For NIMS A

A NEW DETECTOR ARRAY FOR CHARGED PARTICLE SPECTROSCOPY

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Abstract

A compact and highly segmented detector array consisting of 44 gas–silicon–caesium-iodide, position sensitive, particle identification detector telescopes and up to 10 position–sensitive, silicon strip detectors has been constructed for the study of light-ion–heavy-ion reactions including cluster break–up in the energy range $5 \rightarrow 15$MeV/nucleon. The detectors are housed in a purpose built vacuum chamber. The particle identification telescopes are placed in fixed positions, covering the forward hemisphere from $3 \rightarrow 30^0$ in the laboratory with the target placed at 535mm from the front of the telescopes or $6 \rightarrow 52^0$ with the target placed at 215mm. The strip detectors are placed in any of 30 fixed positions in the forward hemisphere.

For 85MeV ^{12}C ions the telescope energy resolution (gas plus silicon) is 345keV with an angular resolution of 0.03^0. Using the gas–silicon section

ions with Z up to 21 can be identified. For ions that pass through the silicon isotopic identification is achieved using the silicon–CsI combination. The strip detector energy resolution is 200keV, with an angular resolution of 0.1^0.

I. INTRODUCTION

In recent years there has been a large amount of theoretical and experimental interest in exotic cluster structures in nuclei [1,2], in particular those with A<40. Several of the experimental studies have used break–up reactions to investigate large scale clustering [3–5], and multiple–alpha particle decays to look at the resonant structures in systems such as $^{12}\mathrm{C}+^{12}\mathrm{C}$ [6,7].

These of measurements demand a flexible detection system capable of efficiently identifying multi–fragment events amongst a high flux of other reaction products. It is necessary to kinematically reconstruct each event to determine the excitation energy of the break–up state, hence accurate energy and angular information are also required.

The majority of studies reported to date have used detection systems consisting of just a few detectors, for example see references [6,8,9]. These have been either position sensitive strip detectors (PSSD) for the multiple α–particle decay studies [10] or $E\Delta E$ telescopes for the break–up studies [15]. These arrays have a relatively low detection efficiency and, because of the small phase space coverage, necessitate the use of several angular settings to provide sufficient data.

To further our knowledge of nuclear clustering it is necessary to investigate a wide range of systems with large energy and angular coverage and to have the capability to perform light-ion–heavy-ion coincidence measurements. The present detector systems do not have the ability to perform these tasks efficiently. To overcome these inadequacies a new Multi–Element Gas–Hybrid Array (MEGHA) has been constructed utilizing new large–area sheet resistance detector technology as well as strip detectors.

This paper discusses the construction and performance of MEGHA. Section II gives a general description of the array. In section III the construction of the detectors, vacuum chamber and gas handling system are described in detail, and in section IV the operation of the detectors is reviewed and the results of some of the initial measurements using the array are presented. Another paper [11] discusses in detail the innovative data acquisition system that has been constructed for use with MEGHA.

II. GENERAL DESCRIPTION

Figure 1 shows a schematic drawing of MEGHA and its associated vacuum chamber. The facility is capable of operating with several different detector configurations, all of which use the same readout system [11].

When used as a particle identification array it has 44 three–detector (gas–silicon–CsI) telescopes which are housed in five, independent, vacuum–sealed modules, each comprising a 3×3 array of telescopes. The modules are mounted in the rear of the vacuum system as in figure 1 and are arranged in the form of a cross about the beam direction, with the central telescope of the central module removed to allow the beam to exit. Propane gas, for the operation of the gas detectors, is supplied through the base of each module. Three preamplifier 'cans', each accommodating the electrical and signal connections for three telescopes are attached directly to the rear of each of the five modules.

When used as a strip detector array up to 10 silicon position sensitive strip detectors (PSSD) can be mounted on any of 30 fixed–position pillars, and are orientated to face the target position. The pillars are fixed to a removable mounting flange, as shown in figure 1, which is attached to the inside of the vacuum chamber.

The facility can also be used in a mixed configuration with both strip detectors and the telescope modules in use. The addition of ancillary detectors is planned to include γ–ray detectors in the backward hemisphere, and segmented liquid scintillator modules, for neutron detection, to be mounted in place of one or more of the telescope modules.

III. DETECTOR CONSTRUCTION

A. Heavy Ion Modules

1. General Construction

Figure 2(a) shows schematically a longitudinal cross section through one of the modules and figure 2(b) shows the layout of an individual telescope. Each telescope consists of an axial field gas ionisation detector, a large area (50 $\times$ 50mm) 2–dimensional position sensitive silicon detector (PSD) and a thallium activated caesium-iodide scintillator (CsI) with a photodiode readout. The gas–PSD combination is used for particle identification and measurement of low energy heavy ions (He to Sc), whilst the PSD–CsI combination is used for identification of high energy light ions that pass through the PSD. In both cases the PSD provides angular information across the full face of the telescope. The telescopes are closely packed into the individual modules with 9 in each of the four 'outer' modules and 8 in the central module. This gives a total of 44 telescopes in the array.

