The Hyperion Particle- γ Detector Array

R. O. Hughes^a, J. T. Burke^a, R. J. Casperson^a, S. Ota^{a,1}, S. Fisher^b, J. Parker^b, C. W. Beausang^c, M. Dag^d, P. Humby^{c,e}, J. Koglin^a, E. McCleskey^d, A. B. McIntosh^d, A. Saastamoinen^d, A. S. Tamashiro^f, E. Wilson^{c,2}, T. C. Wu^g

^aNuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, California 94550, USA

^bScience, Technology and Engineering Division, Lawrence Livermore National Laboratory, Livermore, California 94550, USA

^cDepartment of Physics, University of Richmond, 28 Westhampton Way, Richmond, Virginia 23173, USA

^dCyclotron Institute, Texas A&M University, College Station, Texas 77840, USA

^eDepartment of Physics, University of Surrey, Surrey GU27XH, UK

^fDepartment of Nuclear Science and Engineering, Oregon State University, Corvallis, Oregon 97331, USA

^gDepartment of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112-0830, USA

Abstract

Hyperion is a new high-efficiency charged-particle γ -ray detector array which consists of a segmented silicon telescope for charged-particle detection and up to fourteen high-purity germanium clover detectors for the detection of coincident γ rays. The array will be used in nuclear physics measurements and Stockpile Stewardship studies and replaces the STARLiTeR array. This article discusses the features of the array and presents data collected with the array in the commissioning experiment.

1. Introduction

The measurement of (n,γ) cross sections for short lived nuclei is of keen interest both to Stockpile Stewardship applications and studies of stellar nucleosynthesis [1]. For nuclei with very short half lives (less than about 10 days), direct measurements become very challenging and indirect measurement techniques such as surrogate reactions [2] must be employed. In a surrogate reaction, the Compound Nucleus of interest is populated using a charged particle beam

¹Present address: Cyclotron Institute, Texas A&M University, College Station, Texas 77840, USA

²Present address: Department of Engineering, Lancaster University, Lancaster LA14YR, UK

Preprint submitted to Elsevier

March 3, 2017

26 on a stable target and the (n,γ) cross section can be deduced from the mea-
 27 sured γ -ray probabilities and detailed nuclear structure knowledge. In the last
 28 few years, significant interest in the surrogate measurement of (n,γ) cross sec-
 29 tions has motivated experiments utilizing particle- γ arrays such as STARLiTeR
 30 [3, 4] and SiRi/CACTUS [5, 6] in normal kinematics. The surrogate technique is
 31 also being investigated using inverse kinematics reactions including very recent
 32 measurements utilizing the GODDESS array at Argonne National Laboratory
 33 [7] and the TIGRESS/SHARC array at TRIUMF [8, 9]. A limiting factor in
 34 surrogate measurements of (n,γ) cross sections, particularly for low cross-section
 35 reactions, is the efficiency of the detector array that is utilized, in particular the
 36 efficiency for γ -ray detection.

37 Hyperion is a new particle and γ -ray detector array that is intended to re-
 38 place the STARLiTeR array [10] for use in Stockpile Stewardship and nuclear
 39 structure studies. Hyperion is comprised of a highly segmented silicon telescope
 40 for the detection of charged particles and a surrounding array of up to fourteen
 41 Compton-suppressed, high-purity germanium (HPGe) clover detectors for coin-
 42 cident γ -ray measurements. Hyperion will provide over a factor of two increase
 43 in γ -ray efficiency and particle-gamma efficiency and more than a factor of six
 44 in particle-gamma-gamma efficiency over STARLiTeR.

45 The array was designed, fabricated and assembled at Lawrence Livermore
 46 National Laboratory and moved to the Texas A&M University Cyclotron In-
 47 stitute where it was installed in Cave 4 in May 2015. Hyperion can currently
 48 receive beams of gaseous species from the K150 Cyclotron with a maximum
 49 proton beam energy and current of 45 MeV and 10 μ A, respectively. The ar-
 50 ray is also accessible by the K500 Cyclotron which can produce beams up to
 51 ~ 12 MeV/u uranium.

52 An illustration of the array with one hemisphere open is shown in Fig. 1.
 53 Photographs of the array, showing the inside of the chamber with detector and
 54 target ladder, the outside of the chamber enclosed by one hemisphere, and the
 55 fully enclosed array are shown in Fig. 2.

Figure 1: Illustration of the Hyperion array with one open hemisphere. Two detectors are omitted to allow a clear view of the chamber.

