ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

First data with the Hybrid Array of Gamma Ray Detector (HAGRiD) ☆

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ARTICLE INFO

Article history:
Received 24 June 2017
Accepted 29 June 2017
Available online xxxx

Keywords:
$LaBr_3(Ce)$
γ-Ray detectors
Transfer reaction
β-Decay
HAGRiD
VANDLE
JENSA
ORRUBA

ABSTRACT

The structure of nuclei provides insight into astrophysical reaction rates that are difficult to measure directly. These studies are often performed with transfer reactions and β-decay measurements. These experiments benefit from particle-γ coincidence measurements which provide information beyond that of particle detection alone. The Hybrid Array of Gamma Ray Detectors (HAGRiD) of $LaBr_3(Ce)$ scintillators has been designed with this purpose in mind. The design of the array permits it to be coupled with particle detector systems, such as the Oak Ridge Rutgers University Barrel Array (ORRUBA) of silicon detectors and the Versatile Array of Neutron Detectors at Low Energy (VANDLE). It is also designed to operate with the Jet Experiments in Nuclear Structure and Astrophysics (JENSA) advanced target system. HAGRiD's design avoids compromising the charged-particle angular resolution due to compact geometries which are often used to increase the γ efficiency in other systems. First experiments with HAGRiD coupled to VANDLE as well as ORRUBA and JENSA are discussed.

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1. Introduction

While the understanding of astrophysical processes has progressed significantly in the past decade, there remains a healthy number of open questions. Nuclear physics plays a role in these processes via the nuclear reactions and decays involved. A key tool used in the understanding of nuclei is through the study of nuclear structure, which can be used to indirectly determine astrophysical reaction rates. These astrophysical reactions are required data for models that attempt to explain the origin of the elements observed in our solar system. The astrophysical processes often involve reactions of unstable nuclei, which are difficult to measure directly in the laboratory environment. When it is unpractical to measure the reactions directly, an alternate approach is to measure the properties of the nuclei, including their structure, and make estimates of the reaction rates from that information. This information may also be used to improve models of nuclear structure, which are then used to calculate additional reaction rates.

Nuclear structure studies make use of a number of experimental techniques including particle transfer reactions and β-decay measurements. Transfer reactions have a long history of being used to probe the single particle structure of nuclei [1,2]. In addition to permitting measurements of excitation energies, transfer reactions will selectively populate certain states depending on the chosen reactants and energy, which with angular distributions of the emerging particles may enable spin-parity assignments of those levels. β-Decay measurements, including β-delayed neutron emission studies, allow for measurements of half-lives and β-strengths. In addition, the subsequent de-excitation of the daughter nuclei provides structure information of those nuclei. These types of reactions are now being more frequently used at radioactive ion beam facilities in inverse kinematics to study more exotic nuclei.

1.1. Advantages of particle-γ coincidence

Measuring γ-rays in coincidence with particles provides a number of advantages. Measurements of particles often suffer from

☆ Conference on the Application of Accelerators in Research and Industry, CAARI 2016, 30 October–4 November 2016, Ft. Worth, TX, USA.

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http://dx.doi.org/10.1016/j.nimb.2017.06.028
0168-583X/Published by Elsevier B.V.

poor reconstruction of excitation energy. By measuring the coincident γ-rays, an improved resolution of the excited state energies can be obtained. This not only provides improved precision in measurements, but also permits identification of levels with small separation energies. This, for example, allows transfer reaction studies to be performed in situations where the level density is too high for particle spectroscopy alone to resolve states.

In addition, this technique allows the particle spectra to be more clearly resolved to individual states by gating on an associated γ-ray. By selecting certain particles via coincident requirement with a given γ-ray, specific level angular information can be extracted where it would be convoluted with other levels without the coincident measurement. This coincident gating works in the reverse as well, by requiring the detection of a particle, background in the γ-ray spectrum can be suppressed. Utilizing these two coincident gating techniques together provides a powerful tool in the analysis of these types of measurements.

