Construction and Testing of a Large Acceptance Angle, Double Sided Bragg Ionisation Chamber for Fission Fragment Spectroscopy

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Abstract

This dissertation covers the construction and subsequent operation of a double sided, large acceptance angle Bragg Chamber by Duncan Hodge of the University of Manchester. The project was undertaken as the main body of work for the award of a Research Masters in Nuclear Physics, concluding on the 3rd of September 2012. Assembly and testing of the chamber were undertaken in the Nuclear Laboratory in the Schuster Building at the University of Manchester. The chamber is designed to have a source or target placed at its centre, allowing fission fragments to travel to either end of the chamber. There is an anode to detect fragments at both ends of the chamber; hence, the chamber is described as double sided. Segmented anodes were designed and partially configured to provide angular information of ions stopping in the chamber. Initial tests were carried out using a Californium 252 source placed at the centre of the chamber, ionising the isobutane gas used to fill the volume. Proof of operation of all anode segments was seen from associated preamplifier outputs attached to an oscilloscope. Energy spectra were obtained for an unsegmented anode configuration within the chamber and associated resolutions were extracted for different operating conditions. The most efficient chamber operating conditions used were ascertained by means of a pseudo-energy resolution and ratio between the number of counts in light fragment and heavy fragment peaks.
Contents:

INTRODUCTION........................................................................................................5

CHAPTER 1: THEORY

1.1 Theory of Ion Stoppage in Matter and the Basics of Bragg Chambers.............7
  1.1.1 Basic Theory and Relation to Bragg Curve Spectroscopy.........................6
  1.1.2 Sub-Bragg Peak Spectroscopy................................................................11
1.2 Bragg Chamber Variables and Parameters.....................................................15
  1.2.1 Gas.......................................................................................................15
  1.2.2 Electric Field.........................................................................................17
  1.2.3 Size.......................................................................................................18
1.3 Large Solid Angle Bragg Chambers.................................................................18
1.4 Basic Manipulation of the Anode Signal.........................................................21

CHAPTER 2: BRAGG CHAMBERS FROM THE LITERATURE

2.1 Longitudinal, Constant Field Bragg Chambers.............................................23
2.2 Large Solid Angle Bragg Chambers...............................................................31
2.3 A Sub Bragg Peak Spectroscopy Chamber....................................................39
  2.3 Electronic Configurations..........................................................................41
2.4 Parameter Comparisons.................................................................................46

CHAPTER 3: THE CONSTRUCTED BRAGG CHAMBER

3.1 Chamber Specifications...................................................................................50
3.2 Chamber Assembly.........................................................................................55
  3.2.1 Chamber Housing..................................................................................55
3.2.2 Anodes.................................................................57
3.2.3 Field Ring Chains and Frisch Grids..............................59
3.2.4 Wiring Set-ups.......................................................63

3.3 Gas Delivery System...................................................67
3.4 Voltage Testing..........................................................70
3.5 Pressure Regulation and Leak Checking............................71
3.6 Configuration of Signal Processing Electronics....................73

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Proof of Operation.....................................................77
4.2 Energy Spectra..........................................................80
    4.2.1 Ratio of the Number of Counts in the Heavy Fragment Peak and the
    Light Fragment Peak....................................................87
    4.2.2 Light Peak Resolution.............................................90
4.3 Rise time of Energy Signals and Fission Fragment Depth............95
4.4 The Implications of Results on Chamber Operating Conditions........98
    4.5 Future Developments...............................................100

CONCLUSION..........................................................103

REFERENCES..........................................................105
Introduction

A Bragg ionisation chamber is a spectroscopy tool used to measure the atomic number and energy of heavy ionising particles. The chamber consists of a gas-filled volume in which ionising particles stop, ionising the gas as they do so. The electrons released will induce charge on an anode placed after the end of the ionisation track. An output of the induced charge is taken from the anode and manipulated to extract the particle’s pattern of energy loss. By setting the electric field and gas pressure within the chamber, and by using a series of relationships between the parameters of the chamber, the specific energy loss of the particle and the properties of the source used, proper signal processing can be used to extract the particle atomic number and energy.

Most Bragg chambers rely on a constant electric field within the chamber, used with a narrow beam or acceptance angle, as this gives the easiest signal analysis. However, a large acceptance angle is preferable in many cases in order to capture as many ionisation events as possible from a target or source. The associated problems with the signal processing can be corrected with the aid of a segmented anode.

This dissertation covers the construction and testing of a Bragg chamber with two anodes centred on a Californium 252 spontaneous fission source. The central source and two anodes achieve double the event detection rate of a one anode set-up and can also simultaneously detect two fission fragments from the same decay event. The anodes can be used in a segmented configuration to obtain angular information from the fission fragments for measurements of particle atomic number, but were left unsegmented for initial results. Energy spectra and rise time measurements are
presented with respect to the chamber performance under different operating conditions of pressure and voltage.
CHAPTER 1: THEORY

1.1 Theory of Ion Stoppage in Matter Related to Bragg Chambers

1.1.1 Basic Theory and Relation to Bragg Curve Spectroscopy

Massive positively charged particles on the subatomic, atomic and molecular scales stopping in matter, above a threshold energy, have the same form of energy loss. This shape is known as a Bragg curve:

![Bragg curve diagram](image)

Figure 1: Example of a Bragg curve, [1]. The cross hatched area indicates the Bragg peak, from where atomic numbers can be extracted, the value R on the x axis denotes the particle range and the integral of the curve provides the initial energy of the particle.

The Bragg curve can provide many details about the nature of the particle. The range can be found from the length of the Bragg curve, the initial energy of the particle before entering the stopping medium can be obtained from the area beneath
the curve and the atomic number of the particle can be found from the peak of the Bragg curve (the cross-hatched area in Fig. 1) [1].

The function of a Bragg chamber and associated processing electronics is to extract the relevant information needed from the Bragg curve to define the properties of the particle in question.

A simple Bragg chamber consists of a gas filled chamber containing a parallel anode and cathode held at a known potential difference with a resultant constant electric field between them. To ensure the consistency of the field the potential is dropped in stages between the anode and cathode, generally by a resistive chain linking several conductive rings or inserts held at a constant potential difference to each other. Typically Bragg chambers will be of the order of tens of centimetres long, with rings or inserts separated by centimetres [1, 2, 3].

The chamber is filled with a gas to stop ions that enter the volume. As a particle slows within the chamber it ionises the gas, resulting in a number of positive and negative free charges. The specific ionisation caused by a particle in a gas is proportional to the specific energy loss (in the form of a Bragg curve) in that gas. The free charge resultant from the ionisation of the gas is drawn to the anode and cathode; as such the pattern of the specific ionisation can be detected as the change in charge on the anode and cathode. The electrons have a faster mean velocity through the gas, so the signal is taken from the anode. This ensures a higher rate of event detection as the time between ionisation events will typically be less than the ion flight time to the cathode.

The major obstacle to extracting a meaningful signal is charge induced on the anode by the positive ions moving towards the cathode. This will cause the specific
ionisation pattern from the induced charge of the electrons to be distorted. The problem is solved by placing a Frisch Grid a short distance from the anode.

Frisch grids consist of a mesh of fine wires of diameter on the order of tens of microns, separated by a constant distance of the order of millimetres (see section 2.4). If the Frisch grid is held at a potential of between 10 and 80% [3, 4] of the anode potential, it acts effectively to screen the anode from the ions moving towards the cathode. The charges present in the conducting material of the Frisch grid will redistribute to cancel the induced field of the ions moving towards the cathode, causing the screening effect on the other side of the grid. This is subject to the conditions that the wire has a sufficient conductivity and that the gaps between the wires are of the order of the wavelength of the charges moving between the cathode and grid [5]. The grid is placed a short distance from the anode, restricting the sampling of the induced electron charge to the space between the grid and the anode. This is as a result of the field from electrons moving beyond the grid also being screened. No Frisch grids are 100% efficient but screening efficiencies between 1 and 3% (see section 2.4) are typical.

The energy signal can be obtained by integrating the Bragg curve over the range of the ionisation. The electrons removed from the gas are drawn towards the anode at a constant drift velocity, directly proportional to the electric field generated in the chamber. By measuring the time it takes the electrons to accumulate on the anode and knowing from reference the drift velocity of the electrons, the length of the ionization track can be calculated [6].

The drift velocity function depends on the nature of the chamber and of the gas used. If a ‘cool’ gas is used within the chamber then the drift velocity of the electrons within the gas will not vary significantly under high electric fields from its
thermal behaviour when no field is applied. However, some gases will adopt significantly different behaviour at higher voltages [7]. For small departures from thermal behaviour the drift velocity can be calculated using the following:

\[ v_d = \frac{eE}{m} \tau \]  

Where \( v_d \) is the electron drift velocity, \( E \) is the electric field strength, \( m \) is the mass of the gas molecules through which the electrons are moving and \( \tau \) is the average collision time between electrons and gas molecules.

The classical Bethe formula provides a good approximation for the significant energy loss of an ion in a medium [3]:

\[ -\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} NB \]  

Where \( B = Z \left[ \ln \left( \frac{2m_0v^2}{I} \right) - \ln \left( \frac{v^2}{c^2} \right) \right] \)  

\( v \) and \( ze \) are the initial velocity and charge of the ion, \( N \) and \( Z \) are the number density and charge number of the gas, \( m_0 \) and \( e \) are the rest mass and charge of an electron and \( I \) is the average ionisation potential of the gas. For a Bragg chamber, the properties of the gas should be known beforehand leaving only the two variables of the energy and atomic number of the ion considered. It can be seen that as the ion slows to the drift velocity in the chamber, before electron pickup, the maximum of the specific energy loss is directly proportional to the atomic number of the ion.
If the ionising particle is stopped within the volume it can be seen that the charge resultant from the ionisation is proportional to the initial energy of the particle. As the particle passes through the gas it ionises the gas particles through inelastic collisions, losing part of its kinetic energy each time it does so. As such, ignoring recombination of the free charges, the energy of the particle can be deduced from the number of free charges, if the specific ionisation of the gas used is known.

The atomic number of the ion corresponds to the maximum of the specific energy loss. This maximum occurs where the particle has slowed towards the end of its range. More time is spent by the ion in the vicinity of the gas molecules, leading to higher ionisation of the gas molecules and, hence, specific energy loss. At a certain point the ionising particle will lose enough energy that it will be moving slowly enough to pick up electrons removed from the gas molecules. This reduces its effective charge and ability to ionise the gas molecules.

This point is clearly visible on the Bragg curve and is denoted by the cross-hatched area in Figure 1, where the specific energy loss is seen to drop off sharply. The peak of the curve before the sharp drop off due to electron pickup can then be used to give the original ionic charge of the particle before it enters the gas filled volume and, hence, its atomic number. This peak is ideally the same height for every particle of the same ionic charge regardless of the particles energy.

1.1.2 Sub-Bragg Peak Spectroscopy

Bragg chambers can typically differentiate ionic charge down to alpha particle level and up to atomic numbers of approximately Z~40 by means of Bragg peak spectroscopy [4]. As Z increases, the difference in height between Bragg peaks
decreases, making it increasingly difficult for a chamber to differentiate between individual Z numbers, resolutions are at best approximately 1.2% [2].

Another requirement for the use of Bragg curve spectroscopy is that the energy of the ion stopping in the chamber must be at least 1MeV/u, the point where a distinct Bragg maximum develops [8]. For energies below this the energy and atomic number signals are not independent and accurate measurement of the atomic number or energy by traditional Bragg curve spectroscopy is not applicable.

This is the case for certain fission processes. If the energy per nucleon is lower than 1MeV/u then the fragment will lose energy at a steady rate along its path [9], and a Bragg curve will not form. Figure 2 shows the typical energy loss pattern of a fission fragment with 1MeV/u.

![Fragment Energy Loss Simulation](image)

**Figure 2:** Simulation of fission fragment energy loss patterns obtained using SRIM (Stopping Range of Ions in Matter) code. The large energy loss at the start of the trace is due to the fragment simulated passing into the chamber volume through a mylar window [10].
The Bethe formula approximation still applies, so the energy of a fragment can still be found from its specific energy loss over its range in the chamber. Chambers operating in the sub-Bragg peak energy range can extract the energy of a low energy particle by the same method as used by chambers operating in the Bragg peak range: the specific energy loss of the particle in the chamber can be obtained from the induced charge on the anode if the specific ionization of the gas and particle range is known.

The ionic charge of the particle is still proportional to the maximum of the energy loss, but this is no longer clearly defined by a Bragg peak, so the charge cannot be accurately determined from the maximum.

Due to their typically lower energies, heavy fission fragments will also move much slower through the chamber. As a consequence the fragments will be much more likely to pick up electrons as they move through the chamber, with electron pick-up occurring along the whole fragment range. As such the fragment ionic charge cannot be considered equal, with respect to its energy loss throughout the chamber. The ionic charge, \( Z_a \), has been shown to change by:

\[
Z_a = z^{\frac{1}{3}} \frac{v}{v_B} \tag{4}
\]

Where \( Z_a \) is the apparent ionic charge on the fragment, \( z \), is the atomic number of the fragment, \( v \), is the fragment velocity and \( v_B \), is the Bohr velocity of the electrons which have been picked up.

