pendent of the particle mass and only a function of the respective ranges.

$$(dE/dR)_{R_x}/(dE/dR)_{R_{x-a}}=R_x^{0.425}/(R_{x-a})^{0.425}$$
$$=1/[1-(a/R_x)]^{0.425}. \quad (9)$$

Equation (9) permits us to calculate R_x and consequently R_{x-a}.

However, knowing the residual range of our particle, we are in the same position as before and can assign to our track one of the family of curves in Fig. 2.

Our curves and equations have been compared only with experiments in Ilford emulsion. We can expect, however, that they will be equally valid for Eastman Kodak emulsion, changing slightly the parameters b and c.

PHYSICAL REVIEW VOLUME 75, NUMBER 2 JANUARY 15, 1949

Radioactivity of C^{10} and O^{14}

R. SHERR, H. R. MUETHER, AND M. G. WHITE
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey†

(Received October 4, 1948)

A new activity, O^{14}, has been produced from N^{14} by a (pn) reaction and is found to decay with a half-life of 76.5 ± 2 sec. by the emission of 1.8 ± 0.1-Mev positrons and a 2.3-Mev gamma-ray. Rough threshold measurements indicate that the gamma- and beta-rays are in cascade. C^{10}, formed by a (pn) reaction in B^{10}, has been carefully reexamined and shown to decay with a half-life of 19.1 ± 0.8 sec. by the emission of 2.2 ± 0.1-Mev positrons and a gamma-ray of approximately 1 Mev. The Coulomb energy formula for this type of mirror nucleus is shown to be valid, but the same theoretical difficulties are encountered here as are already known from the long lives of Be^{10} and C^{14}.

INTRODUCTION

IT is well known that an important contribution to the mass of a nucleus is the classical Coulomb energy which arises from the positive nuclear charge. A particularly convincing demonstration of this fact is obtained[1,2] from the study of positron spectra of those "mirror" nuclei which are characterized by having one more proton than neutrons (e.g., Be^7, C^{11}, N^{13}, O^{15}, etc.). The emission of a positron merely interchanges the number of neutrons and protons, and on the assumption that specifically nuclear forces between nucleons in similar states are equal and independent of the charge, one can attribute the entire energy release of the mirror nuclei to Coulomb energy and the neutron-proton mass difference. Coulomb energy can be calculated in a classical way, assuming the nuclear charge to be uniformly distributed over a volume proportional to the number of nucleons. Taking the nuclear radius to be $r=1.44\times10^{-13}A^{\frac{1}{3}}$, where A is the mass number, one obtains $E_c=0.60Z(Z-1)A^{-\frac{1}{3}}$. E_c is the Coulomb energy in Mev and Z is the atomic number. The agreement[1] of this expression with the experimental values obtained from the positron spectra of mirror nuclei shows that the assumptions regarding equality of $p-p$, $n-n$ forces is largely justified, and, further, that the nuclear volume is approximately proportional to the number of nucleons. One important aspect of Fermi's theory of β-decay, the relation between half-life and energy, also receives confirmation from these β-transitions.

The properties of other light nuclei are not so well understood either from the point of view of nuclear structure or β-theory.[2] Thus, in nuclei of the type $A=4n+2$ it is found that two members of the series (He^6 and F^{18}) decay with half-lives which imply allowed transitions between states presumably differing in spin by 1. This experi-

† Assisted by the Joint Program of the Office of Naval Research and the Atomic Energy Commission.

[1] E. Wigner, Phys. Rev. **56**, 519 (1939); M. G. White, E. C. Creutz, L. A. Delsasso, and R. R. Wilson, Phys. Rev. **59**, 63 (1941); Additional references to the present and related questions are given in these papers and also in reference 2 below.

[2] E. J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).

mental fact apparently requires the acceptance of Gamow-Teller selection rules. On the other hand, a more serious difficulty is that presented by other members of the series Be^{10}, C^{14}, Na^{22}, P^{30}, etc., whose (ft)†† values correspond to highly forbidden transitions, whereas allowed transitions are to be expected on the basis of GT rules. The most puzzling transitions of the $4n+2$ nuclei were $Be^{10}\rightarrow B^{10}\leftarrow C^{10}$. Be^{10} and C^{10} are similar to the mirror nuclei discussed above in that they differ only in the interchange of two protons and neutrons; the other quantum numbers of their ground states are expected to remain unchanged. The mass difference $(C^{10}-Be^{10})$ should be accounted for by the additional Coulomb energy of the former, and the transitions of both mirror nuclei to the ground state of B^{10} should be of the same character (i.e., both equally allowed or forbidden). Attempts to explain the allowed character of the $C^{10}-B^{10}$ transitions and the forbidden character of the $Be^{10}-B^{10}$ transition were unsuccessful. The theory of nuclear structure required that Be^{10} and C^{10} be simply related as described above, while the theory of β-decay required that the ground states be quite different.

The present experiment was undertaken to reexamine the radioactivity of C^{10} and to search for the radioactivity of O^{14}, which is related to C^{14} and N^{14} in the same manner as the lighter triad. While some of the measurements cannot be considered as final, sufficient information has been obtained to show that the ground states of Be^{10} and C^{10}, and of C^{14} and O^{14}, are probably of similar quantum character, as required by the theory of nuclear levels of light nuclei. The new results show that the previously reported activity of C^{10} [3] was in error. The presently observed C^{10} is a positron emitter of half-life 19.1 ± 0.8 sec. with a β-spectrum limit of 2.2 ± 0.1 Mev, accompanied by nuclear γ-radiation in the neighborhood of 1 Mev. O^{14} has been found to be a positron emitter of half-life 76.5 ± 2 sec. with a β-energy of 1.8 ± 0.1 Mev, accompanied by nuclear γ-radiation of 2.3 Mev. These results will be discussed later.

EXPERIMENTAL PROCEDURE

In order to permit rapid chemistry on the radioactivities produced by protons on various targets, a gas flow system was used similar to that employed by Sommers and Sherr.[4] The target material was placed in a small copper cell (Fig. 1) which terminated a probe of the usual cyclotron variety. A small amount of finely powdered target material was held in place at the tip of the cell by a mat of glass wool. The internal proton beam of the cyclotron entered through a 1-mil copper foil covering the cell.

