INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®
A THESIS
PRESENTED TO THE FACULTY
OF THE RICE INSTITUTE
IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF
DOCTOR OF PHILOSOPHY

BY

BOB EVERETT WATT

HOUSTON, TEXAS
JUNE, 1946
INTRODUCTION

As there is no direct method of observing nuclear structure, it must be inferred from the energy changes in nuclear reactions. The same problem was met in the case of atomic structure, but was appreciably simplified by the planetary model, the known law of force between the particles, and the simplicity of the radiation. In that case a great deal of information was obtained by noting regularities in the spectra, such as simple energy relations between the various lines and their natural widths and fine structure. In view of such examples it was believed to be important to examine carefully the excitation of various radiations from nuclear reactions, with particular attention to high resolving power and the natural shapes of resonances.

The Bohr "water drop" theory of the nucleus indicated that the density of levels should be higher for higher excitation energies. Further, in the cases where a heavy particle is emitted from the compound nucleus one would expect the particle to escape more quickly when it has higher energy; by the uncertainty principle the levels should then be broader.

The nuclear reactions

\[ ^{19}F + H \rightarrow Ne^{20} \rightarrow ^{0}He + ^{4}He \]

\[ \left\{ ^{0}He + \gamma \right\} \]

\[ \left\{ ^{0}He + \pi \right\} \]

seemed particularly suitable as there is only one isotope of fluorine and the excitation function for the gamma radiation was known to have
many sharp resonances.

The history of the fluorine excitation functions for the radiations now known illustrates the need for high precision. Using a cyclotron, McMillan observed gamma rays from fluorine when bombarded with protons. By measuring the absorption coefficient for the gamma rays in several elements, he concluded that the energy of the quanta was 5.4 Mev and obtained a smoothly increasing excitation curve up to 1.15 Mev. Hafsted, Heydenburg, and Tuve found the excitation function to consist of several well defined resonances. In 1938, Bernet, Herb, and Parkinson found the experimental widths of several of the resonances to range from 9 to 20 kev. Lauritsen, Lauritsen, and Fowler determined the energy of the gamma rays by means of pair production in a lead strip. The obtained value was $6.2 \pm 0.1$ Mev for the gamma ray energy and was found to be independent of the incident proton energy. Fowler and Lauritsen discovered the radiation of electron pairs, which they attributed to the reaction

$$\text{F}^{19} + \text{H}^1 \rightarrow \pi_{\text{Ne}^{20*}}^+ \rightarrow \pi_{0^{16*}}^+ + \text{He}^4$$

The notation used is that of Streib, Fowler, and Lauritsen; the $\pi$ indicates the radiation of electron pairs. Streib, Fowler, and Lauritsen found no cases of agreement in the energies of the resonance levels for electron pairs and gamma radiations, so could not attribute the pairs to internal conversion of the gamma radiation. Oppenheimer and Schwinger calculated that the internal conversion coefficient for electron pair production was less than one half per cent, which gave additional support to the idea that a different kind of energy level in the Ne$^{20}$ nucleus was
excited.

The object of the experiments reported here was to examine the excitation functions of the gamma radiation and the electron pair radiation with higher resolving power than had previously been used.

EXPERIMENTAL REQUIREMENTS

Nuclear resonances will have a natural width which will in general be less than the experimental width. The natural width of a resonance will be observed only if all the protons which produce disintegrations have exactly the same energy. With the present experimental technique there are many factors which tend to spread the velocities of the bombarding protons away from the monokinetic ideal. The important factors producing a spread in energy in the proton beam from the Rice Institute proton accelerator were (1) voltage fluctuations of the high potential electrode, (2) initial velocity spread from the ion source, and (3) secondary ions formed by collisions between the protons and residual gas molecules in the vacuum tube.

Even if all the protons in the beam are monokinetic, the energy of all the protons producing disintegrations is not constant owing to the loss of energy of the protons as they penetrate the target. To obtain a measurable yield the target usually consisted of ten to one hundred atomic layers. The ideal target would be one which had a uniform number of atomic layers. However, in practice thin targets will not be perfectly uniform. For a perfectly uniform target, an infinitely thin resonance, and a monokinetic beam, the observed resonance shape would be a sharp in-
crease on the low energy side of the resonance, a small plateau due to the target thickness, then a sharp decrease on the high energy side. Because of the variations in thickness of the target, an actual experimental curve may not be as sharp on the high energy side of the resonance as on the low energy side. If the targets are made sufficiently thin the width of the plateau can be made quite small.

APPARATUS

The proton accelerator was a pressure insulated electrostatic generator similar to that described by Herb, Parkinson, and Kerst\textsuperscript{8}; for these experiments the most important modification was the addition of an energy selector and a voltage stabilizer.

Energy Selector

A ring magnet which deflected the protons through 90° was used to resolve the molecular and atomic beams. It was simultaneously used to define the energy of the beam striking the target by the addition of a narrow slit at the line where the beam was focussed after being bent through 90°. The arrangement is shown in Figure 1.

The radius of curvature of the beam of protons was 26 cms. and the slit width was set at 0.015 cm. Observation of the focussed beam of protons showed its width to be approximately 0.02 cm. when the proton's energy was approximately 1 MeV. The expected width due to the finite size of the entrance aperture was 0.010 cm. and the maximum energy spread possible due to voltages in the ion source was 0.1 per cent in energy, or 0.012 cm. at the focal line. It was believed that the position spread due to aberrations in the focussing system was less than $\pm$ 0.02 per cent, and the
probable energy spread of the emerging beam was estimated to be \( \pm 0.05 \) per cent, under the condition of maximum current through the slit.

The magnet current was held constant by regulating the voltage applied to the coils. The diagram of the apparatus is shown in Figure 2. The choke coil raised the source impedance for all the high frequency components (commutator contact, period of rotation, etc.) of the supply voltage which was obtained from a 130 volt battery continuously charged by a generator. The potentiometer measured the total current through the coils by measuring the potential drop in the standard 0.1 ohm resistance and was capable of measuring the average current to 0.1 milliampere.

An oscillograph showed that the voltage across the magnet coils had no components in the frequency range 2 to 200,000 cycles per second of amplitude greater than 0.05 per cent of the direct component, and the potentiometer showed no current fluctuations of lower frequency exceeding 0.01 per cent. Owing to the large inductance of the magnet it was believed possible to hold the magnetic field constant to within 0.01 per cent during the time required for each point.

Because of the hysteresis in the iron it took 1.5 per cent greater current to produce the same value of the magnetic field on increasing the field than when decreasing the field; so, in running an excitation curve the convention of always increasing the magnet current was adopted. With this convention it was found that the day to day displacements of the excitation curves were less than 0.2 per cent and the probable displacements were 0.1 per cent; experience indicated that temperature variations in the air conditioned laboratory could explain most of the observed dis-
placements.

Voltage Stabilizer

To reduce the energy spread in the emerging proton beam and to maintain a steady current through the narrow slit, a stabilizer for the proton accelerator's voltage was constructed by insulating the jaws of the slit and constructing an electronic circuit to alter the accelerating voltage so as to maintain equal currents to the two jaws. The diagram of the apparatus is shown in Figure 3. Analysis of the operation of the circuit can be done more easily by considering the equivalent circuit shown in Figure 4.

![Diagram](image)

Figure 4

In the circuit shown in Figure 4, $C_1$ is the capacity of the high voltage electrode of the proton accelerator; $R_1$, its dynamic resistance to ground; $C_2$ and $R_2$, the capacity and resistance of the slit jaws; $C_3$, the capacity of the leads, battery, and filament of the 20l-A; $f$, the fraction
of the filament emission that goes up the vacuum tube to the high voltage electrode; \( \delta \), the total time delay around the circuit which includes the transit times of the protons down the vacuum tube, the electrons in the amplifier circuits, and the electrons up the vacuum tube. The three terminal boxes labeled \( g_1 \), \( g_2 \), and \( g_3 \) are conductances which will be defined in greater detail below.

The sensitivity of the circuit is determined by the product \( R_1 R_2 g_1 g_2 \); oscillations will set in if the product is made too large. The two requirements for any oscillating circuit are (1) phase shift around the network equal to zero (or 360°) and (2) total gain around the circuit greater than unity for a frequency having zero phase shift. From these conditions, it is possible to find the upper limit for the product \( R_1 R_2 g_1 g_2 \).

For the moment, consider that \( i_5 \) is returned to ground rather than to \( C_1 \). Consider the phase and amplitude of the current \( i_5 \) as a function of the frequency of a sinusoidal current \( i_1 \) which has a frequency \( \omega / 2\pi \). Consider only the changes in potential and define \( e_1 \) as the potential change on \( C_1 \), \( e_2 \) as the potential change on \( C_2 \), and \( e_3 \) as the potential change on \( C_3 \). The conductances \( g_1 \) and \( g_2 \) are voltage operated devices such that \( i_2 = e_1 g_1 \) and \( i_3 = e_2 g_2 \). The conductance \( g_3 \) draws a current \( i_4 \) from \( C_3 \) and the magnitude of \( i_4 \) is given by the relation \( i_4 = e_3 g_3 \). Defining \( d_1 = R_1 C_1 \omega \), \( d_2 = R_2 C_2 \omega \), \( d_3 = C_3 \omega / g_3 \), and \( j = \sqrt{-1} \) and using the complex representation for impedance, the following equations are obtained.

\[
\begin{align*}
e_1 &= R_1 i_1 / (1+j d_1), \\
e_2 &= R_2 i_2 / (1+j d_2), \\
e_3 &= i_3 / g_3 (1+j d_3) \\
i_4 &= e_3 g_3, \\
i_5 &= f i_4;
\end{align*}
\]
whence,

$$i_5/i_1 = R_1 R_2 g_1 g_2 f / (1 + j \alpha_1)(1 + j \alpha_2)(1 + j \alpha_3).$$

(1)

When the frequency is very low or zero, this ratio is simply $R_1 R_2 g_1 g_2 f$.