The module body is constructed from stainless steel in three sections. The backplate is machined from solid material 16mm thick and incorporates all the signal and gas connections for the telescopes. There are ten 16–way IDC compatible vacuum feedthroughs; nine are used for the PSD and gas detector signals from the telescopes and the tenth for all the signals and other electrical connections from the nine CsI scintillators. In addition there are 12 hermetically sealed SMC bulkhead connectors, one of which is used for the bias to the gas detector anode; the remainder are available for future developments of the system. Gas input for the ionisation detector is through a 3mm Swagelok connector and the gas leaves the module through a 10mm Swagelok fitting. The main body is made from four 2mm plates welded together with 7mm thick flanges on each end. The rear flange is 232 $\times$ 232mm square and the body tapers to the front flange that is 161.5 $\times$ 161.5mm square over a distance of 95mm. The inner edge of the rear flange forms the vacuum surface to seal the modules against an 'O'–ring into the main vacuum chamber. The front of the module is sealed by a gas tight window held in place by a window clamp formed from 8mm thick stainless steel with a 3 $\times$ 3 array of 52 $\times$ 52mm openings that are aligned to the detector telescopes. The window is made from a single sheet of 3.5μm thick aluminised mylar glued to a thin, 0.5mm, stainless steel sheet with nine 45 $\times$ 45mm square holes which define the entrance aperture of each telescope. This is bolted, against an 'O' ring seal, to the main body and held in place by the window frame. This forms nine 45 $\times$ 45mm windows. The central module has a 15mm internal diameter central tube sealed from the gas volume. This is used to transport the beam out of the scattering chamber into the beam dump situated 2m behind the module. All detector components are mounted from the backplate such that the main body and front window can be removed as a unit to give access to the detection elements

2. Gas Ionisation Detector

The gas detector is an axial field ionisation chamber with a central anode, operated with a continuous flow of commercial grade propane. The gas supply is monitored and controlled by a custom built gas and vacuum control system [12] designed to maintain gas pressures from 40 to 150torr to within $\pm$ 0.1torr. All the telescopes in a module operate in a common gas volume. The aluminised surface of the front window which faces inwards and is earthed through module casing provides one of the two cathodes of the ion chamber. The second cathode is constructed from 20μm gold coated tungsten wires wound with a pitch of 1mm onto a frame constructed from 3.2mm thick printed circuit board (PCB), into which nine 52 $\times$ 52mm sectors are machined. This second cathode is placed immediately in front of the PSDs, as illustrated in figure 2(a). The anode grid that is placed midway between the two cathodes is of a similar construction except that each of the nine sections of the anode is electrically isolated to provide individual gas signals for each telescope. The distance between the cathodes and anode is 25mm. The two gridded electrodes are mounted from the backplate of the module on four 60mm screwed rods as shown in figure 2(a).

Timing, angular information and the principal energy signal (E) are obtained using large area resistive sheet position sensitive silicon detectors (PSD) with an active area of 50×50mm. Two thicknesses of these detectors are available, 385μm [1] and 500μm [2]. Both thicknesses of detectors have a similar construction that is shown schematically in figure 3. The central high resistance p–type surface layer ($20\mathrm{k}\Omega_{\Box}$ for the 385μm PSDs and $11\mathrm{k}\Omega_{\Box}$ for the 500μm PSDs) is produced by implanting boron ions into an n–type silicon substrate. This central area is framed by a square low resistivity area of $2.25\mathrm{k}\Omega$/side produced by boron implantation on the 385μm PSDs and $1.1\mathrm{k}\Omega$/side produced by an evaporated aluminium layer on the 500μm PSDs. The low resistance area reduces the regular 'pin–cushion' position distortion apparent in uniform resistance PSDs [13,14]. The silicon slice is glued to a PCB frame. Four electrodes, a to d, one at each corner are formed from 500μm thick aluminum contacts and are connected to gold pins in the PCB by thin gold wires ultrasonically bonded to the PSD surface then sealed in epoxy resin. The four signals generated at these contacts by resistive charge division are used to determine the position of the incident ion. A fifth signal is taken from the low resistance rear face of the detector via a thin gold wire to a fifth pin, e, in the PCB frame. This signal provides an independent energy measurement. The PSDs are mounted, via the pins a to e, in a 3×3 array on a mounting frame made from standard PCB with nine 50×50mm holes cut into it. The frame is mounted on the same threaded rod used to hold the gas detector grids. This ensures that the sensitive areas of the gas and silicon detectors are aligned. The signals from each row of three telescopes go to a single multi–way connector on the edge of the PCB mounting frame and are passed to the pre–amplifiers using one of the 16–way IDC vacuum feedthroughs in the backplate of the detector. The pre–amplifiers are mounted directly onto the outside of the module

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[1] Manufactured by Hamamatsu Photonics, 1126–1 Ichino–cho, Hamamatsu City, 435–91, Japan.

[2] Manufactured by Eurisys Mesures, Parc des Tanneries–1, Chemin de la Roseraie, Strasbourg

backplate, to reduce noise, in three removable groups of 18. Each group of 18 pre–amplifiers is connected to a row of three telescopes. The pre–amplifiers in each group are shielded from the others by an earthed metal can that fully encloses them.

4. Caesium–Iodide Scintillators

A CsI scintillator[3] is mounted directly behind each PSD. The main function of the scintillators is as a stopping detector for particles that pass through the silicon detectors allowing high energy light ions to be recorded. The construction of the scintillators is illustrated in figure 2(b). They have an active thickness of 10mm, which is sufficient to stop protons and alpha particles with approximately 50MeV per nucleon. Their active area is 50×50mm square to match the dimensions of the gas detector and the PSD. To provide a detector with a compact size without compromising the light collection the CsI crystal is machined to give a 15mm deep section tapering linearly from the 50×50mm section to a 18×18mm square face coupled to a 18×18mm square S3204–03 Hamamatsu photodiode with a quantum efficiency in the range $80 \rightarrow 90\%$. The crystal is wrapped in 6μm thick aluminised mylar, with a single layer on the front entrance window and multiple layers on the sides and taper of crystal. A low noise, high gain pre–amplifier is mounted on a PCB and is closely coupled to the photodiode. The PCB also contains the filter circuits for the pre–amplifier power lines and the photodiode bias supply.