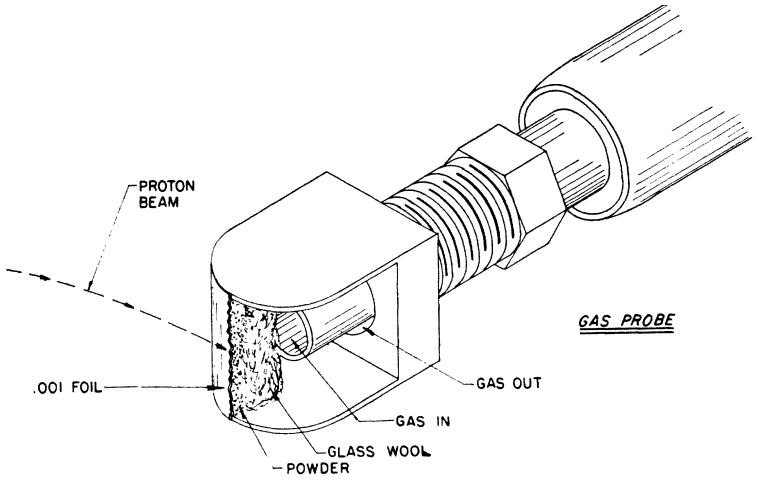

FIG. 1. Cyclotron probe for collection of radioactive gases evolved in the bombardment of powdered targets. These gases are swept to an inspection cell by a flushing gas.

†† The product (ft) should be approximately constant for a given type of transition (see references 1 and 2). In this expression, t is the half-life while f is a certain integral over the energy spectrum of the β-particles and is related to the half-life by $1/t=(1/\log 2)Gf(W_0,Z)$. G depends on the matrix elements of the nucleons. $W_0=1+(E_\beta/mc^2)$ where E_β is the upper limit of the spectrum.

[3] L. A. Delsasso, M. G. White, W. Barkas, and E. C. Creutz, Phys. Rev. **58**, 586 (1940).

[4] H. S. Sommers, Jr. and R. Sherr, Phys. Rev. **69**, 21 (1946).

After or during irradiation the radioactive gases formed and released by the bombardment were swept to an inspection chamber by a flushing gas by way of the concentric tubes in the probe as indicated in Fig. 1. The gas handling system is shown in Fig. 2. The essential features are the various solenoid operated "hose pinching" valves and the inspection chamber. The system was sufficiently flexible to permit varied types of operation (continuous flow, bombardment in vacuum, etc.). For purposes of chemistry or purification, tubes of absorbing materials and traps of various kinds were easily inserted in the flow line. The inspection chamber has two 2-mil copper windows, permitting the simultaneous use of two mica window Victoreen Model "VG" counters. For some of our measurements it was necessary to trap the desired radioactive gases on $CaCl_2$ or NaOH. Powders of these materials were held across the center of the inspection chamber by wire mesh screens with the gas inlet and outlet so arranged that the gas could leave only by passing through the absorbing material. The pulses from the Geiger counters were fed to scaling circuits and finally to a double channel recording oscillograph (Brush Model BL-202). For short period activities decay curves were obtained by counting pulses on the paper tape of the Brush oscillograph as a function of time. By means of an electrical control box the operations of bombardment, flushing, and recording were made automatic, so that measurement could be started within a fraction of a second after ending the bombardment. While this method of production of radioactive gas is very inefficient in terms of the total radioactivity available, sufficient activity could be obtained for most of the measurements.

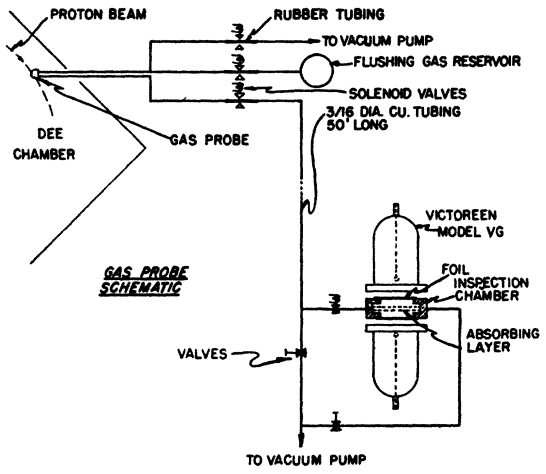

FIG. 2. Schematic drawing of the gas probe system, showing the probe, control valves, and counting arrangement.

The chemical processes by which radioactive gases were obtained from various target materials were a source of considerable puzzlement, but also of great convenience. In bombarding all boron containing substances (H_3BO_3, borax, CaF_2BF_3, and boron metal), the radioactive carbon produced by a (p, n) reaction appeared at the inspection chamber in the form of CO_2. The CO_2 was absorbed in a layer of ascarite (NaOH on asbestos) while nitrogen and neon activities were pumped off. No evidence of formation of CO was found. In the case of the oxygen radioactivities, the compound KSCN was used as target material, and the oxygen appeared in the form of H_2O. The latter was collected on a layer of $CaCl_2$, while carbon, nitrogen, and other activities were pumped off. As was to be expected, the yield of radioactive gas was higher for more finely divided target material.