With the addition of γ-ray detectors the observation of γ-ray cascades is now available providing increased knowledge of the nuclear structure of measured isotopes. By observing these cascades with sufficient timing, resolution lifetimes of various states can be extracted. In decay measurements the γ-decay often provides the bulk of the nuclear structure information.

2. Hybrid Array of Gamma Ray Detectors (HAGRiD)

The Hybrid Array of Gamma Ray Detectors (HAGRiD) provides a flexible configuration of γ-ray detectors. Some previous detector systems designed for measuring particle-γ coincidence, such as TREX + Miniball [3], have chosen to optimize the γ-ray detection efficiency by utilizing a compact detector system. This comes at a cost of sacrificing angular resolution of particles, ranging between 2 and 6°, due to the small radius of the particle detectors. An alternative to this type of array is one with a much larger particle detector radius, such as the Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS) [4], which improves the angular resolution to roughly 1°, but comes at the cost of requiring significantly more high-purity germanium (HPGe) detectors and associated infrastructure to maintain a reasonable γ-ray efficiency.

In addition by shifting the γ-ray detectors to a larger radius, the effect of Doppler broadening in fast beam experiments is reduced due to decreased solid angle coverage of each detector. This reduction due to solid angle is limited as the distance a detector can be moved from the reaction point and reduction of the detector dimensions are constrained due to geometric constraints and the loss of detection efficiency. The situation is similar for scintillator based materials, but as the energy resolution for any detector is dominated by the effect of Doppler broadening and solid angle coverage for fast beam experiments, the effective resolution of HPGe and scintillators are similar. Thus a scintillation material with higher efficiency than HPGe could be used with comparable effective energy resolution, allowing studies of more exotic phenomena.

To address this balance between γ-ray efficiency and particle angular resolution, HAGRiD was constructed from scintillator type detectors, instead of HPGe detectors, allowing a reduction in infrastructure, care, and maintenance. To maintain a large central radius, the γ-ray detectors must also exhibit a high efficiency, as their placement will be further from the reaction point. In addition, timing measurements benefit from a fast timing material.

For these reasons BrilLanCe 380 $LaBr_3$(5% Ce) scintillators manufactured by Saint-Gobain Crystals [5] have been selected for HAGRiD. The array is currently composed of twenty-seven $2'' \times 2''$ cylindrical crystals with the addition of ten $3'' \times 3''$ crystals to extend the array currently being manufactured. These crystals provide an energy resolution of less than 3% and an intrinsic photo-peak efficiency of ∼35% at 661.67 keV. Timing resolution measured between $2'' \times 2''$ scintillators for the subsequent γ-ray emission from a ^{60}Co source is on the order of a few hundred picoseconds.

Hamamatsu R6231-100 two inch photomultiplier tubes (PMTs) have been selected for use with the scintillators. These PMTs are a hybrid between the box-and-grid and linear-focused type PMTs, providing good collection efficiency and timing properties. The -100 series of PMTs makes use of a Super Bialkali (SBA) [6] material which benefits from improved quantum efficiency and thus provides improved energy resolution.

The array can be supplemented with additional γ-ray detectors such as NaI(Tl), CsI(Tl), and HPGe. These combinations can be made to increase total efficiency or provide improved energy resolution. HAGRiD could be extended by including another detector system such as the Apollo array of CsI(Tl) and $LaBr_3$(Ce) scintillators currently coupled with HELIOS [7]. As HAGRiD crystals are of similar dimension to Apollo units, the two detectors from these two arrays can easily be coupled together.

HAGRiD was initially constructed as an early prototype array that included a variety of Hamamatsu PMTs including: R6231-100, R7724 SEL, and R7724-100. The R7724 PMT is a linear focused type, the R7724-100 model included the SBA photocathode, while the R7724 SEL model had the normal Bialkali photocathode, but had been selected for gain ∼10 times greater than those with the SBA.

