CHARACTERISTICS OF A PROPORTIONAL COUNTER

A thesis presented to the Faculty of the Rice Institute in partial fulfillment of the requirements for the degree of Master of Arts.

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**INTRODUCTION**

Since 1908, when the first proportional counter was constructed by E. Rutherford and H. Geiger, it has been widely used as an instrument for the detection of atomic particles. One of the first experiments on the characteristics of a counter was made by C. G. and D. D. Montgomery. They found that as the voltage is increased, the counter passes through the ionisation region, where the magnitude of the pulse for a certain counter depends solely on the ionising ability of the particle—i.e., the chamber collects only the original ions formed, and at higher voltages there is a region where gas amplification takes place. Over a voltage region above the point at which gas amplification begins, the pulse size was found to increase with the voltage while the size of pulses due to different particles was still proportional to their ionizing abilities. Above this proportional region, what is called the Geiger region was reached where pulses due to all particles are of the same size. There is no sudden transition from the proportional to the Geiger region. A region of limited proportionality exists between the two where the ratio of the pulse sizes of different particles approaches unity, but the size of their respective pulses still increases with the voltage.
The advantage of the proportional region over the other regions of operation extends to any use where gas amplification and a distinction between particles of different ionizing abilities are desired. For example, when alpha particles are to be counted in the presence of an electron or gamma ray background, the proportional region is advantageous since it is possible to distinguish between the counts due to the alpha particles and those due to the background because of the difference in pulse size. An advantage of gas amplification concerns the electronic equipment needed. If a counter were operated with a gas amplification of 50, the amplifier used would only need a maximum gain of about 1,000. This means a simpler amplifier could be used than would be required if there were no gas amplification, and there would also be a better signal to noise ratio because of the low gain.

One disadvantage of this region is a consequence of one of its advantages: the fact that the gas amplification depends on the voltage applied between the cylinder and the coaxial wire. No electronic equipment will remain perfectly stable with time, and when operating in the proportional region, a slight drift in the power supply used for the counter voltage will cause a significant change in gas amplification. This disadvantage must be accepted, but in most experiments, suitable precautions can be taken for its detection.
When an atomic particle passes through the window of a counter and enters the chamber, it will collide with the gas molecules, or atoms, and leave a stream of ions in its path across the chamber. The number of ion pairs formed will depend on the particle considered. During a one centimeter path through air at atmospheric pressure, an alpha particle will produce on the average about 50,000 ion-pairs while a 1 Mev proton will produce 12,000 ion-pairs, and the average electron will produce between 50 and 100 ion-pairs. The electrons freed are the principal factor since they are light and can reach the positively charged wire in a matter of microseconds. These free electrons are accelerated towards the coaxial wire by the field and begin to ionize the gas on every collision when the energy gained in one mean free path is greater than the ionization potential of the gas. This gas amplification occurs in the high field region near the wire. The distance from the wire at which gas amplification begins is dependent on the strength of the field, the dimensions of the counter, and the kind and pressure of gas used in the counter.

Considering a counter of length $l$ with a wire of radius $a$ and a cylinder of radius $b$, we can express the electric field at a distance $r$ from the center of the wire by the formula

$$E(r) = \frac{V}{r \log_e \frac{b}{a}}$$
where $V$ is the voltage applied between the wire and the cylinder.

Suppose we consider an electron that had an initial energy of zero at some point $A$ and is being accelerated towards the wire by the field. In order to calculate the distance this electron must travel before it acquires sufficient energy to ionize an atom of argon, we must evaluate the integral

$$
\int_{r_A}^{r_B} E(r) \, dr = 15.69 \text{ volts}
$$

where 15.69 volts is the energy the electron must gain in traveling from $A$ to $B$; i.e., the ionization potential of argon.

In order to show that by far the greater part of gas amplification occurs in the vicinity of the wire, the actual phenomenon is being reduced to a much simplified model. All that is being considered are the electrons, the field, and the atoms of the argon gas used in the counter. It will be assumed that the electrons make perfectly elastic collisions with the argon atoms until they acquire the energy necessary to ionize an atom. When an electron ionizes an atom, one additional electron is freed and the average initial energy of the two electrons is zero. Using this model, the distance one electron must travel before it acquires the necessary 15.69 electron volt energy is calculated. Then repeating the procedure for this electron and the newly freed electron etc., until
the wire is reached, the graph shown below is obtained. The points were calculated taking the dimensions of the counter used in this experiment, A as equal to the cylindrical radius, and V as equal to 500 volts.