The scintillators are held in place in the modules by the combination of an aluminium alloy frame with nine square holes, a front mask with corner 'lips' which prevents forward movement, and individual clamps for each scintillator provided with two springs linked to the alloy frame. Each clamp is machined from nylon in two halves to match the taper on the rear of the crystal. It is assembled around the taper and screwed together; the two springs locate in holes in the clamp and are stretched forward to locate in corresponding holes in

[3]Manufactured by Scionix Holland B.V., P.O. Box 143, 3980 Bunnik, The Netherlands.

the aluminium frame. Connections for the signal, the photodiode bias and the power for the pre–amplifiers for all the scintillators in a module are made via a single 16 way ribbon cable connected to one of the 16–way IDC feedthroughs on the backplate of the module.

B. Strip Detector Array

Figure 1 shows schematically the strip detector array mounting flange, with PSSDs and their mounting pillars located in 17 of the 30 available positions. The detectors in the left half of the forward hemisphere have been removed for clarity. The flange is machined from 12mm thick aluminium alloy with an outer diameter of 650mm. A central 250mm diameter cut–out prevents the flange from masking the downstream telescope modules. The 12 circular cut–outs near the flange perimeter reduce the weight of the assembly to 6kg so that it can be inserted and removed easily by hand.

The flange sits inside the main chamber volume with the upstream face 188mm from the upstream target position. To enable the flange to be periodically removed for maintenance and detector changes, without the need for precise re-alignment each time, it is hung from a single, 15mm diameter, stainless steel dowel on a fixed, aluminium mounting ring (not shown in figure 1) and locked in position using 6 Allan cap screws.

Up to 10 PSSDs can be individually mounted in any of 30 fixed positions. The PSSDs have a 32–pin connector, fixed at 90^0 to the edge of the detector PCB, which locates in a 36–way feedthrough attached to a pillar extension – no other support for the detector is required. The pillar extension is angled such that the line joining the PSSD centre to the target position is normal to the PSSD face.

The PSSDs are manufactured by Hamamatsu Photonics in a similar manner to the resistive sheet PSDs except that the p–type front face is segmented into 16 independent strips each 50mm long, 3mm wide and 500μm thick. Two signals are extracted from each strip via gold wires ultrasonically bonded to both strip ends and connected to pins on a 34–way feedthrough on a detector PCB mount. The signals, generated by resistive charge division along the strip axis, are used to calculate the position of particle incidence, to make an energy measurement, and to provide timing information for up to 16 simultaneous particle hits.

Twisted–pair, 36–way, ribbon cables are attached to the other side of the 36–way feedthrough on the pillar extensions and carry the detector signals to 42–pin 'Amphenol' hermetically sealed connectors fixed in one of the side flanges of the main chamber. The ribbon cables also carry the detector bias. The strip detector preamplifiers are located in racks immediately adjacent to the vacuum vessel.

C. Vacuum Chamber and Gas Handling

Both the strip detector array and the telescope modules are mounted in a purpose built vacuum chamber as illustrated in figure 1. There are two remotely operated target ladders, each with six target positions available. A vacuum interlock at the chamber base enables targets from the upstream ladder to be changed without letting the main vacuum chamber and beam line up to atmospheric pressure. The upstream target position, located 535mm from the front of the telescope modules, can be used with both the modules and the strip detector array. The second target position, located 215mm from the front of the telescope modules, can only be used with the modules as it is located downstream from the strip detectors. The unscattered beam leaves the vacuum chamber through the beam tube in the central module and is measured using an electrically suppressed Faraday cup located in a shielded beam dump situated 2m behind the vacuum chamber.

Access to the inside of the vacuum system is through one of two 280mm diameter ports on the sides of the central section of the chamber. This allows PSD calibration grids to be removed and module windows to be changed without removing the modules from the chamber. One of these ports contains the 42–pin 'Amphenol' feedthroughs for the strip detectors. Alternatively the chamber can be split at the 'chamber split point' shown in figure 1 with the rear of the chamber free to slide towards the beam dump on precision rails to allow greater access. This is necessary for maintenance and access to the strip detector array.

The gas and vacuum handling system performs two basic operations. Firstly to evacuate both the scattering chamber and telescope modules. This is performed in two stages using sequentially a rotary pump, two liquid–nitrogen–cooled sorption pumps and finally two turbo–molecular pumps; one with a rating of 400 l/s is situated immediately below the central section of the chamber and the other, a 230 l/s pump, immediately in front of the beam dump. The system is capable of maintaining a pressure of $5\text{x}10^{-7}$torr in the main chamber with all five modules at a gas pressure of 150torr. Initially the modules and chamber are pumped in tandem using the rotary through a needle valve to control the pumping rate. This ensures that the pressure in the modules is always within $\pm$2–3torr of that in the chamber to avoid damaging the mylar windows. Below 30torr the pumping rate is increased by bypassing the needle valves. The rotary pump is replaced by the sorption pumps at $\sim$ 1–2torr which then take the pressure down to a minimum of $\sim$ 0.03torr. This pressure is an adequate starting point for operation of the gas detectors. Therefore, at this point, the chamber is isolated from the modules. The system usually reaches a pressure of $1\text{x}10^{-5}$torr within 1 hour using the two turbo–pumps. This pressure is sufficient to open the vacuum system to the beam line.