Figure 2: Pictures of the Hyperion array. Top left: Target ladder and silicon detectors inside the target chamber. Top right: side view of the chamber with one hemisphere of the γ -ray detection array closed. Bottom: The closed array in Cave 4 of the Texas A&M University Cyclotron Institute.

56 2. High-Purity Ge Detector Array

57 The array utilizes up to fourteen cryogenically cooled clover HPGe detectors
58 for the detection of γ rays. Each clover contains four adjacent 5 cm by 5 cm
59 by 8 cm leaf crystals in the cryostat. The four leaf configuration allows γ rays
60 that scatter from one crystal into adjacent crystals to be recovered by summing
61 coincident leaf signals in so-called add-back mode. In this mode the relative
62 efficiency of a clover detector is 150% (relative to 3×3 inch NaI(Tl) crystal at
63 1.33 MeV). A detailed account of clover detectors is given by Duchêne *et al.*
64 [11].

65 Each clover is inserted and locked into a Compton suppression shield com-
66 prised of 16 optically-isolated bismuth germanate (BGO) crystals that enclose
67 all sides of the clover crystals, and are connected to individual photo-multiplier
68 tubes providing 16 individual readouts. These shields improve the peak to total
69 ratio of the γ -ray spectra by providing a veto signal for events measured in the
70 clover where the γ ray scatters into the surrounding BGO. Each BGO shield has
71 a high-tungsten alloy ‘heavimet’ collimator, 2.5 cm thick on the front to shield
72 the BGO crystals from incident γ rays from the target position. The clover +
73 BGO configuration is similar to that described in [12].

74 The HPGe detector support structure is separated into two hemispheres
75 held by an 80/20 aluminum frame [13]. This structure was chosen to provide
76 the strength to hold the ~ 1200 lbs for the combined mass of clovers and BGO
77 shields of each hemisphere, as well as flexibility in potential future modifications.
78 As shown in Fig. 1, the hemispheres sit atop a rectangular box support frame on
79 either side of the Hyperion target chamber. Each rectangular support frame is
80 mounted on a rail and worm gear system which enables the entire hemisphere to
81 be moved away from the target chamber for access. An upper rail and worm gear
82 system that sits on top of the rectangular support frames allows the hemispheres
83 to also move in and out from the target chamber. The hemispheres consist of six
84 square aluminum mounting frames on top of the support structure that holds
85 the BGO shields. The frames have four adjustable turnbuckles: one in each

Figure 3: Schematic of the Hyperion clover positions. The clovers are labeled as C1-C14, the blue arrows represent the detectors pointing to the center of the target chamber, and their positions are defined in terms of: a) an angle θ when looking down at the array with the upstream beam line at $\theta = 0^\circ$, and b) a vertical angle $\phi = 45^\circ$, $\phi = 0^\circ$, and $\phi = -45^\circ$ when looking at the array side-on.

corner that allow for adjustments of the detector alignments which includes $\approx \pm 2$ cm of movement closer to or farther from the target position. Turncranks control the movement of both upper and lower rail systems on both sides of the array. Two further HPGe detector positions are placed directly upstream and downstream looking up at the target position at a 45° angle. The positions of the 14 clovers in closed configuration around the target chamber are shown schematically in Fig. 3.

2.1. Gamma-ray efficiency

The Hyperion target chamber was designed to maximize the solid angle coverage of the HPGe detectors surrounding the target while still accommodating the silicon telescope detectors required for charged particle detection. Given the geometry of the BGO Compton shields, the optimal distance for the front face of the HPGe detectors to the center of the target position is ~ 21 cm. This geometry then dictates the solid angle for each clover detector which is 0.2 steradian per detector, up to a maximum 2.8 steradian ($\approx 22\%$) for the full complement of fourteen detectors.

The photopeak efficiency of the array was estimated with six detectors operating in the system using a set of calibrated γ -ray sealed sources that were

placed at the target position inside the target chamber. Sources of ^{152}Eu and ^{133}Ba were utilized which cover an energy range from 31 keV to 1408 keV. Data were collected such that at least 10^4 events were contained within the photopeaks associated with each γ -ray used in the efficiency measurement. The photopeak efficiencies were deduced from the data by measuring the area of each photopeak, normalizing to live counts per second and comparing to the expected γ -ray flux according to

$$\epsilon = \frac{N_p(E_\gamma)}{N_t(E_\gamma) \times \lambda_{BR} \times T_{dead} \times t}. \quad (1)$$

Where N_p is the area of the photopeak, N_t is the calculated total number of decays per second for the γ -ray source, λ_{BR} is the absolute γ -ray branching ratio, T_{dead} is a dead time correction factor, and t is the run time in seconds.