C^{10}

Bombardment of boron metal or boron compounds with 0.5 μa of protons at approximately 17 Mev energy gave carbon activities decaying as shown in Fig. 3. In addition to the well-known 20.5-min. activity of C^{11} produced by a (p, n) reaction in B^{11}, a new period of 19.1 sec. was found. The decay curve of Fig. 3 was obtained from the same boron powder used by Delsasso, *et al.*[3] in the earlier work on C^{10}. No evidence was found at 17 Mev for the shorter period reported by them. Direct measurements were made on the boron powder irradiated at 7 Mev by pushing the bombardment probe to a smaller radius. This target then showed a period of 9–10 sec. However, a similar irradiation with highly purified B_4C showed only a weak 20-sec. period and the C^{11} period. It must be concluded that the 8.8-second activity previously reported resulted from an impurity in the boron powder. In Fig. 4 is shown the decay of the radioactive gases produced in enriched CaF_2, $B^{10}F_3$ containing 95 percent B^{10} instead of 18.4 percent, and trapped by ascarite. The ratio of the 19-sec. activity to

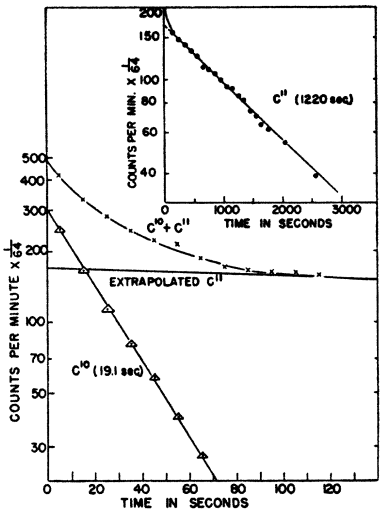

FIG. 3. Decay of radioactive gases from bombardment of boron by protons. The upper graph shows the C^{11} decay, and the lower graph shows the C^{10} decay.

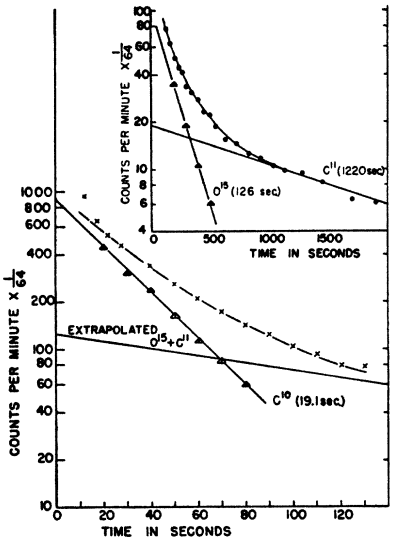

FIG. 4. Decay of radioactive gases from bombardment of CaF_2, $B^{10}F_3$ by protons. The gases have been trapped by ascarite. The upper graph shows the longer period activities, the lower graph shows the C^{10} decay.

the C^{11} activity was enhanced by a factor of the order of 50 over that for ordinary boron, indicating the correctness of the assignment of this new period to C^{10}.

It was observed that for all unenriched targets the ratio of C^{10} to C^{11} remained constant (within the limits imposed by differences in bombarding time). To make certain that the 19-sec. activity was carbon, a series of chemical tests were made by Professor John Turkevich of the Chemistry Department. The radioactive gas was dissolved in a $Ba(OH)_2$ solution. CO_2 was precipitated as $BaCO_3$. A carrier was then provided by addition of Na_2CO_3, which precipitates $BaCO_3$. The solution was filtered and the $BaCO_3$ was placed under the counter. The entire procedure was completed within 20 sec. after ending bombardment. Although recovery was not complete, the C^{10}/C^{11} ratio in the filter paper was the same as in the case where the radioactive gas was trapped on ascarite. The only other likely gaseous activity which would behave like CO_2 in this analysis is SO_2. Additional tests were made to examine this possibility. The radioactive gas was passed for one minute into a solution containing NaOBr. At this point Na_2CO_3 carrier solution was added, the mixture shaken and then treated with HCl liberating copious amounts of gas. The gas was passed over ascarite, which was then found to be radioactive with periods of approximately 19 sec. and 21 min. The purpose of this radiochemical analysis was to eliminate SO_2 as a source of activity. If there were any SO_2 in the original gas it would dissolve in the NaOBr to form sodium sulfate. The latter would not decompose into a gaseous product on treatment with HCl. However, we did detect activity in the ascarite with the original periods and relative strength. These findings are consistent with the view that CO_2 in the original gas dissolved in the NaOBr and was liberated by the HCl, and again trapped by ascarite. We, therefore, ascribe the 19.1-sec. period to C^{10} and the 21-min. period to C^{11}.

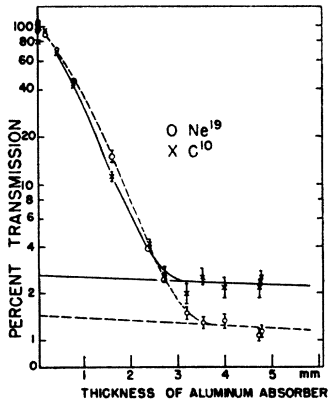

FIG. 5. Positron absorption curves for Ne^{19} and C^{10}, taken under identical geometrical conditions. The abscissae refer to added aluminum absorber.

The sign of the particles emitted by C^{10} was found to be positive by bending them in a magnetic field. In order to determine the maximum energy of the positron spectrum, an absorption curve in aluminum was taken. For calibration purposes a similar curve was obtained for Ne^{19} produced by a (p, n) reaction on PbF_2. Ne^{19} was chosen for comparison because it has a half-life of 20.3 sec.[5] and approximately the same energy. Both activities were examined as gases in the inspection chamber (i.e., no chemical absorbing materials were used), so as to have identical geometries. Measurements on a number of decay curves gave a value of 18.2 ± 0.6 sec. for the half-life of Ne^{19} and 19.1 ± 0.8 sec. for the half-life of C^{10}. The lower value obtained at present for Ne^{19} may be instrumental, although no source of error is apparent. It may be that in the previous work the period was lengthened by the presence of a small amount of impurity in the solid target used. The present decay curves were simple over a factor of 100 in counting rate, while the earlier decay curves were carried over only a factor of 10 in activity.