The gas and vacuum handling system is also required to provide a continuous flow of propane gas to the gas detectors with pressures in the range 40$\rightarrow$150torr. The propane gas is bled into the modules at a rate controlled by an automatic flow control valve. The pressure at the module exhaust is measured by a calibrated pressure transducer which acts as a feedback element to the control valve. The flow rate is controlled manually via a needle valve. The pressure in the module can be quickly stabilised to within 0.1torr of the reference set in the control valve.

So that measurements involving heavy-ion–light-ion coincidences, e.g. α–^{24}Mg, can be made a dual pressure facility has been built into the gas handling system allowing different modules to operate at the optimum pressure for the fragments being detected. Each of the five modules can be fed from one of two duplicate systems, each with a separate manifold, flow control valve, pressure transducer and exhaust needle valve.

As a safety consideration, to prevent a spark ignition of the propane gas, all valves in the system are operated pneumatically, and are physically separated from the electrical components. Correct operation of the many valves is ensured by a programmable–logic–control computer which also protects the system in case of valve, pump or electrical failure.

D. Angular Coverage

Figure 4(a) shows the angular coverage of the full telescope array. The angle θ is the angle to the beam axis from the upstream target position, and ϕ is the azimuthal component of θ in the plane normal to the beam axis. The locii in figure 4(b) show the angular positions along the central axis of each individual PSSD strip, assuming that PSSDs are located in all 30 possible positions. The angular coverage of the telescopes and PSSDs are symmetric about ϕ=0^0 and therefore only half of the full 360^0 range of ϕ is plotted.

Due to the close packing of the PSSDs a small degree of overlap causes masking of portions of some strips, however, the total possible angular coverage obtained from the MEGHA array is very much larger than previously possible [15].

E. Instrumentation

For the initial measurements reported here, the electronics and data acquisition system, with the exception of the pre–amplifiers, were the same as those used for the previous array [15].

The pre–amplifiers for the PSDs and gas detector signals are of a similar design to those used previously [15] except that they are manufactured using surface mount technology. This technique has made them small enough to enable 54 to be attached to the rear of each module. The four signals from the position electrodes of the PSDs are fed to the pre–

amplifiers using a simple resistive network as shown in figure 3. This allows a direct path for the leakage current to ground via the 100kΩ resistor.

Charge ‘offset’ resistors of 1kΩ are placed in series between the position electrode and the virtual earth of the pre–amplifier to produce an offset in the charge division seen by the pre–amplifier. This offset ensures that some resistive charge division occurs for charged particle hits near a PSD corner so that the smallest position signal, which is generated in the furthest electrode diagonally across the detector face, is large enough to exceed the detection threshold for the lowest energy particles to be recorded.

The PSD energy signal pre–amplifiers are identical to those used for the position signals except that there is no charge offset resistor. The detector bias is fed to the rear face of the detector through the energy signal pre–amplifier via a total of 11MΩ load resistance and is filtered using a 10nF capacitor to ground, as shown in figure 3. The high voltage is decoupled from the signal by a 10nF capacitor at the pre–amplifier input. The biases for the PSDs are provided by computer controlled supplies that allow automatic compensation for changes in the junction leakage currents.

For the gas detector signals the pre–amplifier gain is increased by a factor of five. A common bias is fed to all the sectors of the gas detector anode grid using one of the SMC connectors in the backplate of the module. A 1MΩ current limiting resistor is placed in series with the bias for each anode sector and the signal is decoupled from this bias using a 10nF capacitor rated to 1kV and placed at the pre–amplifier input.

The pre–amplifiers for the CsI scintillators are available commercially and were supplied by the manufacturers. They are a high gain, low noise hybrid FET design matched to the characteristics of the photodiode readout. The low power consumption of 180mW allows them to be operated inside the low pressure module environment without any problems of overheating.

An innovative data acquisition system designed for use with the MEGHA system has recently been installed and is described in detail elsewhere [11]. This system will be used in all future experiments.

IV. DETECTOR OPERATION AND PERFORMANCE

The characteristics and optimum operating parameters for the detectors have been determined by the use of radioactive sources and ion beams with a range of mass and energy. This has enabled information on both the low and high energy characteristics of the system to be obtained.

A. Particle Identification Modules

1. Gas Ionisation Detector

To ensure complete charge collection and to maximise the electron drift velocity under all experimental conditions the gas detectors are operated with a pressure dependent bias voltage of 6.25V/torr. Experience with previous gas–silicon hybrid detectors [15] and measurements made using ^{12}C , ^{16}O and ^{24}Mg ion beams with energies in the range 80 to 170MeV has shown that this gives the best resolution and pulse shape characteristics under most operating conditions.

The gas signal resolution is dominated by capacitive noise generated by the detector and signal cables of the order of $\sim$200keV for 85MeV ^{12}C ions depositing 1.85MeV in the gas volume. The energy straggling for these particles passing through 5cm of 60torr of propane is estimated to be of the order of 190keV [16], and the statistical variation in the number of ion pairs produced gives a resolution contribution of $\sim$20keV. Adding these in quadrature with the capacitive noise gives a resolution estimation of 280keV, in good agreement with the values of 220 to 310keV measured using 85MeV ^{12}C ions scattered from a 150μg/cm^2 ^{197}Au target.