It was observed that the efficiency for three of the six clovers were lower than the other three by as much as $\sim 30\%$ below 200 keV. A GEANT4 [14] simulation of the array suggests this discrepancy is predominantly due to γ -ray attenuation caused by the plastic encapsulation of the source, the target ladder and the silicon detector support bars at specific angles, as well as misalignment in the position of these three detectors relative to the target. The target ladder and support bars, that are both constructed from aluminum, are being redesigned to reduce the intervening material between the target position and the detectors at $\theta = 90^\circ/270^\circ$ while future efficiency measurements will use a different γ ray source configuration.

An efficiency curve, measured with the three detectors not affected by reduced efficiency as discussed above, is shown in Fig. 4. The points and associated uncertainties in Fig. 4 have been extrapolated to show the expected total efficiency for the full 14 detector array. The fit to the data points in Fig. 4 uses the following functional form:

$$f(E) = a \times E^{-b} - c \times \exp^{-d \times E} + e, \quad (2)$$

Where E is the energy in MeV and a , b , c , d and e are variable fit parameters. A simulated array efficiency is also presented in Fig. 4. The simulation, which was

Figure 4: Efficiency of the Hyperion array extrapolated from measured efficiency for three detectors in the array (see text). The solid line is a fit to the data points and the dotted line is from a GEANT4 simulation of the array.

performed in GEANT4, uses a model containing the materials of the chamber, STARS detectors and associated support structures, the clover detectors and surrounding BGO shields. The model was validated against the data available for six clover positions. Differences in the simulated and fitted data, for example a lower maximum efficiency of 9.2% at 130 keV in the simulated data, can be ascribed to (i) additional attenuation caused by the STARS detectors and support structure at specific angles, and (ii) the simulation does not include the source encapsulation.

The GEANT4 model of the γ -ray detection capabilities of Hyperion was used to predict the γ - γ coincidence efficiency of the array. For simultaneous detection of the 1173 keV and 1332 keV transitions in ^{60}Co , an efficiency of 0.88% was deduced.

3. Silicon Telescope

The Silicon Telescope Array for Reaction Studies (STARS) was originally described in [10] and remains largely the same. The silicon detectors in the

146 telescope are Micron S2 type detectors which are annular double-sided semi-
 147 conductor detectors with one side segmented into 16 sectors and the other 48
 148 rings. The silicon telescope is usually assembled using a thin ΔE (150 μm or
 149 500 μm) S2 detector and one or two thick E (1 mm or 1.5 mm) S2 detectors,
 150 with a few millimeters distance between the individual detectors. A thin (7 μm
 151 to 160 μm) Al shield is typically mounted on the front and back sides of the
 152 telescope to shield the detectors from δ -electrons (and fission fragments where
 153 applicable). Rings and sectors of the detectors are usually bussed together into
 154 pairs with 8 sectors and 24 rings due to constraints on the number of electronic
 155 channels available, furthermore the particle angular resolution is limited due to
 156 the ≈ 2 -5 mm beam spot size provided by the K150 cyclotron. The telescope
 157 is generally mounted downstream of the target position at distances varying
 158 from 1 cm to 5 cm. At 2 cm the solid angle of the telescope is about 2.5 stera-
 159 dians ($\approx 20\%$) and the angular range is ≈ 29 - 54° . Figure 5 presents a plot of
 160 approximate solid angle and angular coverage for a range of distances of target
 161 to front face of STARS. For actinide measurements of fission fragments, a sec-
 162 ond set of S2 detectors (usually only one, thin detector) is mounted upstream
 163 about 1-2 cm from the target position. This upstream detector is then used
 164 for measuring fission fragments in coincidence with light ions detected in the
 165 downstream telescope.

166 The intrinsic resolution of the S2 detectors is measured using ^{226}Ra and
 167 ^{252}Cf sources. The typical $1\text{-}\sigma$ resolution for the S2 detectors is approximately
 168 30 keV for the 7684 keV alpha peak in ^{226}Ra decay chain. The resolution can
 169 degrade with use, particularly when the detectors are exposed to high beam
 170 currents or to beams with ions heavier than helium.