The absorption curves for Ne^{19} and C^{10} are shown in Fig. 5, where it is seen that the energies are nearly identical. It is to be noted that the γ-ray background activity is higher by a factor of two in the case of C^{10}, showing the presence of nuclear γ-radiation in the decay of this nucleus; the Ne^{19} background is assumed to be solely annihilation radiation.[5] Because of statistical fluctuation near the end point of the positron absorption curve, it is difficult to determine directly a precise range. We have, therefore, analyzed the absorption data of Fig. 5 by the method of Bleuler and Zünti.[6] These authors developed approximate theoretical curves for the absorption of β-spectra of different energies in aluminum and corrected the theoretical curves to agree with experimentally determined curves for various Z as well as E_β. Their results are summarized in Fig. 6 and Fig. 7 of their paper.[6] Their method of determining the energy of an unknown substance from its absorption curve is essentially as follows: the absorber thicknesses corresponding to reduction of the intensity of $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, etc., are designated as d_1, d_2, d_3, etc. To each value of d_n there corresponds an energy, E_n, which is the maximum energy of the β-spectrum. If the spectrum is simple and allowed, the various E_n should be identical. Bleuler and Zünti found that by applying their curves to previously published absorption curves for various radioactivities, they were able to obtain energy values which agreed very well with β-spectrographic values, frequently to a higher degree of accuracy than the values given by the original authors of the absorption data. The success of their method in handling data taken under various experimental conditions and the fact that our geometry is not very different from their own, suggests that an analysis of the present data in this fashion is probably fairly accurate. In Fig. 6, the absorption data for C^{10} and Ne^{19} are replotted with the γ-ray background subtracted in each case. (The abscissa includes the counter windows and copper foil of the inspection chamber.) Comparison with the curves of Bleuler and Zünti gives the following values of E_β (corrected for Z and sign of particle) corresponding to successive d_n: for Ne^{19} 2.33, 2.34, 2.31, 2.33, 2.33, 2.32 Mev, or an average of 2.33 Mev; for C^{10} 2.28, 2.23, 2.17, 2.18, 2.18, 2.17, or

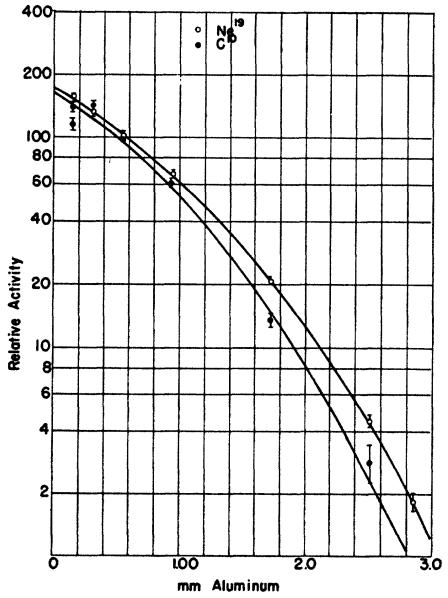

FIG. 6. Positron absorption curves for Ne^{19} and C^{10}. The data of Fig. 5 are replotted with γ-ray backgrounds subtracted. The abscissae have been corrected for the counter window and the inspection cell window.

[5] M. G. White, L. A. Delsasso, J. G. Fox, and E. C. Creutz, Phys. Rev. 56, 512 (1939).

[6] E. Bleuler and W Zünti, Helv. Phys. Acta 19, 375 (1946).

2.20 Mev average. The value of 2.33 Mev for Ne^{19} is somewhat higher than the previously reported value[5] of 2.2 Mev as determined with a cloud chamber, but in good agreement with the value of 2.3 Mev as determined by absorption.[5] In view of the fact that the method of Bleuler and Zünti as used by them in the manner described above on the data of other workers gave values which were frequently in better agreement with spectrographic values than cloud-chamber evaluation, the presently determined values are accepted as essentially correct; i.e., for Ne^{19}, $E_\beta = 2.3 \pm 0.1$ Mev and for C^{10}, $E_\beta = 2.2 \pm 0.1$ Mev.

As noted above, the high γ-ray background of C^{10} indicates the existence of nuclear γ-radiation in addition to annihilation radiation. Many attempts were made to obtain a good lead absorption curve, but since the ratio of C^{10} to C^{11} at the highest proton energy was of the order of 1, it was impossible to obtain the desired accuracy. Attempts to filter out the C^{11} radiation by large thickness of Pb failed, indicating that the C^{10} radiation was not appreciably harder than annihilation radiation. Figure 7 shows the final results of these measurements; for comparison, an absorption curve for C^{11} annihilation radiation is included. For the latter an absorption coefficient of 1.36 cm^{-1} was obtained; this value is lower than the correct value for 510-kev radiation by 25 percent, as a result of the poor geometry used in these measurements. The average absorption coefficient for the C^{10} radiation is 0.68 ± 0.14 cm^{-1}. On the assumption that this value is low in the same ratio as for the 510-kev radiation, a corrected value of 0.85 ± 0.18 cm^{-1} is obtained, corresponding to an average gamma-ray energy of 960 ± 200 kev.

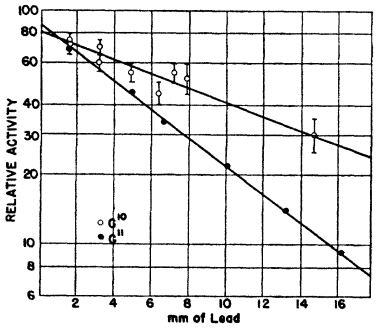

FIG. 7. Absorption of gamma-radiation in lead.

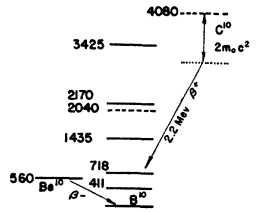

FIG. 8. Energy level diagram of Be^{10}, B^{10}, and C^{10}. The energies are given in kev. The dashed lines represent calculated values.