By substituting the expression for \( Z_a \) into the Bethe formula in place of particle ionic charge, equation five, as shown on the next page is obtained.
\[-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{v_B^2 m_0} N B(v) \quad (5)\]

Equation (5) shows the quantities needed for the extraction of \( z \) values of sub-Bragg peak energy ions:

- Gas properties, \( Z \) and \( N \). These can be set when running the chamber so will be known to a high level of accuracy.
- The specific energy loss of the fragment, which can be recorded through the induced charge pattern from the specific ionisation of the gas in the chamber.
- The velocity of the fragment as it moves through the chamber and the Bohr velocity of the picked up electrons.

The Bohr velocity is typically of the same order of the particle velocity for low energy ions in Bragg chambers, so can be discounted from approximations if the fragment velocity is known. The change in fragment velocity can be linked to the specific energy loss if the mass of the fragment is known.

If both fragments are detected from the same fission event, then the energy of both can be measured. The ratio of the fragment energies is then related to the ratio of the masses such that for two fragments \( 1 \) and \( 2 \) the energy ratio is related to the mass ratio by:

\[
\frac{M_1}{M_2} = \frac{E_2}{E_1} \quad (6)
\]
Where $M$ is the fragment mass and $E$ is its energy. Supposing the mass of the source used in the chamber is known, then the mass of the parent nucleus is also known; as the sum of the two fragments detected equals the mass of the parent nucleus, the mass of each fragment can be calculated.

As the energy of the fragment is equal to the mass of the fragment multiplied by the square of the particle velocity and the mass of the fragment is constant, the function of the changing velocity of the fragment can be calculated from the energy loss of the fragment. Therefore, from equation (5), once the velocity distribution and energy loss are known, the atomic number of the fragment can also be obtained.

Many chambers use this means to extract the atomic numbers of fragments. The Bethe approximation is typically improved upon by using empirical values of $B(v)$, to give a more accurate velocity distribution. The Bohr electron velocity can also be obtained from reference values, or replaced by terms accounting for more complex models of nuclear structure to give more accurate results [11].

1.2 Bragg Chamber Variables:

1.2.1 Gas

As can be seen from the Bethe-Bloch formula, it is very important to consider the properties of the gas for the operation of an efficient Bragg chamber. The gas pressure must be set to a high enough level so that the ion is stopped within the chamber, depositing all its energy. The gas pressure must also be of a high enough level to prevent significant range straggling occurring. The range of an ionising particle passing through the medium is well defined due to the large number of
collisions it undertakes in stopping. However, as the range is statistically based some variation, known as straggling, can exist. Range straggling can be reduced by ensuring that the particle undergoes as high a number of collisions as is possible.

The ionisation potential of the gas must be small enough for a significant number of free electrons to be released due to the passage of the ion. This ensures that the vast majority of the energy of the particle is used to remove electrons from the gas, which can then be detected by the anode.

Ionisation events are separated by the induced charge on the anode at one time being only due to one ionisation event. The collection time of the electrons must be faster than the frequency of events. This is managed by having a high enough drift velocity of electrons, determined by the electric field within the chamber. The gas must be able to hold the field without breaking down, in order to keep the drift velocity at a sufficiently high value.

The drift velocity is also dependant on the pressure, such that it is dependant on the reduced electric field in the chamber, $E/p$. Lowering the pressure of the gas in the chamber can increase the drift velocity. However, in using this means to increase the drift velocity in the chamber, the requirement for there to be enough gas molecules in the chamber to stop the ions and define an accurate range, must be considered. The number of electrons must also be such that the output signal is strong enough to be properly processed without substantial error caused by its passage through the electronics.

It is preferable to have gas being continuously circulated through the chamber. As time passes the gas within the chamber will be gradually ionised by the ions passing through, as such the depleted gas will then not be as strongly ionised by later events, weakening output signals. A steady flow of gas through the chamber can be
managed using a gas control system. It is also important to have a significant purity of gas so accurate measures of the drift velocity can be calculated and also so that the gas holds as much electric field as required. The chamber must be held at vacuum before the gas is inserted to prevent atmospheric gases being present within the chamber. Atmospheric gases, notably water vapour are easily broken down by high voltages allowing sparking between areas of higher and lower potential to occur within the chamber.

1.2.2 Electric Field

The electric field is the other variable that can be set in order to alter the efficiency of the chamber itself. Typically the electric field will be constant as dictated by conductive rings or inserts within the chamber held at equal potential differences with equal spaces between them, such that:

\[ E = \frac{V}{d} = C \]  

Where, \( E \) is the electric field within the chamber, \( V \) is the potential difference between two rings or inserts, \( d \) is the distance between the two rings or inserts and \( C \) is a constant. This can be realised by linking the rings or inserts with resistors of equal value. By applying a voltage to one end of the resistor chain and connecting the other to ground, an equal potential drop will occur across each resistor, providing an equal difference between each ring. A potential can be applied by means of a power supply fed into the chamber via a specialist gas tight feedthrough. Anodes are powered in the same fashion, but are not grounded.
The electric field must be set high enough so that the free electrons travel away from their associated ions with a high enough velocity that they are not recaptured. If the electric field is not set high enough electron recombination can cause the signal detected at the anode to be significantly lessened. The field must be set in conjunction with the pressure of gas in the chamber to give a collection time of the electrons from an ionisation event so that maximises number of events detected without the signal overlap. The field between the cathode and the Frisch grid and the field between the Frisch grid and the anode are typically set to different values, with the value between the Frisch grid and anode typically being higher. This has the effect of further distancing the flight times between the gas ions and electrons, so that the frequency of the ion pulses and electron pulses are further differentiated and any Frisch grid inefficiency is lessened.

1.2.3 Chamber Size

The compact nature of Bragg chambers makes them well suited for use in large detector arrays. The geometry of the chamber can also be varied, with cuboid, cylindrical and conical variants being used [1-4]. The size of the chamber must be large enough, in conjunction with the gas pressure so that ions entering the chamber are stopped fully within the volume.

1.3 Large Solid Angle Bragg Chambers:

For a Bragg chamber with a constant electric field, the reconstruction of the Bragg peak depends on the ionisation taking place perpendicular to the anode in order
for the electrons to arrive with the same order as they were released from the gas. If this requirement is not fulfilled the Bragg peak is seen to increase with angles far from the perpendicular [12]. When a particle enters the chamber at a high angle with respect to the electric field, E, the collection time will be compressed so the amplifier will receive a higher input and the atomic number, Z, will be artificially heightened and the range of the particle is artificially shortened. The shortening of the range also has implications for energy measurements and atomic number measurements of sub-Bragg peak particles. The velocity distribution of the electrons will be distorted, causing inaccuracies in measurements of atomic number.

In order to prevent events with a large angle to the normal of the anode, Bragg chambers must typically have a small acceptance angle for ionising particles entering the volume. The downside to this requirement is that for most sources, or targets radioactive products are emitted over a solid angle of $4\pi$, as such most products are partially or totally undetected by the chamber. Bragg chambers with large acceptance angles are, hence, desirable if solutions can be found to correct the distortion of the output signal at larger angles.

One solution postulated to this problem is to have a radial field that is inversely proportional to the square of the distance from the source of the ionising particles set up within the chamber [4]. The same field will then be experienced by ions moving in all directions in the chamber. As long as all the charge is collected from an event the range of the particle can be obtained, if the pressure and type of gas is known. Once the range is known, the changing influence of the field on the particle velocity and, hence collection time, is known. The specific energy loss can then be extracted by manipulating the signal to reverse the distortion caused by the radial field.
The problem with this method lies in setting the appropriate field within the chamber. The changing of the potential by means of a resistive chain is hard to realize as many links to the chain must be used to establish an accurate potential. Standard resistor values will also not be able to follow the 1/r trend of the potential, requiring either combinations of resistors, which would be inaccurate or the manufacture of another form of resistance that would be either time consuming due to testing, expensive or inaccurate. The angular distribution of fragments emitted from a source is also of interest so a method of incorporating this measurement is also desirable [12].

An alternative solution to changing the variation of the field within the chamber is to segment the anode into concentric circles, with a different output coming from each segment. High angle events will deposit most of the resultant electrons over much of the radius of the anode if a standard longitudinal field is used. High energy particles will result in the majority of the freed electrons arriving at a localised area between the centre and edge of the anode, due to the Bragg peak. Lower energy particles will result in deposition of electrons more evenly over the segments in accordance with their more linear energy loss. The angle of the event can then be determined by ascertaining the proportions of the total induced charge landing on each segment.

Lower angle events will deposit more charge on inner segments and higher angle on outer segments. The outermost segment reading charge will provide the distance that a particle has travelled normal to the chamber axis. As with the previous method mentioned, as long as all charge is collected the range of the particle can then be calculated. The range can then be used with the normal distance to provide angular measurements. The anode signal can then be corrected algorithmically during online
acquisition or after the data is obtained during the analysis. The resolution of chambers built in this configuration compare favourably to those constructed along more conventional lines (see section 2.4).

1.4 Basic Manipulation of the Anode Signal

The processing and passing of the anode signal to an online acquisition system or offline data storage for later analysis is commonly undertaken using a method set out by Schiessl et al for Bragg curve spectroscopy [2]. Two amplifiers with different shaping times are used to output a signal proportional to the Bragg peak and total energy of an ionisation event.

Initially the signal is boosted by a preamplifier. This allows the weak signal to be transferred to the amplifier without being lost in the noise present in the cabling leading from the anode to the amplifier. The peak chamber signal is typically of the order of a few hundred millivolts; as such a loss of resolution of the original signal is possible even along the standard BNC cables used with their normal 50Ω resistance.

The preamp itself has to be close to the anode, to minimise signal losses along wiring, sometimes being placed within the chamber housing itself [13].

From the preamplifier the signal is then typically fed to the two shaping amplifiers which amplify the signal over a set shaping time or range. By having a shaping time longer than the collection time of electrons resulting from an event the total energy of the event can be obtained. This range is typically set using the electron time of flight so that all the charge arriving at the anode from an event is amplified.

The shaping amplifier also acts to manipulate the preamplifier signal for later processing. The preamplifier will output an exponentially decaying signal, with the
time of the decay often longer than the time between events. As such in order for an accurate measurement of the energy the baseline of the preamplifier pulse must be restored before the next pulse arrives; a function which is also undertaken by the shaping amplifier [14].

For measurements of charge, for which the Bragg peak of the ionisation is required, the shaping time is typically much smaller. As the maximum of the ionisation occurs at the end of the flight of the ion causing the ionisation, the electrons relating to the Bragg peak will arrive at the anode first. The signal relating to the Bragg peak can then be isolated by means of a shorter shaping time, which will amplify the peak of the ionisation signal while excluding the rest of the signal. The Bragg peak signal can then be passed to an acquisition system, where the trace can be recorded and manipulated to withdraw the atomic number of the detected ion. Manipulation commonly uses algorithms based on the theoretical relationships covered in Section 2.4 and stopping range measurements empirically obtained for heavy ions [2].

For sub-Bragg peak signals, the energy signal can be extracted reliably using the same method. Charge measurements cannot be directly isolated from a single part of the ionisation track, so must be obtained through analysis of the energy loss obtained from the induced charge signal from the anode.
CHAPTER 2: BRAGG CHAMBERS FROM THE LITERATURE

A number of papers covering the construction and operation of Bragg chambers were examined and reviewed. These provided information on the problems associated with certain methods of construction and chamber types, as well as providing typical values of energy and charge resolution. Operational specifications were also noted and compared to the chamber resolutions in order to ascertain any connections that may be present.

2.1 Longitudinal Bragg Chambers with Constant Electric Fields

The first papers examined in this review [1, 2, 3, 15] concern themselves with testing the principle of operation of Bragg Chambers with constant electric fields and cylindrical shape.

Bragg chamber spectroscopy is first seen to be postulated by Gruhn at the 1979 Symposium of Heavy Ion physics at the Brookhaven Laboratory [15]. At the symposium Gruhn outlined a basic prototype he had constructed. This chamber is a simple, cylindrical Bragg chamber with a constant electric field. Measurements using alpha particles stopping in the chamber were taken to test the principal of the chamber and to ensure that the outputs were of the forms expected. Various algorithms were also tested in analysing the curves, with the aim of developing a “Hardwired electronic algorithm” for high speed online identification of heavy ion energy and atomic number. Two different energies of alpha particle were used from a ThC’ and a ThC” source with the data being stored offline for analysis.
The starting points for the algorithms were the following formulae:

\[ \Delta E_{g.m.} = \left[ \prod_{i=1}^{N} \Delta E_i \omega_i \right] / N \] (8)

\[ E_{total} = \sum_{i=1}^{N} \Delta E_i \omega_i \] (9)

Where (8) is the geometric mean of the specific energy loss, and is the starting point for algorithms to calculate the charge of the measured ion, and (9) is the arithmetic mean of the specific energy loss and measures the total energy of the particle in question. \( \Delta E_i \) is the specific energy loss as measured at point \( i \), \( N \) spans the length of the track and is the length over which measurements are taken and \( \omega_i \) are weighting factors describing the detector filter response function, describing at what signal energy and distance from the target the detector is most efficient. The determination of the detector response filter function \( \omega_i \) is one of the main objectives of the algorithm testing. Due to the prototype stage of the chamber and measurements described by Gruhn, details are sparse with respect to the algorithm development. Future tests of potential problems with Bragg chambers such as range straggling, electron recombination, and energy loss fluctuations along the Bragg curve are mentioned.

Schiessl et al [2] were concerned with the results of an alternative method to the set-up postulated by Gruhn; namely that atomic number and energy measurements could be extracted by shaping the anode signal with two different timing amplifiers, a method subsequently commonly used. This simplifies the data collection compared to
the method postulated by Gruhn, allowing online recording and analysis to be undertaken, without the development of more complex algorithms.