171 **4. Commissioning Experiment**

172 Data from the Hyperion commissioning experiment are presented here. A
 173 beam of 27.64 MeV protons was incident on a 1.8 mg/cm^2 ^{208}Pb target with
 174 an average beam intensity of 0.7 nA and data were collected for 90 minutes
 175 with eleven clovers in operation. STARS comprised a thin, 140 μm and a thick,

Figure 5: Plots of STARS solid angle and angular range for different target-detector distances. Left axis/solid line: Approximate solid angle coverage of STARS. Right axis/dotted lines: minimum and maximum angles subtended by STARS.

1500 μm silicon detector with the front of the telescope placed 19 mm from the target position. The average particle rate on STARS was ~ 12 kHz.

Fig. 6 shows a particle identification (PID) plot of the relative energy loss of incident particles following a proton beam incident on the ^{208}Pb target. The y-axis in Fig. 6 is the range-energy term for different $Z=1$ and $Z=2$ charged particles in silicon and is defined by [15]:

$$T/a = [(E + \Delta E)^{1.7} - E^{1.7}] \times \cos\theta, \quad (3)$$

Where T is the ΔE detector thickness, a is a constant for a given ion relating its energy and range, ΔE and E are the respective energies measured in the thin and thick detectors, θ is the incident angle of the particle and the power 1.7 reflects the stopping power for silicon. In Fig. 6, protons, deuterons and tritons are distinguishable as horizontal bands labelled p, d and t, respectively. The diagonal streak connected to the proton band is indicative of high energy protons that punch through the thick E detector and thus do not deposit all of their energy. Fig. 7 presents γ -ray and particle spectra for $^{208}\text{Pb}(p,d\gamma)^{207}\text{Pb}$ data obtained by isolating deuteron data from the PID plot in Fig. 6. Fig. 7 a) shows γ rays associated with ^{207}Pb and ^{206}Pb (via the (p,dn) reaction

Figure 6: Particle ID plot linearized according to the range-energy equation (see text) showing bands representing protons, deuterons and tritons measured from 27.64 MeV protons on ^{208}Pb . The lower band of protons displays a diagonal backbend indicative of high-energy protons punching through the thick E detector.

channel) with resolutions around ~ 1 keV $1-\sigma$. In Fig. 7 b), a particle spectrum measured in coincidence with the 570 keV γ ray is compared to a normalized spectrum showing deuteron singles. The peaks associated with the solid line in Fig. 7 b) represent directly populated states in ^{207}Pb and their associated width is ~ 100 keV $1-\sigma$. This energy resolution is comprised of the intrinsic detector resolutions, the beam energy resolution, recoil correction uncertainties and energy straggle in the target, δ -shield and detector dead layers. Fig. 7 c) presents the particle- γ time difference spectra for deuterons as well as all particles. The deuteron time-difference spectrum indicates a ~ 20 ns $1-\sigma$ time resolution for prompt deuteron- γ coincidences. There were insufficient statistics to provide adequate particle- γ - γ data.

5. Target chamber

The Hyperion target chamber is constructed entirely out of aluminum. All vacuum flanges use Buna-N O-rings. The chamber is separated into a lower cube and an upper, goblet-shaped chamber with lid as shown in Fig. 8. The

Figure 7: Spectra produced using $^{208}\text{Pb}(p,d\gamma)$ data collected with Hyperion. a) γ ray spectrum observed in coincidence with deuterons. Decays including the 570 keV de-excitation from the first excited state in ^{207}Pb are apparent, as well as γ rays associated with ^{206}Pb produced via $(p,dn\gamma)$ reactions. b) Deuteron particle spectra where energies have been converted to excitation energies in ^{207}Pb . The dotted line shows all measured deuterons normalized to be on the same scale and the solid line shows particles observed in coincidence with the 570 keV γ -ray in ^{207}Pb . c) Particle- γ time-difference spectra for all charged particles (dotted line) and deuterons (solid line). Coincident clover signals are received ~ 800 ns later than particle signals. The smaller peaks visible in the particle- γ total spectrum reflect non-coincident events from beam pulses with the ≈ 12 MHz Cyclotron frequency.

207 lower chamber houses electronic feed-throughs and has a removable panel on
 208 each side for access. Holes on the top and bottom of the lower chamber allow
 209 the upper chamber and target ladder arm to be connected, respectively. The
 210 upper chamber is designed to contain the target ladder, silicon detectors, in-
 211 vacuum camera and collimator. Detector and camera cables are passed down
 212 the cylindrical section to the lower chamber to be read out. The lid of the up-
 213 per chamber consists of a dome and ‘top-hat’ to provide room for the vertical
 214 movement of the target ladder. The upper chamber was machined so that the
 215 aluminum of the upper portion was 0.32 cm thick on all surfaces. This thick-
 216 ness was chosen to provide structural integrity while minimizing the material
 217 contributing to attenuation for γ rays traveling from the target position to the
 218 surrounding HPGe detectors.