![Graph showing the relative number of free electrons as a function of distance from the surface of the wire.](image)

**Distance from Surface of Wire in Millimeters**

**Figure 1**

This shows that the main contribution is made at distances from the center of the wire comparable to its radius. In fact, the point at which the electrons can acquire enough energy to ionize in one mean free path is just about one or two mean free paths from the surface of the wire. If all collisions were inelastic, the points near the surface of the wire would contribute even a larger percentage of the total number of electrons resulting from the initial ionizing event.

After the initial ionization, several events might occur which will affect the magnitude and shape of the resulting pulse. One possibility is that the electrons will never reach the wire because of recombination. This is the
process by which a free electron becomes attached to a positive ion. It is unlikely to happen if the electrons are moving in a strong field since the positive and negative ions must come together without too much kinetic energy. If a counter is operated with a strong field and at a low pressure, the kinetic energies of the positive and negative ions would be too great and they would be separated too soon for recombination to occur.

When water vapor or certain kinds of gases are present in the counter, the free electrons are likely to become attached to or dissociate the molecules. Because of their low mobilities, some of these ions may never reach the wire in time to contribute to the pulse. In the strong field near the wire, those molecules that do arrive in time may not be able to hold the captured electrons, and a small amount of gas amplification will result. The magnitude of this amplification will not be nearly as great as that due to electrons that were never captured since these electrons start ionizing the gas much farther out from the wire.

Straggling in time of arrival at the wire will always be present due to collisions of the electrons with the molecules, or atoms, of the gas. The amount of this straggling should depend on the distance from the wire at which the electrons are freed.

The probability that an electron will collide with a molecule, or atom, of a gas is found to depend on the
energy of the electron. When a rare gas such as argon is used, it is found that the probability of collision for slow speed electrons is extremely small. This is known as the Ramsauer effect.\(^5\)

The magnitude of these events will depend on the kind of gas used, the pressure of the gas, and the amount of impurities and water vapor present.

The two characteristics studied in this experiment are:

1. The variation of pulse height with the distance from the coaxial wire to the path of an alpha particle traveling parallel to the wire.
2. The dependence on the voltage of the ratio of the half width to the mean energy of the differentiated curve.

In 1937, the first characteristic mentioned was covered in work done by E. Pollard and G. Brubaker,\(^6\) who used a variety of different gases and studied this characteristic for each gas at various pressures. Defining the "edge to center ratio" as the ratio of the pulse height caused by a particle traveling along the edge of the counter to that caused by a particle traveling along the coaxial wire, they obtained the results shown below when the counter was filled with air. These results are typical of those observed when the counter was filled with air, nitrogen, hydrogen, carbon dioxide and methane.
When the counter was filled with argon, the edge to center ratio was found to be 0.65 at a pressure of 76 centimeters of mercury, 0.3 at a pressure of 40 centimeters of mercury, and to decrease slightly as the pressure was reduced. Since they found that the edge to center ratio was independent of the size of the wire used and of the strength of the field, the results show that it is best to use argon at a pressure between 30 cm. and 50 cm. of mercury. The counter used in the present experiment was filled with argon at a pressure of 7.6 cm. of mercury.

It is interesting to note Pollard and Drubaker's results when the counter was filled with oxygen. For this gas, the edge to center ratio was 0.3, very much lower than that for other gases, and showed no change with pressure. Most of the other gases tested showed an increase in the edge to center ratio as the pressure of the gas was decreased as is shown in the above graph. This could be attributed to the fact that oxygen is known to be
a gas that readily picks up electrons traveling through it. In other words, the electrons have very little chance of passing through oxygen without becoming attached to the oxygen molecules, thus forming negative ions. For a given gas, the number of negative ions formed should increase with the number of collisions and therefore with the distance traveled. As the pressure is lowered, the number of collisions decrease for a given length of path, and so the edge to center ratio is improved. When a gas, such as oxygen, is used, however, a large number of negative ions will be formed by electron attachment even at the lowest pressures used in a counter, and the edge to center ratio will always be low. The results obtained by Pollard and Brubaker seem to indicate that all of the electrons freed in the initial ionizing event become attached to the oxygen molecules even at the lowest pressures used. If this occurs at the lowest pressures, an increase in pressure would have no effect on the edge to center ratio.