Schiessl et al used 120Mev $^{32}$S ions to bombard a 420μg/cm$^2$ $^{64}$Ni target and analysed the resultant fragments using their set-up. A contour plot of the two amplifier outputs, from the paper, is displayed below:

Figure 3: Plot of Atomic number of ions entering the Bragg chamber against their initial energy. [2]

Distinct regions corresponding to Mg, Al, Si and P can ions can be seen, as well as a region corresponding to elastically scattered S ions (the vertically aligned contour region extending upwards from $Z=16$). The independence of the atomic number and energy signals is verified from the plot by the invariance of the charge values for different energies.
This particular chamber found a peak atomic number resolution for $^{16}\text{S}$ of 1.2% using the target and beam combination described on the previous page. The peak energy resolution was obtained by bombarding a 100µg/cm$^2$ $^{197}\text{Au}$ target with 130MeV $^{16}\text{S}$ ions and was found to be 0.4%. These values show a high level of accuracy of the chamber. However, any average resolutions that take into account other ions are not mentioned so the variation in performance of the chamber with varying atomic number is uncertain. Figure 3 does suggest some degradation in resolution for other elements, but not to a level of indistinction between different Z numbers. The specific peak resolution is directly related to the target and bombarding ions used so different projectiles and targets would provide a more complete picture of performance.

A paper from Asselineau et al. [1] provided a comprehensive analysis of the Gruhn method to test its effectiveness. Initial tests using the chamber used alpha particles from a $^{241}\text{Am}$ source to detect any electron recombination problems. Energy measurements of the alpha particles were taken and compared to reference data from Northcliffe and Schilling’s nuclear data tables. Energy deviation was found to be within instrumental errors so electron recombination was judged to be minimal.

Energy and charge measurements of ions were undertaken using a 300MeV $^{40}\text{Ar}$ beam scattered from a 600µg/cm$^2$ Au target. A charge resolution of 2.7% fwhm was obtained for these measurements and an energy resolution of 0.8%fwhm was obtained.

In order to determine the effect of the energy of incoming ions on the measurements of the ions atomic number, Z number measurements were undertaken using different aluminium absorbers over the beam. This produced a range of beam energies from 74MeV to 270MeV. A dependence on the energy of the particles for Z
number measurements was detected and attributed to screening inefficiency of the Frisch grid. The higher the energy of an ion entering the chamber, the more ionisation occurs and the higher the induced charge from the positive ions. From this it can be deduced that the higher the energy of the ion, the higher the Bragg peak and the higher the charge measurement deducted from the peak. A Bragg peak correction was undertaken using the following equation:

\[ C_m(\text{true}) = C_m(\text{measured}) - k \sum C_j(\text{measured}) \]  

Where \( C_m(\text{true}) \) is the true Bragg peak height, \( C_m(\text{measured}) \) is the measured Bragg peak value and the summation is the value of the pulse deviation due to the inefficiency along the Bragg curve and is applied to the tail of the pulse, round the Bragg peak.

The value \( k \) is empirically chosen so that there is no energy dependence for the charge at \( Z=18 \), the atomic number of the most common reaction product from the beam and target combination used. This method is not satisfactory, as is stated in the paper, as it gives a grid inefficiency value that is several times larger than previous experiments have yielded. The method of empirically determining the value \( k \) is also laborious and varies with \( Z \) number so that if a wide range of fragments is expected yields will still be shifted.

Charge separation experiments are also undertaken using the same set-up and yield good separation about \( Z=18 \). Comparisons of the experimentally obtained curves with reference data show a good agreement, with the exception that the Bragg peak for the experimental data clearly underlies the reference data. The paper states that this does not have a large effect on resolution as all different \( Z \) numbers have
very similar rise times, no figures are given however. An additional factor in the chamber performance is that the electronic set-up used is thought, by the authors, to reduce the Z number resolution.

![Energy loss sample extracted from the Asselineau et al. chamber (solid line) displayed with the equivalent expected Bragg curve for a 270MeV Argon ion stopping in isobutane [1]](image)

*Figure 4: Energy loss sample extracted from the Asselineau et al. chamber (solid line) displayed with the equivalent expected Bragg curve for a 270MeV Argon ion stopping in isobutane [1]*

Simple Longitudinal Bragg chambers continue to be important to this day. Advances in analysis of the Bragg curve and in the electronics have improved the resolution of results but the basic construction of the simple longitudinal Bragg remains the same.

For a chamber built for the use of the University of Sao Paulo in 2000, the same basic construction was used as that laid out by Gruhn. A longitudinal field was applied in a cylindrical parallel plate detector with the electric field kept constant by a
resistive chain linking 12 titanium ring shaped inserts. The signal from the anode is passed via a preamplifier to two shaping amplifiers with shaping times of $\geq 6\mu s$ and $\leq 1\mu s$ for the energy and charge measurements respectively.

Figure 5: Schematic showing the main features of the Sao Paulo Bragg chamber [3]

To test the independence of the Z number signal with respect to the energy of the ions, beams of $^{36}\text{Cl}$ and $^{36}\text{S}$ were unfocused and directed towards the chamber. Results show a good separation of these elements and the peak resolutions detected for the Cl beam are 0.38% for energy and 1.3% for charge. The directionality of the beam used eliminates, in large part, angle straggling and is an important factor in the high resolutions obtained.
Figure 6: Scatter plot showing the separation of Bragg peaks of $^{36}$Cl and $^{36}$S ions varying with energy. The resolution of two ions with the same Z number requires a high charge and energy resolution [3].

For simple Bragg chambers the best results obtained for charge and energy resolution from Schiessl and Santos’ chambers are more accurate than the resolution obtained by Asselineau following the Gruhn method. The simpler method of collecting and analysing the data used by Schiessl and Santos removes much of the uncertainty and problems associated with the electronics used by Gruhn. The more comprehensive series of tests undertaken by Asselineau explore facets of the chamber, with respect to errors, that were not laid down by Schiessl in his paper. However, the fact that the resolution was better for Schiessl implies that these problems were not of the same order for the Schiessl chamber. The fact that several years later the same method of extracting the charge and energy measurements is used by Santos is a vindication of Schiessl’s technique.
The experiments laid out in these initial papers yielded accurate charge and energy resolutions, providing an improvement on more traditional ion chambers and a high degree of independence of charge and energy measurements.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Energy Resolution</th>
<th>Charge Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asselineau</td>
<td>0.8%</td>
<td>2.7%</td>
</tr>
<tr>
<td>Schiessl</td>
<td>0.4%</td>
<td>1.2%</td>
</tr>
<tr>
<td>Santos et al.</td>
<td>0.38%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

*Table 1: Comparison of energy and charge resolution for the simple longitudinal Bragg chambers considered.*

### 2.2 Large Solid Angle Bragg Chambers

In 1983 McDonald [4] constructed a conical Bragg chamber that could be used in a spectroscopic array covering a solid angle of $4\pi$. The reason for this development was the wide range of experiments that could utilise a large angle chamber with a compact geometry and a good charge and energy resolution. Tests were taken to determine whether the charge and energy resolution of ions is maintained for large solid angles. Tests were also taken to test the ability of the chamber to resolve ions with, atomic numbers of greater than or equal to 26. Early Bragg chambers can generally only resolve $Z$ values of less than 26, due to the reduction of the difference between Bragg peak heights for consecutive atomic numbers as $Z$ increases.

Problems with using a more complex geometry than a simple longitudinal chamber come from the motion of the ions within the chamber. If the path of
ionisation deviates from the electric field lines or the drift velocity is not constant then the signal at the anode will be distorted. For the McDonald chamber, the trade off was between having a field to fit the conical geometry and having a constant drift velocity. The former option was chosen and a radial field was used. A 1993 paper by K.A. Farrar et al. [9] at the University of Kansas chooses the option of a longitudinal field with ions not following the field lines.

For McDonald’s chamber four different beams of heavy ions were used: 206MeV $^{28}$Si, 413MeV $^{56}$Fe and 378MeV $^{86}$Kr. 500μg/cm$^2$ Au and Ag targets were used. The chamber was placed in a scattering chamber with the relevant target placed 10cm from the apex of the cone where the ions would enter via a Mylar window. The window to anode distance was 24.5cm. Initial results were taken to test the basic operation of the chamber at small solid angles and to test the chamber’s ability to differentiate between heavier elements. Simultaneous beams of 413MeV $^{56}$Fe and 206MeV $^{28}$Si were scattered off a 500μg/cm$^2$ Ag target.

Figure 7: Drawings of MacDonald’s chamber showing a) the major components of the chamber in exploded view and b) the significant dimensions of the chamber [4].
Data was collected using a similar set-up to the Schiessl chamber; the amplifier collecting the signal for the charge measurement had a shaping time of 0.8μs and the amplifier collecting the energy signal a shaping time of 8μs. Scatter plots of energy against range and charge against range of the scattered products show highly distinct regions of the scattered Si and Fe ions. The region representing Fe ions on the charge against range plot shows a smearing effect that implies a level of Frisch grid inefficiency higher than the approximately 1% cited in the paper. The uncertainty is more noticeable than in previous papers that cite higher Frisch grid inefficiencies. The elimination of this dependency is affected using the same method as that employed by Asselineau.
Figure 8: Scatter plots showing a) the variation of ion range with ion energy and b) variation of ion range with Bragg peak height. Ideally, b) should show two regions corresponding to iron and silicon ions that are Z number invariant. The variation in Z denotes a dependence of the Bragg peak height on the ion range and, hence, energy [4].

Results were also taken for lighter ions created by scattering 670MeV $^{56}$Fe ions off a 500μg/cm$^2$ Au target. Results plotted in a scatter plot of energy against charge show good separation of the lighter ions and a much smaller energy dependency of charge is exhibited. A charge resolution of 1.5% and an energy resolution of 1% are achieved.
The performance of the detector at large solid angles is tested using one of the Fe beams (unspecified) and the Kr beam on the Ag target. Four different solid angles of 1.4, 5.1, 21 and 83 msr were used for the Fe beam and two steps of 5.1 and 83 msr were used for the Kr beam. The different solid angles were achieved by collimating the beam at different orientations to the window. The charge resolution reduced with solid angle but only to a value of 1.9% for the Fe beam and 1.7% for the Kr beam. These values provide a higher resolution for heavy ions at large solid angles than for the simpler Asselineau chamber that was designed to measure far lighter ions.

The 1993 large acceptance, longitudinal Bragg chamber worked on at the University of Kansas [6] differs to the McDonald chamber in that the decision was
made to have a longitudinal rather than a radial electric field. This gives a constant drift velocity of ions moving through the chamber. However, distortion of the Bragg curve will occur due to angle straggling. This chamber was designed exclusively to track light fission fragments. A 188Mev $^{36}$Ar beam scattered from 100 $\mu$g/cm$^2$ Au and 50 $\mu$g/cm$^2$ C targets was used to obtain all final results relating to resolution.

The detector body is of a cylindrical rather than conical geometry but with a more complex internal geometry than a simple Bragg chamber as the anode and cathode are segmented.

A parallel grid avalanche counter (PGAC) was used to provide additional ionisation position information for most runs of the chamber to help counteract the angle straggling caused by the ions not moving along the electric field lines. The anode of the chamber was segmented into four quadrants and connected in a way similar to the Schiessl method, such that three of the quadrant signals were split between two amplifiers with shaping times of 10μs and 1μs and one of the quadrant signals was split between two amplifiers of amplitude 8 μs and 0.75 μs. Splitting the anode to give two different shaping times reduces the uncertainty in the shaping times that need to be selected. This can help to counteract one of the problems with the chamber: that the field will not be completely homogenous due to the complex geometry of the chamber. As the field is inhomogeneous to an unknown degree, the drift velocity of electrons that determines the shaping time used in the amplifiers will not be well known.
Figure 10: Diagram of the segmentation of the cathode and Frisch grid support. The segmentation of the anode takes the same form [12]

The segmentation of the anode in conjunction with the PGAC forms the basis of a selection procedure to eliminate unwanted signals from the analysis. Only events that generate a good signal in the PGAC and are detected in one portion of the anode are analysed. Signals that appear in more than one anode quadrant are discounted due to the increased uncertainty in position that this creates, in turn increasing the uncertainty present in the measured specific energy loss and, as a consequence, the Z number and energy values extracted from the ion's specific energy loss.

The potential problem of cross talk between the anodes, which could have led to more than one anode segment registering a signal, was found to be minimal. Scattering a 163MeV $^{32}$S beam from an Au target onto one of the anode quadrants, was found to generate a signal of 0.03% the strength from the targeted anode in the other anode segments.

Variation in the energy resolution is one of the main drawbacks of the chamber setup. This was found to occur as a result of reduced electron transmission
around the quadrant boundaries and, in the tests undertaken in the paper, loose Frisch grid wires; bowing of the entrance window also has this reduction effect.

A mathematical model was constructed using calculations of the energy deposition at different regions in the chamber volume using path information calculated from the PGAC. This was used to correct the energy measurements by application to the energy signal obtained at the anode, improving the resolution. The corrected average energy resolution of the four quadrants was then found to be 1.1%, an improvement on the uncorrected average value of 2.0%. Changes in the electric field also affect the charge resolution in the same way; the same method of correction based on position data was used on the charge resolution and yielded an average resolution of 1.5% down from an uncorrected value of 3.9%. The shorter shaping time used for quadrant two resulted in more noise due to the reduction in high frequency noise filtering.