If the current $i_5$ is fed back to $C_1$, rather than to ground, then the input current to $C_1$ is $i_1 + i_5$. Considering only the low frequency case where the $\alpha$'s are negligible, and denoting the potential change on $C_1$ as $E_1$, then $E_1$ is given by the equation

$$E_1 = (i_1 + i_5) R_1$$

(2)

and the above equation (1) becomes

$$i_5/(i_1 + i_5) = R_1 R_2 g_1 g_2 f$$

(3)

or

$$i_5 = i_1 R_1 R_2 g_1 g_2 f / (1 - R_1 R_2 g_1 g_2 f).$$

Combining equations (2) and (3),

$$E_1 / R_1 i_1 = 1 / (1 - R_1 R_2 g_1 g_2 f).$$

(4)

Without the voltage regulator the potential change produced on the high voltage electrode by a current fluctuation $i_1$ would be $R_1 i_1$. With the voltage regulator, which produces the current $i_5$, the potential change would be $E_1$. The ratio $E_1 / R_1 i_1$ is then a measure of the voltage stability with and without the regulator. For good voltage stability the product $R_1 R_2 g_1 g_2 f$ should have a large negative value.

Returning to the case where $i_5$ is returned to ground, rather than to $C_1$, the phase shift and relative amplitude of the current $i_5$ are plotted in Figure 5; the values used for the computations are:

$R_1 = 10^{10}$ ohms, $C_1 = 5 \times 10^{-11}$ farad, $R_2 = 10^{7}$ ohms, $C_2 = 5 \times 10^{-11}$ farad, $g_3 = 10^{-4}$ mho, and $C_3 = 5 \times 10^{-10}$ farad. The negative sign of the product $R_1 R_2 g_1 g_2 f$ corresponds to a phase shift of $180^\circ$ for all frequencies.

For a value of $\delta = 2 \times 10^{-6}$ second, the phase shift has been plotted
separately; the total phase shift around the circuit is 360° where the
two curves intersect. At this value for \( \alpha_1 \) the ratio \( (i_5)w/(i_5)_0 \) is
10^{-5}. In order to prevent oscillation, the total gain around the circuit
must be less than unity \( (i_5 \ll i_1) \) at this value of \( \alpha_1 \); therefore,
\( R_1 R_2 g_1 g_2 f < 10^5 \). Experience indicated that the unregulated voltage fluc-
tuations in the Rice Institute high voltage apparatus were of the order
5000 volts; so, the lower limit to the stability which could be achieved
would be of the order 0.1 volt. Because of the many other limits to our
resolving power and the more complicated apparatus necessary, no attempt
to reach the lower limit was made.

It should be noted that the time delay sets a lower limit to the
voltage stability which could be achieved with this circuit. Consider
the case of a perfect amplifier in which \( \alpha_2 \) and \( \alpha_3 \) are negligibly
small (very large bandwidth); the phase shift and relative amplitude of
\( i_2 \) are shown as the dotted lines in the region where \( \alpha_1 \) is large, and
are the same as those computed for the circuit in Figure 4 when \( \alpha_1 \) is
small. The phase shift due to \( C_1 \) is nearly constant at 90° where the phase
shift due to the time delay becomes 90°. For a value of \( \delta = 2 \times 10^{-6} \)
second the total phase shift around the circuit would be 360° when
\( \alpha_1 = 4 \times 10^5 \). The upper limit to the gain at zero frequency would then
be approximately 3 \( \times 10^6 \). The lower limit to the voltage fluctuations
in the Rice Institute apparatus would then be of the order 0.02 volt.

The magnet and slit design used was such that, for the beam
current usually used, the conductance \( g_1 \) was approximately 3 \( \times 10^{-10} \) mho;
the values for \( R_1 \) and \( R_2 \) were approximately \( 10^{10} \) and \( 10^7 \) ohms, respectively;
and the product \( g_2 f \) was approximately \( 10^{-6} \) mho. The total improvement
in the voltage stability was then a factor of 30; so, the expected po-
tential fluctuations were of the order ± 150 volts. This was smaller than the expected spread from the ion source and only one fourth the energy spread permitted by the slit width.

TARGET

The desired target thicknesses were in the range 500 to 2000 volts in stopping power; the thicker targets were used for survey experiments where it was necessary to take large voltage intervals. All targets were prepared by evaporating a fluorine compound from a hot filament placed five centimeters below a polished silver disk 3.2 cms. in diameter which was used as a backing. The compounds tried were CaF₂, CuF₂, and ZnF₂. The ZnF₂ was the most satisfactory because of its convenient melting point and relatively low evaporation temperature. A microbalance was used to weigh the deposit. The area of the disk was eight square centimeters, and the weight of the deposit ranged from two micrograms per square centimeter to nine micrograms per square centimeter. The relative yields obtained from the four targets used, and subsequent checks on the weighing accuracy indicate that the uncertainty in the weight of the deposit was of the order two micrograms per square centimeter.

DETECTORS

From the work of Fowler and Lauritsen⁵ it was known that both gamma and softer radiations had to be considered. As a detector for the
gamma rays, a bifilar electroscope in an iron cylinder seven centimeters in diameter with walls one centimeter thick filled with argon to a pressure of 70 atmospheres was first tried. Next, a single Geiger counter shielded with 1.65 mm. of lead was placed 7 mm. from the bombarded target of fluorine. Comparison of the excitation curves observed in the region of the 862 keV resonance showed that the electroscope was very sensitive to the softer radiations, probably owing to a relatively high efficiency for the annihilation radiation from the positrons observed by Fowler and Lauritsen\(^5\). The Geiger counter shielded with a 1.65 mm. lead absorber was used to count the 6.2 Mev gamma rays since it seemed to be the best detector for this radiation.

To detect the softer radiation (probably electron pairs) a window was cut in the lead shield and the target holder made thin enough to admit beta rays to the counter. The materials in the beta ray path were 0.5 gm/cm\(^2\) of silver, 0.33 gm/cm\(^2\) of aluminum, 0.3 gm/cm\(^2\) of Pyrex glass, and 0.1 gm/cm\(^2\) of copper.

A measure of the intensity of the soft radiation could be determined by subtracting the yield observed with the absorber in place from the yield observed without the absorber. This difference gives the relative intensity of soft radiation and the yield observed with the absorber gives the intensity of high energy gamma radiation. With our experimental conditions the addition of the 1.65 mm. lead absorber increased the efficiency for the 6.2 Mev gamma rays by just enough to compensate for the small absorption of these gamma rays by this amount of lead. The sensitivity of the Geiger counter was checked frequently with
a one milligram sample of radium at a standard position.

The number of protons striking the target was determined by means of a current integrator described elsewhere.

The characteristic x-radiation from the silver was completely absorbed by the additional material in the path (probably silver). A run with a blank silver target showed no increase over background within the experimental error.

PROCEDURE

After setting the magnet current to the desired value, the potential on the proton accelerator was adjusted to be within the range of the voltage regulator.

At each voltage, the time and total charge required to give a specific number of counts in the Geiger detector were observed for the two conditions, lead absorber in position and out of position. The order of the points was reversed at successive voltages.

Over the small regions investigated it was assumed that the magnetic field was linearly proportional to the current in the coils of the magnet. The voltages given by Bernet, Herb, and Parkinson for the more prominent parts of the excitation curve were used to determine the relation between the proton energy and the magnet current.

The absorption coefficient for the gamma rays was determined by placing an additional 1.65 mm. lead shield between the bombarded spot (beam energy 862 kev) and the Geiger counter. When the 1.65 mm. lead absorber was inserted, it was found that the counting rate decreased
20 per cent, giving an absorption coefficient of 1.2 per centimeter.

The background count in the Geiger counter when the target was not bombarded was observed as a function of the x-ray intensity from the high voltage apparatus. In general this background was small in comparison to the effect due to gamma rays at resonances, but was comparable to the gamma ray effect in regions widely removed from resonances. Frequent readings of the x-ray intensity were made and used to compute the background.

RESULTS

The relative gamma ray yield was computed by subtracting the background counts and dividing the remaining number of counts by the number of integrator counts. Each integrator count represented a charge of 0.0416 microcoulomb or $2.62 \times 10^{11}$ protons. Four different targets were used to obtain the data presented here. From the weight per square centimeter and the relative yields obtained from the targets it was believed that the stopping power of the target was small in comparison with the width of the resonance measured with it.

The yield of soft radiation was computed by subtracting the yield with the lead absorber in from the yield with the absorber out. As the differences were often small, the accuracy of each point was not very high. There were no indications of sharp resonances in the yield of soft radiation; so, an average of two or more neighboring points was taken. The results are plotted in Figure 6.
DISCUSSION

The gamma ray resonance at 1.12 Mev was the narrowest observed; it had a half width of 2300 volts. As this is very nearly the estimated resolving power of the apparatus, it is believed that the natural width is less than 1000 volts. Also, it sets an upper bound to the experimental energy spread at ± 0.1 per cent, slightly larger than the estimate of ± 0.08 per cent obtained by adding the target thickness to the estimated energy spread.

Table I gives the observed half widths for the six gamma ray resonances investigated and the "natural widths" computed with the assumption that Experimental Width observed = \sqrt{(natural width)^2 + (experimental spread)^2}.

The sharp resonances at 0.818, 0.890, 1.12, and 1.18 Mev were not previously known and were observed on at least two different runs.

<table>
<thead>
<tr>
<th>Proton energy at resonance (V)</th>
<th>Experimental width</th>
<th>Experimental spread assumed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mev</td>
<td>0.1% V</td>
</tr>
<tr>
<td></td>
<td>ev</td>
<td>ev</td>
</tr>
<tr>
<td>0.818</td>
<td>7300</td>
<td>7200</td>
</tr>
<tr>
<td>0.862</td>
<td>5300</td>
<td>5200</td>
</tr>
<tr>
<td>0.890</td>
<td>4000</td>
<td>3900</td>
</tr>
<tr>
<td>0.927</td>
<td>7300</td>
<td>7200</td>
</tr>
<tr>
<td>1.12</td>
<td>2300</td>
<td>2000</td>
</tr>
<tr>
<td>1.18</td>
<td>3500</td>
<td>3300</td>
</tr>
</tbody>
</table>

TABLE I

Gamma Ray Resonances
It is interesting to note that the resonances at 0.818 Mev and at 0.890 Mev were of comparable intensity and were separated by 62 kev; the resonances at 0.862 Mev and 0.827 Mev were of comparable intensity and were separated by 65 kev; the resonances at 1.12 Mev and 1.18 Mev were of comparable intensity and were separated by 60 kev. There seems to be a broad level in the neighborhood of 1.15 Mev; the present data does not permit any conclusions regarding it. On the low energy side of both the 1.12 Mev and the 1.18 Mev resonances there is a definite decrease in the yield; the resonances appear to be asymmetrical. Although the asymmetry was of the type expected for a non-uniform target, it seemed improbable that the atoms would migrate sufficiently to build up crystals sixty atoms thick; the weight of the target was such that uniform target would have had twenty atomic layers. The decrease in the yield on the low energy side of the resonance lends support to the belief that asymmetry is real, and possibly is connected with the presence of the broad level in the same region.