3. First measurements

While waiting for the delivery of the final PMTs, the prototype array was used for some first measurements. In these measurements HAGRiD was coupled to other detector systems to benefit from coincident measurements with other types of emitted particles. The array was used in various types of measurements including β-delayed neutron emission, transfer reactions and cross-section measurements.

3.1. β-Delayed neutron emission studies at Holifield Radioactive Ion Beam Facility

This early implementation array was used in conjunction with various other detector systems. Some of the first measurements performed with this early array involved being coupled to the Versatile Array of Neutron Detectors at Low Energy (VANDLE) [8]. The first of these measurements was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) [9,10] at Oak Ridge National Laboratory in February through April 2016. The goals of the measurement were to measure β-delayed neutron emission of neutron-rich Br, Rb, I, and Cs isotopes that are expected to have an underestimated β-strength contributing to decay heating of reactors [11]. In addition, the reactor anti-neutrino anomaly may be, in part, due to an underestimation of the β-decay strength as well as β-delayed neutron emission branching [12].

A beam of isotopes of interest was produced by the On-Line Test Facility (OLTF) [13]. The measurement made use of coincident neutron, β, and γ-ray detection. The β detection was performed with a plastic scintillator surrounding an implantation region on a tape drive. Neutron detection was performed via the time-of-flight method using the β scintillator as a start signal and stop signals from VANDLE and Lithium Glass detectors [14,15]. VANDLE was placed in the upper hemisphere around the implantation region and the lithium glass detectors were placed at backward angles. Finally, HAGRiD was used as part of a collection of γ-ray detectors, shown in Fig. 1 which included sixteen $2'' \times 2''$ HAGRiD detectors

Fig. 1. Picture of a portion of the γ-ray detection used with VANDLE at the OLTF. The beamline placed within the square brackets has been removed; beam enters from left to right. The large rectangular detectors are NaI(Tl), the central square shaped detector with circular stickers is the HPGe from CLARION, and the cylindrical detectors are HAGRiD. Some detectors on beam right (bottom side of image) have been removed. VANDLE is not visible as it is placed above the γ-detection array. The beam traversea the setup from left to right and the implantation point was directly above the HPGe.