From the resolutions it can be seen that the Farrar chamber has a comparable average charge and energy resolution to the McDonald chamber. The problems with the inhomogeneous field present in the Farrar chamber are rectified by the presence of the PGAC and additional range measurements not taken by McDonald. The same procedure also corrects the resolution of larger solid angle measurements so that there is no noticeable resolution degradation. The larger acceptance angle of the Farrar chamber can be said to make it a better design in terms of versatility due to a greater variation in position within an array allowed.

A paper from earlier in 1993 [16] explores a similar set-up to the Farrar chamber but with a radial field. A large acceptance Bragg chamber is placed behind a PGAC and a 115MeV $^{28}$Si beam is used to bombard a $^{68}$Zn target. The energy resolution is found to be 1.6% for this beam and target and the charge resolution is
found to be 2.9%. Due to the very similar construction of these two chambers it can be seen that a longitudinal field has advantages in energy and charge resolution. Differences in the construction shall be seen later.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Energy Resolution</th>
<th>Charge Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDonald</td>
<td>1%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Saha</td>
<td>1.6%</td>
<td>2.9%</td>
</tr>
<tr>
<td>Farrar</td>
<td>1.1%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

*Table 2: Comparison of charge and energy resolution for large solid angle Bragg Chambers.*

2.3 A Sub Bragg Curve Spectroscopy Chamber

A 1983 paper by Oed [17] details a method of extracting charge measurements from a chamber when a Bragg peak maximum is not formed. The paper covers initial results of the method so is lacking in some exact details on the chamber performance aside from charge and energy resolutions.

The authors state that the energy loss of particles, of the same energy and mass but of different charge, will differ towards the end of the range. The same total signal strength will be produced, as the number of ion pairs produced in the chamber is only dependent on the energy of the particles used and the range will also be the same for all particles, so the collection time for the total charge will also be the same. However, as the energy loss differs for different particles, throughout their range, by recording the time at which a certain proportion of the charge is reached,
differentiation can be made between particles that differ only in terms of charge number. Through knowledge of the source or target used, the ion groups can then be identified.

The mass separator LOHENGRIN was used to select particles of equal velocity and mass/charge ratio of \( v = 1.38 \text{cm/ns} \) and \( A/q = 97/22 \) respectively. These resulted from neutron-induced fission of a \(^{235}\text{U}\) target. A time pick off system was mounted in front of the Bragg chamber entrance window to provide a start signal to initiate the measurement of the anode pulses. The pick off system was initiated by ions entering the chamber triggering an electron avalanche from an aluminium foil. The Bragg chamber itself was a cylinder with a constant longitudinal electric field regulated by field rings between the anode and cathode, with a Frisch grid placed a short distance from the anode. The entrance window to the chamber also acted as the cathode.

![Figure 11: Schematic of the sub-Bragg peak spectroscopy chamber setup as shown in Oed et al. [17]](image)

The peak energy resolution obtained was 2.32% about \( Z = 39 \) between Strontium, Yttrium and Zirconium with the three having the same mass to charge ratio. The peak energy resolution obtained was 0.49%. The energy of the incoming
fragments was altered in order to test whether the charge resolution degraded over the energy range of fragments likely to be encountered in future tests. No significant degradation was detected. Problems are mentioned with the threshold of the discriminator used not being able to adequately detect the track length of the ions. This had a detrimental effect on the charge resolution. Digitisation of the anode pulse would also allow greater charge separation, improving the charge resolution. The high energy resolution can be attributed, in large part, to the ion selection available from LOHENGRIN.

### 2.3 Electronic Configurations

The electronics used to receive and analyse the anode signal are an important part of the Bragg chamber as they ultimately determine the output. Gruhn’s initial method requires the digitization of the pulse to improve resolution for the charge and energy analysis. The Gruhn prototype achieves this using a Lecroy waveform digitizer (WFD) before storage on magnetic tape. Bragg curve data, for all ions passing through the chamber is thus obtained and analysed offline.

The paper by Asselineau et al. [1] provides an electronic set-up based directly on the Gruhn method. This experiment provides a proper test of the Gruhn method beyond the prototype chamber. A preamplifier is built within the detector body to ensure a short connection with the anode and minimise degradation of the anode signal in wiring or cabling. The signal is fed to an amplifier with a gain of 100 and then to a WFD. A problem present in the use of a WFD is the high amplitude of signals required to obtain a reliable digitized output, the WFD is thus unsuitable for particles that provide a smaller level of ionisation. Drifts in the baseline of the output
also occur due to drifts within the electronics. These drifts are not consistent; the method used to correct the drift in the Asselineau paper takes the average of 40 baselines of the WFD output without any input and assumes this to be the true baseline. This assumption could result in the baseline being skewed to its true value and have knock on effects to the Bragg peak location and charge resolution. For the set-up used by Asselineau, the WFD also adds 1% to the value of the resolution.

An example of a different method of obtaining the anode signal is used by Schiessl et al [2]. The method of obtaining the information from the signal is the same as that detailed from Gruhn but two amplifiers with different shaping times are used to obtain separate information on the charge and energy of an ion.

The anode signal is initially passed through a preamplifier to boost it before it is split. The shaping constants used for the signals were 0.25μs and 4 μs for the charge and energy measurements respectively. A potential pitfall of this method is in selecting a time constant for the charge amplifier that is too long. This will result in a dependence of the Z number on ion energy, skewing the values of the nuclear charge obtained. The signals are then stored online directly to the PDP 8/10 ONLINE system. Schiessl’s method does not digitize the waveform before analysis, but otherwise has a very similar method of analysis. This method is used in relatively modern chambers [98, 00].

An additional step was taken by McDonald et al for their chamber. The signal, after being passed through a preamplifier was split into three different channels. The first two signals were sent in to two amplifiers to obtain the energy and charge, in the same way as for Schiessl. The third signal was sent to a TAC (time to amplitude converter). The TAC was started by means of the initial preamplifier signal being sent through a constant fraction discriminator (CFD), in order for the peak of the preamp
signal to trigger the start of the TAC. It was stopped by the zero crossing time of the bipolar output of the amplifiers; the amplitude of the TAC output is the proportional to the range of the particle. All data was subsequently stored on magnetic tape for offline analysis. This method provides a means of measuring the ion range that is not subject to any particular mathematical approximation or fitting of the Bragg shape so for earlier experiments where more exact analysis programs were not available this provides a method more reliable than that used by Schiessl and Gruhn. With the improvement of algorithm and stopping data programs, however the Gruhn and Schiessl methods can also be used with a high level of reliability.

The nature of the different measurements taken for the sub-Bragg peak spectroscopy, means that the electronic setup is different for the Oed chamber. A basic layout of the electronics can be seen in Figure 10. The start pulse from the pick off detector is passed to a constant fraction discriminator before being used to start a time to amplitude converter (TAC). The TAC is stopped once the anode pulse has reached a certain amplitude.

The anode signal is fed through a charge sensitive preamplifier to increase the signal amplitude before being split into two channels. One of the channels is passed to a shaping amplifier that is then passed to a multi-channel analyzer for storage of data for the energy resolution. The other preamp output is used to stop the TAC. The preamp output is sent through a discriminator, which is set to the desired amplitude used to differentiate ions of different charges. The differences in amplitudes between TAC outputs, due to timing differences, are then used to identify the charge of ions. TAC outputs can then be stored for later analysis.

Tables 3, 4 and 5 indicate the electronic configuration used in all the papers considered in this review and are compared to the detector resolutions:
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Output</th>
<th>Resolution (ΔZ/Z, ΔE/E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gruhn’s Prototype, 1979</td>
<td>Single output from anode to WFD</td>
<td>-</td>
</tr>
<tr>
<td>Schiessl et al, 1981</td>
<td>Dual output from anode to two amplifiers</td>
<td>1.2%, 0.4%</td>
</tr>
<tr>
<td></td>
<td>with different shaping time</td>
<td></td>
</tr>
<tr>
<td>Asselineau et al, 1982</td>
<td>Single output from anode to WFD</td>
<td>2.7%, 0.8%</td>
</tr>
<tr>
<td>Santos et al, 2000</td>
<td>Dual output from anode to two amplifiers</td>
<td>1.3%, 0.38%</td>
</tr>
<tr>
<td></td>
<td>with different shaping times</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Output Signal Set-up for basic longitudinal Bragg chamber papers considered in the review, with charge and energy resolution displayed.

<table>
<thead>
<tr>
<th>Large Solid Angle Bragg Chambers:</th>
<th>Output</th>
<th>Resolution (ΔZ/Z, ΔE/E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDonald et al, 1983</td>
<td>Dual output from anode fed into two amplifiers with different shaping time, additional range and timing information from TAC</td>
<td>1.5%, 1%</td>
</tr>
<tr>
<td>Saha, Agarwal, Deshpande and Roy, 1993</td>
<td>Dual output from anode fed into two amplifiers with different shaping time</td>
<td>2.9%, 1.5%</td>
</tr>
</tbody>
</table>
times, PGAC used to provide additional range and energy loss information

| Farrar et al, 1993 | Dual output from each segmented anode portion fed into two amplifiers with different shaping times. TAC provides additional range and timing information in conjunction with PGAC | 1.5%, 1% |

**Table 4**: Output Signal Set-up for Wide Angle Papers considered in the review, with charge and energy resolution also displayed.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Output</th>
<th>Resolution (ΔZ/Z, ΔE/E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oed, 1983</td>
<td>Preamplifier output fed to TAC for timing information and to shaping amplifier for energy readings</td>
<td>2.32%, 0.49%</td>
</tr>
</tbody>
</table>

**Table 5**: Output and resolutions for the sub-Bragg peak spectroscopy chamber run by Oed et. al.
Improvement on Schiessl’s method of signal extraction can be seen to be minimal with no large changes in resolution occurring. The use of a PGAC and TAC provides necessary additional information for the experiments that do not have high yields of electrons from ionisations. Their use is also important for chambers where electrons do not move along the electric field lines within the chamber or move with varying drift velocities.

Analysis of the anode signals has been vastly improved from the initial algorithms used by Gruhn. Improved data on stopping power of ions in matter such as that provided by and codes such as SRIM (stopping range of ions in matter) improves interpretation of the signal. Mention of the method of analysis is sparse in the papers examined in this review and so conclusions cannot be readily drawn with respect to the effects the different types of analysis have on the overall energy and charge resolution.

2.4 Parameter Comparisons:

The operating voltage across the chambers and the gas pressure determines the electron drift velocity and collection yield of electrons and has a large effect on the data yield as a result. The limit of operation of the voltage is determined by the point where the gas starts to break down and also by effects such as noise from the power supply adding errors onto the anode signal. All electric fields in the papers examined lie between 0.5 and 3.9 V/torr.cm. The correlation between field strength and detector performance exclusively is negligible.
The gas in a Bragg chamber will ideally have a high stopping power and be able to hold a large electric field. With these assets a higher electron drift velocity can be achieved and a lower pressure can be used, improving data collection rates. Also more energetic and heavier particles can be used for testing, as the high stopping power can allow them to stop within the detector. A small number of widely available gases are suitable for use in Bragg detectors and, as can be seen from this review no changes have been made in this area as time has progressed. Gases are generally used based on their availability at the point of research. All the gases below have high stopping powers and are able to hold high electric fields. Table 6 shows the gases used for the chambers mentioned in this review:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Gas</th>
<th>Ionisation Potential (eV) [18, 19]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schiessl 1981</td>
<td>P-10</td>
<td>14.4-15.2 for methane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.7 for argon</td>
</tr>
<tr>
<td>Asselineau 1982</td>
<td>Isobutane</td>
<td>10.7</td>
</tr>
<tr>
<td>McDonald 1983</td>
<td>P-10</td>
<td>14.4-15.2 for methane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.7 for argon</td>
</tr>
<tr>
<td>Oed 1983</td>
<td>Isobutane</td>
<td>10.7</td>
</tr>
<tr>
<td>Saha 1993</td>
<td>Isobutane</td>
<td>10.7</td>
</tr>
<tr>
<td>Farrar 1993</td>
<td>P-10</td>
<td>14.4-15.2 for methane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.7 for argon</td>
</tr>
<tr>
<td>Santos 2000</td>
<td>P-10</td>
<td>14.4-15.2 for methane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.7 for argon</td>
</tr>
</tbody>
</table>
Table 6: The gas chosen to fill the detector body for each of the papers examined in this review. P-10 gas consists of 90% argon and 10% methane.

Most chambers will have a window, through which particles can be admitted while the gas is contained. As with the gases the construction of the windows has not been drastically changed since the inception of the Bragg chamber. All chambers with the exception of the 1993 radial, large acceptance Bragg chamber and sub-Bragg peak chamber have had aluminized Mylar windows of between 1.5 and 2μm thickness. Aluminized Mylar allows for a good transmission of particles passing into the chamber from the target while maintaining a seal at the chamber entrance. The polypropylene used for the 1993 chamber and Parylene C foil used for the sub-Bragg chamber have much the same properties relevant to efficient chamber operation.