The gas amplification could occur when the negatively charged oxygen molecules enter the high field region near the wire. In the presence of such a high field, the oxygen molecules could no longer hold the captured electrons, and they would be pulled free from the molecules.

In their paper, Pollard and Brubaker also gave results of measurements made of the spread of the pulses observed as a function of the distance between the coaxial
wire and the beam path. The spread was measured so that its lower limit was the minimum height and its upper limit was the maximum height of the pulses observed on an oscilloscope. It was found that this spread was independent of the distance between the wire and the beam path.

DISCUSSION OF APPARATUS

Figure 4

A block diagram of the apparatus used is shown in Figure 4.

The counter, C, was made of a brass cylinder one inch in diameter and three inches in length. The wire enters the counter through a glass foveal seal, the surface of which was waxed where it entered the counter to prevent surface conduction caused by moisture. The inside of the counter was carefully sandpaped and cleaned before being used. The background due to radioactive contamination of brass is found to be extremely low when such precautions are taken.7
A 5 mil tungsten wire was used in the counter with a glass bead on the end to prevent distortion of the field. This wire was examined for possible pits and straightened under a microscope before being inserted in the counter. It was then centered as near as possible along the axis of the counter, and the counter was then rotated until the weight of the wire centered it on the axis.

The junction box, B, was constructed of brass and grounded to prevent stray fields from causing a high noise level. It contains a two stage preamplifier consisting of one stage of amplification and a cathode follower. The cathode follower was used to counteract the capacity of the coaxial cable leading to the linear amplifier and thus prevent a loss in the height and shape of the pulse. It was found to give a much sharper pulse than was obtained otherwise.

The regulated power supply used for obtaining the counter voltage was especially constructed for use on counters. A 2X2 half wave rectifier was used with the grid bias of a type 24G controlled by a 2C53 regulator tube. The 2C53 is a high mu triode which was designed especially for power supply regulation. Since negligible current was needed for the counter, it was possible to put a very large resistance-capacitance filter in the output to prevent ripples and corona discharges in the power supply from giving false counts. Further precautions were taken by placing
an additional filter capacitor in the junction box and by waxing all sharp points.

The linear amplifier used had been constructed with special precautions taken towards shielding. It has a band width of about 1 megacycle and a maximum gain of several thousand. Storage batteries placed in shielded boxes were used to supply the filament voltage for all amplifiers used, and the two stage preamplifier circuit was operated entirely on batteries. The use of batteries and the shielding of all outside wires was undertaken to reduce the possibilities of ripples. A test of the linear amplifier with a pulse generator and an oscilloscope showed that the amplifier had very little effect on the shape of the input pulse.

The oscilloscope was calibrated and used to find the noise level before and after each run. It also helped keep a check on the operation of the other equipment.

The bias settings of the discriminator and scale of eight scaling unit were found to be far from linear, and they were calibrated with a Model 1021 pulse generator made by the Instrument Development Laboratories. The generator itself had been previously tested by G. C. Phillips and found to be correct. The bias voltage readings given on all graphs presented are actual voltage readings obtained by means of the calibration chart.

A vacuum sealed, brass pipe, P, is attached to the front of the counter. This pipe is two feet in length and
three inches in diameter. At one end of the pipe is the source, $S$, which is about one millicurie of polonium obtained by depositing polonium on silver. The distance between the source and the counter window is 23 inches.

At the other end of the pipe is the counter and the mechanism used to vary the distance between the coaxial wire and the path taken by the alpha particles. A diagram of this mechanism is given in Figure 3. It consists of a circular plate of brass one sixteenth of an inch thick and with a diameter equal to the outside diameter of the counter. Four holes were drilled at measured distances from the center of the disk. They were spaced so as to make the distance from the wire to the paths of alpha particles coming from successive holes differ by equal increments. These distances were measured again, by means of a traveling microscope, after the holes were bored, and the average of several measurements are given in Figure 3. The four holes were first made 0.05" in diameter, but it was found necessary to double the intensity of the particles entering the counter by doubling the area of the holes. The holes were then made so that, when mounted vertically, the horizontal diameter was about twice the vertical diameter.