Table II lists the resonances for soft radiation and their widths.

### Table II

<table>
<thead>
<tr>
<th>Proton energy at resonance (MeV)</th>
<th>Experimental width (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.830</td>
<td>34,000</td>
</tr>
<tr>
<td>0.925</td>
<td>18,000</td>
</tr>
</tbody>
</table>
The resonance for electron pair radiation at 0.83 Mev seems to be quite broad in comparison with the gamma ray resonances. The resonance for the soft radiation at 0.925 Mev was not observed by Streib, Fowler, and Lauritsen\textsuperscript{5}. At present it seems unjustified to assume that it was also a resonance for pair radiation, as it could be due to a soft gamma ray. Although the accuracy of the points was not high, it was believed that the asymmetry of the 0.925 resonance was real.

CONCLUSIONS

If the observed gamma ray resonances are all due to the reaction

\[ \stackrel{19}_p + \stackrel{1}_H \rightarrow \stackrel{20}{\text{Ne}}^* \rightarrow \stackrel{16}{\text{O}}^* + \stackrel{4}{\text{He}} \]

\[ \rightarrow \stackrel{16}{\text{O}} \]

then it seems that higher excitation energies do not lead to broader resonance widths in the range investigated. The general trend seems to be toward narrower levels. The energy of the escaping alpha particle would be increased from 2.8 Mev at the 0.818 Mev resonance to 3.2 Mev at the 1.18 Mev resonance.
REFERENCES

W. E. BENNETT, T. W. BONNER, EMMETT HUDSPETH AND BOB E. WATT

Protons from $^{14}\text{C}+^7\text{H}^2$

Bower and Burcham\textsuperscript{1} and also Pollard\textsuperscript{1} have observed a group of protons which they attributed to the reaction $^{14}\text{C}+^7\text{H}^2 \rightarrow ^{14}\text{C}+^7\text{H}^3+Q$. Bower and Burcham found a 48-cm group of protons when ordinary carbon was bombarded by 800-kev deuterons. The calculated $Q$ value of this group is 5.9 Mev, which is in satisfactory agreement with the energy release calculated from the change in mass. We have confirmed that the proton group must be attributed to the above reaction by using a target of concentrated $^{14}\text{C}$. The target was prepared by one of us (BEW) from methane in which the $^{14}\text{C}$ had been concentrated by thermal diffusion.

We bombarded the target with 1.22-Mev deuterons and used a linear amplifier to detect the protons. Long range protons were found and an absorption curve (Fig. 1) showed that they had a range of 53 cm, as expected. The ratio of the intensity of this group to the intensity of the group of 15-cm protons from the reaction $^{14}\text{C}+^7\text{H}^2 \rightarrow ^{14}\text{C}+^7\text{H}^3$ was found to be 0.11 percent. A target in which $^{14}\text{C}$ was depleted was then bombarded and the ratio was only 0.029 percent. This showed that the $^{14}\text{C}$ had been concentrated in the first target relative to the second by a factor of 3.8, whereas the separation factor had been calculated from the dimensions of the thermal diffusion apparatus as 3.7. The average of these two ratios (0.07 percent) is consequently the ratio of the yields from ordinary carbon at 1.22 Mev bombarding energy. This ratio would vary considerably with different bombarding voltages since the yield of protons from $^{14}\text{C}$ shows resonances at 920 and 1220 kev.\textsuperscript{9}

An excitation curve has also been obtained for this reaction and is shown in Fig. 2. The indicated error is the probable error increased by a factor of two, since it was necessary to make observations in two separate runs, which were joined at 1450 kev. The change in range of the protons with bombarding energy might be a source of systematic error in a curve of this type. To avoid this, the bias on the recording circuit was made low enough to count all the protons passing through the ionization chamber, and as an additional precaution absorbers were added as the bombarding voltage was increased to insure that the protons were always counted at the same distance from the end of their range.

The yield curve shows a maximum at about 1500 kev. This may be interpreted as a resonance in the yield, which would indicate an excited state in the intermediate nucleus ($^{14}\text{N}$) at 17.55 Mev. This is a surprisingly high energy at which to find isolated excited states, even in so light a nucleus. However, the experimental distribution might result from a resonance or a group of overlapping resonances of higher intensity than the neighboring overlapping levels which may appear as a continuum.

W. E. BENDT
T. W. BONNER
EMMETT HUDSPETH
BOB E. WATT

The Rice Institute,
Houston, Texas,
August 13, 1940.

\textsuperscript{2} E. Pollard, Phys. Rev. 56, 1168 (1939).
\textsuperscript{3} M. M. Rogers, W. E. Bennett, T. W. Bonner and Emmett Hudspeth, Phys. Rev. 58, 180 (1940).
The Energy of the Ionization from the Disintegration of Fluorine by Protons and Deuterons

W. E. Bennett, T. W. Bonner, and Bob E. Watt

The Energy of the γ-Rays from the Disintegration of Fluorine by Protons and Deuterons

W. E. Bennett, T. W. Bonner and Bob E. Watt
The Rice Institute, Houston, Texas
(Received March 31, 1941)

The maximum energy of the γ-rays from the disintegration of a thick target of fluorine by protons has been determined at 0.90 Mev and 1.7 Mev. The energy of the γ-rays was found to be the same at both bombarding voltages. The γ-rays from the disintegration of fluorine by deuterons have been studied with 1.3-Mev deuterons. The γ-rays were found to be complex and to have a maximum energy of 6.7 ± 0.3 Mev. This indicates that the highly excited states of Ne²⁰ at 9.0 and 10.1 Mev, which were found in the reaction F²¹(d, p)Ne²⁰, break up into O¹⁸ and He⁴ instead of emitting γ-rays.

Because the character of the resonances above 1.1 Mev appears to change, we thought that some of these higher resonances might be caused by a different reaction and give γ-rays of different energy. Consequently we have investigated the energy of the γ-rays at a bombarding energy of 1.7 Mev.

When fluorine is bombarded by deuterons, three different reactions are known to take place. Lewis, Livingston and Lawrence⁷ in 1933 reported the emission of a group of alpha-particles of 3.8-cm range. Later Burcham and Smith⁶ carefully studied the reaction:

\[ \text{F}^{19} + \text{H}^1 \rightarrow \text{(Ne}^{21}) \rightarrow \text{O}^{17} + \text{He}^4 + Q \]  (1)

and found five groups of alpha-particles with Q values equal to 9.84, 9.01, 6.89, 6.07 and 5.35 Mev. The lower energy alpha-particles are emitted when the O¹⁷ is left in excited states at 0.83, 2.95, 3.77 and 4.49 Mev.

Bower and Burcham⁸ found 5 groups of protons with ranges of 13.0, 18.8, 21.0, 24.2 and 31.0 cm from the bombardment of fluorine by deuterons. These protons come from the reaction:

\[ \text{F}^{19} + \text{H}^2 \rightarrow \text{(Ne}^{21}) \rightarrow \text{F}^{18} + \text{H}^1 + Q \]  (3)

The lower energy proton groups correspond to excitation energies of 0.7, 1.0, 1.35 and 1.9 Mev in the F¹⁸ nucleus.

Bonner⁹ has investigated the neutrons from

as that described in the preceding paper.\textsuperscript{10} The energy of the $\gamma$-rays was determined by observing the maximum range of the Compton electrons in aluminum placed between coincidence Geiger counters. This method was first used by Bøthe\textsuperscript{11} and later was improved by Dee, Curran, and Petržílka.\textsuperscript{12}

In the present work we used two alcohol-filled Geiger counters and recorded the passage of the electrons through both counters. They were 1.6 cm in diameter and 6 cm long and were placed far enough apart that there was space for 2 cm of absorber between the counters. Each wall of the counters had a thickness equivalent to 1.25 mm of aluminum. The coincidence circuit had a resolving time of $2.0 \times 10^{-4}$ sec. and would count coincidences properly when there were 20,000 single counts in each counter per minute.

**RESULTS**

The $\gamma$-rays from ThC\textsuperscript{14} were first studied in order to check the apparatus and in order to get a calibration value on the range of the electrons from 2.6-Mev $\gamma$-rays. The maximum range of the electrons was found to be 4.3 mm of aluminum.

\begin{equation}
\text{F}^{19} + \text{H}^2 \rightarrow (\text{Ne}^{20}) \rightarrow \text{Ne}^{20} + \pi + Q \quad (4)
\end{equation}

and has found seven groups of neutrons. The neutrons with energy less than the maximum indicate excited states in Ne\textsuperscript{20} at 1.5, 4.2, 5.4, 7.3, 9.0 and 10.1 Mev. The excited states in Ne\textsuperscript{20} at 5.4, 7.3, 9.0 and 10.1 Mev are energetically unstable against alpha-particle emission and so they may either break up into O\textsuperscript{16} and an alpha-particle or radiate a photon. We have investigated the energy of the $\gamma$-rays from fluorine bombarded by deuterons to try to see how these highly excited states in Ne\textsuperscript{20} lose their excess energy.

**EXPERIMENTAL ARRANGEMENT**

The arrangement for bombarding targets with high energy protons and deuterons was the same

\begin{itemize}
\end{itemize}
Next the $\gamma$-rays from a thick target of CaF$_2$ which was bombarded by 0.9-Mev protons were investigated. The solid circles of Fig. 1 show the absorption curve for the secondary electrons from these $\gamma$-rays. The maximum range of the electrons is 11.7±0.5 mm of aluminum, Above the maximum range of 11.7 mm the counting rate is greater than should be expected from chance coincidences between singles in the two counters. We made a test to see whether the counts with thick absorbers were chance coincidences by decreasing the current on the target by a factor of 2. If the counts beyond 11.7 mm of aluminum were chance coincidences they should have decreased by a factor of 4. Actually the counting rate decreased about a factor of 2, indicating that most of this background was caused by real coincidences. It seems probable that these coincidences are produced by a Compton electron in the second counter and its recoil photon which is scattered backward into the first counter. The intensity of the background on the absorption curve seems of the right order of magnitude to be explained by this process.

Also this background usually drops by a factor of two when 14 mm of aluminum absorbers are added. This is about what is expected for the absorption of recoil photons since they would have an energy of 0.25 Mev.