The pulse height for monoenergetic particles varies over the face of each gas detector due to variations in the electric field. Calculations [12] of the equipotential contours surrounding the anode grids show a reduced potential gradient along the anode edges adjacent to a module wall and especially along an edge next to the earthed beam pipe. A reduced potential gradient produces longer charge pulses due to a decreased electron drift velocity, to cause a pulse height deficit towards the anode edges. The worst deficit (up to 40%) is measured along the anode edges adjacent to the beam pipe. Figure 5 shows the uncalibrated energy response of a gas detector for 85MeV ^{12}C ions elastically scattered from a 150μg/cm^2 ^{197}Au target. The ^{12}C ions passed through 5cm of propane at 60torr, with the anode bias held at 375V. The pulse height is plotted as a function of position across the gas detector face using the position information generated by the PSD.

An absolute energy calibration of the gas signal is unnecessary since this signal is used only for particle identification. Compensation for the energy lost by an ion traversing the gas section is made after particle identification using the PSD energy signal by calculating the energy loss in the gas using the appropriate stopping power for the detected particle. This technique is described in more detail in reference [15]. The advantage of discarding the gas detector generated signal is two–fold. Firstly, the gas detector contribution to the system energy resolution is limited to energy straggling in the gas only. Secondly, the position dependent signal deficit due to the non–uniform electric field does not affect the measurement. For 65MeV ^{12}C ions scattered off a ^{197}Au target the PSD energy resolution is 320keV. When the gas detector is filled with propane to a pressure of 60torr the resolution of the PSD signal plus the calculated gas energy increases to 345keV, indicating a gas straggling contribution of $\sim$ 130keV, in good agreement with the calculated value of 140keV [16].

2. Position Sensitive Silicon Detectors

The initial operating parameters from these detectors were determined using a ^{241}Am α–particle source and are listed in table I. The results from 85MeV ^{12}C beam tests are listed in table II. All tests described in this paper were performed using ORTEC 572 spectroscopy amplifiers in combination with Silena 4418/V ADCs. Signal timing was achieved using leading edge discriminators in the main amplifiers which act as stop signals to LeCroy TDCs. The TDC start signal is common to all TDC channels.

The optimum operating bias was determined by simultaneously maximising the pulse height and minimising the capacitive noise contribution. The intrinsic energy resolution quoted is the FWHM for α–particles hitting a 1mm^2 area around the centre of the detector. This was found to be a minimum using a shaping time of 3μs for both thicknesses of detectors.

When the α–particles are allowed to illuminate the whole face of the PSD the energy signal shows a position–dependent, ballistic deficit. The ballistic deficit occurs due to incomplete shaping in the amplifier of the charge pulses. This effect has been modelled extensively [14]. Although both the position and energy signals are affected by the ballistic deficit, it has been shown [14] that over a wide range of shaping times the degree of distortion induced in the position pattern is relatively independent of the shaping time, whereas the ballistic deficit in the energy signal is strongly dependent upon the amplifier shaping time, and requires shaping times (τ_f) longer than $2R_{\square}C/5$ seconds for less than 1% ballistic deficit. $R_{\square}$ is the resistance of the PSD surface per unit area and C is the junction capacitance.

The effect of the ballistic deficit on the α–particle energy spectrum from the 385μm PSD is illustrated in figure 6 for a range of amplifier shaping times. At 1μs the lower peak in the spectrum corresponds to α–particle hits near the PSD centre where the ballistic deficit is worst. Events near the upper part of the distribution are from α–particle hits near the PSD corners where the ballistic deficit is minimal even for low shaping times. As the shaping time is increased to 6μs more charge is collected from the centre of the PSD and the recorded energy distribution becomes approximately Gaussian, with a FWHM of 60keV. A comparison of the ballistic deficit measured at the centre of both types of PSD is made in figure 7 and clearly shows that amplifiers with long shaping time constants are required to operate these detectors at their optimum. The thicker PSD has a lower capacitance and surface resistance and therefore the signals are more prompt – consequently the ballistic deficit is lower for all values of the amplifier shaping time.

The typical measured intrinsic energy resolution for 85MeV ^{12}C ions scattered from a

$150\mu g/\mathrm{cm}^2$ ^{197}Au target is 230keV for the 385μm PSD and 205keV for the 500μm PSD. These values were obtained with no mylar windows on the modules. In figure 8 the spectrum shown as a dashed line is the raw pulse height spectrum obtained for the energy signal taken from the rear face of the 385μm thick PSD via the electrode *e*. This spectrum was obtained using 65MeV ^{12}C ions elastically scattered from a ^{197}Au target with a shaping time of 5μs. The broadening of the mono–energetic peak to give a low energy tail is again due to the position dependency of the ballistic deficit. This dependence can be removed using the simultaneously generated position information for the event and a knowledge of the angular variation of the energy of the scattered ions. The correction is made by bi–cubic–spline fitting a surface to the ratio of the raw pulse height ($E\ (channel)$) to the kinetic energy of the particle ($E\ (MeV)$) to produce a position dependent energy calibration,

$$E(MeV) = \frac{E(channel)}{\zeta(X,Y)} \tag{4.1}$$

The surface, $\zeta(X,Y)$, and hence the ballistic deficit, was found to be independent of particle energy, agreeing with the model calculations of Cowin and Watson [14]. NAG library [17] routines E02DDF and E02DFF were used to generate the spline surfaces. The energy spectrum corrected using this method is shown as a solid line in figure 8. For 65MeV ^{12}C ions scattered from a ^{197}Au target the resolution after correction is $\sim$ 320keV, compared to the expected value of 300keV when considering the intrinsic resolution folded with the angular variation in the elastics energy, indicating a residual position dependence of the order of 100keV.