It was necessary to leave the vertical diameters unchanged for two reasons. First, the collimation of the beam of alpha particles is more critical in the vertical direction. Second, it is necessary that there be sufficient
space between adjacent holes that the slide will expose one, and only one, hole at a time to the radioactive source.

The disk was then soldered on the end of the two foot pipe, and the window of the counter cemented on the outside surface of the disk. To prevent possible leakage between the counter and the pipe the edges of the foil were painted with glyptal until only a narrow region covering the holes themselves was left. Using the disk as a support for the window made it possible to have a thin window without the loss in intensity caused by a microphonic grid. The two steps to improve the intensity were undertaken for other reasons than to gain more counts per unit time. They were taken in consideration of the problem of collimation since the only other alternatives would be to enlarge the source or move it closer. The thin window used, in order to minimize scattering, was an aluminum foil weighing 5 milligrams per square inch. Taking the air equivalent of aluminum given by Bethe and Livingston, it is found that this thickness is equivalent to 0.4 centimeters of air. Since alpha particles from polonium travel 3.8 centimeters in air, the particles from the source will traverse the length of the counter when the large pipe is evacuated.

The length of the two foot pipe and the small area of the holes were chosen so as to give a well collimated beam and to have the beam as near parallel to the coaxial wire as possible. The vertical spread of the beam of alpha particles after they enter the counter is 50 minutes.
for the hole nearest the center and 45 minutes for the second and third holes from the center. Since the edge to edge distance between adjacent holes is one sixteenth of an inch and the total vertical rise of an alpha particle after entering the chamber is one sixty-fourth of an inch, the beam from one hole will never enter the region covered by the beam from an adjacent hole. It can also be seen that the respective beams will effectively be parallel to the coaxial wire.

A brass slide, as shown in Figure 3, one sixteenth of an inch thick and with a slit slightly wider than the diameter of the holes was used. Before sealing the apparatus for vacuum tightness, a check was made to see that the slide exposed only one hole at a time to the radioactive source, and a calibration was made so that settings for the different holes could be made after the system was sealed.

To get reliable results, it was important that the pipe containing the source and slide be evacuated to as high a degree as possible and that this vacuum was not disturbed in the course of the experiment. If the mechanism for moving the slide changed the degree of evacuation of the pipe, the energy of the particles entering the counter would be changed, and the comparison of different settings would mean nothing.

In order to control the slide and preserve the vacuum, a sylphon bellow was used as shown in Figure 3. Although the total stretch needed to include all of the
holes was almost twice the maximum stretch listed in the catalogue, the small number of times stretched for this apparatus would allow even a larger maximum stretch than was used.

EXPERIMENT AND RESULTS

The first set of data was taken for the change of pulse height with the distance of the beam from the wire when the counter was filled with 7.6 cm. of 99.6% pure argon. The gas was passed through a P₂O₅ trap placed between the tank and the counter, and after flushing the counter two or three times, it was filled to the above pressure. This and all later sets of data were taken within twenty-four hours after filling the counter to lessen the possibility that water vapor would enter the chamber from the brass walls and mix with the gas.

The two foot pipe was evacuated, and the degree of evacuation was read on a pirani gauge bridge circuit. The bridge had been previously calibrated with an ionization gauge, and the final pressure was about 10⁻⁴ centimeters of mercury.

All of the electronic equipment, with the power supply set at the desired proportional region voltage, was turned on about one hour before a set of data was taken. This was necessary to prevent drifts in gain or voltage which usually accompany the "warming up" period.
Curves were then taken plotting the corrected discriminator bias settings against the number of counts per two minutes when operating with a gas amplification of 15. These curves are given in Graph 1. Also shown in Graph 1 are the resulting curves obtained by finding the slope at various points on the original set of curves, and then plotting slope versus the corrected discriminator bias settings. The probable error due to statistical fluctuations is given by the formula

\[ P.E. \approx \frac{0.645}{\sqrt{N}} \times 100\% \]

The number of counts, \( N \), taken for each point plotted was never less than 675 except for the last two points at the high bias end which had very slow counting rates. These points are well past the half widths of the differentiated, or slope versus discriminator bias, set of curves. This would give the probable error as being slightly less than 2.5%.