The range of the electrons produced by these fluorine $\gamma$-rays gives us a calibration point on the range-energy curve at 6.2 Mev. Since Curran, Dee and Petříčka have shown that the range-energy relation is linear above 2.6 Mev, the two calibration points are sufficient to define a range-energy curve for our experimental arrangement. This curve is given in Fig. 2.

The energy of the $\gamma$-rays from a thick CaF$_2$ target which was bombarded with 1.7-Mev protons was next investigated. The absorption curve of the Compton electrons in aluminum is given by the open circles of Fig. 1. It is immediately apparent from Fig. 1 that there is very little if any difference in the energy of the $\gamma$-rays at these two different bombarding voltages. In view of the fact that a 5.5-Mev $\gamma$-ray, which had an intensity of only 5 percent that of a 3-Mev $\gamma$-ray which accompanied it, was easily detected by the same method (see preceding paper), we believe this experiment shows there is less than 1 percent of radiation of 10 Mev or higher energy from a thick target of CaF$_2$ bombarded by 1.7-Mev protons.

The $\gamma$-rays from CaF$_2$ bombarded by deuterons were studied at a bombarding voltage of 1.3 Mev. The absorption curve for the secondary electrons from these $\gamma$-rays is given in Fig. 3. The maximum range of the electrons is 12.7 mm of aluminum which gives a quantum energy of 6.7±0.3 Mev. The thickness of aluminum where the counting rate falls to half-value is 1.9 mm for these $\gamma$-rays, while the half-value for the homogeneous $\gamma$-rays from F$^\mathrm{+H}$ was 1.9 mm of aluminum. This shows that the $\gamma$-radiation from F$^\mathrm{+H}$ although no doubt complex, consists largely of the penetrating components.

It seems natural to associate the 6.7±0.3-Mev $\gamma$-rays found in this experiment with the excited level in Ne$^{29}$ at 7.3±0.3 Mev which was found from a study of reaction (4). The fact that no $\gamma$-rays of energy higher than 6.7 Mev were observed indicates that the Ne$^{29}$ nucleus when excited to the 9.0- and 10.1-Mev levels breaks up into O$^{14}$+He$^1$ before it can emit a $\gamma$-ray.
The Disintegration of Carbon by Deuteron

W. E. Bennett, T. W. Bonner, E. Hudspeth, H. T. Richards and B. E. Watt

Reprinted from THE PHYSICAL REVIEW, Vol. 59, No. 10, pp. 781-792, May 15, 1941
The Disintegration of Carbon by Deuterons

W. E. Bennett; T. W. Bonner, E. Hudspeth,* H. T. Richards and B. E. Watt
The Rice Institute, Houston, Texas
(Received March 31, 1941)

The excitation curves for the emission of γ-rays, neutrons, and protons from the disintegration of C⁶³ by deuterons were investigated. Resonances for γ-ray emission were found at 0.92, 1.16, 1.30, 1.43 and 1.74 Mev. The resonance at 1.43 Mev has a half-width less than 10 kev while the other resonances are considerably broader. Resonances for neutron emission were found at 0.92, 1.16, 1.30, 1.74 and 1.82 Mev. Resonances for proton emission are found at 0.92, 1.16, 1.23 and 1.74 Mev. The γ-rays from C⁶³ were shown to come from the reaction C⁶³(d, p)C⁶⁴⁺. The short range protons from this reaction were observed and had a range of 1.1 cm. The Q value for this 1.1-cm proton group is -0.52±0.07 Mev. The excitation curves for the emission of γ-rays and protons from the disintegration of C⁶³ by deuterons were investigated. Both curves showed a resonance at 1.55-Mev deuteron energy. The γ-rays from C⁶³ have an energy of 5.5 Mev and come from the reaction C⁶³(d, n)N¹⁴⁺. The low energy group of neutrons from this reaction were found when a 23-percent C⁶³ target was used. The Q value for this group of neutrons is 0.40 Mev. The relative and absolute yields of the various reactions were determined.

The protons from the disintegration of carbon by deuterons were observed by Cockcroft and Walton¹ in 1934. When they bombarded carbon with 0.5-Mev deuterons they observed protons with a range of 14 cm which they attributed to the reaction:

\[ {^{12}C} + {^2}H \rightarrow (N^{14}) + {^1}H \rightarrow Q_1 \]  

(1)

This reaction has been extensively studied since that time and the value of \( Q_1 \) is now accurately known to be 2.71±0.05 Mev.²

Radioactive nitrogen from the bombardment of carbon by deuterons was simultaneously observed by Crane and Lauritsen¹ and by Henderson, Livingston and Lawrence.³ The production of radioactive nitrogen was attributed to the reaction:

\[ {^{12}}C + {^2}H \rightarrow (N^{14}) \rightarrow N^{12} + n + Q_2 \]  

(2)

Tuve and Hafstad⁴ found that the neutrons produced in this reaction were of low energy. Later Bonner and Brubaker⁵ obtained an accurate measurement of the range of the recoil protons produced by these neutrons in a cloud chamber. From the range-energy curve for protons which was available at that time a value of \( Q_2 = -0.37 \) Mev was obtained. Later, when a more accurate range-energy curve for protons was obtained from the experiments of Parkinson, Herb, Bellamy and Hudson,⁶ a recalculation⁷ from these data gave a value of \( Q_2 = -0.25±0.03 \) Mev. Another value of \( Q_2 \) was obtained by Lewis and Burcham⁸ from the observation that the formation of N¹⁴ begins at 0.32 Mev. This gives a value of \( Q_2 = -0.28 \) Mev which is in good agreement with the value of Bonner and Brubaker.

Bonner and Brubaker also found a neutron group representing about 1 percent of all the neutrons from carbon for which a \( Q \) value of 5.2 Mev was determined. They also observed another weak group of neutrons corresponding to a \( Q \) value of 1.2 Mev. The production of these two high energy groups of neutrons was attributed to the C¹⁴ isotope according to reaction:

\[ {^{14}}C + {^2}H \rightarrow (N^{14}) + N^{14} + n + Q_3 \]  

(3)

Gamma-rays from the bombardment of carbon by 0.8-Mev deuterons were first reported by Lauritsen and Crane.⁹ From absorption experi-

---

³ M. C. Henderson, M. S. Livingston and E. O. Lawrence, Phys. Rev. 45, 428 (1934).
The discovery of a weak group of 48-cm protons from carbon bombarded by 0.8-Mev deuterons was made by Bower and Burcham.\textsuperscript{14}

The protons come from the reaction:

$$\text{C}^{14} + \text{H}^2 \rightarrow (\text{N}^{14}) \rightarrow \text{C}^{14} + \text{H}^1 + Q_e.$$  \hspace{1cm} (4)

This reaction was also independently observed by Pollard\textsuperscript{15} at higher bombarding voltage.

Recently we have reported in a Letter to the Editor in The Physical Review that the excitation curve for the emission of $\gamma$-rays from carbon bombarded by deuterons shows resonances.\textsuperscript{16} Resonances were reported at 0.92, 1.16, 1.30, 1.43 and 1.74 Mev. Furthermore it was found\textsuperscript{17} that the neutrons from reaction (2) showed some of these same resonances; namely, those at 0.92, 1.16, and 1.30 Mev and an additional resonance at 1.80 Mev. Further experiments\textsuperscript{18} showed that the 14-cm protons from reaction (1) also showed the resonance at 0.92 Mev. A later Letter\textsuperscript{19} gave results on the yield of the high energy protons from C\textsuperscript{14}. The present paper is a report of extended results on the yield of the products from carbon bombarded by deuterons.

![Diagram of the observational end of the Rice pressure Van de Graaff generator.](image)

The weak $\gamma$-rays of 4 Mev (or higher) were attributed by Bonner and Brubaker to reaction (3) involving C\textsuperscript{14}. There is sufficient energy available in this reaction for these $\gamma$-rays to come from an excited N\textsuperscript{14} after the emission of a low energy group of neutrons.


![Gamma-ray resonances from F\textsuperscript{14}+H\textsuperscript{2} which were used in calibrating the electrostatic voltmeter of the Van de Graaff generator. The observed 8.5-kev half-width is thought to be chiefly experimental and represents the minimum width which could be obtained for other resonances.](image)
EXPERIMENTAL ARRANGEMENT

The Rice Institute pressure Van de Graaff machine was used in the experiments on the disintegration of carbon by deuterons. A complete description of the apparatus will be published elsewhere. For a description of the present experiment, it is sufficient to say that the machine is of the same general type as the pressure machine developed by Herb and collaborators\(^a\) at the University of Wisconsin.

A schematic diagram of the observational end of the high voltage apparatus is given in Fig. 1. The ion beam passes through a gate valve after emerging from the accelerating tube. Then the beam passes through a box which contains an electrically operated shutter. After passing through the shutter box the beam is bent through 90° by a large electromagnet, which resolves the beam into different components, corresponding to the different values of \(e/m\) for the positive ions. The current then enters a Faraday cage before falling on the target. The ion current on the target is measured by a current integrator of the neon discharge type.\(^2\) The voltage at the high potential center electrode is measured by means of an electrostatic voltmeter. This voltmeter was calibrated by observing the resonances for the emission of \(\gamma\)-rays from the bombardment of fluorine by protons. The \(\gamma\)-rays were detected by a Wulf type electroscope filled with argon at a pressure of 70 atmospheres. Figure 2 gives the results that were obtained when a thin target of CaF\(_2\) was bombarded with protons. The resonances at 0.862 and 0.927 Mev were used to obtain the value of the constant of the electrostatic voltmeter. The resonances at 0.660 and 1.363 Mev were also observed and each resonance voltage gave very nearly the same voltmeter constant. The subsequent readings of the voltmeter were thought to be reliable to at least 20 kev. In order to stabilize the voltage and to facilitate making small changes in the voltage, a corona current of from 50 to 100 microamperes from the central electrode to an adjustable probe was used. This current passed from the probe to ground through a variable high resistance balanced against the e.m.f. of a battery. Small changes in the voltage could be noted by observing the change in the corona current from the high potential electrode. Over a region of about 0.10 Mev the change of corona current was found to be proportional to the change in voltage, and so could be used to measure the change in voltage.

\(^2\) B. E. Watt, Rev. Sci. Inst. in press.