DISCUSSION OF RESULTS FOR C^{10}

On the basis of present measurements it is difficult to derive the decay scheme of C^{10}. However, in combination with the known levels in B^{10} and the decay energy of Be^{10}, a tentative decay scheme can be presented. The β-ray absorption curve (Fig. 5) shows that there is an appreciable amount of γ-radiation per β-particle. The C^{10} positron absorption curve (Fig. 6) appears to be simple, whereas if the 2.2-Mev β-transition corresponded to a transition to the ground state of C^{10}, one would expect the β-absorption curve to be complex. Certainly no softer component of the order of 1 Mev with intensity comparable to the 2.2-Mev spectrum can be present. It is therefore assumed that the C^{10} decays to an excited state of B^{10} with subsequent emission of gamma-radiation. In comparing isobars of type $(4k+\nu\pi)$, $(4k+\nu\nu)$, and $(4k+\pi\pi)$, where k is a low integer and ν and π represent a neutron and proton, respectively, one is permitted by the Pauli principle to have both extra nucleons in the *same* orbital state. The differences in binding energies are then to be attributed to differences in Coulomb energy and to differences in the spin interactions of the extra nucleons with each other and with the alpha-particle core. The extra proton and neutron in $(4k+\nu\pi)$ are expected to have parallel spins, as in the ground state of the deuteron, while in $(4k+\nu\nu)$ and in $(4k+\pi\pi)$ the extra particles almost certainly have antiparallel spins. However, since C^{10} differs from Be^{10} only in the interchange of the two extra neutrons and protons, one expects from the equality of $p-p$ and $n-n$ forces that the ground states of these two nuclei are of similar quantum mechanical character. As we remarked earlier, this hypothesis has been verified for simple mirror nuclei of the type where only one

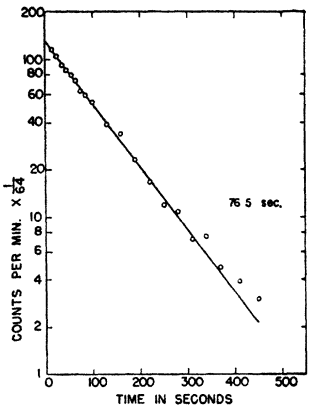

FIG. 9. Decay of radioactive gases produced by bombardment of KSCN by protons and trapped by $CaCl_2$.

nucleon is interchanged. If this assumption is correct for the interchange of two nucleons, then the difference in binding energy of C^{10} and Be^{10} is due to Coulomb forces alone and can be calculated by Eq. (1). Furthermore, by use of the experimentally known $Be^{10}-B^{10}$ mass difference and the Coulomb formula, one can obtain the $C^{10}-B^{10}$ mass difference in the following way. There should be an excited state, B^{10*}, which has exactly the same quantum-mechanical character as the ground states of Be^{10} and C^{10}. The non-Coulomb forces should be the same for these isobars,††† and consequently one can calculate the mass differences from the Coulomb formula above, not forgetting the neutron-proton mass difference. From the alpha-particle model point of view we consider the three isobars as consisting of a core of two alpha-particles *plus* either two neutrons, a neutron and a proton or two protons *all* with antiparallel spins and *all* in the same orbital state. On the above basis one obtains $B^{10*}-Be^{10}=1.48$ Mev and, since $Be^{10}-B^{10}$ is measured[7] to be 0.560, we find $B^{10*}-B^{10}=2.04$ Mev. Similarly, $C^{10}-B^{10*}=2.04$ Mev from the Coulomb formula and, therefore, $C^{10}-B^{10}=2.04+2.04=4.08$ Mev.

A detailed consideration of known B^{10} excited states and their relation to our observations is presented in Fig. 8 where levels found by Lauritsen *et al.*[8] are indicated. These levels occur at 411, 718, 1435, 2170, and 3425 kev. In addition to these levels there may be levels at 1024 and 2924 kev. It must be borne in mind that these levels were stimulated by heavy particles in the reactions $B^{10}(p, p\gamma)B^{10}$, $Be^{9}(dn)B^{10}$, and $Be^{9}(p\gamma)B^{10}$; so there is always the possibility that β-ray transitions cannot excite them. The dashed level in B^{10} at 2040 kev is the one we have calculated on the assumption that it is identical in quantum-mechanical character with the ground state of Be^{10}, and the dashed ground level in C^{10} at 4080 was obtained from Be^{10} as explained above. The agreement between the calculated level at 2040 kev and that observed by Lauritsen at 2170 kev lends support to the model we have used. On the basis of this diagram positron transitions to the various levels below 3 Mev should be possible. The corresponding values of E_β would be 0.9, 1.6, 2.3, 2.7, and 3.1 Mev (and also 2.0 Mev if there is a level at 1024 kev).

The positron energy of 2.2 ± 0.1 Mev observed by us agrees well with the assumption of a beta-transition to the 718-kev level of B^{10}. Our observation of an average gamma-ray energy of 960 ± 200 kev accompanying the C^{10} decay is

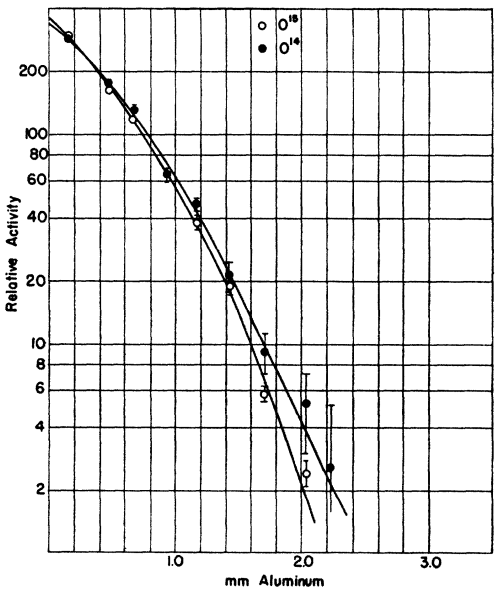

FIG. 10. Positron absorption curve for O^{14} and O^{15}. The gamma-ray backgrounds have been subtracted.

††† It is to be noted that the present assumption that the specifically nuclear $n-n$, $p-p$, and $p-n$ forces are identical is broader than that required for a discussion of the usual mirror nuclei (C^{11}, N^{13}, etc.), which require only equality of the $n-n$ and $p-p$ forces.

[7] E. M. MacMillan, Phys. Rev. **72**, 591 (1947).

