black carbon method and we gave it up with great relief when it was shown (Fergusson in New Zealand and de Vries in Holland) that CO_2 proportional counting worked well. By that time, however, we had laboriously processed several hundred samples. Incidentally we still have the carbon blacks for most of these early measurements in case anyone would like to check the dates.

2. Retrospect and prospects

The long experience with radiocarbon dating has taught us two things: On simultaneity it apparently is reliable but on absolute dates it can be incorrect by as much as 600 or 700 years at the peak of the deviation some 7000 years ago. The simultaneity principle is that two samples taken from any place in the world for any past epoch will give the same date. This of course, follows from the principle of good mixing described previously, i.e. Dr Anderson's finding the same concentration of natural radiocarbon all over the world and in different life forms nearly guaranteed this result.

The bristlecone pine tree ring chronology of Fergusson & Bannister (Fergusson, cf. XII Nobel Symposium) has made possible the determination of the extent of the deviations of the radiocarbon dates by Suess, Ralph & Damon (cf. XII Nobel Symposium) back to some 7500 years ago. The dates appear to start falling slightly too young about 3000 years ago and continue deviating in that sense until what may be the peak deviation of some 700 years is reached about 5000 years ago when the deviation appears to level off. There is some evidence of a decrease back to agreement at 10 000 to 11 000 years. This evidence is from the Swedish varve chronology, according to Tauber and others (XII Nobel Symposium). In addition to the broad general sweep of the main deviation there appears to be a short-term fine structure of somewhat erratic nature, according to Suess (XII Nobel Symposium) (cf. figure 3).

The speculation at the moment is that the main deviation is due to a weakening of the Earth's magnetic field observed by Bucha and others (XII Nobel Symposium) according to the principle pointed out by Elsasser long ago and that the fine structure is due to variations in the intensity of the solar wind which fends off the cosmic rays. The Earth's field normally deflects about half the cosmic rays so weakening could cause the observed effect. A third possibility is that solar cosmic rays also play a role. It appears to be unlikely that the intensity of the galactic cosmic rays themselves varies since the radioactivities found in meteorites seem to agree only with the assumption of constancy, i.e. the long-lived and shorter lived radioactivities occur in intensities which fit only this assumption. Unfortunately the accuracy with which this assertion can be made is limited due to the paucity of data. A benefit for radiocarbon dating is anticipated here from the Moon samples. Their large size and freshness may allow more accurate measurement of the intensities of the radioactivities induced by the cosmic rays in the surface rocks. High energy protons from accelerators are used to calibrate for the relative efficiencies of production of the various radioactive atoms.

The question of the solar proton contributions remains somewhat open at the moment. Counters on space probes seem to say that there must be some such contribution but the energy spectrum and the intensity remain uncertain. The Earth's magnetic shield is so strong that it may be difficult for these relatively low energy cosmic rays to play a role.

The argument for the fine grained deviations being due to something solar is persuasive, but just how the effects occur is less clear and further work is necessary. It may be anticipated that when these points are settled the information may prove to be of value to solar and astrophysics.

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The main effort now underway is the Bristlecone Pine programme (Fergusson, Suess & Damon, XII Nobel Symposium), but the work of Stuiver on lake sediments is very promising (Stuiver, XII Nobel Symposium) as well. His results seem to agree with the Bristlecone curve in many respects but they do not seem to agree with the Swedish varve results in the older periods beyond 7500 years ago. Since the method is questionable (the counting of annual layers of sediment and the association of organic matter in a particular layer with that layer), as is