The Frisch grid is an essential part of all Bragg chambers due to the necessity, for good chamber resolutions, of removing as much induced charge on the anode due to the movement of gas ions as possible. Table 7 compares the composition of the Frisch Grid and its distance from the anode and cathode compared with its screening efficiency:

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Cathode to Grid Distance (cm)</th>
<th>Anode to Grid Distance (cm)</th>
<th>Wire Material</th>
<th>Wire Diameter (μm)</th>
<th>Wire Spacing (mm)</th>
<th>Grid Inefficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schiessl 1981</td>
<td>16</td>
<td>1</td>
<td>Copper-Beryllium</td>
<td>50</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Asselineau</td>
<td>22.5</td>
<td>0.5</td>
<td>Copper</td>
<td>150</td>
<td>0.8</td>
<td>1.5%</td>
</tr>
<tr>
<td>Year</td>
<td>Material</td>
<td>Electrode Material</td>
<td>Thickness</td>
<td>Conductivity</td>
<td>Efficiency</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------</td>
<td>--------------------</td>
<td>-----------</td>
<td>--------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td>McDonald</td>
<td>Tungsten</td>
<td>38</td>
<td>0.625</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>Oed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>Saha</td>
<td>Phosphor, Bronze</td>
<td>75</td>
<td>1.27</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>Farrar</td>
<td>Silver plated</td>
<td>254</td>
<td>1.27</td>
<td>0.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper-Beryllium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>Santos</td>
<td>Gold coated tungsten</td>
<td>20</td>
<td>1</td>
<td>1.7%</td>
<td></td>
</tr>
</tbody>
</table>

*Table 7: Frisch Grid Compositions and the related screening inefficiency.*

As can be seen from the table many different types of metal can be used for grid chamber construction as long as a metal with reasonable electrical conductivity is selected. The size of all chambers considered with the exception of the sub-Bragg peak spectroscopy chamber are shown to be of the order of tens of centimetres. The smaller scale of the chamber used by Oed is due to the slower ions used. The reduction in speed means they can be stopped in less distance than the lighter ions detected in the other chambers.

The balance for a good Frisch grid for a Bragg chamber is in allowing a high rate of electron transmission while screening to a high degree the positive charges...
heading towards the cathode. Large angles of incidence on the grid will heighten inefficiency. Due to this the Frisch grid configuration used by Farrar can be said to be the best available as this has the maximum screening efficiency from the above grids despite being a constituent of a large solid angle chamber. The resolution for the Farrar chamber is also better than many simpler chambers, indicating that the high level of screening does not impede large numbers of electrons.

The variety of Bragg chambers with respect to size, electronic set-up, gas pressure and electric field has been examined. The resolution of the chambers examined has been consistently accurate. Information on the various chambers parameters notably those used by Farrar and Oed are taken into consideration in the construction and operation of the double sided chamber.
CHAPTER 3: THE CONSTRUCTED BRAGG CHAMBER

3.1 Constructed Chamber Specifications:

The purpose of the Bragg chamber constructed is to determine the energy and atomic number of fission fragments. It is ultimately designed to obtain detailed information on the different energies of fission products, while also obtaining information on the atomic number distribution of the primary fission fragments and the angular distribution of the fragments. Initial testing is undertaken at the Nuclear Lab at the University of Manchester using a spontaneous fission source Californium-252. The chamber is to be moved to the LPSC in Grenoble in late 2012 to be used with a Thorium-232 target bombarded by a fast neutron beam, resulting in exotic fission fragments.

A wide acceptance angle was desired to detect as many events as possible, while both fission fragments from a single fission event are to be detected simultaneously. In order to satisfy these requirements the chamber is designed to house the target or source at the centre of the chamber. The chamber is a 34cm long cylinder with a separate anode being present at both ends. The distribution of the two primary fragments is such that one fragment will usually travel towards the opposite chamber end to the other fragment. If a fragment is detected by one of the anodes, the other fragment is then generally detected by the anode at the other side of the chamber. The double-sided nature of the chamber also makes it more compact than two separate chambers positioned either side of a source or target. This gives it greater versatility for use in a variety of arrays.
The distortion of the ionisation signal caused by wide angle events is combated by segmenting the two anodes into six segments each. One of the anodes shall be segmented into six concentric circles (anode 1), while the other shall be split into six wedges (anode 2).

Figure 12: Drawings of the configurations of anode 1 (concentric circles) and anode 2 (wedges). All segments, both wedges and rings, have the same area. The gaps between segments are 1.5mm thick.

Anode 1 can provide information on the angle of events. By detecting the relative quantities of charge induced on each anode segment by an event, the ionisation pattern can be detected and the angle of the event can be deduced. This allows distortion of the output due to angle straggling to be corrected. From the fact that the two fragments will travel in opposite directions to each other accurate positioning data of each fragment can be undertaken from this method, as each fragment will need to have its signal corrected in equal measure.

Each segment has the same area, whether ring or wedge so that there is no bias towards greater collection on any one segment. Anode 2 is used to provide azimuthal angular information of the fission fragment direction. This can be used to provide
positioning information to heighten the accuracy of gamma ray measurements that may be taken with the chamber as part of a larger array.

A constant, longitudinal electric field rather than a radial field is chosen for both sides of the chamber. This provides a constant drift velocity for electrons travelling through the chamber which can be used with the segmented anode system to correct for large angle events, while still maintaining a large acceptance angle.

Atomic number measurements were not taken with the initial results due to limits on signal analysis and the acquisition system. MIDAS (Maximum Integration Data Acquisition System) was to be used to obtain data. This would have allowed energy spectra and charge measurements to be recorded concurrently. However, no MIDAS software was set up at the time that data was taken. Algorithms for the extraction of the charge from wide angle events have also not been developed at this stage. Partial segmentation of one of the anodes was still undertaken in order to test that the outputs were of the expected form and amplitude.

The field is set by a series of equidistant copper rings for each side of the chamber. These are connected by equal valued resistors to bring the potential down in constant intervals. At the end of the resistor chains nearest the anode, Frisch grids are present to screen the anodes from the gas ions moving towards the chamber centre. Both chains are grounded from the field ring at the end of the chain opposite the anode; these rings effectively form the cathodes of the chamber. The chains share a common ground connected to the ring at the other end of the chain from the anode to ensure that the potential difference across both chains is the same. The field ring connected to ground on the anode 1 side has a section removed allowing the source to be placed in the centre of the chamber via an aligned port in the chamber side.
Several ports exist on the chamber ends allowing different numbers of feedthroughs to be used, for different configurations of power supplies to, and signal outputs from, the anode segments.

Separate power supplies exist for both chains of field rings. Due to restrictions on the number of outputs that could be processed the anodes were wired so that neither were fully segmented. Ultimately a separate supply may exist for each segment but initial results were taken with anode 2 being powered by only one supply and anode 1 being powered by three supplies. In this configuration anode 2 forms a complete unsegmented anode. The segmentation of anode 1 is reduced by halving the effective number of segments. Each segment is paired with another, each sharing the same power supply and signal output. The anodes are separated from the resistor chain and the Frisch grid so that the field between the anode and grid can be set independently to maximise the efficiency of the chamber. Figure 12, displayed on the following page, shows the configuration of the two chains of field rings bound together as well as the configuration of the feedthroughs on the chamber end associated with anode 1.
Figure 13: Photo of part of the technical drawing of the chamber showing the two ends of the chamber. The ends are depicted outside the housing, bound together by threaded rods. Two gas feedthroughs and four high voltage feedthroughs are shown on the end of the chamber displayed. The field rings are displayed fitted into PTFE supports, the Frisch grids are shown with black circles round their circumferences, denoting the screws used to hold the two parts of the frame together. The numbers on the diagram denote a blanking flange (8) and the screw used to hold it in place (25)

For the initial results taken a spontaneous fission source, Californium 252 was used. The Californium was dissolved in a hydrochloric acid solution. A drop of the solution was then applied to a thin gold foil; the acid evaporated, depositing the californium. The foil is placed over a washer fitted into a metal slide. The metal slide
was slotted into a Teflon pillar, which was in turn screwed into a blanking flange covering one of the chamber ports. The length and positioning of the pillar is such that the source is perpendicular to both anodes and is positioned at the chamber centre.

3.2 Chamber Assembly

3.2.1 Chamber Housing

The chamber housing and ends are made of aluminium and have a number of ports in which components can be attached. Rubber O rings are used at all ports to create a tight vacuum seal. The field rings, Frisch grid and anode for each side are held in place by grooved PTFE supports (see figure 13), which are fed through each chamber end and bolted in place externally. Six holes for feedthroughs exist on either end of the chamber.

The anode 1 side of the chamber has 3 high voltage feedthroughs, two BNC feedthroughs and one blanking flange to cover the remaining port. The three high voltage feedthroughs were used to power each anode segment. A shortage of high voltage feedthroughs led to the use of a BNC feedthrough to supply the Frisch grid, no problems were detected with the power supply to the Frisch grid as a result of this. The remaining BNC feedthrough was used in place of a blanking flange.

The anode 2 end of the chamber had two HV feedthroughs, two alternative gas ports and two blanking flanges. The HV feedthroughs were used to power the anode and Frisch grid on the unsegmented side of the chamber. The alternative gas supply ports were blanked off, the gas being fed in and out of the chamber through two ports
located on the main chamber body. A top down view of the main housing is shown in figure 14 below:

![Figure 14: Top down view of the chamber. The source is placed into the chamber via the large port displayed on the top of the chamber. One of the two ports depicted on the chamber sides was blanked off while the other had the pressure gauges attached. One of the gas feedthroughs on the chamber sides was not built onto the chamber while the other two were used for the gas supply and return.](image)

3.2.2 Anodes

The first requirement for the construction of the chamber was the design and manufacture of the anodes. For the segments to be segregated while holding high
voltage a 1.5mm gap was decided upon between segments based on previous examples present in the laboratory and on successful segmented anode Bragg chambers found in literature [12].

The concentric circled anode has more dead area than the anode with wedges due to the greater length of the dividing channels. The anode rings require dead area rings of increasing circumference between them as the segments progress outward. The maximum area of segment is then the minimum required dead area between circles subtracted from the entire surface of the anode visible to the charge travelling through the chamber divided by six. The maximum width of each ringed segment in millimetres was calculated by the formula below:

$$r_n = \sqrt{r_1^2 + \left(\sum_{m=1}^{n-1} r_m + 1.5(n-1)\right)^2 - \sum_{m=1}^{n-1} r_m + 1.5(n-1)} \quad (11)$$

While satisfying the requirement that:

$$\sum_{m=1}^{6} r_m \leq 67.5\,mm \quad (12)$$

Equation (12) ensures that the anode segments will be within the inner circumference of the field rings, ensuring that every part of every segment is visible to the free electrons moving towards the anode.

Once the area of the segments was determined, the anodes were made using a printed circuit board technique. This used a 3D printer to deposit a thin layer of copper over a nylon base. After the anodes had been made up a pillar drill was used to make holes through the backing for wires to be inserted through and contact with the copper covering on the front of the anode.
3.2.3 Field Ring Chains and Frisch Grids

The field rings are made of copper due to its availability and good electrical conductivity. They have an outer diameter of 175mm and an inner diameter of 150mm; the Frisch grid and anodes also having the same inner and outer diameters. One of the field ring chains was joined with 9.1MΩ resistors while the other was connected using 10MΩ resistors. The resistor values had to be the same for each chain so that the potential was dropped by the same interval over each gap. However, the specific value does not matter as long as the resistance is high enough to tolerate the high voltage. The Frisch grid consists of gold-plated tungsten of wire of diameter 50μm and spacing between wires of 2mm. Gold-plated tungsten was chosen due to its availability and its prior use in Frisch grids with a low inefficiency value of 1.7% [3]. The wire was held between two copper ring frames. A strip of indium passed round the circumference of the copper frame to hold the wire in place in conjunction with the screws used to hold the frame together.

The PTFE supports for holding the field rings, Frisch grid and anodes were constructed in the University of Manchester workshop. The field rings were available in the laboratory from previous Bragg chambers. The rings were manually slotted into the related slots present in the supports. The slots were in several cases found to be too small so significant force had to be applied, resulting in two of the field rings being replaced due to being buckling.

The nylon bases of the anodes were also slightly too thick to fit in the supports and had to be sanded down in order for to fit into their slots. Difficulties were encountered with evenly sanding the anode on all sides so that the copper surface remained perpendicular to the approaching charges. The bases were sanded in the
areas where they had to be inserted into the supports and were successively measured with a setsquare held at the anode between the anode and support to ensure the correct angle was reached to a high level of accuracy. Initially sandpaper was used for this operation but after this proved too slow, a dremmel was used.

Once all supports had been attached to the field rings attempts were made to place the pillars in to the chamber to ensure they still fitted, the ends often proved to be splayed outwards so more sanding was periodically undertaken. The combination of the angles of the anode with the four supports still proved problematic and the widening of slots or the use of a thinner backing sheet for the anode is a necessity for future developments.

The fragility of the Frisch grids proved a problem during this process, the force that had to be applied to fit the grids into their supporting slots led to some of the wires breaking or becoming slack. At first attempts were made to tighten the slack wires by drawing them through the frame of the grid using pliers, but there was found to be no effective way to keep the wires at tension. It then became necessary to split the frame of the Frisch grid in order to insert new wires. However, this has the effect of removing tension from the remaining wires in the grid rendering them slack as well. The intricacy of keeping the wires individually under tension, while in their correct alignment and spacing was too great. As such the grid had to be entirely reconstructed.

The reconstruction utilised a rotating frame with threaded semi cylinders affixed to the sides of a Perspex board, which could have its height adjusted with respect to the semi cylinder by means of it being mounted on threads with nuts above and below. The wire used in the grids was fed over the frame from a spool and was attached to the frame by means of tying it to the threads used to raise and lower the
Perspex platform. The Frisch grid frame was mounted on the Perspex and screwed in place. The platform was then raised so that the level of the top of the grid frame was marginally above the level of the semi cylinders. By rotating the frame by hand and making sure that the wire fed from the spool was fed into the equally spaced threads on the semi cylinders a taut array of evenly spaced, parallel wires could be formed over the half of the Frisch grid frame.