Variations in the individual detector response arise due to small differences in the amplifier shaping and detector resistances and capacitances, and cause variation in the degree of ballistic deficit. To correct all detectors simultaneously the spline correction surface must be scaled according to the depth of the minima $\zeta(0,0)$ for each PSD. The residual position dependencies when using a single surface to correct many detectors gives a contribution to the resolution of typically less than 200keV at 65MeV.

The position of a particle incidence on a PSD can be determined approximately from the ratios of the four position signals using the relationships,

$$X = \left\{ \frac{(C+B)-(A+D)}{(A+B+C+D)} \right\}$$

$$Y = \left\{ \frac{(C+D)-(A+B)}{(A+B+C+D)} \right\} \tag{4.2}$$

where A to D are the measured pulse heights from the four position electrodes, *a* to *d*. The zero of the co–ordinate system is at the PSD centre, with the X and Y axes parallel to the detector sides. Due to the extra charge division produced by the offset resistors, the calibrated position co–ordinates are not simply given by the uncalibrated values multiplied by the half–length of the detector edge, $L/2$. Therefore, to provide angular settings for the calibration and to check the linearity of the position response, a removable grid of precision drilled holes is placed in front of each module. The grid is placed directly in front of the mylar window and consists of nine sets of 17×17 1mm diameter holes spaced at 3mm intervals, with each set aligned to a telescope in the module. Scattered particles incident on the PSD form an image of the grid. An example of this for one PSD is shown in figure 9. The missing holes in the centre of the pattern determine the orientation of the pattern with respect to the PSD.

A linear mapping of the centroid of the peaks observed in the position spectrum to the scattering angles defined by the grid holes is sufficient to provide accurate angular position information for the incident ions. However, there are some residual non–linearities which arise from three sources. The first is due to the approximation of zero ring resistance used to derive the algorithms determining the (X, Y) values [18]. The non–linearities introduced from this source are typically less than 2% [13]. Secondly, incomplete charge collection in the position signal amplifiers leads to further distortions. This contribution tends to dominate for these large area PSDs where the charge pulse shape is very much elongated compared to smaller detectors [14]. Both these distortions can be corrected [14] from a knowledge of the PSD resistances, capacitances and signal shaping times. The third source is due to irregular inhomogeneities in the silicon resistivity which disrupt the charge division – this contribution is negligible for the two types of MEGHA PSDs.

The position resolutions listed in table I were determined from the FWHM for the position spectrum of α–particles passing through a single 1mm diameter hole in a 1mm thick mask placed 2mm above the PSD. The best resolution occurs for the shortest shaping time.

The position resolution was investigated further in the beam tests. In figure 10(a) the resolution, measured at both the centre and at the centre of one edge of the 385μm PSD, is plotted as a function of shaping time from 0.5μs to 3.0μs. It can be seen that the resolution varies over the face of the PSD, especially at low values of the shaping time, due to increases in the distortion of the position pattern as the ballistic deficit in the position signals increased. PSD model calculations [14] predict a 'barrel' distortion in the position pattern at low shaping times which compresses the pattern at the PSD edges and leads to the poorer resolution – this can be seen in the pattern for the 385μm PSD taken with 0.5μs shaping and shown in figure 10(b). The extra position signal ballistic deficit has caused the smallest signals generated in the top–right electrode to fall just below detection threshold, resulting in the hole at the bottom–left of the pattern. This illustrates a further disadvantage of operating these detector with low shaping times. The position signals should be shaped to at least 1.5μs to reduce the position distortion, improve the overall position resolution and to reduce the energy threshold.

The measured position resolutions for the two PSDs for 0.5μs shaping are listed in table II. Hasebe et al [18] propose that the intrinsic position resolution of these detectors can be calculated from the energy resolution. The values calculated using the Hasebe formalism are also listed in the table and are seen to be much lower than the measured values. The difference is due to the convolution of the grid hole size and scattering off the hole edges being included in the measured value.

In order to completely reconstruct the energy and position of a particle hit within a PSD, the five signals have to be larger than the detection threshold (E_{detect}), that is,

$$E_{PSD},\ A,\ B,\ C \text{ and } D\ >\ E_{detect} \tag{4.3}$$

Bruno *et al.* [19] noted that the four position signals are proportional to the energy deposited in the PSD, viz,

$$\begin{aligned} A &= E \,.\, f(X,Y) \\ B &= E \,.\, g(X,Y) \\ C &= E \,.\, h(X,Y) \\ D &= E \,.\, l(X,Y) \\ E_{PSD} &= E \end{aligned} \tag{4.4}$$

and that, from conservation of electric charge,

$$f(X,Y) + g(X,Y) + h(X,Y) + l(X,Y) = 1 \tag{4.5}$$

and from the symmetry properties of the PSD,

$$f(0,0) = g(0,0) = h(0,0) = l(0,0) = 0.25 \tag{4.6}$$

(where $(X,Y) = (0,0)$ is the PSD centre). Using the PSD model described in reference [14] the values of f, g, h and l were found to lie in the range 0.106→0.605 for the 385μm PSD. From equations 4.3 and 4.4 the minimum energy (E_{thresh}) which must be deposited in the PSD for all signals to be measured above threshold is seen to be,