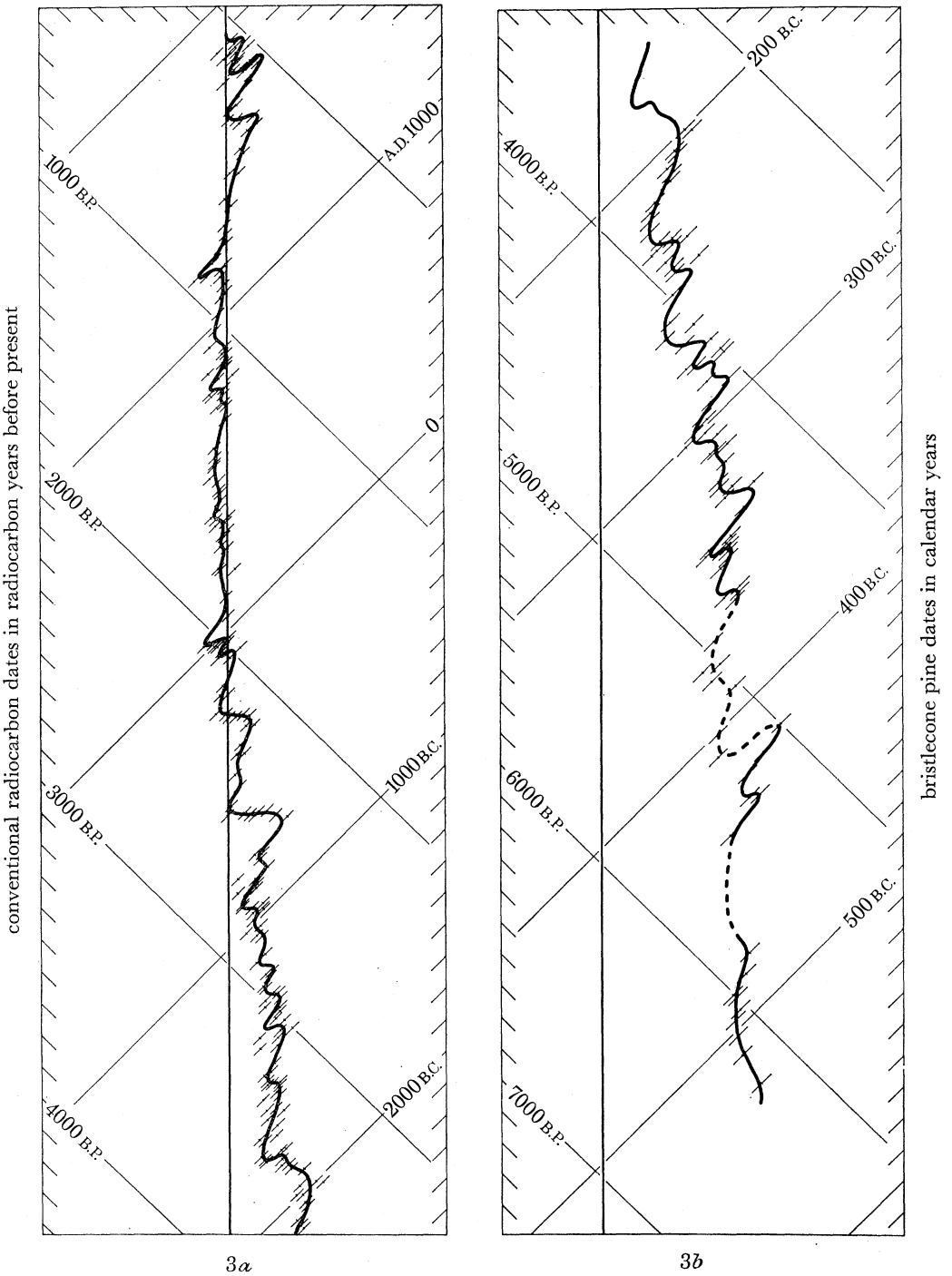

FIGURE 3. Empirical correlation between conventional radiocarbon ages based on 5568-year half life and bristlecone pine tree-ring ages after Suess.

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true also of the Swedish varve method in some respects, we are left uncertain about the course of the curve prior to 7500 years ago. So we are driven back to the Bristlecone Pine to extend the chronology backward to glacial times about 11000 years ago.

Fergusson reports finding a piece of wood in the White Mountain (California) area which radiocarbon dates at about 9000 years. So, presumably, if an overlapping piece or pieces can be found there, the chronology could be extended from the present 7500 year limit in the White Mountain area back to 9000. A second area near Ely (Nevada) has a Bristlecone chronology reaching back to about 5000 years. Other known stands of which there are several have not been dated dendochronologically but it would seem that they offer some additional hope for future work. Every effort to preserve ancient wood on the ground in these forests should be made for they are of prime scientific value possibly embodying our main opportunity to check radiocarbon dates back to 10000 years.

The principle of simultaneity means that radiocarbon dates are the same at any given epoch over the entire Earth so a calibration at any one locality is equivalent to a world wide calibration.