Once the inner diameter of the half frame was covered by the wire array, indium was pressed into a groove present in the frame of the Frisch grid in order to help keep the wire at tension from within the grid frame. The indium was compressed and held in place by the other half of the Frisch frame, which was screwed tightly onto the half remaining on the rotating apparatus. The wire remaining outside the frame was then cut off flush to the Frisch grid frame using wire cutters, while the wire within the Frisch grid was then still held at tension by combination of the screws and indium in the frame. The apparatus is shown on the following page.
Figure 15: Frisch grid mid-construction. The rotating frame is seen with a Frisch grid attached. Wire is fed over the grid from the spool in the background of the picture. It is then fed into the grooves of the thread seen along the edge of the frame as the frame is rotated. The groove into which the indium is pressed is seen running around the frame of the Frisch grid.

 Resistors were connected to the field rings using conducting silver epoxy glue. This technique has the advantage over soldering of not needing to heat up the field rings as a means of gaining adhesion. The size of the copper rings impairs the use of solder due to the large heat capacity of the copper. Attempts were made to use solder, due to the stronger connections it offers. However, after an hour of heating the ring and the addition of aids such as solder flux connections can rarely be made.
The epoxy is easily applicable and easy to remove with alcohol should changes need to be made. Before application the epoxy is formed by mixing two different substances in equal measures to form the glue. If the ratio of the two substances is other than one to one then the epoxy has a tendency to become “tacky” and less pliable. This caused some of the glued areas to be bigger than desired, with prominences that had to be removed due to the potential for sparking to occur from these areas under high voltage.

Sparking occurs when parts of the chamber surfaces holding electric potential discharge to points of lower potential. This can occur due to dust or other impurities being present on the surfaces allowing shorter distances over which to discharge.

### 3.2.4 Wiring Set-ups

Enamelled 1.5mm diameter copper wire was used to connect the anode to the feedthroughs. This had the advantage of being rigid but pliable, so it could be shaped to where it was needed for connections but maintained its position once it had been bent. The enamel coating also provides an insulating cover, removing the need for a bulkier additional layer to be added. Due to the absence of a large number of high voltage feedthroughs some BNC feedthroughs had to be used, though these were shown to be able to hold the required voltages in later tests of voltage application.

The initial wiring set-up on both anodes consisted of a central wire being affixed to the back of the anode using the non-conducting epoxy Arudite. One end was then soldered to a feedthrough which could be attached by a cable to a supply. Three points on the anode had the enamel sanded off. At these points shorter wires, were laid across the central wire, contacting at their midpoint. The enamel coating
from the shorter wire was also sanded off at this point. Silver epoxy was used to ensure the contact while non-conducting epoxy, Arudite, was used to reinforce it. The ends of the smaller wires were then each fed through one of the drilled holes in the anode to make contact with the copper surface; the ends of the copper wire protruding above the level of the surface were filed down to prevent sparking occurring.

This had the effect of unifying the anode segments, in effect unsegmenting the anode. The entire anode could then be run to obtain ion energies but not atomic numbers. Volts were applied to 1000V on the anodes and 900V on the Frisch grids to this set-up without difficulty. The lack of feedthroughs and preamps necessitated this combining of some of the circuits in addition to the restrictions on the acquisition software used. Future developments of the chamber could include preamp resistor networks being set up within the chamber, with one supply feeding all anodes but six different outputs resulting.
Figure 16: Basic schematic of A) the unsegmented wiring configuration and B) the partially segmented wiring configuration. The red line marks where wires leave the chamber at a feedthrough. The preamplifier unit receives power from the high voltage supply and conveys it to the anodes via a cable attached to a feedthrough. The same cable also conveys a signal corresponding to the charge on the anode to the preamplifier, which amplifies the signal before passing it onto the data acquisition system and its associated electronics.
Anode 1 was partially segmented to test that signals could be extracted from a segmented anode. The partial segmentation of the anode also provides an initial set up for charge measurements once effective algorithms and an effective acquisition system are available.

In this configuration, the anode was split into three segments, with signals extracted from the outermost two segments the innermost two segments and the middle two segments of the concentric circled anode. Three feedthroughs were used with two enamelled copper wires soldered to each. These were fed through the two appropriate holes in the anode to form three segments and held in place by silver epoxy and Arudite. The protrusions were again filed down and the surfaces further smoothed by the addition of a small amount of silver epoxy.

The two field ring circuits were powered by means of direct attachment of wires already present on the feedthroughs to the outer ring of the Frisch grids by means of silver epoxy. The two circuits were then grounded at the same point to ensure the same potential difference for each circuit.

Both grounding wires were attached to one of the chamber ends as this was the only method that allowed the grounds to be connected inside the chamber body. A shallow threaded hole is present in one of the chamber ends into which an M3 screw can be inserted. The grounding wires, of the same type as used for the anode connections, had solder tags attached through which a screw could be threaded. This allowed both wires to be attached to the hole in the chamber end. The other ends of the wires were attached to the field rings furthest from the anodes, by means of silver epoxy.

This method of attaching the grounding wire to the field ring proved to be satisfactory for the circuit associated with the end where the grounding was made but
for the further circuit the connection proved to be too brittle, as the weight of the cable caused cracking of the silver epoxy. The weakening of this connection caused periodic noise to appear on the anode output signals. The addition of Arudite was tried but found not to have a great improvement on the contact, so Solder paint was eventually used. The paint is applied to the field ring and grounding wire while the two are in contact and then heated using a heat gun to form a strong connection.

3.3 Gas Delivery System

The gas chosen was isobutane due to its availability at the University of Manchester and its ability to hold a large electric field without breaking down [20]. The gas was flowed in and out of the chamber by means of the gas delivery system in the laboratory. The diagram below shows the set-up:

![Diagram of Gas Delivery System](image)

*Figure 17: Diagram Detailing the Passage of Gas through the Experimental Set-up. Arrows denote direction of flow.*
Initially the chamber is brought down to a vacuum of $1.3 \times 10^{-5}$ mbar: to approximately $1 \times 10^{-2}$ mbar by rotary pump1 and to the final value by the turbo pump, which can be activated once the pressure in the chamber reaches $5 \times 10^{-2}$ mbar. These pumps vent the gases from the chamber directly into the atmosphere. It is necessary to bring the chamber down to a high vacuum to ensure the purity of the isobutane once it is pumped into the chamber. If atmospheric gases are present the drift velocity of the electrons may be altered, distorting range measurements. Sparking may also occur as atmospheric gases are more readily broken down by strong electric fields. This is especially true of water vapour.

Out gassing may occur from the components within the chamber. This occurs due to the presence of dirt or grease on the components within the chamber trapping pockets of atmospheric gas. The chamber must be pumped down for a significant amount of time to ensure the majority of the gas is removed. Additionally, it is important to keep the components as clean as possible during construction and maintenance in order to minimise the cause of out gassing.

Once the chamber is pumped in gas is fed through the gas system within the lab from the bottle to the gas cabinet. There are two valves to shut off the gas before it reaches the gas cabinet as well as a solenoid valve that is connected to a gas detector. These can all be used to isolate the system centred on the cabinet or chamber if a leak is detected.

The gas cabinet has a valve that can be set to allow gas into the system to maintain a set pressure, referred to as an auto set valve. The barotron measures the pressure at the inflow into the chamber and relays the pressure to the valve, which can be set to maintain the pressure value desired for the input. The valve will then open and close automatically depending on whether the pressure in the inflow is too low or
too high respectively. A valve is present between the inflow and the entrance to the chamber. If this is open the pressure within the chamber will eventually be equal to that of the inflow. The inflow reading is then set to the desired level for the rest of the chamber. The response time on the valve limits the accuracy of the pressure to be set accurately within ±2mbar. Through multiple adjustments the desired pressure can be reached but this commonly takes several hours. The slow response of the valve results from the vastly different volumes of the inflow pipe and the chamber, so the pressure takes time to equalise and is often not at the desired value. The dial used to set the desired pressure point also has an error of +7 to +8 millibar further impeding accuracy.

In order to keep a large proportion of the gas in the chamber un-ionised, the gas is steadily vented from the system. Provided the rate of gas output is not too high the auto set valve can compensate for the slow leakage by opening to a point where it inputs gas at the same rate as the gas is vented. The gas is expelled from the chamber through a pipe connecting to the gas cabinet where a valve is used to adjust the rate of pump out from the chamber. A gauge is located just after the pump out valve and has an associated valve showing the pump out pressure. By adjusting the valve so that the display read approximately $5 \times 10^{-1}$ mbar the gas pressure in the chamber can be maintained. The outflow is driven by a rotary pump, which expels the gas into the exhaust system present in the lab, where it is disposed of safely.
3.4 Voltage Testing

Testing of the ability of the chamber to hold the volts required for successful operation was undertaken before the input of gas into the chamber. High Voltage supply units were used, powered by their insertion into a nimbin. The units can output up to 2000V if required over two channels each. The trip levels could be set on the units and digital displays of both current and voltage from the outputs were available.

If the entirety of the volts required is applied at once sparking from the components forming the anode and Frisch grid circuits will likely occur. Components that are required to hold high voltage generally need to be “conditioned”, whereby the components are held at increasingly high amounts of voltage for extended amounts of time.

The chamber was pumped down to $1.3 \times 10^{-5}$ mbar and volts applied to the anode segments and Frisch grid circuits in increments of 50V until sparking was seen to occur as evidenced by the current readings on the power units being different to those expected. The expected current readings for the Frisch grid circuits could be calculated from Ohm’s law as both the value of the resistive chain and the voltage applied were known. The anodes were floating with no ground, so a value of 0µA should be constant. From these values the trip levels on the Power units could be accordingly set to a point allowing for minor sparking but to stop persistent sparking which could cause damage to the chamber occurring.

Severe sparking was found to occur at around 700V, too low for successful operation of the chamber. The resistor chain connections were filed down to make the connections as smooth as possible, with some connections being replaced. Arudite
was added to the anode connections to add insulation and the wires coming through the anode were filed further.

3.5 Pressure Regulation and Leak Testing

The pressure within the chamber was regulated by two pressure gauges attached to one of the chamber ports. One of these was a Pirrani gauge to measure the chamber at low pressure and the other an absolute gauge to measure high pressure values. These gauges could be used in conjunction with those on the gas system to ensure accurate rates of pumping through the system and also to ensure that there were no major discrepancies due to leaks in the system as a whole. Another gauge was also present above the turbo pump to ensure that the rate of pump out was satisfactory.

Before isobutane was pumped into the chamber the system was leak checked. For the chamber to be sufficiently gas tight the pressure in the pumped down chamber should reach $1 \times 10^{-5}$ mbar, as such the detection of a leak was initially undertaken by checking the pressure gauges. If the pressure did not drop below 1 mbar with the valve to the rotary pump fully opened then a severe leak was known to be present. The location of large leaks could be undertaken by applying alcohol to the suspected areas, notably the ports of the chamber sealed by o-rings as perishing of the rubber can occur over time. If there was a change in chamber pressure after the application of alcohol then a leak was present at that area. The alcohol can either act to temporarily fill the gap, lowering the pressure in the chamber for a short time or leak straight into the chamber, immediately raising the pressure. This method was used successfully to
ascertain that the large o-ring present at the anode 1 end of the chamber was ineffectual and had to be replaced.

Once the pressure was found to drop towards $1 \times 10^{-5}$ mbar, another gas leak detection system was used. This consisted of a spectrometer mounted above the turbo pump that was capable of detecting different masses and quantities of gases within the chamber. This system could only be activated at $5 \times 10^{-5}$ mbar to avoid damaging the filaments that constituted part of the detection apparatus so was not available for all leak checking.

The spectrometer was linked to a PC with the program Spectra RGA installed. This allowed a distribution of all gases detected in the chamber and their relative pressures within the chamber to be shown. Large quantities of nitrogen oxygen and water vapour indicate a leak. If the display was kept refreshing over a period of 10 minutes and the pressures of these three gases had not been shown to reduce and stabilise then a leak was almost certainly present [21].

To detect the source of a leak another function of the program was used. This allowed a high pitched tone to be emitted from the PC when a certain gas was detected by the spectrometer, the higher the gas pressure detected the higher the tone emitted. The program was calibrated to emit a tone when helium was detected and the ports and welds on the chamber were sprayed with helium from a compressed gas bottle. By this means very small leaks could be located. The large anode 1 o ring was found to still have a significant leak at several points along its circumference. On examining the chamber interior several narrow grooves that could allow gas to circumvent the o ring were discovered. These were smoothed out using wire wool, proving an effective solution to the areas of the leaks.
3.7 Configuration of Signal Processing Electronics:

Initial energy measurements were undertaken using the MAESTRO acquisition system. The MAESTRO software is able to generate energy spectra from a PCI card mounted on the motherboard of the computer with the software installed. The PCI card is able to generate an energy spectrum from a shaping amplifier output fed through an analogue to digital converter (ADC) [22].

The disadvantage of this system is that it only has one input so the unsegmented anode signal had to be used. A single anode segment will rarely detect all the charge from an event and hence will not be able to detect the total energy of an event; this precludes the use of a single anode segment to build an energy spectrum. As well as the input from the amplifier the ADC also requires a gate in order to record the relevant part of the amplifier signal. The output from the shaping amplifier is of a semi Gaussian form with the peak of the Gaussian type signal corresponding to the total energy of the event so the ADC must be gated about this peak. The electronic set-up is shown in figure 18, displayed on the following page.
Figure 18: Diagram showing the path of signals from the anode and Frisch grids of the chamber for generation of an energy signal and trigger respectively.