These curves show the change in pulse height as was detected by Pollard and Brubaker, and the shapes of the curves are essentially the same. Although data were taken for all four holes, that for the fourth hole cut from the center was not used. It was found that the intensity of the alpha particles entering this hole was extremely low which was most likely caused by the glyptal paint. The other three holes were known to be all right, but there was doubt about the fourth one at the time of the painting.
Since it would have taken too long to get enough counts for a low probable error, the fourth hole was omitted.

This part of the experiment was repeated with a mixture of argon and 2% carbon dioxide in the counter at a pressure of 7.6 cm. of mercury. The pressure was read from a vacuum gauge whose smallest division was $1/4''$, but by finding the ratio of the volume of the counter to that of the pipes in the system, it was possible to fill the counter in such a way that the smallest reading on the vacuum gauge required was $3/4''$. Three sets of data were taken. One was taken when the counter was operating in the ionisation region; the second was taken in the proportional region with a gas amplification of 10; and the third was taken in the proportional region with a gas amplification of 33. The results are shown in Graphs 2, 3, and 4. It can be seen that the mean pulse height, which is the bias setting at the maximum of a differentiated curve, is independent of the distance from the wire to the beam of alpha particles for all three sets of data taken. The probable error for each point taken was never greater than 3% except for the end points mentioned in the first part of the experiment.

Graph 4 shows the mean pulse height of hole number 2 to be a little lower than the mean pulse heights of the other holes. This was not caused by a change of distance between the wire and the beam path but to a drift in the power supply. The power supply was turned on about three hours before the sets of data were taken for Graphs 2 and 3, but it was only on about one hour before the points for
Graph 4 were taken. For this graph the holes were taken in the order: 2, 1, and 3. It is evident that the power supply had not reached a stable voltage when data for hole number 2 were taken because if the change in mean pulse heights was caused by a change in the distance between the wire and the beam path, it would not be in the order shown. The amplifiers and the discriminator were checked before and after each run and were found to be stable, but the voltmeter used for reading the counter voltage could not be read to less than 2 volts. On the steep part of the proportional curve used, a two volt change in the power supply could easily have caused the small differences shown.

The curves plotted when the counter was filled with argon show a maximum deviation in mean pulse heights of 39% while the maximum deviation in mean pulse heights when the mixture of argon and carbon dioxide was used is only 7%. As mentioned in the above discussion, the 7% variation was caused by a drift in the power supply. Within experimental error, therefore, the mean pulse height is independent of the distance between the wire and the beam path when a mixture of argon and 2% carbon dioxide is used in the counter.

The second part of the experiment was to find the dependence of the ratio of the half width to the mean pulse height of the differentiated curve on the counter voltage used. In addition to the curves shown in Graphs 1 - 4, this characteristic was studied at other voltages listed in the table given below.
<table>
<thead>
<tr>
<th>Gas Used</th>
<th>Counter Voltage</th>
<th>Half Width to Mean Pulse Ratio</th>
<th>Signal to Noise Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>300</td>
<td>0.21</td>
<td>12</td>
</tr>
<tr>
<td>Argon and CO₂</td>
<td>350</td>
<td>0.14</td>
<td>9</td>
</tr>
<tr>
<td>Argon and CO₂</td>
<td>405</td>
<td>0.15</td>
<td>11</td>
</tr>
<tr>
<td>Argon and CO₂</td>
<td>500</td>
<td>0.21</td>
<td>35</td>
</tr>
<tr>
<td>Argon and CO₂</td>
<td>567</td>
<td>0.16</td>
<td>35</td>
</tr>
<tr>
<td>Argon and CO₂</td>
<td>530</td>
<td>0.15</td>
<td>91</td>
</tr>
<tr>
<td>Argon and CO₂</td>
<td>595</td>
<td>0.19</td>
<td>79</td>
</tr>
<tr>
<td>Argon and CO₂</td>
<td>620</td>
<td>0.24</td>
<td>108</td>
</tr>
<tr>
<td>Argon and CO₂</td>
<td>650</td>
<td>0.14</td>
<td>104</td>
</tr>
</tbody>
</table>

The half width to mean pulse ratios show fluctuations, but there is no definite trend. The fluctuations are attributed to the inaccuracy in plotting the differentiated curves, and it is concluded that the half width to mean pulse ratio is independent of the counter voltage.