The corrections themselves are of most interest to geophysicists and solar and astrophysicists. The source of the Earth's magnetic field remains unknown although the evidence accumulates suggesting that it is related to the metallic nature of the Earth's interior and the Earth's rotation (Venus is of about the same size as the Earth and therefore presumably has a metallic interior but does not rotate—241 Earth days per day; Mars is much smaller and may have no metallic interior even though it rotates at about the same rate as the Earth; and the Moon is smaller still. None of these bodies has a magnetic field. Jupiter, on the other hand, has a very strong field—about fifty times stronger than the Earth—and it rotates more rapidly—10 h and is larger than the Earth).

Now, the evidence seems to indicate that the over-all strength of the field decreased substantially perhaps 7000 or 8000 years ago and then subsequently renewed its intensity about 5000 years ago. It is only the over-all strength that matters since world wide mixing is so efficient. A mere shift of direction (which is well known to have occurred in historic times) would not be recorded by radiocarbon.

On a longer time scale—millions of years—it has been discovered that complete reversal of the direction actually occurs repeatedly. These very ancient data seem to give little evidence about over-all intensity. However, it is natural to suppose that the fact of reversal at least suggests the possibility of intensity variation.

The solar and astrophysicists expect to learn about the constancy of solar activity over the last 40 millenia as more work is done on radiocarbon dating. They also can expect strict limits to be set on the intensities of past super novae bursts since these could have given γ ray bursts which would have given short-termed peaks (of the order of 50 years wide) in the deviation curve (Lingenfelter, XII Nobel Symposium and private communication, 1969).

A short-termed perturbation as we have had recently in the atmospheric nuclear explosions which have raised the ^{14}C content of the atmosphere and biosphere by about 50 % lasts about 50 years before mixing with the ocean occurs and gives a dilution of some thirtyfold. Thus radiocarbon is particularly sensitive to short-term perturbations but the method requires samples from the particular years involved. Thus it has been shown that the Siberian meteorite of 1908 could not have contained anti-matter (Cowan, Atluri & Libby 1965) by measuring wood from tree rings in the years following.

The correction curve itself is primarily of interest to historians and archaeologists. With it we now can say that the Egyptian chronology currently accepted probably is correct. Further work is needed to clarify detailed points and the possibilities of substantial clarification of the

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history of the first dynasties appear to be good. The opportunities for pre-dynastic Egypt extending back into the palaeolithic seem to be very substantial (Säve-Söderbergh & Wentdorf, XII Nobel Symposium).

In Europe the main new result seems to be a redating of the neolithic (Neostupny, XII Nobel Symposium) at about 2 millenia older than previously believed, although further work is needed.

In the Americas it has given a quantitative chronology with relatively few surprises, except for the continued failure to firmly establish preglacial man. A 17 000-year-old skull was reported (Berger and Libby) as having been found at Laguna Beach, California, but further excavation of the site recently has given no further evidence of human remains.

Earth scientists are interested in the curve itself for dating vertical earth movements and the eustatic rase of the seas following the last glacial period. Climatologists use radiocarbon dates to establish on a world-wide basis climatic changes.

The method itself has been improved in several respects. It now is possible to date bone using the small protein content. The prospects for developing a reliable method for shell samples appear to be brighter (Wentdorf, XII Nobel Symposium).

The study of the nuclear test radiocarbon and its rate of movement into the sea promises to give detailed understanding of the mechanism and rate of uptake of CO_2 from the air by the sea—a matter of concern as the rate of burning of coal and oil continues to increase. It also will allow more quantitative evaluations of the fine structure in the curve of deviation. A somewhat unexpected result that the rate may be controlled by an enzyme has recently been obtained (Berger and Libby) by studying subsurface sea water (60 m deep) and finding that it equilibrates more rapidly with atmospheric CO_2 than does surface water (Santa Monica, California beach) and that the surface water can be brought into agreement by addition of the enzyme carbonic anhydrase in a few parts per million.

'Half-life' and 'average life'

The law of radioactive decay is $2^{-t/t_{\frac{1}{2}}}$ or $e^{-t/\tau}$ where e is the naperian base and $t_{\frac{1}{2}}$ and τ are the 'half life' and 'average life', respectively. If you average the life you obtain τ.