219 The chamber is mounted on a 5-axis adjustable platform supported by an
 220 80/20 frame that allows for pitch, turn and yaw position adjustments for the
 221 chamber. For the chamber beamline alignment, removable target fiducials are
 222 installed in the front and back beamline flanges on the chamber and a transit
 223 telescope is sighted through the chamber along the beamline axis.

224 The target ladder (shown in Fig 2) contains nine target positions for mount-
 225 ing 3.8 cm $\times$ 2.5 cm aluminum target frames. The ladder is mounted on a
 226 high-vacuum linear shift transfer arm built by UHV design [16] that is con-
 227 nected to the vacuum chamber from below via a flexible bellows. The vertical
 228 motion of the ladder is propagated by a stepper motor produced by McLennan
 229 [17]. The ladder movement is monitored by a linear magnetic encoder from Ren-
 230 ishaw [18] to minimize hysteresis in the motion and to provide 10 μ m precision.
 231 The motor is controlled remotely via a serial computer connection and custom
 232 software.

233 A small VGA CCD camera from Kimpok [19] is installed in the upper cham-
 234 ber next to the upstream beamline flange and focused on the target position.
 235 The camera can be operated in conjunction with phosphor targets which lumi-
 236 nesce when struck by particle beams allowing for visual tuning of the beam spot
 237 during an experiment. The back side of the CCD camera is encased in epoxy

Figure 8: Illustration of the Hyperion array showing the cross section of the upper and lower chamber. The target ladder is mounted on a rod that is moved vertically using a stepper motor mounted below the chamber.

and attached to the chamber wall with copper tape. The epoxy and tape provide sufficient contact with the chamber to allow for thermal conduction which prevents the camera from overheating while in vacuum.

6. Electronics and data acquisition

The acquisition system is VME-based and uses a ΔE -E silicon coincidence signal as the acquisition trigger. A 40 MHz clock and CAEN reset module are used for the trigger logic. Particle-gamma and particle-fission triggers can also be employed for specialized experiments. The electronics and software were previously developed for the STARLiTeR array and were described briefly elsewhere [20]. The high-voltage for the silicon, BGO and HPGe detectors is

248 provided by various modules in an ISEG MPOD control unit.

249 The silicon detector signals are read out and the high voltage bias supplied
250 through 68 pin Yamaichi cables connected to breakout boards contained in the
251 lower chamber. From the breakout board the channels travel through vacuum
252 feed-throughs to the outside of the chamber. The 32 signals for each detector
253 enter two 16 channel preamp boards. The preamps are housed in a copper
254 shielding box with brushless fans providing cooling from below. The signals
255 then travel through 60 foot cables to CAEN N568B spectroscopy amplifiers
256 and then on to CAEN programmable discriminators. Energy signals from the
257 amplifier are transported to Mesytec ADCs while the amplifier fast outputs are
258 sent through discriminators and on to a 128 channel CAEN TDC and the ΔE -E
259 coincidence trigger logic.

260 The clover signals are preamplified in the detector and the four channels on
261 each clover are sent to Mesytec shapers via 60 foot coaxial cables. The fast
262 signal output of the shapers is sent to the CAEN TDC and trigger logic while
263 the shaped and amplified signals are sent to Mesytec ADCs. The BGO signals
264 are also read into Mesytec shapers and on the Caen TDC and Mesytec ADCs.
265 There is no trigger logic for the BGO's and their signals are recorded passively
266 with silicon- or γ -triggers as required.

267 The online acquisition is performed using MIDAS [21]. The acquisition fron-
268 tend is on the VME onboard computer and online data are transported to an
269 acquisition computer outside the experimental cave via a 1 Gigabit fiber optic
270 dedicated network. Custom OpenGL-based graphical online acquisition soft-
271 ware, previously developed for STARLiTeR, is used for observing online data.
272 In acquisition mode, raw data can be collected simultaneously on two external
273 hard disks for redundancy.

274 **7. Cryogenic fill system**

275 Individual HPGe clovers are cooled by an automated liquid nitrogen (LN)
276 fill system every 8-12 hours. Two 180 liter cryogenic storage tanks are each
277 used to fill 7 clovers on each side of the array. During the fill, two detectors

are filled at a time (one on each side) and the entire fill takes about 60 minutes to complete. When filling, LN is transported from the storage tanks to dewars attached to the individual clovers through 3-6 m long insulated naphthalene hoses at ~ 20 psi. Steel bayonets with inlet and outlet ports are attached to the back of the individual dewars to inject the LN liquid and to allow gas to exhaust.