[8] T. Lauritsen, C. B. Dougherty and V. K. Rasmussen, Phys. Rev. **74**, 1566 (1948).

consistent with the emission of 718-kev radiation, but may indicate the presence of more energetic γ-rays.

It is to be noted that we have assumed that the shape of the beta-absorption curve indicates a simple spectrum. However, transitions to other levels with intensity of the order of 10 or 20 percent cannot be excluded without more extensive verification of the application of the method of Bleuler and Zünti to the present data. One might expect transitions to the other available levels in B^{10}. A transition to the ground state would be inconsistent with the forbidden character of the Be^{10} decay. A transition to the 411-kev level could also occur in the Be^{10} decay if such transitions were allowed; as it has not been observed in Be^{10}, it may be assumed to be an improbable mode of decay for C^{10}. (Lauritsen *et al.*[9] have observed that the ground level and the 411-kev level must be similar in character and very different from the 718-kev level.) There remains the possibility of transitions to the 1435- and 2170-kev levels, which would give β-energies of 1.6 and 0.9 Mev. It is not possible to evaluate the probability of the former transition, but the latter transition is certainly allowed if it in reality corresponds to the level in B^{10} analogous to the ground state of Be^{10} and C^{10}. Assuming that the decay probability is proportional to W_0^5, one would expect a 0.9-Mev beta-transition to occur about 1/30 as frequently as the observed 2.2-Mev transition. This represents too small a relative intensity to be observed in the present experiment.

Feenberg and Goertzel[10] have calculated the Coulomb energy by a quantum-mechanical method which takes into account the effect of the Pauli exclusion principle on the mean separation of the protons. Above mass number eleven their results depart very little from the classical description, but at mass ten and below they predict measurable departures and can apparently account for the well-known oscillatory characteristics of the Coulomb energy of light nuclei. If one computes the Coulomb energy difference of $C^{10}-B^{10}$ by a straightforward application of

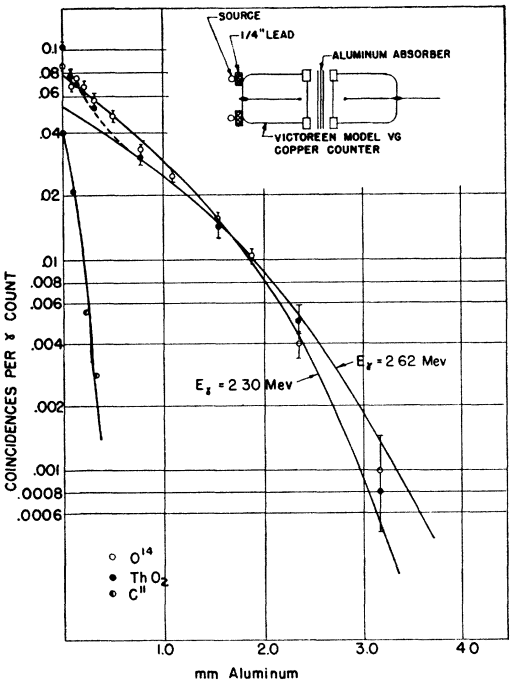

FIG. 11. Coincidence absorption measurements of gamma-radiations of O^{14}. The insert shows the counting arrangement.

their theory, one gets $C^{10}-B^{10}=3.7$ Mev instead of 4.08 as previously calculated. Also, $B^{10*}-B^{10}=1.70$ Mev. For two reasons we find these energy differences subject to doubt. First, their $C^{10}-B^{10}$ energy difference, taken with our β-energy of 2.2 Mev, would leave only 0.5 Mev for a γ-ray, assuming cascade. This quantum energy is not consistent with our measured γ-ray energy. Second, the $B^{10*}-B^{10}$ energy difference implies a level in B^{10} at 1.7 Mev which to date has not been found.

If one employs the minimum values allowed by Feenberg and Goertzel's theory, there is no disagreement either with classical Coulomb calculations or with experiment. The flexibility in the theory arises from allowing the nuclear radius of the lightly bound $4k+1$ nuclei to depart slightly from the assumed smooth $A^{\frac{1}{3}}$ dependence. A slight expansion in radius of this nuclear series reduces the amount of symmetry effect which has to be introduced to make the Coulomb energy agree with experiment. When the theory is then applied to the more tightly bound $4k+2$ nuclei there is little difference, for mass ten and

[9] T. Lauritsen, W. A. Fowler, C. C. Lauritsen, and V. K. Rasmussen, Phys. Rev. **73**, 636 (1948).

[10] E. Feenberg and G. Goertzel, Phys. Rev. **70**, 597 (1946).

above, between the classical and the quantum-mechanical Coulomb energy.

The ratio of the cross section for production of C^{10} from B^{10} and C^{11} from B^{11} is ~ 0.03 at 17 Mev. At an energy of ~ 7 Mev, the ratio is 5×10^{-4}. Threshold for C^{10} on the basis of the above level diagram is 5.4 Mev, while for C^{11} it is 2.98 Mev. The small ratio at 17 Mev could be due either to an abnormally low cross section for the (p, n) reaction in B^{10} or to more effective competition by other possible reactions than in the case of the B^{11}. The present energy and half-life of C^{10} lead to an (ft) value of 2020. This value is somewhat higher than that for He^6 (1160) but lower than the usual values observed for allowed transitions.[2]

O^{14}

O^{14} has not hitherto been reported in the literature. Using the gas flow technique developed for C^{10} we have discovered a 76.5-sec. activity in several nitrogen containing compounds as well as in nitrogen gas. The most intense activity was obtained by trapping the gases from KSCN on $CaCl_2$. Apparently the activity from the KSCN is carried away in the form of water. Nitrides of titanium, zirconium, magnesium, and calcium were tried with only moderate success. A proton beam current of 0.5 microampere at 17 Mev was used in most of the bombardments.

Using the KSCN powder as target material and $CaCl_2$ as absorbing agent for the radioactive gas decay, curves of the type shown in Fig. 9 have been obtained. The decay curves were simple over a factor of 50 or more. Averaging over a large number of runs gave a half-life of 76.5 ± 2 sec. Magnetic analysis identified the particles as positively charged.