$$E_{thresh} = \frac{E_{detect}}{f(X,Y)}\text{, or }\frac{E_{detect}}{g(X,Y)}\text{, or }\frac{E_{detect}}{h(X,Y)}\text{, or }\frac{E_{detect}}{l(X,Y)} \tag{4.7}$$

whichever is the largest. The largest threshold, $\frac{E_{detect}}{0.106}$, occurs at each corner of the detector where one of the denominators in equation 4.7 is a minimum, and the minimum threshold, $\frac{E_{detect}}{0.25}$, occurs at the detector centre. The calculated variation in the energy threshold is plotted in figure 11. The large thresholds developed at the detector corners can be reduced by lowering the position signal thresholds below the noise level. Position signals then generated by random noise can be effectively removed by triggering the acquisition of the five signals from the energy signal only, and can be further filtered in software by requiring all five signals to be present.

The CsI scintillators were tested with a mixed (^{239}Pu, ^{241}Am and ^{244}Cm) α–particle source and ^{137}Cs and ^{60}Co γ–sources. The energy resolution, measured after calibrating to the three α–particle peaks was 250keV (4.6%) for the α–particle peaks and $\sim$150keV for the γ–ray peaks and was minimised with a shaping time greater than 2μs. The pulse height was maximised with 35V bias across the photodiode.

The performance of the CsI scintillators for high energy light ions was investigated using a 170MeV ^{24}Mg beam incident on a ^{12}C target was used. Hydrogen, helium and lithium isotopes were produced with sufficient energy to pass through the PSD and enter the CsI to give a signal above detection threshold. The CsI signal is non–linear in energy, therefore, in a similar manner to the gas detector, the energy deposited in the CsI is derived from the calibrated PSD energy signal. The range in silicon as a function of energy ($R_{PSD}(E)$) of a particle emerging from the PSD is given by,

$$R_{PSD}(E_{after}) = R_{PSD}(E_{before}) - X_{PSD} \tag{4.8}$$

where X_{PSD} is the PSD thickness. The subscripts on E refer to the particle energy *before* and *after* encountering the PSD. The energy measured in the PSD is the difference between these two values. The energy of each particle entering the CsI detector ($E_{after} = E_{before} - E_{PSD}$) can then be determined from the measured value of E_{PSD} and the fixed silicon thickness, X_{PSD}, by using tabulated range–energy curves to determine the value of E_{before} that satisfies the relation,

$$R_{PSD}(E_{before}) - R_{PSD}(E_{before} - E_{PSD}) = X_{PSD} \tag{4.9}$$

The fraction of E_{after} deposited in the mylar coating of the crystal can be calculated from its known thickness of 6μm. The response of the CsI detector to three different ions with varying energy is shown in figure 12 as a function of the calculated energy deposited in the crystal. The figure shows clearly that the detector output is particle type dependent. Over this energy range the response for ^{4}He and ^{6}Li is slightly non–linear, in agreement with the measurements of Viesti et al. [20] made using similar detectors.

4. Particle Identification

One of the prime requirements of MEGHA is good particle identification to enable the ions of interest to be identified in a large background flux of other reaction products. This is achieved in MEGHA using the standard $E\Delta E$ two dimensional plots. For heavy ions the gas ionisation detector provides the energy loss signal (ΔE) and the PSD the energy signal (E). A plot of the raw ΔE vs E gives the usual loci corresponding to particles of different Z. The operating gas pressure is dependent on the Z range of interest. For light ion with Z<5 a pressure of >80torr is normally used to ensure that the energy loss of the ions is above the gas detector threshold which is equivalent to 0.1MeV. Because of the increased energy loss for heavier ions a lower gas pressure of approximately 30–60torr is normally used to lower the telescope energy detection threshold.

A sample spectrum for a single telescope for 170MeV ^{24}Mg ions interacting with a $75\mu g/\mathrm{cm}^2$ ^{12}C target is shown in figure 13. The gas detector was filled to 60torr with propane and biased to 375V. The different reaction products observed are identified in the figure. From the figure it is clear that the loci for different Z are resolved, but the ΔE resolution is such that mass identification is not possible in most cases.

The upper limit of Z resolution for the gas–PSD section was investigated using the reaction products from 200MeV ^{35}Cl ions interacting with a $75\mu g/\mathrm{cm}^2$ ^{12}C target. These measurements indicate that ions up to a least scandium (Z=21) can be identified, and that a minimum pressure of 60torr of propane was necessary to resolve these ions.

For light ions and for high energy heavy ions that only give a small signal in the gas detector particle identification is made using the PSD as the passing detector (ΔE) and the CsI as the stopping detector (E). Figure 14 shows an $E\Delta E$ spectrum obtained using the PSD–CsI combination for a 170MeV ^{24}Mg beam incident on a ^{12}C target. Loci corresponding to protons, deuterons, tritons and ^{3,4}He can be clearly identified and there is also evidence for ^{6}Li and ^{7}Li. The vastly improved ΔE resolution obtained from the PSD allows this combination to give charge and mass identification, a feature that has enabled similar detector combinations to be used to investigate the breakup of a ^{12}Be beam from the LISE spectrometer at GANIL [21].