For instance:

$$\int_0^\infty 2^{-t/\tau} t \, dt = \tau \quad \text{and} \quad \int_0^\infty 2^{-t/t_{\frac{1}{2}}} t \, dt = \int_0^\infty e^{-(t/t_{\frac{1}{2}})\ln 2} t \, dt.$$

So

$$\tau = \frac{t_{\frac{1}{2}}}{\ln 2}.$$

Figure 4 shows this less mathematically.

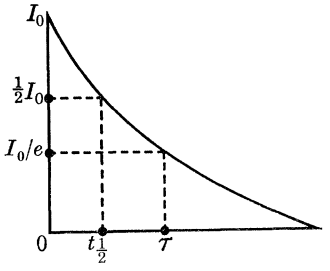

FIGURE 4

REFERENCE (Libby)

Cowan, C., Atluri, C. R. & Libby, W. F. 1965 *Nature, Lond.* **206**, 861.

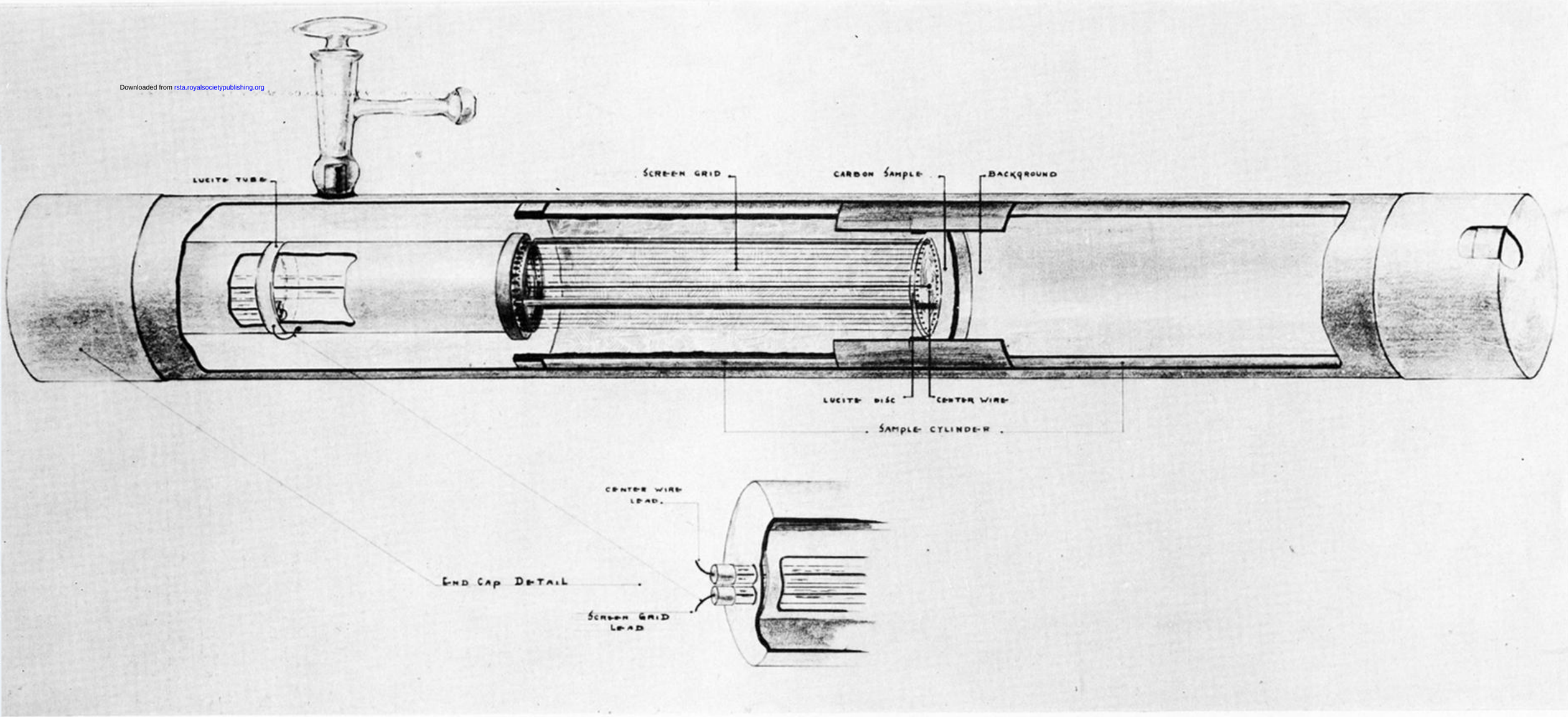

FIGURE 1. Screen wall counter.