There remained the possibility that a slight amount of 126-sec. O^{15} produced from N^{15} was present. However, the half-life remained unchanged when measured through a thickness of lead which reduced the relative intensity of annihilation radiation by a factor of 50. Since the abundance $N^{14}/N^{15}=262$, one would expect at most only a few percent of O^{15}. Curves of various mixtures of 76-sec. and 126-sec. activities were drawn and compared with the decay curves. From this comparison it was concluded that there was certainly less than 10 percent O^{15} present in the decay curves at 17 Mev. From this figure it is estimated that $\sigma_{15}/\sigma_{14}<25$, a somewhat more favorable ratio for the production of O^{14} than that for production of C^{10}, for which $\sigma_{11}/\sigma_{10}=30$.

The chemical behavior of the 76.5-sec. period was studied in the following way. A mixture of 70 percent nitrogen gas and 30 percent hydrogen gas, bombarded in a carefully cleaned probe tip, was continuously swept through a filter of ascarite, then through a tube of platinized asbestos and finally through a layer of $CaCl_2$ in the inspection chamber. The purpose of the ascarite was to remove $C^{11}O_2$ (C^{11} from $N^{14}(p\alpha)C^{11}$) and H_2O^{14}, but allowing O_2, NO, etc., to pass through. With the catalyst at room temperature an equilibrium counting rate of 200 (arbitrary)/min. was obtained, but with H_2 turned off the rate dropped to 8/min. Also, H_2 alone, and H_2+N_2 without the catalyst gave no activity. These tests are consistent with the view that the 76.5-sec, activity is oxygen, and that the oxygen and hydrogen in the presence of the catalyst unite to form H_2O which is trapped on the $CaCl_2$. It was found that at elevated temperatures (100° or more) it was unnecessary to add H_2 to obtain the activity in the $CaCl_2$. Presumably, there was sufficient adsorbed hydrogen in the system to carry through the conversion under the more efficient operation of the catalyst at higher temperatures.

For purposes of comparison of absorption curves, O^{15} was produced by proton bombardment of PbF_2. The Ne^{19} activity was pumped off while the O^{15}, produced presumably by a $F^{19}(p, \alpha n)O^{15}$ reaction, was trapped as water in $CaCl_2$. The average half-life obtained for O^{15} was 126 ± 2 sec., in excellent agreement with the accepted value of 126 sec.[11] Absorption curves for O^{15} and O^{14} were obtained which were very similar to those for Ne^{19} and C^{10} (Fig. 5). In the present case, the γ-ray background for O^{14} was 6 percent of the zero absorber yield, while for O^{15} it was 2.0 percent, indicating the presence of nuclear γ-radiation in the O^{14} decay. From the ratio of these figures, 3.0, and assuming linear energy response of the counters to γ-radiation, one may expect a single γ-ray of the order of 2 Mev or several softer rays to be associated with the decay of O^{14}.

[11] G. T. Seaborg, Rev. Mod. Phys. 16, 1 (1944).

The β-ray absorption curves of O^{14} and O^{15} with background subtracted are shown in Fig. 10. It is seen that the O^{14} is slightly more energetic than O^{15}. Application of the technique of Bleuler and Zünti as described above gave for O^{15} the values 1.66, 1.68, 1.68, 1.68, 1.69, 1.68, 1.68 Mev for successive values of E_n. The average value of 1.68 Mev is in excellent agreement with the accepted value[11] 1.7 Mev. For O^{14} the successive values of E_n are 1.81, 1.80, 1.77, 1.76, 1.78, 1.80, 1.84 Mev, giving an average value of 1.78 Mev. Considering the slight scatter of the measured points, the positron energy of O^{14} is taken to be 1.8 ± 0.1 Mev. The O^{14} β-spectrum appears to be simple, and if a harder component, of the order of 3–4 Mev, is present, its intensity must be less than 5 percent of the 1.8-Mev spectrum.

An absorption curve of the γ-radiation of O^{14} in lead showed that the radiation detected was predominantly hard, the absorption coefficient corresponding to the minimum in lead. To determine the energy more precisely, the absorption of the Compton secondaries was measured using counters in coincidence in the usual fashion.[6,12] The results and a sketch of the arrangement are shown in Fig. 11. Because of the difficulty in determining the range of the secondaries, the curve was analyzed with the aid of the curves given by Bleuler and Zünti[6] for this type of measurement. For calibration purposes there was available a quantity of ThO_2 of unknown history. The ThO_2 was used under the same geometrical conditions as the O^{14}; the results are given in Fig. 11. The ThO_2 curve is obviously complex; the solid curve corresponds to a 2.62-Mev gamma-ray as given by Bleuler and Zünti and has been fitted to the last four points. The agreement is very good. With this reassurance, the best fit to the O^{14} data was found to be the curve drawn through the O^{14} points and represents an energy of 2.30 Mev. As is evident from the absorption curve for annihilation radiation (C^{11}) in Fig. 11, the contribution of secondaries due to the annihilation radiation in the O^{14} curve is negligible except for the smallest absorbers. On the basis of range comparison, disregarding the complexity of the ThO_2 curve, it would appear that the O^{14} radiation was as hard as the 2.62-Mev ThC″ gamma-ray. As a lower limit, the range of the secondaries is greater than 0.86 g/cm², corresponding to an $h\nu$ of 2.1 Mev. In view of the uncertainty of the calibration source (a single line source would be preferable) the gamma-ray energy of O^{14} is taken to be $2.3^{+0.3}_{-0.1}$ Mev. If the curves of Bleuler and Zünti[6] can be applied to the present data, one can conclude that the γ-spectrum is essentially simple. Assuming that the sensitivity of the counters is a linear function of the gamma-ray energy, one can estimate the ratio of the backgrounds of O^{14} and O^{15} as obtained in the β-absorption curves to be 3.3, in reasonable agreement with the observed ratio of 3.0.