\(^b\) E. J. Bernet, R. G. Herb and D. B. Parkinson, Phys. Rev. 54, 398 (1938).
γ-RAYS FROM C+H²

The excitation curves for the γ-rays have been obtained by using thin carbon targets which were usually made by the evaporation of paraffin onto silver disks. The thickness of most of the targets was only a few thousand volts. The γ-rays were detected by means of coincidences of Geiger counters and by measurement with the Wulf type electroscope filled with argon at 70 atmospheres. Since the electroscope gave a greater accuracy for a given time of observation than the counters, it was used in most of the work. Figure 1 of reference 16 gives the excitation curve for the γ-rays from 0.55 up to 2.0 Mev. This curve shows resonance at 0.92, 1.16, 1.30, 1.43 and 1.74 Mev. The experimental half-widths of the resonances vary from about 0.25 Mev for the resonance at 1.74 Mev to 10 kev for the resonance at 1.43 Mev. The narrow resonance at 1.43 Mev was investigated further by using a target 1/2 as thick as that used to get the curve of reference 16. The results obtained with this thinner target are given in Fig. 3. The half-width of the resonance remains 10 kev, and so it is shown that the target thickness is not responsible for the experimental width of the resonance. The two possibilities that remain are that the 10-kev width is due to the spread in the energy of the deuterons, or that the real width of the resonance level is 10 kev. Since this is about the same width as we obtained for the resonances from F+H¹, we are inclined to think that at least most of the 10-kev experimental width is due to the spread in the energy of the deuterons, and so the real width of the level might be considerably less.

We have studied the excitation curve for γ-rays in more detail than is shown in reference 16. Figure 4 gives a sample set of such data which were taken in the energy interval 1.24 to 1.36 Mev. This curve shows that the level at 1.30 Mev has a half-width of about 40 kev.
It is difficult to be certain how the $\gamma$-rays originate without information about their energy. Consequently a series of absorption experiments on the $\gamma$-rays were made at each of the resonances. We found that the absorption coefficient in Pb was near the theoretical minimum value and that the $\gamma$-rays from each of the resonances had the same absorption coefficient. We have also measured the energy of the $\gamma$-rays at each of the resonances by determining the range of the Compton electrons produced by the $\gamma$-rays. We used a similar technique to that described in the following paper. Curve (A) of Fig. 5 gives the average results of the coincident Geiger-counter measurements on the $\gamma$-rays from an ordinary carbon target. The results for each resonance agreed within the probable error with this average curve. The absorber thickness at which the number of coincident counts falls to half-intensity indicates a $\gamma$-ray energy of roughly 3 Mev, but the actual end point of the curve indicates an energy of about 5.1 Mev. This suggests that there is a strong $\gamma$-ray with an energy of 3.0 Mev and a weak $\gamma$-ray with an energy of 5.1 Mev. Similar results were obtained from a cloud-chamber study of these $\gamma$-rays by Bonner, Becker, Rubin and Streib in Pasadena. When a potential of 1.0 Mev was used they found a $\gamma$-ray with an energy of $3.0 \pm 0.2$ Mev and another $\gamma$-ray with approximately 5 percent relative intensity near 5.5 Mev. Using separated isotopes they found that the 5.5-Mev $\gamma$-ray comes from C$^{14}$. We have also carried out some experiments with 23-percent C$^{14}$ which has been kindly supplied to us by Professor H. C. Urey. Curve (B) of Fig. 5 shows the absorption in aluminum of the secondary electrons produced by the $\gamma$-rays. A thick carbon target was used for this experiment and the bombarding deuterons had an energy of 1.5 Mev. It is apparent from curves (A) and (B) that the average quantum energy of the $\gamma$-rays is considerably higher for the 23-percent C$^{14}$ target. This confirms the results quoted above that the higher energy component of the $\gamma$-radiation is from C$^{14}$, and the curve gives a more accurate value of


---

**Fig. 6.** Excitation curve for the 5.5-Mev gamma-radiation from C$^{14}$-H$^1$. Curve (B) is obtained by subtracting the dotted curve from curve (A). Curve (B) then represents the shape of a resonance which is superposed upon the general rise in the excitation function.
the maximum range of the Compton electrons than we obtained before. This maximum range is $10.3 \pm 0.3$ mm of aluminum. From the range-energy relation for such electrons, we find that this corresponds to a quantum energy of $5.5 \pm 0.2$ Mev. This is in good agreement with the cloud-chamber results of Bonner, Becker, Rubin and Streib.\textsuperscript{24}

Since the $\gamma$-ray excitation curves of Figs. 3, 4, and of reference 16 were obtained using ordinary carbon targets, it is apparent that about 95 percent of the $\gamma$-rays recorded there were from the bombardment of $^{12}$C. We have carried out a separate experiment to get the excitation curve for the $\gamma$-rays from $^{12}$C. We were able to count $\gamma$-rays from $^{12}$C by using coincident Geiger counters with sufficient absorber between them to prevent 3-Mev rays from producing coincident counts. A target of 2-percent $^{12}$C was used in these experiments. It was prepared by one of us (B.E.W.) from methane in which $^{12}$C had been concentrated by thermal diffusion. Its thickness was found to be about 30 kev from

the observation that the resonance at 1.43 Mev showed a width of 30 kev. Figure 6 shows the excitation curve for $\gamma$-rays with an energy of 5.5 Mev. The curve is smooth except for a resonance at 1.55 Mev which will be discussed in detail later in this paper.

Since it seemed possible that the 1.43-Mev resonance for $\gamma$-rays was of a different character from the other broader levels, we thought that the $\gamma$-rays from that level might have a different quantum energy. We carefully searched for a sharp resonance in the yield of high energy $\gamma$-rays at 1.43 Mev but found no effect. To further investigate the energy of the $\gamma$-rays from the 1.43-Mev resonance, we put sufficient absorber between two coincidence counters to prevent 2.5-Mev $\gamma$-rays from producing coincident counts. We then investigated the resonance at 1.43 Mev and obtained the same resonance curve as before. This showed that the $\gamma$-rays from the 1.43-Mev resonance have an energy greater than 2.5 Mev and the previous experiment had already shown that the $\gamma$-rays from the resonance were less than 4 Mev. All these results indicated that the radiation from the 1.43-Mev level is from $^{12}$C and that the $\gamma$-rays have the same energy as those from the other broader levels.

The intensity of the $\gamma$-rays from a thick graphite target was compared with that obtained from the bombardment under similar conditions of a thick crystal of CaF\textsubscript{2} by 1.5-Mev protons. The $\gamma$-rays from C+H\textsubscript{2} were found to be 3.0 times as intense as those from CaF\textsubscript{2} when an electroscope shielded by one cm of iron was

![Fig. 7. Energy distribution of the neutrons from C+H\textsubscript{2} as inferred from recoil protons in a methane-filled cloud chamber. A target containing 23-percent C\textsuperscript{12} was bombarded with 1.4-Mev deuterons.](image1)

![Fig. 8. Integral range curve for recoil protons from the neutrons of C\textsuperscript{12}+H\textsubscript{2}, (Fig. 7).](image2)
used to detect the \( \gamma \)-rays. The absolute yield of the \( \gamma \)-rays from carbon was determined at 1.0 Mev by the use of a Geiger counter, assuming that it counted \( \gamma \)-rays with an efficiency of two percent. For 1.0-Mev deuterons the yield of \( \gamma \)-rays from carbon was \( 17 \times 10^4 \) quanta per micro-coulomb of deuterons. This shows that the \( \gamma \)-rays have about 4 times the intensity of those from \( \text{CaF}_2 + \text{H}_2 \) at this same bombarding voltage.

**The Neutrons from C+H\(^2\)**

We have investigated the excitation curve for the neutrons from carbon bombarded by deuterons. To detect the neutrons we have used a Wulf type electroscope filled with hydrogen at a pressure of 7 atmospheres. We have also studied the radioactive \( \text{N}^{13} \) which is formed whenever a neutron is emitted according to reaction (2). The electroscope was placed in the forward direction to the incident deuteron beam and it gave, therefore, the excitation curve for neutrons in the forward direction. The amount of radioactive \( \text{N}^{13} \) formed in a thin paraffin target was measured by means of a thin-walled Geiger counter placed outside a thin window on the target tube. The procedure was to bombard the target for ten minutes, then shut off the high voltage and follow the activity of the target. The half-life of the \( \text{N}^{13} \) activity was found to be ten minutes in agreement with the known half-life of 9.93 minutes.\(^{15}\)

Figure 1 of reference 17 shows the excitation curves obtained from the ionization currents in hydrogen and from the radioactivity of the \( \text{N}^{13} \). Since some of the ionization in hydrogen is due to \( \gamma \)-rays, a correction had to be made to compensate for this effect. By using a radium source filtered by 1.0 cm of lead, we found that the \( \gamma \)-ray intensity measured by the electroscope filled with hydrogen was only 4.75 percent that of the argon-filled electroscope which was used in the \( \gamma \)-ray experiments. The total intensity from a carbon target bombarded by 1.525-Mev deuterons was measured by using the electroscope filled with argon and then with hydrogen. From the ratio of the two ionization effects it was possible to calculate that the \( \gamma \)-rays were responsible for 19 percent of the ionization in hydrogen at 1.525 Mev. A corresponding correction was made at all other voltages. Curve (3) gives this corrected ionization due to the neutrons alone. Both curves (1) and (3) show resonances at 0.92, 1.16 and 1.30 Mev. These are the same resonances as those found for the emission of \( \gamma \)-rays. However the \( \gamma \)-ray resonance at 1.43 Mev does not show up as a resonance for neutron emission. Above 1.43 Mev the hydrogen ionization data show a resonance at 1.74 Mev and 1.82 Mev. The resonance at 1.74 Mev partially disappears after the \( \gamma \)-ray correction is made, and it is uncertain whether the resonance at 1.74 Mev is truly a resonance for neutron emission.

Although curves (1) and (3) of reference 17 agree in showing the same resonances, the relative heights of the resonances are different. The differences might be explained by supposing that

---

neutrons from the different excited levels of the intermediate nucleus have different angular distributions; whereas curve (1) gives the total yield of N\textsuperscript{14} (and neutrons), curve (3) gives the yield of neutrons only in the forward direction. Experiments to study these angular distributions would be of interest.