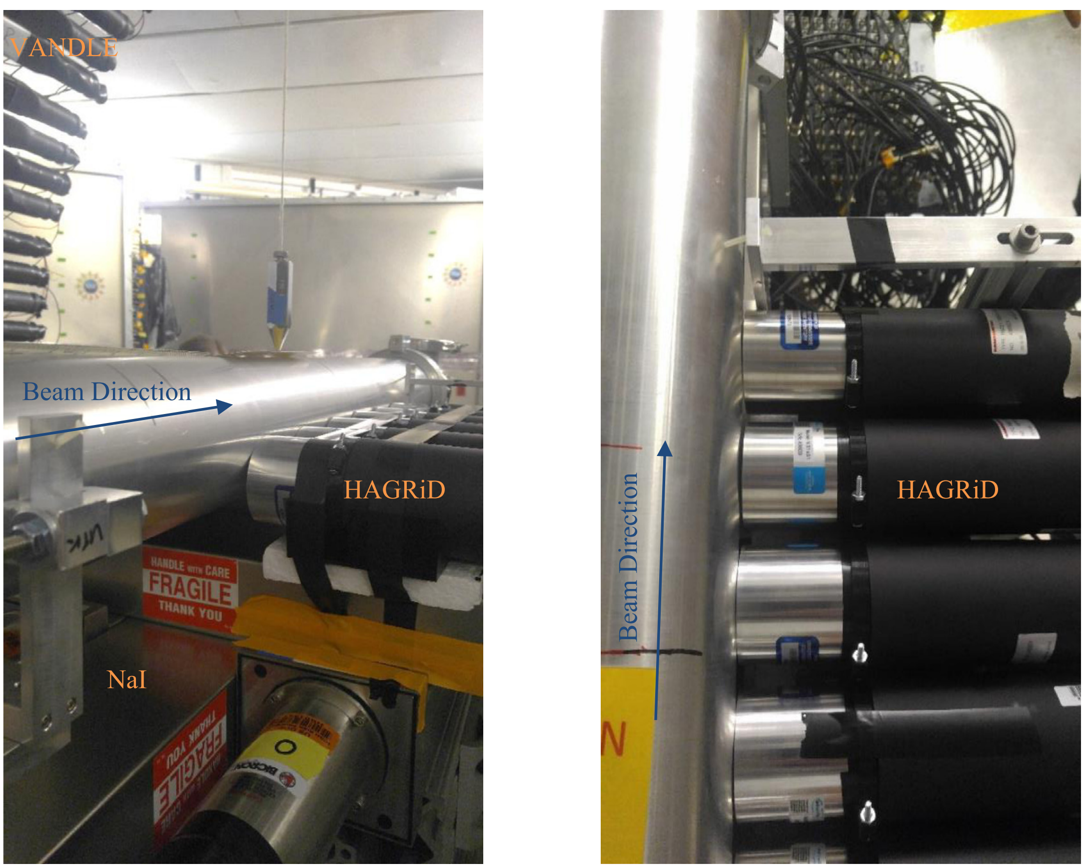

Fig. 2. Setup of β-delayed neutron emission of neutron-rich cobalt isotopes study at the NSCL. (a) Beam line (beam entering from left to right) surrounded with VANDLE (top left), NaI(Tl) detectors (below) and HAGRiD (right). The implantation detector is not visible within the beam line. (b) A close up of the HAGRiD array surrounding the beam line.

(assembled with R7724 SEL PMTs), 10 NaI(Tl) scintillators, and a single HPGe clover detector from the Clover Array for Radioactive ION beam (CLARION) [16]. These γ-ray detectors were placed in the lower hemisphere of the setup.

3.2. β-Delayed neutron emission study of neutron-rich cobalt

HAGRiD was again implemented with VANDLE at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State

University in October 2016. This measurement sought to understand the β-delayed neutron emission of neutron-rich cobalt. The β-decay *Q*-value of cobalt isotopes in this region exceeds 10 MeV while neutron separation energies S_n are between 3 and 5 MeV. These energy differences suggest that these nuclei would have a large probability of neutron emission (P_n value), while observations have indicated that the P_n values have been found to be <7% [17]. Recent studies in this region [18,19] have indicated that the β-decay strength is enhanced compared to current theoretical models [20].

This measurement attempts to perform the first neutron spectroscopy of the β-decay of the neutron-rich cobalt isotopes as well as measuring emitted γ-rays. The setup used is similar to that of the measurements at HRIBF discussed above. VANDLE occupied the upper hemisphere surrounding an implantation detector while an array of NaI, HPGe and HAGRiD γ-ray detectors were placed in the lower hemisphere. The setup is show in Fig. 2.

3.3. Jet experiments in nuclear structure and astrophysics with HAGRiD

HAGRiD was used in conjunction with the Oak Ridge Rutgers University Barrel Array (ORRUBA) [21] of silicon charged particle detectors, specifically SuperORRUBA detectors [22] and Silicon Detector Array (SIDAR) [23], were placed around the Jet Experiments in Nuclear Structure and Astrophysics (JENSA) [24] at the ReA3 facility [25] of the NSCL in February and May of 2016. The measurement was designed to improve understanding of the astrophysical reaction $^{34}Ar(\alpha,p)^{37}K$ which plays a role in the αp-process expected to occur during an X-ray burst on the surface of an accreting neutron star [26,27].