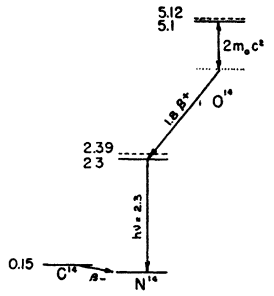

FIG. 12. Energy level diagram of O^{14}, N^{14}, and C^{14}. The energies are given in Mev. The dashed lines represent calculated values.

DISCUSSION OF RESULTS FOR O^{14}

The radiation of O^{14} appears to be a simple positron spectrum of maximum energy 1.8 Mev, followed by a γ-ray of 2.3 Mev. The β-energy in combination with the 76.5-sec. half-life give an (ft) value of 3350. If there are any transitions to the ground state of N^{14}, our absorption curves suggest that they occur with a probability less than five percent of that for the 1.8-Mev transitions.

Hornyak and Lauritsen[13] have summarized the experimental evidence for the excited states of N^{14}. The lowest of these levels is at 4.0 Mev according to their analysis. Of particular interest here is the designation of a level at 5.4 Mev on the basis of the observation of neutrons and gamma-rays from the $C^{13}(d, n)N^{14}$ reaction. This level was taken to be confirmed by the measurements of the energies of gamma-radiation from

[12] W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Rev. Mod. Phys. 20, 236 (1948).

[13] W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. 20, 214 (1948).

the $C^{13}(p, \gamma)N^{14}$ reaction by Lauritsen *et al.*[14] The gamma-rays found by the latter were 8.1, 5.4, and 2.8 Mev. However, these values have been revised by Fowler *et al.*[12] on the basis of new field coil calibrations for their cloud chamber to 8.1, 5.8, and 2.3 Mev. These new values may indicate the existence of a level at 2.3 Mev, the 5.8-Mev gamma-ray representing a transition from the 8.1-Mev level to the 2.3-Mev levels. Our presently observed gamma-ray of 2.3 Mev supports this interpretation.

It is, of course, possible that the 2.3-Mev radiation of O^{14} represents a transition between levels above 4 Mev in N^{14}. The subsequent harder radiation could hardly be overlooked in the γ-ray measurements. Additional evidence for the assumption that the 2.3-Mev gamma-ray found by us follows the 1.8-Mev β-transition is found in a rough determination of the threshold for the (p, n) reaction. The gas probe was progressively inserted to shorter radii in the cyclotron and bombardments carried out as previously. The threshold was found to be $6.0\ ^{+0.5}_{?}$ Mev, the lower limit being indeterminate as it was difficult to determine the loss of energy in passing through the copper foil of the gas cell. This threshold value is definitely too low to allow the 2.3-Mev radiation to come from high lying levels in N^{14} and is in reasonable agreement with the calculated threshold of 6.3 ± 0.3 Mev for the suggested sequence of a 1.8-Mev β-transition followed by a 2.3-Mev γ-transition.

Calculations of the energy N^{14*} and O^{14}, assuming that their wave functions are the same as for C^{14} and using Eq. (1) (cf., discussion of C^{10} above), give the following results: $N^{14*}-N^{14}=2.39$ Mev and $O^{14}-N^{14}=5.12$ Mev.†††† A positron transition to the N^{14*} level gives a positron energy of 1.71 Mev, while the subsequent γ-ray $N^{14*}\rightarrow N^{14}$ would have an energy of 2.39 Mev. The agreement of these values with the observed values of $E_\beta=1.8\pm0.1$ Mev and $E_\gamma=2.3\pm0.2$ Mev is excellent. These results are summarized graphically in Fig. 12.

CONCLUSION

On the basis of these preliminary results on the radiation from C^{10} and O^{14}, it appears safe to conclude that beta-transitions from the ground states of these nuclei to the ground states of B^{10} and N^{14} have a forbidden character. As the corresponding transitions $Be^{10}\rightarrow B^{10}$ and $C^{14}\rightarrow N^{14}$ are also forbidden, the present results agree with the prediction of nuclear theory that the isobaric pairs C^{10} and Be^{10}, and O^{14} and C^{14} should have similar configurations. Theoretical expectations that the mass differences of these isobaric pairs can be attributed to the excess Coulomb energies of the isobars of higher atomic number are confirmed by our measurements. Moreover, the calculated position of the excited level in B^{10} and in N^{14} which corresponds to the ground state configuration of $Be^{10}-C^{10}$ and of $C^{14}-O^{14}$ seems to be checked by experiment. In contrast to these successful predictions of nuclear theory,[15] there remain the theoretical difficulties in explaining the forbidden character of the beta-transitions to the ground states.‡

The authors are pleased to acknowledge valuable discussions with Professor E. Wigner on the theoretical implications of these experiments. We are indebted to Professor J. Turkevich of the Department of Chemistry for his advice and assistance in establishing the chemical identity of the radioactive isotopes. We also wish to thank the members of the cyclotron group and the electronic shop for their cooperation and assistance.

[14] T. Lauritsen, C. C. Lauritsen, and W. A. Fowler, Phys. Rev. **59**, 241 (1941).

†††† Calculations on the basis of the method of Feenberg and Goertzel (reference 10) give essentially the same results for the present case.

[15] The arguments concerning the similarity of Be^{10}, B^{10*}, and C^{10} and of C^{14}, N^{14*}, and O^{14} given in this paper used a specific nuclear model (i.e., α-particle substructure). However, Wigner has shown (Phys. Rev. **51**, 106 (1937)) that this similarity arises quite generally from the essential equality of the forces between nucleons.

‡ *Note added in proof:* These theoretical difficulties may have been resolved in the case of $Be^{10}-B^{10}$ by the recent measurements of the spin of B^{10} by W. Gordy, H. Ring, and A. B. Burg [Phys. Rev. **74**, 1191 (1948)]. These authors find a spin of 3, rather than the previously assumed value of 1. With the assumption that Be^{10} has spin 0, the ΔJ for the β-transition is 3. (See also M. Goldhaber, Phys. Rev. **74**, 1194 (1948).) On the other hand, the C^{14} and N^{14} spins are known to be 0 and 1 respectively.