Since it seemed likely that the 5.5-Mev \(\gamma\)-rays from C\textsuperscript{12} were produced in reaction (3), we looked for low energy neutrons when a thick target of 23-percent C\textsuperscript{12} was bombarded by 1.4-Mev deuterons. The neutron energies were measured by the method of finding the energy distribution of the recoil protons photographed in a cloud chamber containing methane. The neutrons were observed at an angle of 90\(\pm\)10\(^\circ\) to the direction to the deuteron beam. Two thousand stereoscopic photographs were taken on which there were numerous recoil protons. One thousand and ten of these protons were in the forward direction (0–10\(^\circ\)) and their track lengths were measured. The energy distribution of these recoil protons is given in the curve of Fig. 7. The group of neutrons at 0.9 Mev is the group from reaction (2) which was previously measured by Bonner and Brubaker. The \(Q\) value obtained in the present experiment was \(-0.19\pm0.05\) Mev. This agrees with the value of \(Q_2 = -0.25\) Mev which was obtained by Bonner and Brubaker. The group of neutrons at 1.5 Mev was not observed by Bonner and Brubaker in their original experiments. For this reason and because of energy considerations this group must be from C\textsuperscript{13}. An accurate calculation of the \(Q\) value for this group of neutrons was calculated by the method of Livingston and Bethe.\textsuperscript{24} The integral number vs. range curve of the recoil protons is given in Fig. 8. The extrapolated range of the recoil protons is 4.4\(\pm\)0.2 cm of standard air. The energy of the neutrons coming from the surface of the target at 90\(^\circ\) to the incident beam was found to be 1.49\(\pm\)0.03 Mev. The disintegration \(Q\) value was then calculated from the relation \(Q = (15/14)E_a - (6/7)E_d\). \(Q_4\) was found to be 0.40\(\pm\)0.05 Mev. The best value of the energy evolved in reaction (3), when the products are left unexcited, is that calculated from the masses of the atoms concerned and these give \(Q_4 = 5.5\pm0.2\) Mev. The neutron group at 1.5 Mev must then leave the N\textsuperscript{14} nucleus in an excited state at 5.1\(\pm\)0.3 Mev. This excited N\textsuperscript{14} nucleus would give a \(\gamma\)-ray of this energy when it returns directly to the ground state. This group of neutrons from C\textsuperscript{13} then seems to explain the 5.5\(\pm\)0.2 Mev \(\gamma\)-rays which are also produced in the disintegration of C\textsuperscript{13}.

**Protons from C+H\textsuperscript{3}\**

Since the \(\gamma\)-rays and neutrons from the bombardment of carbon by deuterons show many of the same resonances, we might expect the 15-cm protons from reaction (1) also to show the same resonances. These resonances correspond to excited states in the intermediate N\textsuperscript{14*} nucleus, and we might expect the emission of neutrons, protons and \(\gamma\)-rays to be competing processes.

The excitation curve for the emission of 15-cm protons was studied with an ionization chamber 2.5 cm in depth connected to a linear amplifier. Such a deep chamber was used so that the protons would give large pulses and would be counted far from the end of their range. This was useful because the range of the protons from reaction (1) changes with bombarding energy. As an additional precaution to insure the counting of all protons, absorbers were added as the bombarding voltage was increased so that the protons were always counted at the same distance from the end of their range. Figure 9

\textsuperscript{24} M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 281 (1937).
gives the excitation curve for the 15-cm protons from reaction (1). The curve shows the resonances at 0.92 Mev and 1.16 Mev that were found in the emission of \( \gamma \)-rays and neutrons. The proton curve shows a resonance at 1.23 Mev which did not appear for \( \gamma \)-rays or neutrons. The resonance at 1.30 Mev which was shown by both neutrons and \( \gamma \)-rays appears to be missing in the proton excitation curve. Above 1.35 Mev the proton curve shows a rise of about 25 percent and then stays nearly horizontal up to 1.7 Mev, where it begins to decrease rapidly.

The relative yield of 15-cm protons and neutrons at 0.92-Mev bombarding energy was obtained by counting the number of \( \text{N}^{14} \) atoms formed and comparing it with the number of protons from the same thin target. At 90° to the bombarding direction, the ratio of protons to positrons from \( \text{N}^{14} \) is 1.9. The number of \( \gamma \)-rays in comparison to the number of protons was also obtained at 1.60 Mev. The number of counts produced by \( \gamma \)-rays in a single Geiger counter was obtained at the same time that the 15-cm protons were counted by the linear amplifier. After allowing for the differing solid angles and for the efficiency of the Geiger counter for counting 3-Mev \( \gamma \)-rays (2 percent), we obtained 1.0 as the ratio of the number of \( \gamma \)-rays to the number of protons. This shows that all three processes, the emission of neutrons, of 15-cm protons, and of 3.0-Mev \( \gamma \)-rays are about equally probable.

The apparent explanation of the 3-Mev \( \gamma \)-rays from \( \text{C}^{12} \) is that they come from a \( \text{C}^{12} \) nucleus which is left excited to 3 Mev after the emission of a short range proton group. Consequently, we have looked for such a group of protons. The \( Q \) value for this group of protons should be equal to \( Q_1 - E \), which is numerically equal to 2.71 - 3.0 = -0.29 ± 0.25 Mev. Since the expected proton group would have a range less than that of the scattered deuterons, we used an experimental arrangement which could detect particles with shorter ranges than the scattered deuterons. The deuteron beam was allowed to pass through an aluminum foil with a stopping power of 6.5 mm of air into a gas target chamber which was filled with methane at a pressure of 2.5 cm. The protons and scattered deuterons were observed in a cloud-chamber at an angle of 90° to the direction of the deuteron beam. The disintegration particles entered the cloud chamber through a Nu-Skin foil which had a measured stopping power of 1.3 mm of air. The cloud chamber was operated at a pressure, when expanded, of 0.5 atmosphere of helium and water vapor. The high voltage apparatus was adjusted to give a beam of 1.7-Mev deuterons during this experiment, and the deuterons, after passing through the aluminum foil and 3.9 cm of methane, had an energy of 1.47 Mev at the center of the gaseous target. The part of the gaseous target from which it was possible to get disintegration particles entering the cloud chamber was 1 cm deep in the direction of the deuteron beam; thus the \( \text{CH}_4 \) target had a thickness equivalent to approximately 0.03 cm of air.

At this bombarding voltage we obtained about one track per expansion coming from the gaseous target. The scattered deuterons had an actual track length of 10.2 cm in the cloud chamber. We took a total of 4000 cloud-chamber pictures with this experimental arrangement and on these photographs we measured 2030 tracks. The length of the tracks in helium was converted to range in standard air by taking the stopping power of He equal to 0.20. To the range in the cloud chamber was added 0.39 cm, which was the air equivalent of the Nu-Skin foil and the thickness of methane absorber between the deuteron beam and the foil. The resulting range distribution of the tracks in terms of standard air is given in Fig. 10. The 15-cm protons from \( \text{C}^{12} \) were observed in the cloud chamber, but

\[ \text{FIG. 11. Long range protons from a 23-percent } \text{C}^{14} \text{ target bombarded by 1.00-Mev deuterons. The rise at 18-cm range is from the long range (15 cm) protons from } \text{C}^{12} + \text{H}^2. \]
these went entirely across the chamber, so they are not indicated on the curve of Fig. 10. The group of particles with a range of 1.61 cm are the scattered deuterons. The expected range of the scattered deuterons was computed using the 1938 Cornell range-energy relation and was found to be 1.50 cm which agrees to within 7 percent with the experimental range of this group. The group of scattered deuterons appears to be symmetrical and has a half-width of 0.18 cm of standard air. Besides the strong group of scattered deuterons there is a weaker group of particles with a range of 1.10±0.10 cm. The ratio of the number of 1.1-cm particles to the number of 15-cm protons was found to be 0.44. Since we previously found that the number of γ-rays was 1.0 times the number of 15-cm protons, we should have expected that there would have been 1.0 times as many short range protons as 15-cm protons, if the short range proton groups had a spherical angular distribution. The fact that the experimental ratio is 0.44 indicated that the number of short range protons must be a factor of 2 to 3 greater in the forward direction. Another possible explanation of the 1.1-cm group is that it arises from a small amount of molecular hydrogen ions in the beam of mass 2. We found that our ratio of current in the mass 2 beam was usually about 2 to 3 times as large as the current in the mass 4 beam. We also had 7 percent as many protons (mass 1 beam) as deuterons (mass 2). Consequently we would expect that about 1 percent or less of the mass 2 beam was composed of molecular hydrogen atoms each of which had half the bombarding energy. The energy of these molecular hydrogen ions at the scattering target was calculated, and the range of these scattered protons was computed to be 0.70 cm of air. This eliminates the possibility that the group at 1.10 cm could be caused by scattered molecular hydrogen ions.

The Q value corresponding to this 1.10-cm group of protons was calculated from the relation: \( Q_t = (14/13)E_R - (11/13)E_D \) and a value of \(-0.52±0.07\) Mev was obtained. From these data the energy of the γ-ray should be \(2.71±0.53 = 3.24±0.08\) Mev which agrees with the experimental value of \(3.0±0.2\) Mev. Since each low energy proton is accompanied by a quantum of γ-radiation, the excitation curve for the production of low energy protons is the same as for the 3-Mev γ-rays (reference 16).

It is interesting to note that the ratio of disintegration protons from carbon to the number of scattered deuterons was 0.37, which indicates that at this angle a disintegration is nearly as probable as an elastic scattering.

We have also investigated the protons that come from C\(^{14}\) according to reaction (4). In order to be able to count weak groups of particles in the presence of neutrons we have used a deep ionization chamber (2.5 cm) connected to a linear amplifier. When the bias is set so that only the largest pulses are counted, the background
due to neutron recoils is found to be very small. We bombarded a thick target of 23-percent C\textsuperscript{14} with 1.00-Mev deuterons and obtained the curve shown in Fig. 11. The group of protons from C\textsuperscript{14} has an extrapolated range of 53.7±2.6 cm. The value of \( Q_4 \) was found from this value of the extrapolated range to be 6.09±0.2 Mev. This agrees with the value of \( Q_4 \) calculated from the masses which is 6.13±0.19 Mev.