These studies included a commissioning run of JENSA in addition to the first direct measurement of the $^{34}Ar(\alpha,p)^{37}K$ reaction. A beam of ^{14}N or radioactive ^{34}Ar was provided by ReA3 for the commissioning and radioactive runs, respectively. The beam was delivered to JENSA impinging upon a pure gas jet of helium with

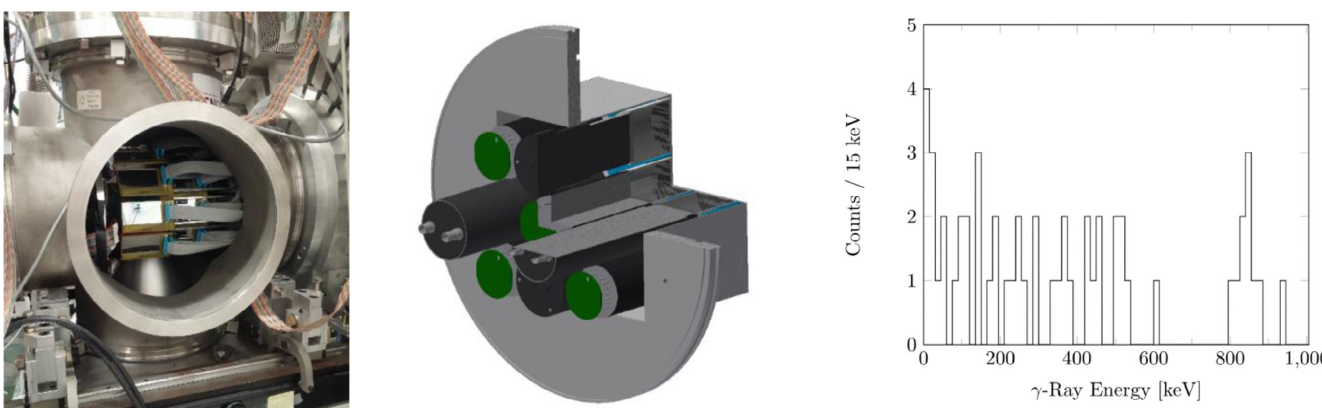

Fig. 3. (a) The JENSA scattering chamber with the HAGRiD flange removed, SuperORRUBA is visible inside the chamber. (b) Three-quarter section drawing of the HAGRiD arrangement within the recessed flange. The central detector is placed facing the reaction region at 90° from the beam axis. (c) Preliminary online γ-ray spectrum gated on coincident protons from $^{14}N(\alpha, p_1)$, the 871 keV line from the de-excitation of ^{17}O is visible. (Calibration is approximate.)

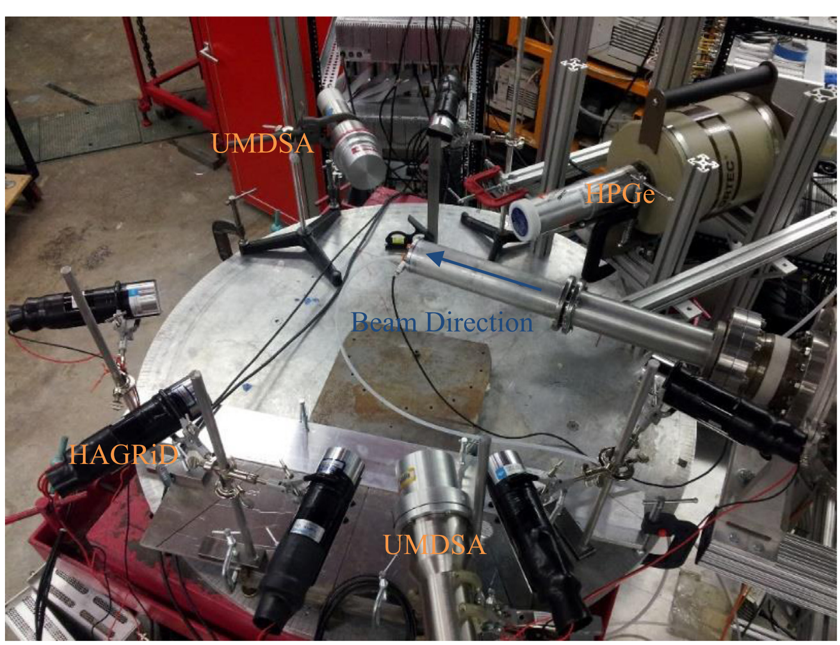

Fig. 4. Picture of setup used for measurement of $^{13}C(\alpha, n)^{16}O$. Visible is the implantation target (long cylinder coming from right side of the page) surrounded by one HPGe, two deuterated liquid scintillators from UM-DSA, and six $LaBr_3(Ce)$ from HAGRiD.