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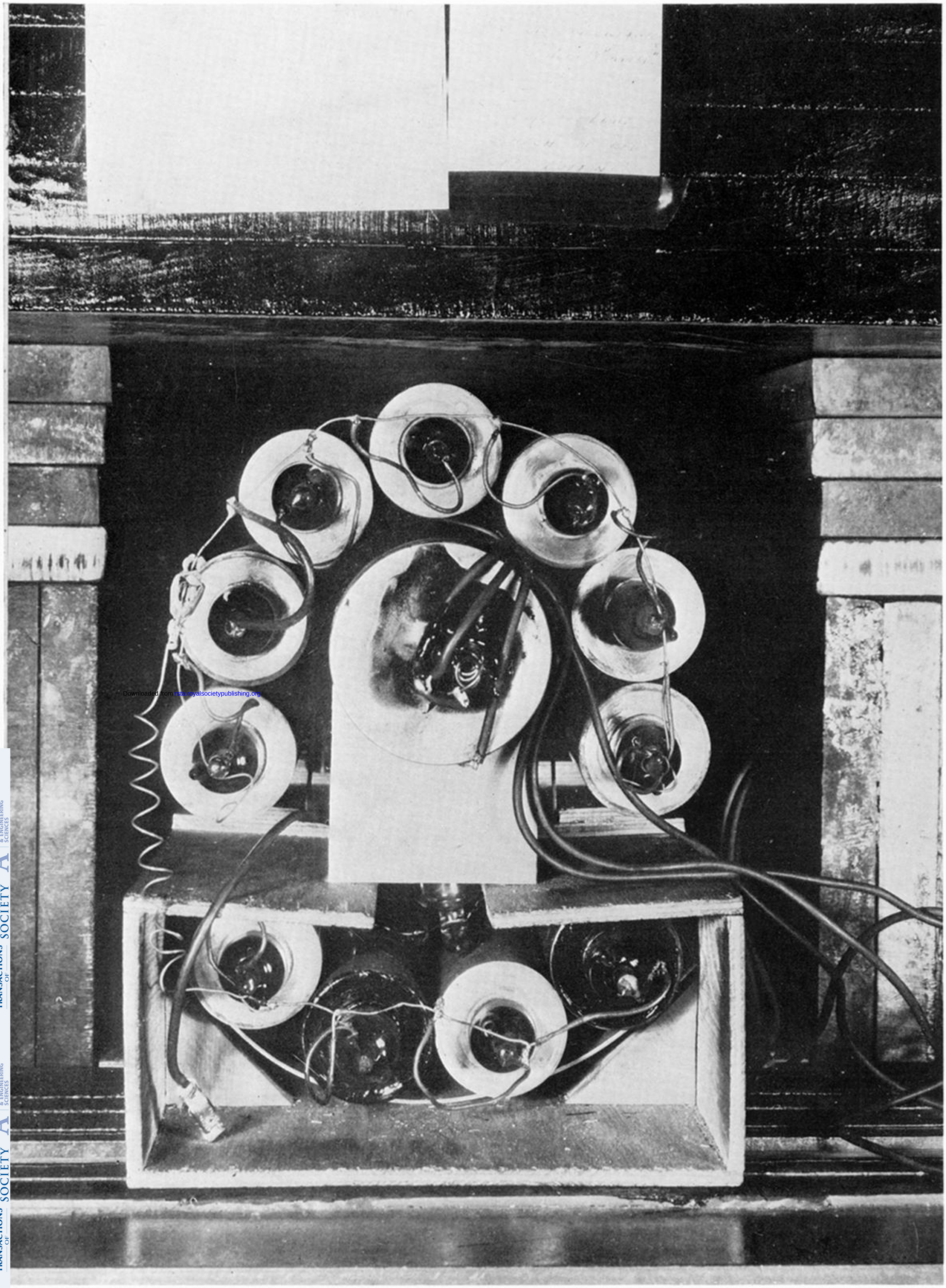

FIGURE 2. The first anti-coincidence counter.