CONCLUSION

The phenomenon that causes the change in mean pulse height with the distance from the wire to the beam path is pointed out in the experiment performed by Pollard and Brubaker, and this is the capture of electrons by the molecules of the gas, or water vapor, in the counter. Whether this is due to oxygen which might be present in the gas as an impurity or to water vapor is not known. Attempts were made to find out if oxygen was one of the impurities,
but the office from which the argon was bought did not have
the information.

Straggling in time of arrival at the wire is another
possibility. For electrons having to travel a greater dis-
tance in order to reach the wire, there will be more col-
lisions made with the molecules, or atoms, of the gas, and
the spread in the time of arrival of the electrons will be
greater than for electrons starting near the wire. This
means that instead of having the high, narrow pulse that
results when all of the electrons arrive in one surge,
straggling will cause each individual pulse to be smaller in
height and wider. In addition to increased straggling, the
electrons starting farther out from the wire will be in a
weaker field and will make more collisions which will in-
crease their chances of becoming attached to a molecule, or
atom, of the gas.

The effect, resulting from the addition of 2% carbon
dioxide to the argon, on the variation of the mean pulse
height with the distance from the wire to the beam path is
shown in Graphs 2, 3, and 4. An explanation can be given
by means of the curves shown in Figure 5.10
In this graph, $F_0$, the number of collisions, per unit electron current, per unit length of path, per unit pressure at 0°C, is plotted as a function of the energy of an electron. When argon is used in the counter, an electron will make almost perfectly elastic collisions with the atoms until it acquires enough energy to ionize the gas. This energy corresponds very closely to the peak of the argon curve shown in Figure 5. The energies of the electrons will, therefore, be in the range where the probability of colliding with an argon atom is very high. Since the electrons are likely to rebound in any direction after making an elastic impact, even away from the wire, their drift velocity will be low. This would make all of the possible phenomena mentioned above of importance, and the mean pulse height would depend on the distance between the wire and the beam path as is shown in Graph 1.

In his paper, Brodie gives the formula for the mean free path in terms of $F_0$ as

$$pL = \frac{1}{F_0}$$

where the pressure, $p$, is in millimeters of mercury, and the mean free path, $L$, is measured in centimeters. Using this formula, the mean free path of an electron in carbon dioxide, at the pressure used in this experiment, is 0.02 cm. This shows that the electrons will make collisions with the carbon dioxide molecules since the radius of the counter is 1.5 cm. Now at a point half way between the wire and the wall of the counter the electric field is about 16 volts per millimeter when the counter voltage is
650 volts. Since the mean free path in carbon dioxide is 0.2 mm., an electron could not gain more than 3 or 4 electron volts energy before colliding with a carbon dioxide molecule. In such an inelastic collision, it is likely that the electron will lose most of its energy and it will, therefore, always be operating on the lower part of the argon curve of Figure 5. The electrons will never have over 4 or 5 volts energy until they are less than one-fourth the cylindrical radius from the center of the wire. Since in this voltage region the probability of making a collision with an argon atom is very small, the drift velocity of the electrons will be greatly increased and the phenomena mentioned above will become less significant. This is proved by the results shown in Graphs 2, 3, and 4.

The results of the second part of the experiment show that the counter voltage chosen for operation has no noticeable effect on the half width to mean energy ratio. If a high signal to noise ratio is desired, it is best to operate as high as possible in the proportional region since operating at a lower voltage does not improve the half width to mean energy ratio while it does give a lower signal to noise ratio. If a constant gas amplification is essential, it is best to sacrifice the high signal to noise ratio and operate on the part of the proportional curve where the change of gas amplification with the counter voltage is not so critical. It can be concluded from the results of the experiment that these are the only two factors that need be considered.
The writer of this paper wishes to express his appreciation to Dr. T. W. Bonner, Dr. J. R. Risser, and Mr. G. C. Phillips for their help and guidance on this experiment. Appreciation is also due to Mr. J. F. Van der Henst for his help in building the apparatus.
Graph 1

Argon Only
GAS Amplification=15
Graph 2

CORRECTED DISCRIMINATOR BIAS - VOLTS

Slope of INTEGRAL CURVE

COUNTS PER TWO MINUTES

ARGON PLUS CO₂
Gas Amplification = 1
Graph 3

ARGON plus CO₂
GAS AMPLIFICATION = 10

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