Please cite this article in press as: K. Smith et al., First data with the Hybrid Array of Gamma Ray Detector (HAGRiD), Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.06.028

a density of about 10^{19} atoms/cm^2. Reaction protons, as well as scattered α particles, were detected in the SuperORRUBA barrel surrounding the jet. Nine 2″ × 2″ HAGRiD detectors (assembled with R6231-100, R7724-100, and R7724 SEL PMTs) were placed in a recessed flange (see Fig. 3(a and b)) on the beam-left side of JENSA around 90° in the lab and detected γ-rays in coincidence with the charged particles.

Total photo-peak efficiency of the array in this configuration was found to be ~1% for a ^{60}Co source at 1332 keV. A preliminary online γ-ray spectrum in coincidence with protons from the ^{14}N(α, p_1)^{17}O reaction, collected during the commissioning run, as seen in Fig. 3(b), shows the expected 871 keV line from the de-excitation of ^{17}O. More details available in K. Schmidt et al. 2016 [28] and K.A. Chipps et al. 2017 [29].

3.4. Measurement of the ^{13}C(α,n)^{16}O reaction cross-section

The HAGRiD was also used at the Nuclear Structure Laboratory at the University of Notre Dame in May of 2016 in a measurement seeking to better understand the ^{13}C(α,n)^{16}O reaction. This reaction is often a source of background in many other measurements [30–32]. A beam of He was produced by the Stable ion Accelerator for Nuclear Astrophysics (Santa ANA), a National Electrostatics Corporation 5U Van da Graff accelerator capable of producing 5 MV potential and delivering beams exceeding 100 μA [33]. The beam was transported to the stopped-beam beamline and then impinged on a target of ^{13}C, enriched to 98%.

Emitted neutrons were measured with deuterated liquid scintillators from the University of Michigan Deuterated Scintillator Array (UM-DSA) [34]. γ-Rays emitted from the de-excitation of ^{16}O were measured by six 2″ × 2″ HAGRiD detectors (assembled with R7724 SEL PMTs) placed at various angles around the reaction target. In addition, a HPGe detector was placed at a fixed angle to provide a reference. This setup provides a method of measuring the differential cross-sections as a function of energy for this reaction. Fig. 4 shows a picture of the setup. The detector systems successfully measured the expected emissions, a further analysis of the measurement is ongoing.

4. Conclusion

The HAGRiD array has been used for the first time to collect data in a variety of measurements. It was successfully employed during a β-delayed neutron emission experiment, a transfer reaction measurement as well as direct measurements. This early array helped accomplish the scientific goals of these measurements even prior to the construction of detectors with the final selection of PMTs.

The final construction and characterization of the HAGRiD 2″ × 2″ detectors is ongoing. The 3″ × 3″ crystals as well as the selected PMTs for these crystals have been ordered and we are awaiting their delivery. Multiple measurements involving the array are being proposed and planned.

Acknowledgements

This work is supported in part by the U.S. Department of Energy, Office of Science Nuclear Physics Program under Contracts No. DE-FG02-96ER40983 (UTK) and DE-AC05-00OR22725, and the National Science Foundation, grant PHY-1067906 and sponsored in part by the National Nuclear Security Administration under the Stewardship Science Academic Alliance program through DOE Cooperative Agreement No. DE-NA0002132. The authors would like to thank the VANDLE and JENSA collaborations.

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