A manifold of solenoid valves regulates the LN flow from the tanks to the detector dewars which is controlled by an Arduino Mega 2560 [22] micro controller board. The programmable control system on the Arduino monitors the readout of four-wire Resistance Temperature Detectors (RTDs) attached to the exhaust line from each clover dewar. When a clover dewar is full, LN is measured in the exhaust line. Once the RTD resistance reaches a predefined threshold level associated with LN temperature, the Arduino sends commands to close the control valve and cycle to the next detector fill. Short and long fill times result in a fill failure and the system will show an alarm flag for that detector. The fill system is monitored and controlled using custom software developed in Python installed on a dedicated fill computer that is connected to the Arduino via a USB cable. The dedicated computer can be accessed remotely for monitoring and controlling the fill system as well as allowing the system to send out fill alarms.

In order to protect the clovers in the case of an LN fill failure, bias shutdown (BSD) signals from the individual clover detectors are connected to the MPOD high voltage modules to provide a high voltage interlock. When the BSD signals transmit a ‘warm’ signal for a given detector, the high voltage is inhibited.

8. Summary

Hyperion is a new high-efficiency National Nuclear Security Administration array for charged-particle γ -ray detection in low energy nuclear physics experiments. The array is intended to be used for nuclear structure and nuclear astrophysics studies as well as for surrogate measurements of nuclear cross sections relevant to Stockpile Stewardship. The array comprises a silicon telescope placed just downstream of the target for the detection of charged particles and

up to fourteen BGO Compton-suppressed HPGe clover detectors surrounding the target position for the detection of γ rays. The array is currently housed in cave 4 at the Texas A&M University Cyclotron Institute.

9. acknowledgments

The authors are grateful for the efforts of the Texas A&M University Cyclotron Institute's operations and facilities staff. This work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract No. DE-AC52-07NA27344. Special thanks to K. L. H. Burke for her help on this project.

References

- [1] F. Käppeler, R. Gallino, S. Bisterzo, and W. Aoki, Rev. Mod. Phys. Vol 83 (2011).
- [2] J. E. Escher, J. T. Burke, F. S. Dietrich, N. D. Scielzo, I. J. Thompson, and W. Younes, Rev. Mod. Phys. Vol 84 (2012).
- [3] N. D. Scielzo *et al.*, Phys. Rev. C 81, 034608 (2010).
- [4] O. Delaune *et al.*, Eur. Phys. Jour. Web of Conf. 93, 02010 (2015).
- [5] J. N. Wilson *et al.*, Phys. Rev. C 85, 034607 (2012).
- [6] Q. Ducasse *et al.*, Phys. Rev. C 94, 024514 (2016).
- [7] A. Ratkiewicz *et al.*, AIP Conf. Proc. 1525, 487 (2013).
- [8] C. E. Svensson *et al.*, J. Phys. G: Nucl. Part. Phys. 31, S1663 (2005).
- [9] C.A. Diget *et al.*, J. Instrum. 6, P02005 (2011).
- [10] S. R. Leshner *et al.*, Nucl. Instr. Meth. Phys. Res., Sect. A 621, 286 (2010).
- [11] G. Duchene *et al.*, Nucl. Instr. Meth. Phys. Res. A 432, 90 (1999).
- [12] C.W. Beausang *et al.*, Nucl. Instr. Meth. Phys. Res. A 452, 431 (2000).

- 332 [13] 8020 website: <https://www.8020.net>
- 333 [14] S. Agostinelli *et al.*, Nucl. Instr. Meth. Phys. Res. A 506, 250 (2003).
- 334 [15] F. S. Goulding, D. A. Landis, J. Cerny, and R. H. Pehl, Nucl. Instrum.
335 Methods 31, 1 (1964).
- 336 [16] UHV design website: www.uhvdesign.com
- 337 [17] McLennan website: <http://www.mclennan.co.uk>
- 338 [18] Renishaw website: <https://www.renishaw.com>
- 339 [19] Kimpok website: <http://www.kimpok.com>
- 340 [20] R. J. Casperson *et al.*, Phys. Rev. C 90, 034601 (2014).
- 341 [21] Midas website: <https://midas.triumf.ca>
- 342 [22] Arduino website: <https://www.arduino.cc>