No other group of particles from C\textsuperscript{14} was obtained with ranges greater than 20 cm although a group with an intensity of \( 1/5 \) that of the 50-cm group could have been detected. We also looked for protons from C\textsuperscript{14} below the 15-cm group of protons from C\textsuperscript{12}. No groups were observed, but only groups considerably more intense than the 50-cm group could have been detected in this region. The experiment indicates that there are probably no excitation levels in C\textsuperscript{14} below 2.8 Mev. The 3-cm group of alpha-particles from carbon was observed both with an ordinary carbon target and with a 23-percent C\textsuperscript{14} target. Since the number of alpha-particles was much greater from the C\textsuperscript{14} target this definitely shows that this group had been properly attributed\textsuperscript{17} to the reaction:

\[
\text{C}^{14} + \text{H}^2 \rightarrow (\text{N}^{15*}) \rightarrow _4\text{Be} + _2\text{He}^4 + Q_4. \tag{5}
\]

The ratio of the intensity of the 50-cm group of protons to the 15-cm protons from C\textsuperscript{12} was determined with a target in which the C\textsuperscript{14} had been concentrated. With this target and 1.22-Mev deuterons, the ratio of the intensity of the 55-cm group to the intensity of the 15-cm group of protons was 0.11 percent. A target in which the C\textsuperscript{14} was depleted by approximately the same factor was then bombarded and the ratio was only 0.029 percent. This showed that the C\textsuperscript{14} had been concentrated in the first target relative to the second by a factor of 3.8, whereas the separation factor had been calculated from the dimensions of the thermal diffusion apparatus as 3.7. The average of these two ratios (0.07 percent) is consequently the ratio of the yields from ordinary carbon at 1.22-Mev bombarding energy. This ratio would vary considerably with different bombarding voltages since the yields for both groups of protons show resonances.


The excitation curve has also been obtained for the 50-cm protons. A target of 2-percent C\textsuperscript{14} prepared from methane and with a thickness of 30 kev was used in this experiment. The deep ionization chamber was again used to count protons, and the bias on the recording circuit was made low enough to count all protons passing through the ionization chamber. Absorbers were also added as the bombarding voltage was increased to insure that the protons were always counted at the same distance from the end of their range. The excitation curve is given in Fig. 12. The indicated error is the statistical error increased by a factor of two, since it was necessary to make observations in two separate runs, which were joined at 1.45 Mev. The curve shows a maximum at 1.52 Mev. This may be interpreted as a resonance in the yield which would indicate an excited state in the intermediate nucleus (N\textsuperscript{14*}) at 17.5 Mev.

\textbf{Discussion of the Results C\textsuperscript{12}}

The sharp resonances obtained from the disintegration of C\textsuperscript{12} by deuterons are surprising because of the fact that the intermediate nucleus (N\textsuperscript{14*}) is excited to 11 Mev and might be expected to emit a neutron or a proton in such a short time that the level in N\textsuperscript{14*} would be wide. The width of the level is given by the uncertainty relation \( \Delta E \Delta t \approx h \). The level at 1.30 Mev had a width of 40 kev and consequently the intermediate N\textsuperscript{14*} nucleus must exist for a time

\[
\Delta T = \frac{1.04 \times 10^{-27}}{1.60 \times 10^{-4} \times 0.040} \approx 1.6 \times 10^{-20} \text{ sec.}
\]

This shows that it takes more than \( 1.6 \times 10^{-20} \) sec. to emit a neutron with an energy of 0.8 Mev from the excited N\textsuperscript{14*} nucleus. The lifetime of the intermediate N\textsuperscript{14*} nucleus can be estimated from the relation

\[
\Delta T = R/\nu,
\]

where \( \nu \) is the velocity of the neutron in the N\textsuperscript{14*} and \( R \) is the nuclear radius. If we take \( R = 4 \times 10^{-13} \) cm and a neutron velocity of 1/20 that of light, we get a value of \( \Delta E = 1.2 \) Mev. This is more than 30 times the observed width and so it may be necessary to invoke a selection rule to explain
this result. The emission of neutrons and 15-cm protons from the 1.43-Mev resonance level in $^{14}\text{N}$ must have a strong selection rule forbidding such modes of disintegration.

The experiments with $^{12}\text{C}$ show what the three modes of disintegration, the emission of (1) a neutron, (2) a 15-cm proton, and (3) a short range proton, are all about equally probable from the levels in $^{14}\text{N}$ corresponding to the resonances at 0.92 and 1.16 Mev. However the 15-cm protons show a resonance at 1.23 Mev which is not shown by either of the two competing processes. It seems possible, however, that this level may be the same as that shown for neutron and $\gamma$-ray emission at 1.30 Mev. A shift in the position of the maximum of 0.07 Mev might be produced through a different interference with the background, or it might be caused by the theoretical considerations discussed by Breit.  

The 15-cm proton group seems to show the resonance at 1.74 Mev as shown by the sharp decrease in the curve above 1.74 Mev, and another broad resonance at from 1.5 to 1.6 Mev. A broad resonance in this region is probably needed to explain the plateau which is experimentally observed from 1.45 to 1.75 Mev.

$^{12}\text{C}$

In the disintegration of $^{12}\text{C}$ by deuterons the competing processes are reaction (3), (4) and reaction (5). Unlike the case of $^{14}\text{C}$ the three competing processes for $^{12}\text{C}$ have very unequal probability. The 5.5-Mev $\gamma$-rays (consequently 1.5-Mev neutrons) are approximately 70 times as numerous as are the 50-cm protons. The alpha-particles from reaction (5) were found to be roughly 50 times as probable as the 50-cm protons. Thus it seems that the emission of low energy neutrons and alpha-particles from $^{12}\text{C}$ are about equally probable but that the emission of 50-cm protons is very unlikely.

The excitation curves for 5.5-Mev $\gamma$-rays and 50-cm protons both show the same resonance at 1.55-Mev bombarding voltage. This indicates that an excited state in the intermediate ($^{14}\text{N}$) nucleus at 17.5 Mev may break up either into low energy neutrons or 50-cm protons. It is surprising that an isolated resonance at this high excitation of the intermediate $^{13}\text{N}$ nucleus is observed.

The principal difference in the excitation curves for 50-cm protons and 5-Mev $\gamma$-rays is that the emission of $\gamma$-rays appears to come mainly from a continuum, while the emission of 50-cm protons comes mainly from the resonance at 1.55 Mev. The fact that very few of the 50-cm protons come from the continuum may explain why this reaction is so much more improbable than the emission of 5-Mev $\gamma$-rays.

The width of the level in the $^{14}\text{N}$ at 17.5 Mev may be calculated as was done for the level in $^{14}\text{N}$ by the relation $\Delta E \Delta T = h$ and $\Delta T = R/\nu$. The width of this level is fixed by the neutron emission which is the most probable reaction. A calculation gives the value of $\Delta E = 1.7$ Mev for the width of this level. It may not be necessary to invoke the use of selection rules forbidding disintegration into neutrons and protons from this level to explain the experimental half-width of this level as 0.25 Mev. It is reasonable that the actual width of the level is smaller than the estimated width because the estimate does not take into account the internal rearrangements necessary for concentrating the necessary energy on either a neutron or a proton.

It would be interesting to determine the excitation curve for the alpha-particles to see if they show the same resonance at 1.55-Mev bombarding energy since they come from the same $^{14}\text{N}$ nucleus.

---

18 G. Breit, Phys. Rev. 58, 1068 (1940).
High Energy Gamma-Ray from Li+D

W. E. Bennett, T. W. Bonner, H. T. Richards and R. E. Watt
Rice Institute, Houston, Texas
May 2, 1941

A 440-KEV gamma-ray is the only one reported to
have been observed when lithium is bombarded by
deuterons.1 We have observed gamma-rays from this
reaction which are more energetic and more intense than
the 440-kev gamma-rays. The latter have not been ob-
served in our experiments.

An absorption curve in lead of the gamma-radiation
showed that its energy was considerably greater than
440 kev. The energy was measured more accurately by
using coincidence counters to find the maximum range of
the Compton electrons in aluminum.2 The maximum range
was 8.7 mm corresponding to a gamma-ray energy of
4.9±0.3 Mev. Effects from the nuclear beta-rays from Li+D
were avoided by using 7.2 g/cm² of carbon as an absorber
between the target and the Geiger counters.

To get the absolute yield of gamma-rays a thin target
of LiOH (13.4 kev thick) was bombarded by 770-kev
deuterons and the gamma-rays were counted by a single
Geiger counter, assumed to be 2 percent efficient in coun-
ting gamma-rays of these energies. From the number of
gamma-rays produced in this thin target, the number
produced in a thick target of lithium was calculated for
770-kev deuterons from an excitation curve for the gamma-
radiation which we had taken. The intensity of the gamma-
radiation was found to be 3.0×10⁶ quanta per micro-
coulomb. The yield of neutrons for this reaction is known,³
and we find the ratio of gamma-rays to neutrons to be
3.3 percent.

The gamma-rays were observed from thick and thin
targets of LiCl and thin targets of LiOH deposited on
copper and on silver. This makes it fairly certain that the
gamma-rays were not produced by bombardment of any
other material. Furthermore the excitation curve for the
gamma-rays was similar to that for the neutrons from Li+D
and for the beta-rays from Li+ formed by the bombardment
of lithium by deuterons. All three excitation curves showed
resonances at about 700 and 1000 kev of deuteron energy.

It still seemed possible that the observed gamma-ray
might have been produced by inelastic scattering of the
neutrons or beta-rays (bremsstrahlung) from lithium in
neighboring materials. We first verified that the gamma-
rays originated in the immediate neighborhood of the
target by moving the counters to different distances and
comparing the change in counting rate with the inverse
square law. We found that, at 10 cm from the target, 80 per-
cent of the gamma-radiation and 97 percent of the harder
components in it originated at the target. The materials
near the target (brass, aluminum, Pyrex glass) were tested
by placing additional amounts in front of the target
(Fig. 1) and measuring the increase in the gamma-
ray intensity at the side. Effects were found for all ma-
terials, but calculations showed that the amounts normally
present were enough to increase the intensity of gamma-
radiation by only 9 percent. Similarly the gamma-rays
produced by neutrons and beta-rays in the carbon blocks
used to absorb the beta-rays amounted to 10 percent at
most. To check whether the neutrons were counted in any
manner by the Geiger counter, the carbon blocks were
replaced by a block of paraffin of equal absorbing power for
gamma-radiation. The neutron intensity behind the
paraffin was 0.48 of its value behind the graphite blocks,
the ratio being measured by using an electroscope filled
with methane at high pressure. The counting rate was the
same whether the Geiger counters were shielded by carbon
or by paraffin, and we conclude that the neutrons were not
affecting the counting rate in any way. If the beta-rays
from Li+D had affected the counters either directly or
indirectly the gamma-effect would have decayed with a
period of 0.9 second when the bombardment was stopped.
We found that at least 90 percent of the gamma-effect
stopped immediately when the beam was cut off by a
shutter. There were longer period activities induced in the
counters by neutron bombardment, but these effects were
always subtracted as part of the background count.