The signal was passed from the anode through a preamplifier unit attached via a short HV cable; of approximately 20cm, the shortest length available in order to minimise loss of signal resolution. The power supply was also fed through the preamp unit. The preamplifier circuitry is powered by a 12 volt supply provided by the shaping amplifier inserted in the nimbin. The output of the preamp is then sent to a timing amplifier with a shaping time of 0.5μs and a gain of 58 before being sent to the MAESTRO system.
The trigger was formed from outputs from the two Frisch grids. This gives an effective trigger for the formation of the gate as the gate is initiated approximately 2μs before the signal is detected by the anode, allowing the peak of the amplifier output to fall within the gate given sufficient gate width. The preamplifier signals are initially sent to two spectroscopy amplifiers to provide a peak signal which can then be sent to a discriminator. The Spectroscopy amplifiers were used as they can manipulate the longer Frisch grid pulses, which cannot be accurately achieved by the conventional shaping amplifiers.

The discriminator eliminates low energy outputs from the amplifier to ensure that only events caused by fission fragments are used as triggers. From the discriminator two signals are sent to separate gate and delay generators to allow delay to be applied to the signals if required. This ensures that the two signals are in coincidence when they arrive at the logic unit, in case there are discrepancies in the field on either side of the chamber or differences in the speed of the signals processed up to this point.

The logic unit is set to a coincidence level of two so that only when two fission fragments are emitted from the source, arriving at the two Frisch grids almost simultaneously, an output signal is resultant. This acts to further discriminate the trigger and lowers the event rate for better processing by the ADC. This trigger is then passed to two additional gate and delay generator for the generation of the gate to be sent to the ADC.

The gate and delay generators used were found to have too short a maximum gate width, of 4μs, to detect all the events. This was due to the collection times of the events being often greater than the gate length. The solution to this was to send the trigger from the logic unit to two gate and delay generators. One of the generators had
a delay set equal to the width of the gate so that the outputs of the two generators formed two gates with combined width of 8μs. The gates were then sent to another logic unit to sum the two gates. The summed gates were sent to a sum and invert generator, which changed the polarity of the output so that it could be recognised by the ADC. The second logic unit may not be necessary for future runs as its function can also be performed by the sum and invert generator.

The alignment of the gate and the pulses being sent from the shaping amplifier was undertaken using an oscilloscope triggered on the amplifier signal. By adjusting the delay on the two final gate and delay generators the gate and the amplifier signal could be seen to align on the scope as required. This process was undertaken whenever conditions within the chamber were changed to ensure that the gate always aligned with the amplifier signal. The oscilloscope could also be used to check the rise times of the signals and set the voltage and pressure in the chamber to change this. The rise times of the pulse must be less than 8μs in order for the total charge from an event to be detected in a time shorter than the gate. This requirement must be fulfilled so that the acquisition system is able to accurately measure the energy of the event.

Testing of the cables used was undertaken to ensure that noise levels were at a minimum. Many of the high voltage cables were found to be poorly grounded and signals from the related outputs would show low frequency noise. Tinfoil was used over connections and feedthroughs in some places to screen wires from background noise. Several of the BNC cables connected to the feedthroughs also proved to be poorly grounded and had to be replaced. Many of the preamps showed noise levels above the minimum acceptable level of 20mV. This level was chosen as the threshold of acceptability due to the standard pulse height of 400mV, giving an error of 5%.
CHAPTER 4: RESULTS AND DISCUSSION

4.1 Proof of Operation

Initially the Bragg chamber was tested in order to determine that all circuitry was connected and that the anodes were picking up signals from the ionisation of the gas in the chamber. This was determined by connecting the preamplifiers directly to an oscilloscope. The following outputs were recorded from the oscilloscope to verify that all chamber segments were detecting fission fragments operating as expected:

Figure 19: Traces from preamplifiers connected to the three segments of anode 1, averaged over 512ms. The traces, from top to bottom, represent the innermost circular segment, the outer ringed segment and the middle segment. Showing average pulse heights of: 180mV, 2mV and 4mV respectively. The anode segment voltages
were set at 1300V and the Frisch grid voltage at 1000V. The chamber pressure was 94.7 mbar

Evidence of fission fragment detection is shown on all channels, though the outer segments have a very small average pulse height. The pulses are shown to decay exponentially as expected from preamplifier outputs. Although high angle events will still deposit much of their charge on the central segment, a significant proportion should also be detected by the outer segments. As such, the vast discrepancy between the pulse height of the inner segment and outer segments indicates a definite bias towards lower angle events.

Figure 20 shows the trace from the unsegmented anode obtained under the same conditions:

![Figure 20: Traces from the central anode segment of anode 1 (top trace indicated by 1) and the unsegmented output from anode 2 (indicated by 2) averaged over 512 ms. Average pulse height of the unsegmented anode is 130±10 mV](image)

Figure 20: Traces from the central anode segment of anode 1 (top trace indicated by 1) and the unsegmented output from anode 2 (indicated by 2) averaged over 512 ms. Average pulse height of the unsegmented anode is 130±10 mV
The unsegmented side is also shown to detect pulses resultant from fission fragments. The fact that the trigger on the oscilloscope is set to the unsegmented channel, but also triggers pulses from the central segment is significant. This indicates that signals are being received from fission fragments being ejected simultaneously into both sides of the chamber, causing simultaneous detection at both anodes.

The lower pulse height of anode 2 compared to the height of the central segment of anode 1 can be explained by the direction of the source. Initially, the side of the gold foil to which the californium was applied was facing towards anode 1. Fragments detected by anode 2 then had to pass through the foil, resulting in lower energies detected. The washer, over which the foil was mounted, acted to narrow the acceptance angle of fragments emitted towards anode 2. This resulted in the absorption of higher angle events, lowering the count rate and the average value of the pulses detected by the unsegmented anode. For future measurements taken using anode 2, the source was turned so the uncollimated side faced the unsegmented side.

Figure 21, displayed below, shows the validity of the trigger used:
The trace above shows the validity of the trigger used. The leading edge of the trigger signal falls at the same time as the anode pulse is seen to rise. This ensures that a minimum of low energy noise is recorded before the pulse arrives and maximises the efficiency of the gate width.

4.2 Energy Spectra:

Energy spectra were recorded for changing gas pressures and anode and Frisch grid voltages to ascertain the energy resolution under changing conditions. The cleanest spectra and best resolution indicate the best settings for the chamber to be run at.

Energy Spectra were obtained using MAESTRO, providing a digitised image of all measured energies, with each channel corresponding to an energy range and each channel count corresponding to the number of events detected within that energy range.

The spectra were transferred to a program called Dataview, to obtain information on the different parameters of the energy and shape of fission spectra. An ideal spectrum has two equally sized peaks corresponding to light and heavy fragments emitted by the source. The rate of detection of light and heavy fragments should be equal, so each peak should contain the same number of counts.
By using a double Gaussian to fit the raw spectra, the number of counts in each peak can be obtained. This can be used to give information on the comparative rates of detection of light and heavy fragments. In practice the nature of the target, the trigger and the conditions within the chamber will have an effect on the relative rates of detection. The spectra with the most even ratio between light and heavy fragments can be used to give an idea of the best conditions for running the chamber.

The spectra presented on the following pages were obtained for changing chamber pressures and electric fields (effected by changing the Frisch grid voltages).
Figure 22: Spectra obtained for different pressures within the chamber while the anode and Frisch grid voltages were held at 1300 V and 1000 V respectively, in millibar: A) 49.2 B) 56.8 C) 65.7 D) 75.9 E) 85.1 F) 94.6. Peak heights, number of counts in each peak, standard deviation values and chi squared values are shown beneath each spectrum.
A) View 0: Spectrum '300to1200.txt' Chan 1 to 4095 - **Focus**

Fit to Sum of 2 Gaussian Function(s) performed: Solution parameters follow:

\[ E = 1651.80(0.73) \quad A = 2.57 \times 10^{-45} \quad \sigma = 3966 \quad H = 2312 \quad \sigma = 2.256 \quad \text{Reduced Chi}^2 = 2.550017 \]

B) View 0: Spectrum '300to1100.txt' Chan 1 to 4095 - **Focus**

Fit to Sum of 2 Gaussian Function(s) performed: Solution parameters follow:

\[ E = 1684.10(0.46) \quad A = 6.70 \times 10^{-45} \quad \sigma = 5398 \quad H = 5080 \quad \sigma = 3.673 \quad \text{Reduced Chi}^2 = 4.616201 \]
Figure 23 (previous pages): Spectra obtained for different Frisch Grid Voltages with the pressure in the chamber held constant at 94.7mbar and the anode voltage held at 1300V. The spectra peak heights, number of counts in each peak, standard deviation values and chi squared values are shown beneath each spectrum.

4.2.1 Ratio of the Number of Counts in the Heavy Fragment Peak and the Light Fragment Peak

All spectra recorded show a greater number of peaks in the heavy peak than in the lighter peak. The charts below show the ratio of counts for each spectrum, varying with electric field, pressure and reduced electric field.

A)
The heavy peak to light peak count ratio, in all cases, indicates a greater rate of detection of heavy ions than light ions. The change in the ratio is seen to be minimal for the change of the electric field between the Frisch grid and source, with a much greater variation occurring for the change of pressure in the chamber.
This indicates that for lower pressures, the faster moving light ions are not stopped within the chamber. Therefore, the ions will not deposit the entirety of their energy within the chamber, causing the removal of fewer electrons from the gas. This in turn causes light fragment events detected to be shifted towards the lower energy heavy fragment peak, as the entirety of their energy is not detected at the anode. The heavy peak then has an artificially high number of counts, skewing the ratio between the light and heavy peaks.

This is also visible from the shape of the spectra as the lower pressure spectra have less distinct peaks. A lower number of counts should separate the peaks, forming a “valley” between them. As the pressure lowers, the valley is seen to disappear from the associated spectra and the peaks are seen to become less distinct, eventually merging. Fitting was attempted for a pressure value of 38.2mbar, but the distortion of the spectrum was such that a double Gaussian fit could not be used.

The lack of distinction of the peaks has an impact on the error of the ratio of counts, as the width of each peak and, hence, the number of counts in each is not as well defined. More favourable operating conditions would result in less uncertainty in the number of counts per peak and better fits by Dataview.

Errors in the reduced electric field and Frisch grid voltages are primarily caused by the lack of significant figures on the displays of the power supply units, from which the values of voltage were taken. More accurate units were inoperable at the time the data was taken and should be used in future runs of the chamber.
4.2.2 Light Peak Resolution

The energy resolution is the most common measure of the efficiency of a chamber in measuring the energies of different fragments. The energy resolution of the chamber is usually obtained from the following:

\[
R_E = \frac{FWHM}{E} \tag{13}
\]

Where \( R_E \) is the energy resolution, FWHM is the full width half maximum value of the peak and \( E \) is the peak energy. The full width half maximum can be obtained, if the standard deviation is known from:

\[
FWHM = 2\sqrt{2 \ln 2} \sigma \tag{14}
\]

Where \( \sigma \) is the standard deviation of the distribution.

The data obtained using the MAESTRO system takes the form of a broad spectrum, rather than providing a width for the peak energy, so the resolution cannot be extracted by this means.

A similar form of the standard calculation of energy resolution can be obtained using the following quantity \( R \) defined as:

\[
R = \frac{\sigma}{E_{lp}} \tag{15}
\]
Where $\sigma$ is the standard deviation of a spectrum and $E_{lp}$ is the peak energy of the light fragment peak. This quantity can be plotted against changing electric field and pressure to provide another measure of the efficiency of different chamber operating conditions. Higher values suggest a loss of resolution under the corresponding operating conditions. Values for the standard deviation and light peak energy of all spectra are tabulated below.

<table>
<thead>
<tr>
<th>Pressure (mbar)</th>
<th>Standard Deviation ($\sigma$)</th>
<th>Light Peak Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.2</td>
<td>184.80</td>
<td>2469.18</td>
</tr>
<tr>
<td>56.8</td>
<td>183.14</td>
<td>2505.79</td>
</tr>
<tr>
<td>65.7</td>
<td>197.17</td>
<td>2340.43</td>
</tr>
<tr>
<td>75.9</td>
<td>219.06</td>
<td>2209.16</td>
</tr>
<tr>
<td>85.1</td>
<td>237.86</td>
<td>2060.87</td>
</tr>
<tr>
<td>94.6</td>
<td>254.21</td>
<td>1765.23</td>
</tr>
</tbody>
</table>

*Table 8: Standard deviation and light peak energy of the spectra obtained for changing chamber pressures.*

<table>
<thead>
<tr>
<th>Frisch Grid Voltage (V)</th>
<th>Standard Deviation ($\sigma$)</th>
<th>Light Peak Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>352.39</td>
<td>2825.05</td>
</tr>
<tr>
<td>1100</td>
<td>352.86</td>
<td>2788.77</td>
</tr>
<tr>
<td>1000</td>
<td>380.10</td>
<td>2996.09</td>
</tr>
<tr>
<td>900</td>
<td>344.50</td>
<td>2489.6</td>
</tr>
</tbody>
</table>
Figure 25 shows the variation of the quantity $R$ with pressure, Frisch grid voltage and reduced electric field:

A)

```
<table>
<thead>
<tr>
<th>Chamber Pressure (mbar)</th>
<th>σ/E (keV⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.02</td>
</tr>
<tr>
<td>50</td>
<td>0.04</td>
</tr>
<tr>
<td>60</td>
<td>0.06</td>
</tr>
<tr>
<td>70</td>
<td>0.08</td>
</tr>
<tr>
<td>80</td>
<td>0.10</td>
</tr>
<tr>
<td>90</td>
<td>0.12</td>
</tr>
<tr>
<td>100</td>
<td>0.14</td>
</tr>
</tbody>
</table>
```

B)

```
<table>
<thead>
<tr>
<th>Frisch Grid Voltage (V)</th>
<th>σ/E (keV⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>0.07</td>
</tr>
<tr>
<td>800</td>
<td>0.09</td>
</tr>
<tr>
<td>900</td>
<td>0.11</td>
</tr>
<tr>
<td>1000</td>
<td>0.13</td>
</tr>
<tr>
<td>1100</td>
<td>0.15</td>
</tr>
<tr>
<td>1200</td>
<td>0.17</td>
</tr>
<tr>
<td>1300</td>
<td>0.19</td>
</tr>
</tbody>
</table>
```
Figure 25: Plots showing the variation of $R$ with A) Pressure B) Frisch Grid Voltage and C) Reduced Electric Field

Higher reduced electric fields show a clear improvement of the $R$ values. Changes in Frisch grid voltage have a limited effect on the $R$ values while lower pressures are seen to have lower associated values of $R$. Lower chamber pressures are seen in table 8 to generally result in both higher light peak energies and smaller standard deviation from the Gaussian fit.