B. Position Sensitive Silicon Strip Detectors

Except for the method of mounting, the PSSDs used in the MEGHA system are identical in construction to those used previously [15]. A summary of their performance, along with methods of operation and calibration, are presented in references [10,15]. The energy resolution for these detectors is 200keV for 85MeV ^{12}C ions scattered from a $150\mu g/\text{cm}^2$ ^{197}Au target. The position resolution at this energy is 200μm along the strip, giving an angular resolution in the MEGHA system of $\sim 0.07^0$.

V. SUMMARY

A new detector system with up to 44 triple–detector telescopes and 10 silicon strip detectors has been constructed. Each telescope comprises a gas ionisation detector, a large area (50 $\times$ 50mm) two–dimensional resistive sheet position sensitive detector backed by a CsI scintillator with photodiode readout. The telescopes are closely packed in five modules which are mounted in a purpose built vacuum chamber covering the forward hemisphere from $3 \rightarrow 52^0$ in the laboratory. The pre–amplifiers are mounted directly onto the rear of each module. The strip detectors are mounted in any of 30 fixed positions in the forward hemisphere, covering $6 \rightarrow 90^0$ in the laboratory.

Measurement to determine the performance of the array have been made using α–particle sources and ^{7}Li , ^{12}C , ^{24}Mg and ^{35}Cl ion beams with energies ranging from 27 to 200MeV. It has been shown that to optimise the PSD performance it is necessary to use long ($>5\mu$s) shaping times for the energy signals to reduce the ballistic deficit and shorter ones (1.5μs) for the position signals to improve the resolution. Position dependencies in the PSD energy signal and non–linearities in the position information can be corrected in the off–line analysis. The gas detector signals show a variation of pulse height with position of the incident ion which can also be corrected off–line.

It has been demonstrated that the system is capable of identifying ions from protons to scandium. The measured energy resolution for 85MeV ^{12}C ions scattered from a $150\mu g/\mathrm{cm}^2$ ^{197}Au target is of the order of 200keV in the PSD which, combined with the energy straggling in 60torr of propane gas, gives a total system energy resolution of $\sim$ 345keV. The angular resolution, with the target set at 600mm from the PSD plane is $\sim 0.03^0$.

The excellent particle identification capabilities of the new array will permit the study of break–up reactions to be extended over a wider range of systems. The addition of CsI stopping detectors will allow the study of higher energy systems. The large angular coverage and high segmentation of the PSSDs give the MEGHA system a high efficiency for detecting tertiary and higher multiplicity reactions.

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+ DL design team

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FIGURE CAPTIONS

Figure 1. Schematic diagram of MEGHA and its vacuum vessel.

Figure 2. (a) Longitudinal cross–section through a MEGHA module (b) Schematic layout of an individual detector telescope. All dimensions are given in mm.

Figure 3. Schematic diagram of the construction of a large area resistive sheet position sensitive detector and the associated electronics.

Figure 4. Angular coverage from the upstream target position (a) for the telescope array, (b) angular positions along the central axis of each individual PSSD strip.

Figure 5. Variation of the signal height across the gas ionisation detector for 85MeV ^{12}C ions elastically scattered from a $150\mu g/\mathrm{cm}^2$ ^{197}Au target.

Figure 6. Pulse height spectra for 5.5MeV α–particles incident across the whole face of a PSD for various shaping times in the main amplifiers.

Figure 7. Ballistic deficit as a function of main amplifier shaping time. For comparison the ballistic deficits predicted by the model of reference [14] are shown as dashed lines.

Figure 8. Pulse height spectra taken from the rear face of a PSD for 65MeV ^{12}C ions elastically scattered from a ^{197}Au target. The spectra are explained in the text.

Figure 9. Two dimensional position spectrum obtained with the calibration grid in place for 85MeV ^{12}C ions elastically scattered from a ^{197}Au target.

Figure 10. (a) Position resolution, measured at the centre and edge of the 385μm PSD, as a function of the position signal shaping time. The resolutions for the α–particle testing for both PSDs are also shown. (b) Position pattern for the 385μm PSD shaped to 0.5μs.

Figure 11. Calculated energy threshold in the 385μm PSD as a function of the position co–ordinates.

Figure 12. The response of the CsI scintillator to high energy ^{3}H, ^{4}He and ^{6}Li ions produced from 170MeV ^{24}Mg ions interacting with a 75μg/cm^2 ^{12}C target.

Figure 13. $E\Delta E$ spectrum from the gas–PSD detector combination for 170MeV ^{24}Mg ions interacting with a 75μg/cm^2 ^{12}C target. The different reaction products are identified in the figure.

Figure 14. $E\Delta E$ spectrum from the PSD–CsI detector combination for 170MeV ^{24}Mg ions interacting with a 75μg/cm^2 ^{12}C target. The different reaction products are identified in the figure.

TABLES

PSD thickness (μm)	385	500
Optimum Bias (V)	132	114
Leakage current (μA)	1.8	0.6
Intrinsic energy resolution (keV)	79	67
Maximum ballistic deficit (% @ 3μs)	1.05	0.35
Position resolution (mm @ 0.5μs)	1.55	1.69

TABLE I. Summary of α–particle tests of the PSDs.

PSD thickness (μm)	385	500
Energy resolution (keV)	230	205
Ballistic deficit (%)	1.08	0.50
Measured position resolution (mm)	0.85	0.96
Calculated position resolution (mm)	0.27	0.24

TABLE II. Summary of the various measurements of PSD performance made in the 85MeV ^{12}C ion beam tests. The PSD energy signal was shaped to 5μs and the position signals to 1.5μs.

FIGURES

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