It is fairly certain that the 4.9-Mev gamma-ray is
produced by the bombardment of Li+ and not of Li+D
because the excitation curve (unpublished) is typical of
Be⁰ as the intermediate nucleus. The gamma-ray might
indicate an excited level of either He⁰ or Be⁰ from energy
considerations alone, but no group of alpha-particles has
been observed which would correspond with the formation
of He⁰ in an excited state. There is some evidence⁴ of a
neutron group which corresponds to the formation of Be⁰
in an excited state at 4 to 5 Mev so we take the existence
of this gamma-ray as further evidence of an excited state
in Be⁰ which emits a gamma-ray before breaking up into
two alpha-particles.

2. The experimental arrangement is described by Bennett, Bonner and Watt, Phys. Rev. 99, 783 (1946).
An Integrator for Small Currents

Bob E. Watt
The Rice Institute, Houston, Texas
(Received March 18, 1941)

A current integrator employing a neon bulb has been used; it is found to require no correction of any kind, and to be independent of power supply fluctuations. The lowest current for which the integrator can be considered reliable is 0.05 micromapere. Currents up to 30 microamperes have been integrated properly, and it is believed that currents up to 200 microamperes could be integrated by a similar circuit.

Introduction

The use of a neon bulb in the integrator for a scaling circuit constructed by T. H. Johnson suggested its use in an integrator for the beam current of the Rice Institute pressure electrostatic generator. Integrators useful for the currents found in such apparatus employ the measurement of the voltage change on a known capacity, or, its equivalent, the measurement of the number of times the unknown charge is capable of charging a capacity through a constant voltage. Streib, Fowler and Lauritsen employ the first method, while the present integrator and others employ the second. The integrator to be described differs from that of Herb et al. by the use of a neon bulb as the discharging agent rather than a thyatron. This change renders the integrator insensitive to power supply fluctuations. W. B. Nottingham has investigated the characteristics of a type WL-759 "trigger" tube (a cold-cathode glow discharge tube), and shown that it may be used to integrate currents down to $10^{-10}$ ampere. J. B. Horner Kuper, F. S. Brackett and Maynard Eicher have used the tube to integrate photoelectric currents, and report that occasional large changes in the tube's characteristics were observed.

Operation of the Circuit

Figure 1 gives the circuit diagram of the complete unit. The incoming current charges $C$ (here $C$ will refer to the integrating condenser being used; $C_2$ with the switch $S$ in the position shown) until the voltage across the neon bulb, $N$, reaches the discharge voltage. The arc formed draws charge from $C$ until the voltage across $N$ falls to the extinction voltage. The arc then goes out, $C$ is recharged and the cycle repeated. Since the discharge and extinction voltages remain constant, the voltage change on $C$, hence the charge removed, is constant. The number of times the cycle is repeated is then a measure of the charge passed to ground.

INTEGRATOR FOR SMALL CURRENTS

When the neon bulb discharges, a negative pulse is passed to the type 56 tube, amplified, inverted and passed to the slightly modified Dunaig\(^4\) counting circuit. The discharges of the neon bulb are thus recorded on the mechanical counter, \(K\), and the count becomes a measure of the charge passed to ground.

The remaining circuit elements form the power supply.

**DESIGN CONSIDERATIONS**

The mathematical calculations are too simple to warrant reproduction here. The results show that: For a perfect integrator the relation between the counting rate and current is a straight line passing through the origin, while for one in which leakage following Ohm’s law is present (and no bias is used on the neon bulb) the relation is displaced toward lower counting rate, but otherwise is unchanged in regions where the leak is small compared to the charging current. When a bias on the neon bulb is used, such that the average leak is zero, the displacement is eliminated. The counting rate is then proportional to the current so no correction is needed.

The difference in charge on \(C\) at the start and end of an integration represents a maximum error of one count. To make the error from this source small, a reasonably large number of discharges (100 for an accuracy of one percent) must be counted. The calibration curves shown in Fig. 2 enable an estimate to be made of the proper value for \(C\) for a particular application. Of course, \(C\) cannot be made so low that the mechanical recorder jams because of too high a counting rate. For example, if a charge of 0.1 micromicrofarad is to be integrated to an accuracy of one percent the 5000-\(\mu\)F condenser cannot be used, as only 40 discharges would be counted. The 500-\(\mu\)F condenser would give about 300 counts, so would be used. However, if the incoming current were above 1 microampere the counting rate would be too high for the mechanical recorder, hence the 5000-\(\mu\)F condenser must be used.

**CALIBRATION**

The integrator was calibrated by determining the counting rates for known currents. To obtain relatively steady currents, in spite of the fluctuations of potential on \(C\), a rectifier having adjustable voltages up to 1700 volts was used. Three different resistors of about 10\(^4\) ohms were used in various combinations, together with variations in the supply voltage, to cover the calibration range desired. The currents were measured by inserting an RCA ultra-sensitive d.c. meter (stock number 9819) in place of the integrator before and after a run. Leakage between the primary and secondaries of the integrator’s power transformer prevented series measurement. The relations obtained when no bias was used showed the expected downward displacement corresponding to the directly measured leakage of 0.01 microampere. The relations obtained when the bias was applied are shown in Fig. 2. These relations are accurately linear between 0.03 microampere and 10 microamperes (upper range not shown, and does not apply to the 500-\(\mu\)F condenser) and at least approximately so to 30 microamperes. At the latter value the counting rate was too high for accurate recording, so no definite statement can be made. When extrapolated the relations pass through the origin, hence the counting rate is directly proportional to the current and requires no correction.

The lower current limit thus deduced agrees well with that found from Fig. 2. Experimentally, the upper limit has not been found, beyond noting that currents of 30 microamperes were handled properly. Runs several hours long on the same current showed that the counting rate was constant within one percent. No check has been made to see if the rates have changed with time, other than rough comparisons good to five percent.

**Use**

The integrator has been in use for about six months, during which time a few minor changes have been made resulting in the circuit shown in Fig. 1. To prevent any difficulties connected with insulation, pick-up, etc., of the lead to the input terminal of the integrator from arising, the integrator was placed near the target. Overhead lamp-cord leads about twenty feet long went to the mechanical recorder and control switch at a central station. Another counter was simultaneously controlled through a double pole switch, greatly speeding the taking of data when few operators were on hand.

Upon attempting to integrate the current to a thick calcium fluoride crystal it was found that the sparking from the surface of the crystal produced surges which gave spurious counts. Bernet, Herb and Parkinson have eliminated the sparking by means of a fine wire touching the bombarded surface.

The fluctuations in target potential have been found not to affect a linear amplifier counting protons. However, the powerful surges in the overhead counter leads necessitated complete shielding of the amplifier and power supply.

**Precautions and Suggestions**

Good insulation of all the circuit elements and leads connected to the input terminal is imperative. The leak should be less than $10^{-8}$ ampere with 45 volts on the input terminal (no bias on the neon bulb). A porcelain lead-through insulator affords a good binding post, and a convenient way to lead through the chassis. The condensers $C_1$ and $C_2$ should be of the silvered

---

Fig. 2. Calibration chart. The chart gives the counting rate when a known, steady current is put into the integrator.

The sharp break at 0.024 microampere was only slightly affected by the removal of the bias, so could not be explained on the assumption of ohmic leakage. Corona leakage in the bulb was suspected, so the current to the base terminals of a similar bulb was measured as a function of the voltage between them. The relations obtained are shown in Fig. 3.

Curve II is the leakage across the base terminals of the bulb. The slow rise below 77 volts appears to be ohmic leakage, but could be electrolytic conduction. Above 77 volts the corona becomes important, rising rapidly to a maximum value of 0.023 microampere at 80.6 volts. Above this point the bulb breaks into the glow discharge, giving 80.6 as the discharge voltage. Curve I gives the relation between the voltage and current of the glow discharge. The minimum voltage which will support the arc is 58.2, and the corresponding current is 0.2 milliampere. Below 58.2 the arc goes out, giving 58.2 as the extinction voltage.

An integrator employing such a bulb could not be expected to operate below 0.024 microampere, as the glow discharge would never start. Similarly, above 200 microamperes the discharge would never extinguish and the integrator would not operate. This limit could be raised by the use of a voltage regulator tube such as the VR-90 (which requires a higher minimum current to maintain the arc) in place of the neon bulb.

---

mica type, as their leakage is extremely small, and the capacity is nearly independent of the temperature. Selected molded Bakelite mica condensers were tried, but found unsatisfactory because of their high leakage, which increased rapidly with temperature. Laminated Bakelite was avoided for the same reason; switch S was then constructed on a Lucite block. Selection of the neon bulb for minimum corona leakage seems desirable, though the results of Figs. 2 and 3 seem to indicate that all the bulbs of this type are very nearly the same.

![Graph](image)

**Fig. 3.** Curve II gives the leakage as a function of the voltage across the neon bulb. The value 0.023 microampere is the maximum steady corona, the bulb breaking into the glow discharge above this point; the corresponding discharge voltage is 80.6. Curve I gives the current in the glow discharge as a function of the voltage across the bulb. 0.2 milliamperes is the minimum stable current which the bulb will pass, and the corresponding extinction voltage is 58.2.

The capacity $C_4$ and limiting resistance $R_4$ will have to be adjusted to suit the mechanical recorder used, but the remainder of the circuit is not at all critical. The usual radio parts serve admirably.

If counting rates above about 1000 per minute are contemplated (with the attendant high current drain), the power supply regulation should be improved by using a choke input filter with a type 83 or 5V4-G rectifier tube. If this is done, a transformer supplying 350 volts on each side of the center tap may be used without danger of exceeding the 300-volt maximum plate voltage allowable on the type 885. Both the transformer and the choke should be rated for at least 150 milliamperes. Substitution of a type 55 for the type 56 shown would give ample reserve in pulse size to fire the counter circuit, regardless of lowered plate voltage. The filter condenser, $C_1$, should of course be large compared to $C_4$.

As the leakage is small unless the voltage is very near the discharge voltage, an alternating voltage somewhat larger than a volt in the grounded lead of the neon bulb might reduce the lower limit of the integrator considerably. A convenient way to do this would be grounding through the heater windings. However, the use of the WL-759 is definitely preferable if the changing discharge voltage (a function of the time between discharges) does not seriously affect the linearity of the integrator at higher counting rates.