The smaller peak energies registered for higher pressures suggest a loss of charge carriers arriving at the anode. The actual distribution of the energies of fission fragments is unaffected by the chamber conditions so the reduction in the peak energy is due to energy losses within the chamber.

The reduction of the number of charge carriers present in the chamber can be explained by electron recombination. The greater number of gas molecules present in the chamber for higher pressures will increase the number of collisions that the electrons travelling towards the anode will encounter. If an electron is slowed
sufficiently by a number of collisions it can be captured by a gas molecule and as such will not induce a charge on the anode.

By maintaining a higher electric field and, hence, drift velocity this can be counteracted. The changing of the rates of heavy and light fragment detection for lower pressures, indicate that electron recombination is combated more preferably by a higher Frisch grid voltage than by a lower pressure.

The fact that other chambers have been run at lower fields with good levels of energy resolution suggests that electron recombination may not be the soul cause of the reduction in peak energy.

Inefficiency of the Frisch grid used could also contribute. The increase in the number of positive ions generated in the chamber for higher pressures will cause a larger positive charge to be induced on the anode, reducing the charge induced by the electrons. The Frisch grid will screen much of this but will not have 100% efficiency. Loose wires were also present at several points on the grid, further reducing the grid efficiency. Additionally, the simultaneous emission of two fragments into the chamber will cause twice as many positive ions to be released from the gas as for single anode Bragg chambers. The positive ions on the anode 1 side of the chamber will also be driven towards the anode 2 side by the charge held on the anode 2 segments. This will further lower the peak energy for higher gas pressures.

Loss of resolution and lowering of the peak energy can also result from inconsistencies in source depth. The variable thickness of the source causes variation in the energy loss of fragments emitted by the source, as some fragments will have to pass through much more of the source than others. This explains the variation in peak energies of the measurements taken for changing electric field strength in the field, as these measurements will have the same rate of electron recombination. The method of
applying californium to the gold foil using an acid solution can result in an uneven distribution of californium atoms on the foil. Due to the high rate of corrosion of the hydrochloric acid used, the source may also contain impurities both from the solution and from the gold and surrounding aluminium slide as the acid reacts with its surroundings before evaporating.

4.3 Rise Times and Fragment Depth

In order to determine whether fission fragments are being stopped within the chamber or not the depth that they reach within the chamber must be calculated. Rise times were obtained for varying pressure within the chamber using the rise time function on the oscilloscope. The rise time was taken for the average signal of the anode 2 preamp over a period of 512ms. Using formula (16), for the average drift velocity of electrons in isobutane under the influence of an electric field, the average depth the ions reach in the chamber can be calculated. Assuming that electrons colliding with isobutane are completely stopped within the chamber, and that collisions will occur due to thermal movement much more than due to the field influence, formulas (16) and (17) can be used [7]:

\[ v_d = \sqrt{\frac{2eE}{m}}l \] (16)

Where, \( e \) is the charge on an electron, \( E \) is the electric field strength within the chamber, \( m \), is the electron rest mass and \( l \) is the mean free path of electrons and is given by:

\[ l = \frac{RT}{\sqrt{2} p \sigma} \] (17)
Where \( R \) is the ideal gas constant, \( T \) is the chamber temperature, \( p \), is the chamber pressure and \( \sigma \) is the collision cross section of the free electrons with the isobutane molecules. The values of \( p \) and \( T \) were measured while \( \sigma \) values were taken from reference data of electron collision cross sections in isobutane [23].

Initial signals indicated that some ions were being stopped after the Frisch grid resulting in distorted outputs from the anode due to movement of the gas ions beyond the screening effect of the grid. The distortion of the energy spectra used with lower pressures also indicates that this was the case. Rise times for pressures from 69.7mbar to 126mbar were recorded. The variation of depth with chamber pressure is displayed below:

![Graph showing the variation of average fission fragment depth in the chamber with chamber pressure](image)

*Figure 26: The variation of average fission fragment depth in the chamber with chamber pressure*

The Frisch grid to source distance is 10cm. The plot shows that, for pressure values below 105mbar, the average distance of fragment is most likely over 10cm.
This suggests that the chamber should be run at a pressure of at least this value. Conversely the pressure of the isobutane should not be so great as to lengthen the rise time to a degree where it is longer than the gate on the trigger for the ADC. In order to maintain the rate of electron connection at the anode the electric field should be increased to compensate. However, if the electric field within the chamber is high enough, the drift velocity of electrons will be high enough to ionise gas molecules that have been unaffected by the presence of fission fragments. The additional electrons released will distort the energy spectra to give a higher count for light fragments. The limit for the electric field that can be applied must be examined in future work.

The classical approach used to calculate the range is simplistic, assuming that electrons in isobutane behave in the same way under a high electric field as they do under the influence of a small or non-existent electric field. The assumption that electrons are stopped after every collision is also highly flawed.

The data used for electron collision cross sections was also taken from low energy measurements. The electrons in the chamber, accelerated by the electric field present were around the maximum energy for which the cross-sectional data could be used, increasing the error on the mean free path measurements. Future values should be calculated using data obtained of electron behaviour under strong electric fields in isobutane.

Errors present on the ion depth measurements also result from inaccuracies in measuring the temperature and pressure within the chamber. The temperature in the chamber was taken as not differing significantly from the laboratory due to the constant flow of gas through the chamber, though this did not take into account the low pressure of operation and heating effects of the high current through the field rings.
An error on the pressure was extracted through observation of the pressure gauge present on the gas cabinet. Changing of the pressure in the system was seen when it was meant to be at a constant value. This is thought to be as a result of the constant flow of gas through the system being regulated by the autoset valve. As this valve systematically opens and closes to keep the pressure constant there is a delay in the system response and small fluctuations in the gas pressure can occur. This is more apparent in the small diameter piping around the gauge. By mounting a pressure gauge on the chamber itself, the fluctuation in pressure can be observed in the chamber. The fluctuations should have a lesser effect in the chamber body due to its increased volume, by observing the chamber pressure directly this could be verified or discounted and the actual fluctuation in pressure measured. If the fluctuations are lessened within the chamber then the error in pressure is reduced.

4.4 Implications for Chamber Operating Conditions:

The major problems for the efficiency of data collection and the accuracy of data collected are the stopping of all fission fragments within the chamber before the Frisch grid and the elimination of electron recombination. None of the operating conditions used satisfied both of these requirements. The spectrum that provided the best compromise can be seen from the plot of heavy peak counts/light peak counts x $R$ against electric field shown in figure 27.
Figure 27: Heavy Peak Counts divided by Light Peak Counts multiplied by R plotted as a function of reduced electric field in the chamber.

The spectrum giving the best operating conditions is seen to be that which was obtained for an operating pressure of 85.1 mbar and an electric field of 100V/cm. The large errors and lack of a discernible trend when both data sets are considered to indicate both that more spectra need to be taken to provide a more accurate measure of the ideal operating conditions and that both electron recombination and the non-stopping of ions within the chamber both distort energy spectra in roughly equal measure.

The range measurements obtained show that a significant proportion of the fragments are not fully stopped in the chamber for a pressure of 85.1 mbar, and further emphasise the fact that these conditions of operation are still not ideal. A higher pressure within the chamber, coupled with a higher electric field is thought to be an effective solution to electron recombination and fragment stopping. Future runs of the chamber should be undertaken at higher values of both Frisch grid voltage and chamber pressure to test this.
4.5 Future Work and Developments

As mentioned in the previous section the chamber must be run for longer with a higher electric field and pressure. A value for the energy resolution shall be calculated, for which a different acquisition program to MAESTRO must be used to output a form of the energy peak for which a FWHM maximum value can be obtained. This would provide a point of comparison with other chambers, as well as an accurate measure of the error in peak measurements.

The improvement of the screening efficiency of the Frisch grids should also be undertaken. The movement of positive ions towards the centre of the chamber could account for losses in the chamber resolution. Both Frisch grids had loose wires, reducing their efficiency. The rewiring of the Frisch grids shall be undertaken to reduce the inefficiency of each grid and to ensure that the whole of each anode is effectively screened. The addition of a grid at the centre of the chamber surrounding the source shall be undertaken in order to screen one side of the chamber from the ion movement in the other side of the chamber. This will be a split disc of mesh attached onto the ends of one of the sets of the support pillars and will have the same dimensions as the field rings.

The purpose of Bragg chambers is to measure the atomic number and energy of ionising particles entering the chamber. As such, it can be stated that the chamber constructed is at this stage only fulfilling half of its function. An improved acquisition system should be used, which can accept more than one input, for use with the segmented anodes. The MIDAS acquisition system, will be used once the software can be set-up. This will improve the resolution of spectra taken and enable the
recording of multiple inputs at once, allowing simultaneous atomic number and energy readings to be taken.

A method for calculating the atomic number of the fission products based on the relationships discussed in section 1.1.2 will be implemented. The masses of the fragments should be calculated for future runs using a source of reliable mass. This also requires improvements to the energy resolution of the chamber. Differences in TAC outputs as used by Oed could be used to differentiate between different Z values, with the digitisation of pulses providing lower resolution in conjunction with MIDAS.

Algorithms need to be developed to process the data to account for large angle events that will distort the range and specific ionisation measurements necessary for the extraction of charge measurements for Bragg and sub-Bragg measurements. More accurate measurements of the drift velocity in the chamber will be required for more accurate range values required as a basis for the algorithms.

For higher energy events, large angle events will compress the measured stopping range and increase the height of the Bragg peak. By using the energy measurement to ascertain the actual range of a particle of that energy in the chamber, the change in height of the Bragg peak can be ascertained. By also identifying the segment on which the Bragg peak falls, the signal can be corrected. Many studies have resulted in empirical models of the behaviour of electrons in isobutane under high electric fields [7]. Data from such a study would improve the performance of any algorithm.

Full segmentation of anode 1 must also be undertaken in order to provide better angle resolution than the set up with three segments. High voltage feedthroughs must be used in place of BNC feedthroughs where possible to ensure that excessive
noise or restrictions in applicable voltage are minimised. Additional preamps need to be used to process all signals. Eventual movement of all preamps into the chamber housing should be undertaken in order to reduce noise picked up in transit along the wires from the anode.

A better model of electron drift velocity in the chamber would also benefit calculations of the depth inside the chamber attained by fragments. This would allow the pressure to be more accurately changed to give a good event rate while ensuring that fragments are stopped within the chamber.
CONCLUSION

In conclusion the Bragg chamber was built to specification and was shown to be able to obtain energy spectra from a fission source placed at the centre of the chamber. The variation of a form of resolution of the spectra with different chamber pressures and voltages was measured. Although this indicated problems with the operation of the chamber at low pressure and voltage and with Frisch grid inefficiency, these can be corrected to improve the resolution of the chamber for future experiments.

Signals were obtained from all anode segments, proving that all segments worked in the fashion anticipated, although the order of magnitude of signals from the wider angle segments was not as high as was expected. The trigger used for the acquisition system was found to be accurate and provided a gate with an adequate time gap to register the charge from events. The MAESTRO system provided a good system of recording energy spectra but future measurements should preferably be made over several channels simultaneously, in order for the segmented anodes to be used and charge values to be obtained for the fragments.

The methods of construction and materials were found not to be detrimental to the performance of the chamber. Greater accuracy in the dimensions of components, such as the anode circuit board thickness and slot width, would make assembly for future chambers easier. Aside from this all techniques used allowed the chamber to be constructed in a satisfactory timeframe.

Future tests that should be taken to improve chamber performance include running with a different gas to isobutane, and running the chamber at a higher reduced field as a result of higher voltages and chamber pressures.
Despite the problems associated with the running of the chamber to this point, the proof of operation of a chamber with such a large acceptance angle provides a good basis for future developments to be undertaken. Electron recombination and the incomplete stopping of ions in the chamber can be remedied by changing the chamber operating conditions, and Frisch grid inefficiency can be lessened by repairs to both current Frisch grids and the addition of another central grid. If the energy resolution is improved and a system is developed for ascertaining the atomic number of heavy ionising particles, the chamber will prove to be a valuable tool for fission fragment spectroscopy.
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